

25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-0424

INDUSTRIAL SCALE CIRCULATING FLUIDIZED-BED GASIFICATION OF REFUSE-DERIVED FUEL

Vitor Alberto Lemes Monteiro
Washington Martins da Silva Júnior
Cassius Ricardo Nascimento Ferreira
Valério Luiz Borges

Solidônio Rodrigues de Carvalho

Universidade Federal de Uberlândia, Faculdade de Engenharia Mecânica, Avenida João Naves de Ávila, 2121, 38408-100, Uberlândia-MG, Brazil

vitoralbertolemes@hotmail.com

washington.martins@ufu.br

cassiusferreira@hotmail.com

valerioluizborges@ufu.br

solidonio@ufu.br

Luciano Reis Infiesta

Carbogás Energia, Avenida Guaraciaba, 659, 09370-840, Mauá-SP, Brazil

luciano@carbogas.com.br

Alam Gustavo Trovó

Universidade Federal de Uberlândia, Instituto de Química, Avenida João Naves de Ávila, 2121, 38400-902, Uberlândia-MG, Brazil

alamtrovo@ufu.br

Abstract. *The management of municipal solid waste is a growing problem that waste-to-energy technologies attempt to solve. However, there is a lack of studies approaching large-scales projects as the situation requires. Thereby, this work presents a commercial scale gasification power plant for refuse-derived fuel processing and energy generation. The circulating fluidized-bed gasification system was designed to produce 72 ton day⁻¹ of syngas, with lower heating value of 4.6 MJ kg⁻¹, from 30 ton day⁻¹ of refuse-derived fuel. A steam power cycle consumes the gas to generate 1.5 MWh of electrical energy. Characterization of the syngas produced demonstrate good thermal properties and its use for generation of electrical energy indicates low levels of pollutants emissions, such as NO_x, SO_x and dioxins and furans, which demonstrate the feasibility of the proposed technology as a renewable energy source.*

Keywords: *municipal solid waste, syngas, renewable energy, large-scale, waste-to-energy*

1. INTRODUCTION

Many technologies aim to solve or reduce the human being impacts to the environmental. Waste management has become a problem due to growing generation of municipal solid waste (MSW), approximately 440 kg person⁻¹ annually (Bhoi *et al.*, 2018). On the basis of the sustainable development, the gasification enables energy recovery, since it converts the biomass in a synthesis gas, named syngas, by heating under controlled conditions. However, the lack of financial investments (Motta *et al.*, 2018) and governmental feasibility for the commercialization of electric power (Sikarwar *et al.*, 2017) limit advances related to industrial scale gasification process.

Although there are some studies involving plasma gasification in large scale, nothing was reported in literature involving the fluidized-bed reactors at commercial scale.

The fluidized-bed reactors have various advantages related to waste gasification, since its configuration generates small amounts of tar when compared to fixed-bed reactors (Basu, 2010). It is operationally flexible, which can work with different gasification agents (air, oxygen, steam), temperatures, residence times or, eventually, the use of catalyst (Arena *et al.*, 2010). Pre-treatment is required in this configuration to obtain small biomass particles to contribute to the fluidization and maximize the contact with the reacting agents (Widjaya *et al.*, 2018). That gasifier's types are the most promising configuration due to its good mixture of the reacting materials, uniformly distributed temperature that enable the waste gasifying (Materazzi *et al.*, 2016).

Therefore, this work presents the design of a commercial scale circulating fluidized-bed gasification system with capacity to process 30 ton day⁻¹ of refused-derived fuel (MRDF) obtained from MSW and the production of 72 ton day⁻¹ syngas, by gasification process.

1.1 Brazilian Waste Gasification State of Art

Some information of waste gasification technology companies was compiled by Arena (2012), but none of those involves industrial waste gasification for power generation. The Brazilian perspective on this subject is still at lab-scale. Table 1 shows recent Brazilian studies involving waste gasification technologies, also the lower heating value (LHV) of the biomass and the syngas. Due to lack of information, LHV values could not be pulled in the same unit system.

Table 1. Brazilian waste gasification studies

Reference	Gasifier Type	Biomass	Biomass LHV (MJ kg ⁻¹)	Gas LHV
Oliveira et al. (2018)	Downdraft fixed-bed	Coffee wood	18,56	7,76 ± 1.27 MJ Nm ⁻³
Oliveira et al. (2018)	Downdraft fixed-bed	Eucalyptus chips	17,3	6,81 ± 0,34 MJ kg ⁻¹
Oliveira et al. (2018)	Downdraft fixed-bed	Coffee husk	18,07	5,45 ± 0,42 MJ kg ⁻¹
Lopes (2018)	Moving grate bed	MSW	7,95	3,327 MJ kg ⁻¹
Casademont et al. (2018)	-	Olive oil mill waste	-	-
Pacioni et al. (2016)	-	Agro-industrial biomass residues	13,83 - 28,49	-
Corrêa Jr. et al. (2019)	Bubbling fluidized-bed	Rice hulls	13,29	2,87 MJ m ⁻³
Galindo et al. (2018)	Downdraft fixed-bed	Eucalyptus wood	18,06	4,47 ± 0,5 MJ Nm ⁻³
Sales et al. (2017)	Downdraft fixed-bed	Eucalyptus wood	18,39	4,20 - 5,02 MJ Nm ⁻³
Martínez et al (2011)	Downdraft fixed-bed	Eucalyptus wood	18,14	4,5 MJ Nm ⁻³

2. MATERIALS AND METHODS

2.1 Gasification Power Plant

The proposed industrial scale Gasification Power Plant (GPP) basically involves three units: the Solid Waste Processing Line (SWPL), the Gasification Plant (GP) and the Steam Power Plant (SPP), showed in Fig. 1. The first one is where MSW is converted in 30 ton day⁻¹ of MRDF, a suitable fuel for the gasification technology proposed. At this process, the MSW is selected, removing stones and metals, crushed and dried (Fig. 2), to reduce its moisture from approximately 50 wt% to 15 wt% during those steps. The MRDF has essentially carbon rich products from waste and can be stored at the MRDF Stock Warehouse (Infiesta et al., 2019) or addressed to the GP, according to demand of power generation process.

The main equipment of the gasification system consists of the circulating fluidized-bed gasifier, which is continuously feed by MRDF – with average moisture content of 17 ± 8 wt% and average LHV of 14.6 ± 1.3 MJ kg⁻¹, processed by the SWPL (Infiesta *et al.*, 2019) – and bed material composed by silica and limestone.

The air is utilized as gasification agent, pre-heated and insufflated at 400 °C by the bottom of the reactor at 2,076 kg h⁻¹ mass flow rate. It operates at pressure slightly above atmospheric 14.7 kPa and temperature 850 °C to produce about 3.8 MWh of thermal power, with dry ash formation, discarded at a rate of 325 kg h⁻¹. The reactor has an external diameter of 3.1 m and height of 22 m, being built in structural carbon steel and thermal insulation of refractory brick in the inner part. It has the capacity to consume 1,252 kg h⁻¹ of MRDF and produce 2,988 kg h⁻¹ of syngas.

All preliminary studies, including the syngas analysis, were performed at the reduced scale reactor from a pilot plant unit (Fig. 3), which is situated at the Carbogás Energia Ltda installations from Mauá (23° 40' 00" S, 46° 27' 44" W), Brazil.



Figure 1. Layout of the industrial scale gasification power plant.

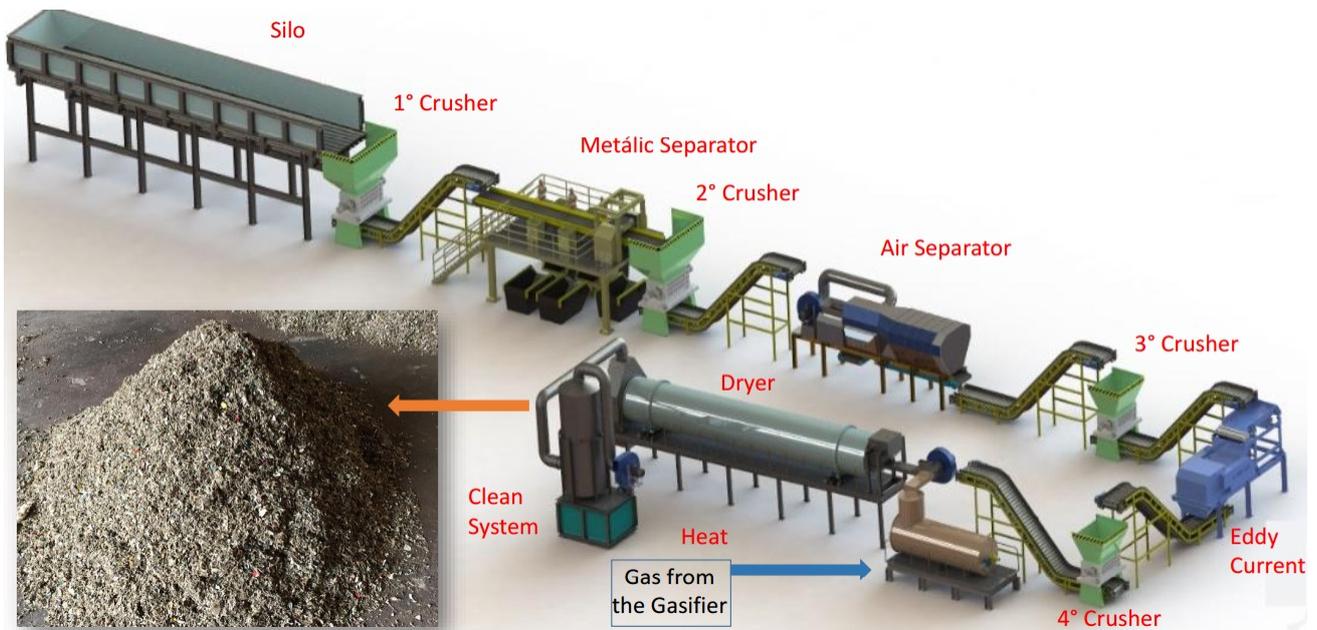


Figure 2. Solid Waste Processing Line (Adapted from Infiesta et al., 2019).

Limestone was added at a rate of 5.15 kg h^{-1} to minimize the formation of sulfur oxide (SO_x) during following syngas combustion at the boiler (Sulaiman *et al.*, 2018). The Fig. 4 shows the aspect of the extracted ash from the bottom of the reactor during the process. After gasification, the syngas is addressed to a humid gas cleaning system, where solid particles are removed, gas temperature is decreased and chlorine concentrations are minimized with second addition of calcium oxide. After cleaning system, 20.15 kg h^{-1} of unconverted biomass and limestone is discarded. All by-products produced, such as ashes and cleaning residues can be reused at construction, as raw material for cement manufacture (Basu, 2010).

Finally, the syngas can be addressed to its use as gas fuel. A small quantity of this produced gas, about 183 kg h^{-1} is burned in a furnace to generate heat at the drying stage at the SWPL and the other, 2805 kg h^{-1} , to the SPP where it is burned in a boiler to produce around 5000 kg h^{-1} of steam. For the estimation of the electrical power generation of the GPP, the regenerative Rankine Cycle (Fig. 5) was proposed for thermodynamics calculations.

The mass and energy balance of this process was conducted based on the available syngas mass flow (\dot{m}_{syngas}) produced by the gasifier. Once the LHV of the gas (LHV_{syngas}) was calculated by the stoichiometric combustion, the energy balance applied at the boiler is:

$$\dot{m}_{\text{syngas}} LHV_{\text{syngas}} = \dot{m}_v h_2 - \dot{m}_v h_1 \quad (1)$$



Figure 3. Pilot plant gasifier.



Figure 4. Ash bottom extraction.

According to the steam turbine manufacturer, the selected equipment was an extraction turbine, which uses part of the produced steam to heat the water at the deaerator, to increase the steam power cycle efficiency. Therefore, some of the steam mass flow (\dot{m}_{ext}) is extracted to that finality and the majority (\dot{m}_{exa}) is exhausted to a condenser. The power of the steam turbine (\dot{W}_t) was estimated by:

$$\dot{W}_t = \dot{m}_v h_2 - \dot{m}_{ext} h_4 - \dot{m}_{exa} h_3 \quad (2)$$

Finally, the electrical power of the generator (\dot{W}_{ge}) can be calculated:

$$\dot{W}_{ge} = \dot{W}_t \cdot \eta_{ge} \quad (3)$$

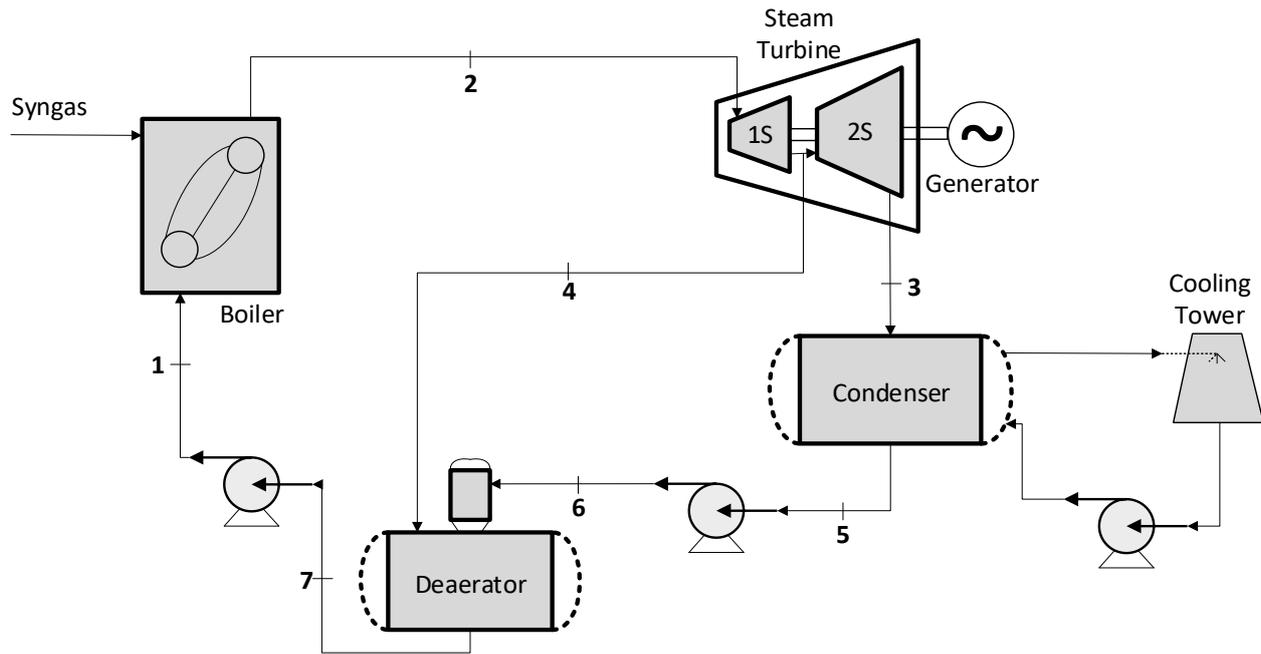


Figure 5. Simplified Regenerative Rankine Cycle from the SPP.

The thermodynamic properties, like enthalpy (h), was determined under the boiler and turbine-generator set information, such as temperatures and pressures of the interested numbered points (Tab. 2). The electrical generator efficiency (η_{ge}) informed by the manufacturer is 83%.

Table 2. Technical information for the selected boiler

Description	Variable	Value	Units
Water/Steam Pressure	P_1	42	bar
Water/Steam Temperature	T_1	105	°C
Fuel LHV	LHV_{syngas}	4.6	MJ kg ⁻³
Steam Temperature	T_2	420	°C

Source: Steam Master (2016)

All the mass flow rate, capacity, sizing and equipment selection was carried by the stoichiometric calculations to design the gasification plant with SSP with the capacity to generate up to 1.5 MWh of electricity. Besides that, all the GPP is self-sufficient in terms of energy, which about 15% of the generated electrical energy is sufficient to carry out the demand from SWPL, GP and SPP. Figure 6 shows the current state of the construction of the industrial scale gasification power plant at the city of Boa Esperança (21° 05' 24" S, 45° 33' 57" W), Brazil.



Figure 6 – Under construction Gasification Power Plant.

The GPP was arranged near the dump of the city (Fig. 7) to keep the 24-hour operations of the plant. Such configuration allows the processing of dumped waste and residential collected waste.



Figure 7 – GPP configuration near the dump of Boa Esperança city.

2.2 Chemical analysis

The characterization of the syngas was determined by a gas chromatography equipped with a thermal conductivity detector, which was carried out by the company White Martins. The chemical analysis of the flue gases produced from syngas combustion were performed by SGS Air Services company – an accredited Brazilian laboratory – according to the methodologies cited in the Tab. 3:

Table 3. Description of the chemical analysis of the flue gases and corresponding methodology

Parameter	Expressed as	Methodology	Reference
Particulate matter	-	CETESB Method L9.225	CETESB, 1995a
Sulphur oxides	SO ₂	CETESB Method L9.228	CETESB, 1992a
Nitrogen oxides	NO ₂	CETESB Method L9.229	CETESB, 1992b
Hydrochloric acid and chlorine	HCl	EPA Method 0050	U.S. EPA, 1996
Metals	-	EPA Method 29	U.S. EPA, 2014a
Dioxins and Furans	-	EPA Method 23	U.S. EPA, 1995
Carbon monoxide	-	EPA Method CTM 030	U.S. EPA, 1997
Fluorides	Hydrofluoric acid	CETESB Method L9.213	CETESB, 1995b
Total hydrocarbons	Methane and Non-methane	EPA Method 25A	U.S. EPA, 2014b

3. RESULTS AND DISCUSSION

3.1 Syngas analysis

The large-scale thermochemical reactor was design based on some parameters obtained from a pilot gasification plant (Fig. 3). Table 4 shows the volumetric composition (% v/v) of the syngas obtained. This analysis is important for the calculations of the syngas LHV and adiabatic flame temperature, that conducts the power cycle sizing and power generation, as shown in Section 2.

Those results show the profile of the syngas. The most important compounds produced was CO, H₂ and CH₄, that affects directly the LHV of the syngas. Other hydrocarbons contribution was obtained in lower quantities. As expected, N₂ corresponds to the majority of the syngas, due to the use of air as gasification agent.

That composition of the syngas obtained (Tab. 4) is similar to a bubbling fluidized-bed gasification of palm empty fruit bunch performed on a pilot plant by Lahijani and Zainal (2011). However, the conditions of the gasification process are strongly dependent of the composition of the biomass, gasifier type and parameters, such as pressure and temperature, affecting the LHV of the syngas (Couto *et al.*, 2013). The obtained LHV of the syngas produced was 4.6 MJ kg⁻¹ and there was no evidence of tar and heavy hydrocarbons, which makes the syngas suitable for energy generation directly by motors and turbines (Asadullah, 2014).

When compared to some gasification experimentations of other biomass with higher LHV, such as wood pellets (Plis and Wilk, 2011), the gasification technology of the present work produces a syngas with better calorific properties.

Table 4. Volumetric composition (% v/v) of the syngas produced from the gasification of the MRDF.

Parameter	Obtained Values
Hydrogen (H ₂)	5.6 ± 0.8
Oxygen (O ₂)	1.8 ± 0.6
Nitrogen (N ₂)	60.0 ± 1.1
Carbon monoxide (CO)	9.5 ± 0.8
Carbon dioxide (CO ₂)	12.4 ± 0.8
Methane (CH ₄)	5.0 ± 0.5
Ethane (C ₂ H ₆)	0.2 ± 0.06
Ethylene (C ₂ H ₄)	2.2 ± 0.2
Propane (C ₃ H ₈)	0.8 ± 0.07
<i>iso</i> -Butane (C ₄ H ₁₀)	< 0.01 ± 0.00
<i>n</i> -Butane (C ₄ H ₁₀)	0.08 ± 0.007
<i>iso</i> -Pentane (C ₅ H ₁₂)	< 0.01 ± 0.00
<i>n</i> -Pentane (C ₅ H ₁₂)	< 0.01 ± 0.00
<i>n</i> -Hexane (C ₆ H ₁₄)	< 0.01 ± 0.00

3.2 Pollutants Emissions

The technology viability in terms of the environmental emissions was evaluated through the chemical analysis of the flue gas obtained from the syngas burning, meeting the requirements of Brazilian legislation (CONAMA 316/2002; SMA 79/2009). That analysis Tab. 5 shows the characterization obtained by three samples realized.

All analyzed parameters were lower than the reference values (Tab. 5). In special, the concentration of dioxins and furans was 0.0086 ng Nm⁻³, which corresponds to less than 10% of the established in SMA resolution (0.10 ng Nm⁻³).

Table 5. Flue gases results obtained from chemical analysis, corrected to 11% of O₂ with Resolution SMA n^o 79

Parameter (mg Nm ⁻³)	Average	Standard Deviation	Reference Values (mg Nm ⁻³)*	
Particulate matter	17.6	2.4	30	
Sulfur oxides	74.5	6.1	200	
Nitrogen oxides	98.1	2.8	400	
Hydrochloric Acid	7.0	1.3	60	
Hydrofluoric Acid	3.3	0.2	4	
Total Hydrocarbons	2.0	0.2	20	
Metals Emissions	Cd + Tl	0.003	0.000	0.05
	Hg	2.0 × 10 ⁻³	0.9 × 10 ⁻³	0.05
	Pb + As + Co + Ni + Cr + Mn + Sb + Cu + V	2.2 × 10 ⁻¹	0.8 × 10 ⁻¹	0.5
Dioxins and Furans	8.6 × 10 ⁻⁹	0.3 × 10 ⁻⁹	1.0 × 10 ⁻⁷	
Carbon Monoxide	8.1	3.0	100	

* Source: Acceptable limit values corrected to 11% of O₂, according to SMA Resolution No. 79 (SMA, 79/2009)

The reference values of the São Paulo Environmental Secretary (SMA, 79/2009) (0.1 ng Nm⁻³) was adopted since it has lower admitted limit values for all substances analyzed than Brazilian National Council for the Environment (CONAMA) (0.5 ng Nm⁻³) and others regulations, such as in Japan (0.1 to 0.5 ng Nm⁻³) and USA (0.1 to 0.3 ng Nm⁻³). Once all parameters analyzed were below legislation limits, there is no need for any cleaning system to the gasification power process described.

4. CONCLUSIONS

This study demonstrates a large-scale circulating fluidized-bed gasification process of MRDF to produce syngas for power generation.

The syngas produced at the pilot gasification plant has lower heating value and quality suitable for the purpose which it is intended. The studies demonstrate more feasibility of the Rankine cycle for the present project due to manufactures availability and flexible and robust functionality.

On this occasion, the flue gases from the burned syngas in a boiler does not require advanced cleaning systems. Generated pollutants substances are under the environmental legislation limits.

Such results supported the construction of the industrial scale gasification power plant, which is designed to process 1,252 kg h⁻¹ of MRDF, producing approximately 2,988 kg h⁻¹ of syngas. This plant is under final stage of construction in the city of Boa Esperança, Minas Gerais, Brazil.

Furthermore, the technology seems to be an WTE alternative both for the reduction of waste environmental impact and as a renewable energy producing.

5. ACKNOWLEDGEMENTS

The authors thank the Brazilian companies Furnas Centrais Elétricas S.A. and Carbogás Energia Ltda., as well as the government agencies ANEEL, CAPES, CNPq and FAPEMIG for their financial support. Alam G. Trovó is grateful to FAPEMIG (PPM-00509-18) and CNPq (Project 405043 / 2018-0 and the Research Fellowship 305215 / 2018-3).

6. REFERENCES

- Arena, U., 2012. "Process and technological aspects of municipal solid waste gasification. A review". *Waste Management*. Vol. 32, pp. 625-639.
- Arena, U., Zaccariello, L., Mastellone, M. L., 2010. "Fluidized bed gasification of waste-derived fuels". *Waste Management*, Vol. 30, pp. 1212-1219.
- Asadullah, M., 2014. "Barriers of commercial power generation using biomass gasification gas: A review". *Renewable and Sustainable Energy Reviews*. Vol. 29, pp. 201-215.
- Basu, P., 2010. *Biomass Gasification and Pyrolysis. Practical Design and Theory*. Elsevier.
- Bhoi, P.R., Huhnke, R.L., Kumar, A., Indrawan, N., Thapa, S., 2018. "Co-gasification of municipal solid waste and biomass in a commercial scale downdraft gasifier". *Energy*. Vol. 163, pp. 513-518.
- Casademont, P., Cardozo-Filho, L., Meurer, E., Sánchez-Oneto, J., Portela, J. R., 2018. "Gasification of olive oil mill waste by supercritical water in a continuous reactor". *The Journal of Supercritical Fluids*. Vol. 142, pp. 10-21.
- CETESB, 1992a. "Determinação de dióxido de enxofre, névoas de sulfúrico e trióxido de enxofre em dutos e chaminés de fontes estacionárias". Companhia Ambiental do Estado de São Paulo. 11 Mar, 2019. <<https://www.esaat.com.br/metodologia>>.
- CETESB, 1992b. "Determinação de óxidos de nitrogênio em efluentes gasosos de dutos e/ou chaminés de fontes estacionárias". Companhia Ambiental do Estado de São Paulo. 11 Mar. 2019. <<https://www.esaat.com.br/metodologia>>.
- CETESB, 1995a. "Determinação de material particulado em dutos e chaminés de fontes estacionárias". Companhia Ambiental do Estado de São Paulo. 11 Mar. 2019. <<https://www.esaat.com.br/metodologia>>.
- CETESB, 1995b. "Determinação de fluoreto total pelo método do eletrodo de íon específico". Companhia Ambiental do Estado de São Paulo. 11 Mar. 2019. <<https://www.esaat.com.br/metodologia>>.
- CONAMA, 2002. "RESOLUÇÃO CONAMA nº 316, de 29 de outubro de 2002". Companhia Ambiental do Estado de São Paulo. 11 mar. 2019. <<http://www.mma.gov.br/port/conama/legiabre.cfm?codlegi=338>>.
- Corrêa Jr., P. S. P., Zhang J., Lora E. E. S., Andrade, R. V., Pinto, L. R. M., Ratner, A., 2019. "Experimental study on applying biomass-derived syngas in a microturbine". *Applied Thermal Engineering*. Vol. 146, pp. 328-337.
- Couto, N., Rouboa, A., Silva, V., Monteiro, E., Bouziane, K., 2013. "Influence of the biomass gasification processes on the final composition of syngas". *Energy Procedia*. Vol. 36, pp. 596-606.
- Galindo, A. L., Lora, E. E., Andrade, R. V., Giraldo, S. Y., Jaén, R. L., Cobas, V. M., 2014. "Biomass gasification in a downdraft gasifier with a two-stage air supply: Effect of operating conditions on gas quality". *Biomass & Bioenergy*. Vol. 61, pp. 236-244.
- Infiesta, L.R., Ferreira, C.R.N., Trovó, A.G., Borges, V.L., Carvalho S.R., 2019. "Design of an industrial solid waste processing line to produce refuse-derived fuel". *Journal of Environmental Management*. Vol. 236, pp. 715-719.
- Lahijani, P., Zainal, Z.A., 2011. "Gasification of palm empty fruit bunch in a bubbling fluidized bed: A performance and agglomeration study". *Bioresource Technology*. Vol. 102, pp. 2068-2076.
- Lopes, E. J., Okamura, L. A., Maruyama, S. A., Yamamoto, C. I., 2018. "Evaluation of energy gain from the segregation of organic materials from municipal solid waste in gasification processes". *Renewable Energy*. Vol. 116, pp. 623-629.

- Martínez, J. D., Lora, E. E. S., Andrade, R. V., Jaén, R. L., 2011. "Experimental study on biomass gasification in a double air stage downdraft reactor". *Biomass & Energy*. Vol. 35, pp. 3465-3480.
- Materazzi M, Lettieri P, Taylor R, Chapman C., 2016. "Performance analysis of RDF gasification in a two stage fluidized bed-plasma process". *Waste Management*. Vol. 47, pp. 256-266.
- Motta, I.L., Miranda, N.T., Filho, R.M., Maciel, M.R.W., 2018. "Biomass gasification in fluidized beds: A review of biomass moisture content and operating pressure effects". *Renewable and Sustainable Energy Reviews*. Vol. 94, pp. 998-1023.
- Oliveira, J. L., Silva, J. N., Martins, M. A., Pereira, E. G., Oliveira, M. C. T. B., 2018. "Gasification of waste from coffee and eucalyptus production as na alternative source of bioenergy in Brazil". *Sustainable Energy Technologies and Assessments*. Vol. 27, pp. 159-166.
- Pacioni, T. R., Soares, D., Domenico, M. D., Rosa, M. F., Moreira, R. F. P. M., José, H. J., 2016. "Bio-syngas production from agro-industrial biomass residues by steam gasification". *Waste Management*. Vol. 58; pp. 221-229.
- Plis, P., Wilk, R.K., 2011. "Theoretical and experimental investigation of biomass gasification process in a fixed bed gasifier". *Energy*. Vol. 36, pp. 3838-3845.
- Sales, C. A. V. B., Maya, D. M. Y., Lora, E. E. S., Jaén, R. L., Reyes, A. M. M., González, A. M., Andrade, R. V., Martínez, J. D., 2017. "Experimental study on biomass (eucalyptus spp.) gasification in a two-stage downdraft reactor by using mixtures of air, saturated steam and oxygen as gasifying agents". *Energy Conversion and Management*. Vol. 145, pp. 314-323.
- Sikarwar, V.S., Zhao, M., Fennel, P.S., Shah, N., Anthony, E.J., 2017. "Progress in biofuel production from gasification". *Progress in Energy and Combustion Science*. Vol. 61, pp. 189-248.
- SMA, 2009. "RESOLUÇÃO SMA n° 79, de 04 de Novembro de 2009". Secretaria de Infraestrutura e Meio Ambiente do Estado de São Paulo. 11 Mar. 2019. <http://arquivo.ambiente.sp.gov.br/resolucao/2009/2009_res_est_sma_79_republicada.pdf>.
- Steam Master, 2016. "Relatório de Informações Técnicas de caldeira aquatubular - Caldeira JPO 05/16". Technical Proposal to Carbogas Energia Ltda company.
- Sulaiman, S.A., Roslan, R., Inayat, M., Naz, M.Y., 2018. "Effect of blending ratio and catalyst loading on co-gasification of wood chips and coconut waste". *Journal of the Energy Institute*. Vol. 91, pp. 779-785.
- U.S. EPA, 1995. "Determination of Polychlorinated Dibenzo-p-Dioxins and Polychlorinated Dibenzofurans from Stationary Sources". United States Environmental Protection Agency. 11 Mar. 2019. <<https://www.epa.gov/emc/method-23-dioxins-and-furans>>.
- U.S. EPA, 1996. "Determination of Hydrogen Chloride (HCl) and Chlorine (Cl₂) Emissions In Stack Gas Emission Samples from Hazardous Waste Incinerators". United States Environmental Protection Agency. 11 Mar. 2019. <<https://www.epa.gov/hw-sw846/sw-846-test-method-0050-isokinetic-hydrogen-chloride-and-chlorine-emission-sampling-train>>.
- U.S. EPA, 1997. "Determination of Nitrogen Oxides, Carbon Monoxide, and Oxygen Emissions from Natural Gas-Fired Engines, Boilers and Process Heaters Using Portable Analyzers". United States Environmental Protection Agency. 11 Mar. 2019. <<https://www.epa.gov/emc/emc-conditional-test-methods>>.
- U.S. EPA, 2014a. "Metals Emissions from Stacionary Sources". United States Environmental Protection Agency. 11 Mar. 2019. <<https://www.epa.gov/emc/method-29-metals-emissions-stationary-sources>>.
- U.S. EPA, 2014b. "Determination of Total Gaseous Organic Concentration using a Flame Ionization Analyzer". United States Environmental Protection Agency. 11 Mar. 2019. <<https://www.epa.gov/emc/method-25a-gaseous-organic-concentration-flame-ionization>>.
- Widjaya, E. R., Chen, G., Bowtell, L., Hills, C. 2018. "Gasification of non-woody biomass: A literature review". *Renewable and Sustainable Energy Reviews*. Vol. 89, pp. 184-193.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.