

EMISSION CHARACTERIZATION FOR A DOWNDRAFT GASIFIER

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Abstract. Gasification is the thermal-chemical conversion of biomass into combustible gas, which can be used as combustion fuel in internal combustion motors or syngas with applications across the chemical industry. To check the performance of a gasifier one needs to quantify the contained energy in the produced gas as well as the quantity of produced carbon for the calculation of mean energy efficiency and the carbon conversion factor of the gas using experimentally obtained data. Energy efficiency is quantified value that describes the relationship between the respective quantities of energy contained in the biomass used and the gas produced, in the same sense, the carbon conversion is a quantity of carbonaceous compounds present in used biomass and the amount of carbon in the produced gas. The present document evaluates the energy efficiency and the carbon conversion factor of a prototype model of a downdraft gasifier from India that was modified by a local company. The nominal parameters of the gasifier's function are as follows: gas production capacity running on 45 kW, biomass consumption (açai seeds) of 15 kg/h. The gasifier dimensions are as follows: diameter of 150 mm and height of 2000 mm). The energy efficiency and the carbon conversion rate are quantified, the pressure loss due to the bed reactor and the temperature of the gases are also measured at the reactor exit; the tar, particle composite and non-condensable gas (CO, CO₂, CH₄, SO₂, N₂ e NO_x) concentrations were measured in the produced gas at the cleaning process.

Keywords: Downdraft Gasifier, energy efficiency, carbon conversion efficiency.

1. INTRODUCTION

During the late 70s many countries started developing in a new phase of the energy sector; due to the rising cost of electrical energy. They were motivated by increasing environmental consciousness, the optimistic outlook of new technologies, and the recession of industrialized countries; as well as the oil crisis that led many countries to take incentive to create institutional reforms in the energy industry. The idea being that these reforms would create more space for small scale electrical production with an intensive focus on renewable energy recourses (Walter e Nogueira, 1997).

One renewable energy source option is gasification. Gasification is the process of converting biomass into a gas resource. The creation of this field would increase employment by creating jobs; it also would have direct applications in the industrial industry, including the following: heat-treatment, ceramic, bakery, greenhouses, dryers, calcinations, boilers, metal foundry furnaces and etc (Costa, 2007; Rosenberg et al., 2005). Despite the viability of gasification, there have occurred numerous problems in reference to the gasifier design, operation and the necessity to clean the produced gas using a secondary process. With time the development of new gasification technologies and the improvement of existing ones will lead to advancements in the potential of the field. Around the world, including Brazil, there exist various research centers and companies that are working on improving gasification technology; that can process biomass waste such as bark, straw, sawdust, wood chips, sugar cane bagasse, rice hulls, cottonseed and others (Sanchez et al, 1997; Kinto et al, 2002).

India stands out as a country that holds a large stake in the gasification industry (Purohit (2009) and Jorapuree (1997)); using over 320 million tons of industrial waste per year for energy applications, having the potential to generate more than 290 TWh of electrical energy every year. One of the country's most promising gasification technology was developed by Mukunda (1993), Indian Institute of Sciences. A variation of this technology, which was created by a local company, is the subject of this study.

Fernandes et al (2000), proved the economic feasibility of gasification system application for rural electrical production; using elephant grass and rice hulls as a gas fuel source. Ângulo (2002) also conducted experiments using a rice husk gasifier in a fluidized bed, getting cold gas yields of 48% and an LHV reading of 3.2 MJ/Nm³. Leal (2004) used sugar cane bagasse and straw in a fluidized bed getting gas with an LHV result of about 5 MJ/Nm³. He concluded that high temperatures promote improved carbon conversion (> 95%). Three years later, Ribeiro (2007) called the performance of diesel power generators, for rural electrical production, an attractive alternative; using a stratified downdraft type gasifier, he measured the average reduction in NO_x emissions (83%), CO₂ emissions (14%) when compared with diesel engine emission and the large production of CO qualifying such gas to be used as synthesis gas, syngas, in chemical and 2nd generation synthetic renewable liquid fuel production.

Martinez (2009) presented a study of an experimental moving bed gasifier with extraction from below containing two stages of air supply. Gases produced had LHV of 4.53 MJ/Nm³ and 50 kWt of capacity. According to Martinez, the configuration of dual-stage air supply proved to be an effective method in reducing the tar content of gas produced. Coelho (2006 and 2002) yields good results with a type downdraft gasifier brought from India, through projects and

Gaseifamas and Gaseibras that seeks to develop technology and human resources to be applied in the north of Brazil. Tests were performed using as fuel eucalyptus chips, bark, cupuaçu and other local biomass, obtained gas with HHV of 5.7 MJ/Nm³ able to generate 20 kW_e and, according to Coelho, was able to reduce by 80% the consumption of fossil fuels consumed by a diesel engine.

To improve the quality of a gasifier one must work to improve the thermal efficiency (output power for a given input), carbon conversion factor (amount of CO) and reduce the amount of existing tar existing in the produced gas. The work of this project seeks to systematically measure the performance parameters of a downdraft gasifier that was developed by a local company; determining the characteristics of the biomass used and resulting gas that is produced, quantifying energy efficiency of the system, thermal power of the gas, and the carbon conversion rate. Further goals of the study are to measure the pressure drop due to the bed reactor, temperature of the output gas, the equivalence ration, and the superficial velocity of the process, as well as the concentration of tar particulates and gases not condensed (CO, CO₂, CH₄, SO₂, N₂ and NO_x) in the combustion gases after the cleaning system.

2. METHODOLOGY

2.1. Description of the equipment

The subject of this study is a downdraft gasifier with an open top with a production capacity of 45 kW_t; biomass consumption (açai seeds) 15 kg/h; 150 mm internal diameter and height of 2000 mm. The gasifier is made of a reactor, waste collector, gas cleaning system and flare, as shown in Figure 1.a. Gasification occurs in the reactor which produces a gas mixture containing CO, H₂, CH₄, CO₂, H₂O and N₂; among others. This gas is dragged from the reactor to the cleaning system through an exhauster located after the cleaning system. In the cleaning system, initially the gas passes through an aqueous current that washes the gas. The water containing tar and particulate are removed through a cyclone. The gas is driven up onto a water separator where tar and humidity are removed. The system still has two filters, one containing açai pits and another automotive type, which complete the gas cleaning system. From there, the gas is burned and released into the atmosphere through a flare. In this experiment, açai seeds (free from lint) were used as fuel due to occur in abundance and accessibility.

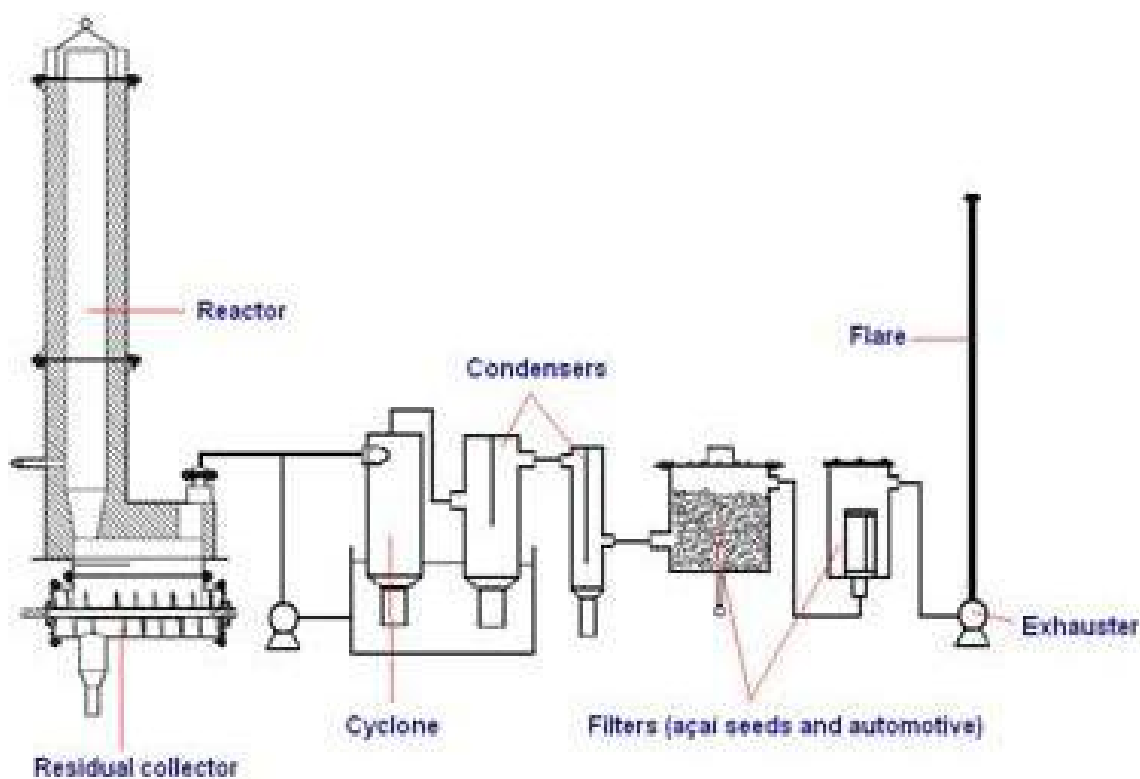


Figure 1.a. The feeding system gasifier.

To remove and quantify tar and soot in the flue gases an isokinetic sampling system named – CIPA (Figure 1.b) was applied. After the CIPA, there are two instruments for measuring the gas concentration: Tempest 100 (SO_x, NO_x) and the Greenline (CO₂, CO, C_xH_y) whose limitations are included in Table 1 below:

Table 1.0. Gas measurement equipments range and error.

Greenline			Tempest 100		
Element	Range	Error	Element	Range	Error
CO ₂	0 -20%	+/- 0,3%	SO ₂	0-0,2%	>100 ppm: +/- 5% fsd
CO	0-15%	+/- 0,3%	NO	0-0,1%	
C _x H _y	0-5%	+/- 5% (f.s)	NO _x	0-0,2%	>20 ppm: +/- 5% fsd

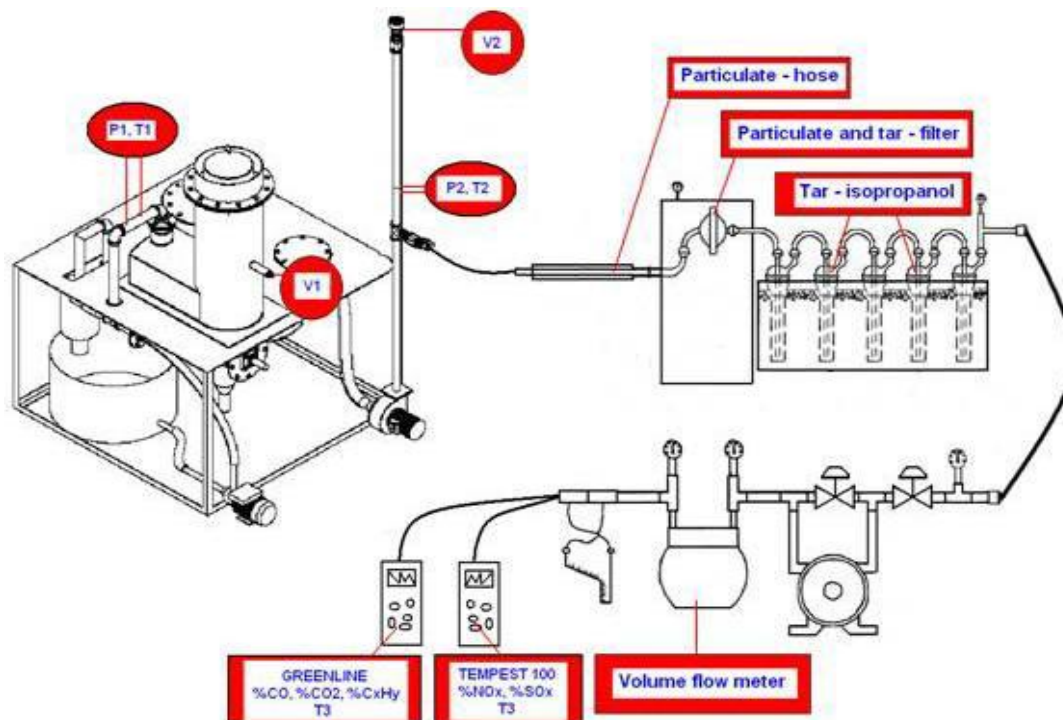


Figure 1.b. Sampling gear connected to gasifier.

To measure inlet air and outlet gas velocities (V1 and V2), a turbine anemometers TESTO 350 m/XL and TESTO 454 were used including a range from 0 to 20 m/s and error of $\pm 0.03\%$. Temperature measurements were done with thermocouple type tip immersion model MTK-13 (Minipa) with range between -50°C to 700°C , being placed at the exit of the reactor (T1) and at the exit of flare (T2), and also at position where gas samples were taken (T3). The gas pressure was taken at reactor exit (P1) and pressure difference at orifice plate (P2) using a pressure gauge in "U" shape, which indicates the pressure in mm of water head.

The CIPA uses isopropanol to capture tar, having a paper filter that captures soot in the gas. The amount of tar and soot removed is quantified by weighing the isopropanol and paper before and after the experiment in a balance with sensitivity of 0.001 g. The amount of gas that passed through the CIPA during the experiment was measured through a displacement volume meter installed after the isopropanol. The readings were corrected for temperature and pressure, according to standards ABNT on effluents (MB-3355/NBR 12020). The accuracy of gas holder used in CIPA uncertainty is $\pm 2\%$.

3. GOVERNING EQUATIONS

3.1. Mass flow

Air flow was calculated using air velocity readings taken in accordance to figure 1.b., an air density value of 1.16 kg/m^3 (for an average air temperature of 28°C with a composition of 79% N₂ and 21% O₂), and air inlet area value of $3,14 \cdot 10^{-4} \text{ m}^2$.

The biomass mass flow rate was evaluated based on Eq.(1), where A_{st} is the gasifier cross area ($1.8E10^{-2} \text{ m}^2$), h is the height of consumed bed with apparent density for the açai seeds being 232 kg/m^3 , and t is the operation time. The height was measured every 10 minutes using a calibrated ruler.

$$\dot{m}_{bio} = \frac{A_{st}(h_2 - h_1)r_{ap}}{t} \quad (\text{kg/h}) \quad (1)$$

To determine the gas flow rate, an orifice plate was placed in the flare pipe, which has a cross area of $5.07 \times 10^{-4} \text{ m}^2$. The orifice plate was calibrated using air, comparing the pressure variation at the gauge and the speed measured using a turbine anemometer. The calibration result can be seen in Table 2.

Table 2. Relation between pressure difference at orifice plate gauge and mean air velocity.

ΔP (mmca)	V (m/s)
16	2,1
12	1,7
10	1,5
8	1,4
6	1,25
4	0,9

Equation (2) was used to quantify de volumetric gas flow rate using Table 3 to convert ΔP into speed and the pipe cross area.

$$\dot{Q}_{measuredgas} = v_{gas} \cdot A \quad (\text{m}^3 / \text{h}) \quad (2)$$

During experiments, air leakage was identified through gasifier deformities without the possibility to be fixed. To accommodate this problem, the air leakage flow rate was measured; its value was found to correspond to 22% of the normal inlet air flow rate, i.e. to get the actual value gas flow rate of gas produced in the reactor, the air leakage must be subtracted from the measured gas value; as expressed by Eq.(3).

$$\dot{Q}_{gas} = \dot{Q}_{measuredgas} - 0,22 \dot{Q}_{air} \quad (3)$$

Equation 3 can be transformed to express the mass flow of the gas, shown in the equation below:

$$\dot{m}_{gas} = \dot{m}_{measuredgas} - 0,22 \dot{m}_{air} \quad (4)$$

The amount of residual charcoal and tar which was either removed from the reactor or trapped in the filter pipes or water, were added together and named as residual mass flow. This resulted in Eq. 5 which relates all mass flow in the system.

$$\dot{m}_{residual} = (\dot{m}_{biomass} + \dot{m}_{air}) - \dot{m}_{gas} \quad (\text{kg/h}) \quad (5)$$

3.2. Density

The gas specific mass was calculated using the ideal gas equation, considering the environment pressure 101,325 Pa and universal gas constant 8315 J/kmol-K. The molecular weight was determined through Eq.(6) after the measurement of species volumetric fractions in the gas.

$$MW_{gas} = \frac{(28[CO] + 44[CO_2] + 16[CH_4] + 30[NO] + 46[NO_2] + 64,1[SO_2] + 28[N_2])}{100} \quad (\text{kg/kmol}) \quad (6)$$

3.3. Superficial velocity

The superficial velocity (u_s) of a gasifier is a ratio between the normal gas volumetric flow rate and the gasifier cross area (Reed, 2002), Eq.(7). It is a fundamental parameter to measure its performance, which influences directly over the rate of gas production, the energy content in gas, the rate of fuel consumption, the production of coal and tar.

$$u_s = \dot{Q} / A_{st} \quad (\text{m/s}) \quad (7)$$

3.4. Thermal efficiency and power

The thermal efficiency was determined according to the Eq.(8).

$$h_{thermal} = \frac{\dot{Q}_{gas} \cdot LHV_{gas}}{m_{biomass} \cdot LHV_{biomass}} \quad (8)$$

The lower heating value of this gas was obtained using Eq.(9) obtained from Rendeiro and Nogueira (2008). Biomass lower heating value was experimentally obtained at EBMA's Laboratory and it is included in Table 4.

$$LHV_{gas} = 5,9417 - 8,2893 \cdot 10^{-3} \Psi \quad (\text{MJ} / \text{Nm}^3) \quad (9)$$

Ψ is named reactor specific rate which is the ratio between the biomass mass flow rate of mass of biomass and the reactor cross area. Eq.(9) only applies if the reactor specific rate lies between 100-400 kg/m²-h. The gas thermal power was obtained using Eq.(10) where, the units of the lower heating value and the volumetric flow rate are respectively kJ/Nm³ and Nm³/s.

$$Pot_{thermal} = LHV_{gas} \cdot \dot{Q}_{gas} \quad (\text{kW}_t) \quad (10)$$

3.5. Carbon conversion efficiency

Coal income can be obtained through Eq.(11) described below:

$$h_{carbon} = \frac{\sum \dot{m}_{gas} \cdot y_{carb.gas}}{\dot{m}_{biomass} \cdot y_{carb.bio}} \quad (11)$$

\dot{m}_g stands for the gas mass flow rate, \dot{m}_b represents the biomass mass flow rates, $y_{carb.bio}$ is equal to the mass fraction of carbon in biomass (Table 4) and $y_{carb.gas}$ is the mass fraction of carbon present in gas that can be calculated from the Eq.(12), and %CO, %CH₄ e %CO₂ species volumetric fraction measured in the gas.

$$y_{carb.gas} = \frac{\%CO}{100} \cdot \frac{12}{28} + \frac{\%CH_4}{100} \cdot \frac{12}{16} + \frac{\%CO_2}{100} \cdot \frac{12}{44} \quad (12)$$

3.6. Equivalence ratio

Equivalence ratio (Φ) is used to indicate if the reactant mixture is rich ($\Phi > 1$, where the lack of oxygen), poor ($\Phi < 1$, where there is excess oxygen) or stoichiometric ($\Phi = 1$, no excess nor lack oxygen). In combustion processes takes approximately $\Phi = 0.95$ and for gasification $\Phi \approx 3$ according Nogueira (2008). The equivalence ratio is determined according Eq.(13).

$$\Phi = \left(\frac{m_{comb}}{m_{ox}} \right)_{real} / \left(\frac{m_{comb}}{m_{ox}} \right)_{st} \quad (13)$$

Being that, m_{ox} and m_{comb} correspond respectively to the mass of oxidizing and fuel respectively and $()_{st}$ refers to condition stoichiometric. Where:

$$\left(\frac{m_{comb}}{m_{ox}}\right)_{st} = \frac{n_{bio(s)}WM_{bio(s)} + n_{H_2O}WM_{H_2O}}{n_{ox}(WM_{O_2} + 3,76WM_{N_2})} = \frac{1 \times 97,78 + 1,12 \times 18}{4,185(32 + 3,76 \times 28)} = 0,21 \frac{kg_{bio}}{kg_{ar}} \quad (14)$$

$$\left(\frac{m_{comb}}{m_{ox}}\right)_{real} = \frac{\dot{m}_{bio}}{\dot{m}_{ar}} \left(\frac{kg_{bio}}{kg_{ar}}\right) \quad (15)$$

3.7. Tar and particulate measurement

Particulate is measured by sampling the mass retained by filter paper in the filtration apparatus: the filter roll is weighed before and after the experiment in a precision balance, this difference is equal to the mass retained from particulate and tar for a given volume of gas. The particulate retained in the hose is quantified as follows: after the experiment the hose was washed with an isopropyl solution, after the cleaning, the resulting solution is filtered and dried at room temperature. The remaining residue is weighted and added to the amount of particulate retained by the filter.

The amount of tar contained in the gas was retained in an alcoholic solution of isopropyl, being distributed in three bottles, whose solutions have different colors, ranging from dark yellow to a clear solution. At the end of the experiment, the solutions are mixed and then weighed. The weight difference between before and after the experiment is the amount of tar (and also particulates) trapped. Tar concentration is obtained through Eq.(16) where the amount of tar is divided by the amount of gas measured using the volumetric flow meter.

$$C_{tar} = m_{tar}/V_{gas} \quad (16)$$

4. RESULTS

Açaí Pit was chosen as the biomass to be used for this particular experiment. Its physic-chemical and energy properties were obtained experimentally in a cooperative effort between the Mechanical Engineering School at UFPA and the Universidade de Santa Catarina through intensive chemical analyses. The results obtained are included in Table 3. They are divided into three parts; Proximate Analysis, Ultimate Analysis and High Heating value. LHV was calculated using the Eq.(17). UFSC completed the ash analysis.

$$LHV = HHV \times (1 - w_{wb}) - [9 \times H \times (1 - w_{wb}) \times h_{lv}] - w_{wb} \times h_{lv} \quad (17)$$

w_{wb} is the moisture contained in the biomass (wet basis) which was obtained from proximate analysis, H is the biomass hydrogen mass fraction obtained from the ultimate analysis and h_{lv} is the difference between the enthalpy of saturated liquid and enthalpy saturated vapor of water at atmospheric pressure.

Table 3. Physic-chemical and energy property from biomass.

Property	Biomass Açaí pit
Proximate Analysis	
Ash [% , d.b. ¹]	0.87
Matter Volatile [% , d.b.]	71.95
Carbon fixed [% , d.b.]	27.18
Moisture [%]	16.53
Ultimate Analysis [% , d.b.]	
C	47.00
H	6.58
N	1.07
S	0.85
O ²	44.22

Cl	0.21
F ³	< 0.20
P	0.067
Biomass heating value [Kcal.kg⁻¹, d.b.]	
HHV	4,018.0
LHV	3,786.1
Ash compositions [% , d.b.]	
Fe ₂ O ₃	0.13
CaO	5.65
MgO	6.82
Na ₂ O	1.18
K ₂ O	30.15
SiO ₂	24.39
Al ₂ O ₃	0.31
TiO ₂	0.04
P ₂ O ₅	24.53
MnO	2.66
SO ₄	4.15

¹ Dry basis;

² Value obtained by difference;

³ Not determined by method detection limit less than 0.2 ppm.

Source: Laboratory chemical analyses – UFSC

Figure 2.a shows the pressure measures at the reactor exit (P1). Such ambient is under vacuum and the figure shows the depression compared against the environmental pressure (Pe). Figure 2.b indicates the measures temperatures. Gas temperature at the exit of the reactor (T1), gas temperature after the cleaning system (T2) and gas temperature at location where the species analyzer take samples (T3).

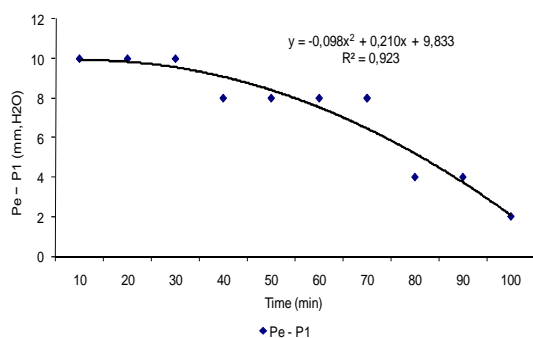


Figure 2.a. Vacuum at gasifier.

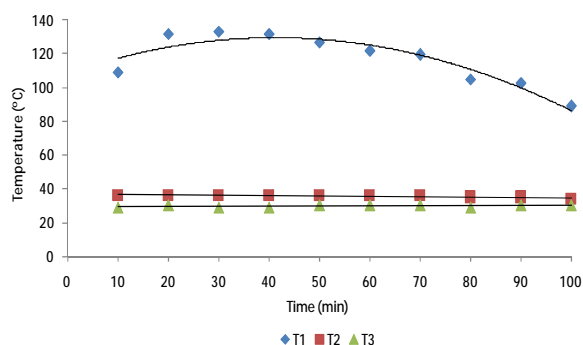


Figure 2.b. Temperature at gasifier.

The relationship between the reagents (air and biomass) and products (gas and waste) throughout the experiment is shown in Figure 3.a. The gasifier consumed about 6 kg/h of biomass and 14 Nm³/h of air producing 16.5 Nm³/h gas and 3 kg of waste (coal, tar and particulate), the superficial gas velocity was calculated and presented in Figure 3.b. One can see that during steady state, the gasifier superficial gas velocity of the process is approximately 0.25 m/s.

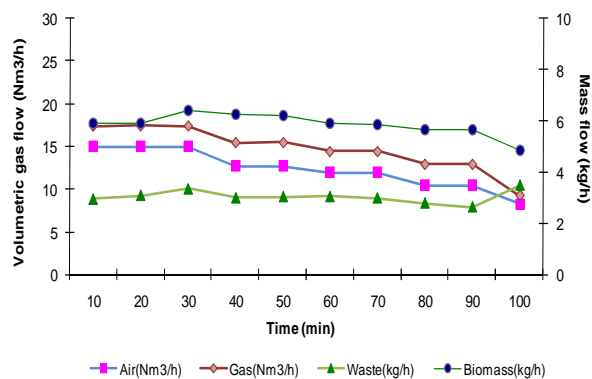


Figure 3.a. Reagents/products measure in gasifier.

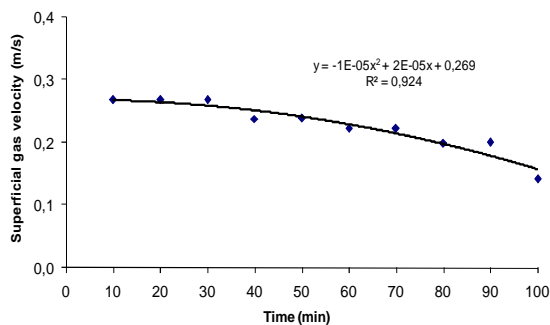


Figure 3.b. Superficial gas velocity.

Figure 4.a shows the species composition in the gas, during a more stable period, which have the approximate values of 18% for CO, 11% for CO₂, 2.5% for CH₄, 0.025% NO₂ and 0.45% for SO₂. Figure 4.b presents species concentration as function of equivalence ratio. One can see that the gasifier had the best performance (based on CO and CH₄, production) at equivalence ratio of $\Phi = 2.2$.

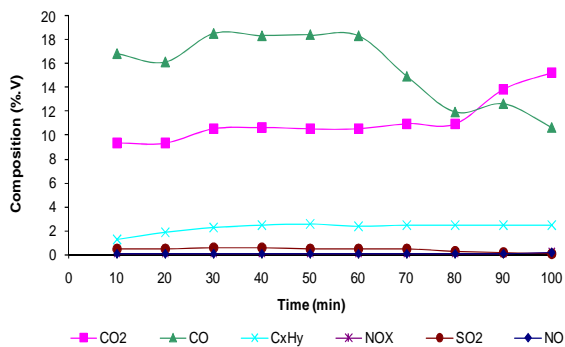


Figure 4.a. Gas species composition.

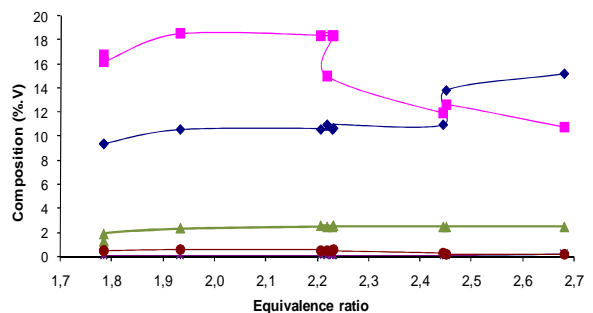


Figure 4.b. Equivalence ratio x gaseous composition.

The figure 5.a. presents the calculated thermal and carbon conversion efficiency. 80% was the best carbon conversion efficiency and 60% was the best yielded thermal efficiency; this highlights the improving quality of such a volatile gas product, which is no longer cracking in the form of tar. Figure 5.b presents the lower heating value and the thermal power generated by gas product.

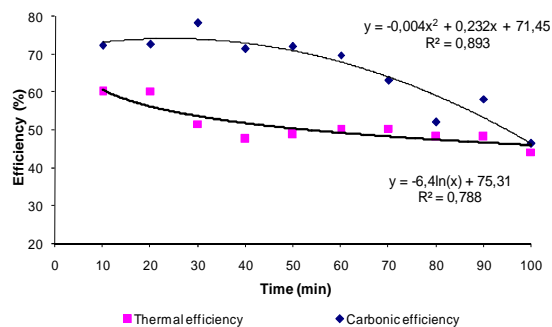


Figure 5.a. Thermal and carbonic efficiency.

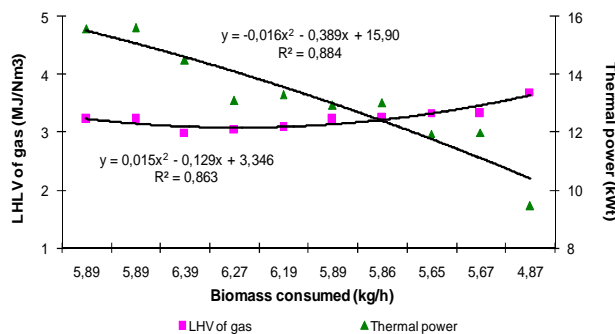


Figure 5.b. LHV and thermal power for gas.

Table 4 refers to data acquired with isokinetic (CIPA), which shows the mass of residual particulate in hose, the mass of particulate-soaked tar retained by filter paper and tar captured by the solution of isopropyl. This table also shows the volume of gas used by equipment for analysis, from a direct read in reader gas holder, however, it is not the actual value of the volume of gas which was suctioned by equipment, because there had occurred mass withdrawal (tar and particulate).

Table 4. Data obtained with CIPA

Property	Value
$m_{\text{particulate-hose}}$ (kg)	0,0001
$m_{\text{particulate and tar}}$ (kg)	0,0015
V_{out} (m ³)	0,988
ρ_{gas} (kg/m ³)	1,19
$m_{\text{gasCIPAout}}$ (kg)	1,1757
m_{tar} (kg)	0,0116
$m_{\text{gasCIPAenter}}$ (kg)	1,1873
V_{enter} (m ³)	0,9977

The actual value of the volume of gas is essential for calculating concentrations of tar and particulate; only through the use of the volume of gas output and the specific mass medium of gas, seen in Table 5, can the mass of gas in the output be determined.

Table 5. Data obtained from tar and particulate

Property	Value
Conc.tar and particulate _{filter} (g/m ³)	1,5283
Conc.particulate _{hose} (g/m ³)	0,1002
Conc.tar _{isopropanol} (g/m ³)	11,6658

5. CONCLUSION

The gasifier managed to produce gases from gasification açai seeds with percentages of 18% CO and 2.5% CH₄, LHV yield values of 3 MJ/Nm³ and 15 kW thermal output power. This gasifier consumed 6 kg/h of biomass and 14 Nm³/h air, producing 16.5 Nm³/h gas and 3 kg/h of waste (coal, ash, particulate and tar). The best performance run yielded a gasifier equivalence ratio of $\Phi = 2.2$ and gas velocity of 0.25 m/s. The produced gas presented very high quantities of tar and particulate, around 11000 mg/Nm³ and 2000 mg/Nm³, respectively.

There was an operational difficulty to keep the gasifier functional after 1 h and 40 min of experimentation (average time using açai pit). This difficulty was a consequence of air intake disruption due to obstruction in the throat by accumulation of charcoal at the grate which consequentially halted gas production.

The açai seeds used in gasification process were free from lint; this was due to the fact that all attempted trials performed used açai with lint resulted in operational problems due to açai clustering.

Other problematic factors included the low vacuum of the reactor which promoted the flow of gas through the air intakes valves, included the output exhaust; this limited the operation performance of the gasifier when running in a closed environment, such as the laboratory used to perform this experiment. The combustion region had a single air intake, which facilitated the non-uniformity of the combustion zone, creating priority paths for the gases where tar passes without being cracking. This explained the large quantity of tar that yielded in the produced gas, something that is neither typical nor anticipated for a downdraft gasifier. All discussed issues limited gasifier performance.

Modification in the gasification process could greatly improve the gasification process; these mainly include structural changes, in addition to recreating testing conditions that were found to yield improved results. Furthermore, there is a great need to experimentally implement the use of such gas in electrical generator application; which would help demonstrate the feasibility of gasification of açai berries, one of earth's greatest assests.

6. ACKNOWLEDGEMENTS

Thanks to the support of CNPQ, FINEP, UFSC and EBMA which made it possible.

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