# TECHNIQUE TO QUANTIFY TAR CONTENT IN ELUDED GAS AND PERFORMANCE OF A DOWNDRAFT BIOMASS GASIFIER

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***Abstract.*** *One promising sources for renewable energy is vegetable biomass. A more efficient process and also able to wider solid biomass applications is its conversion from solid to gas phase through a gasification process. The bottleneck for such technology is the high tar and solid particle concentratios in the gasifiers eluded gas. These two species are toxic, carcinogenic and have potential to deteriorate mechanical equipments, reducing their useful lifetime, increasing maintenance frequency and finally defining the gasifier quality. Based upon it, this paper presents a performance study of an open-top and fixed bed downdraft gasifier using açai seed (biomass fuel) applying a locally developed sampling equipment which is able to separate and quantify tar, soot and non condensable gases concentration and evaluate gasifier thermal and carbon conversion efficiency. Results obtained show that açai seed has 16.795 MJ/kg of Higher Heating Value, lower than the average value for biomasses. Furthermore, the locally developed sampling line was able to quantify soot, tar and non-condensable gases concentration and allowing the low heating value calculation in dry basis as 2.266 MJ/kg.*

***Keywords****: Biomass Gasification, Açai Seed, Tar Measurement, Performance.*

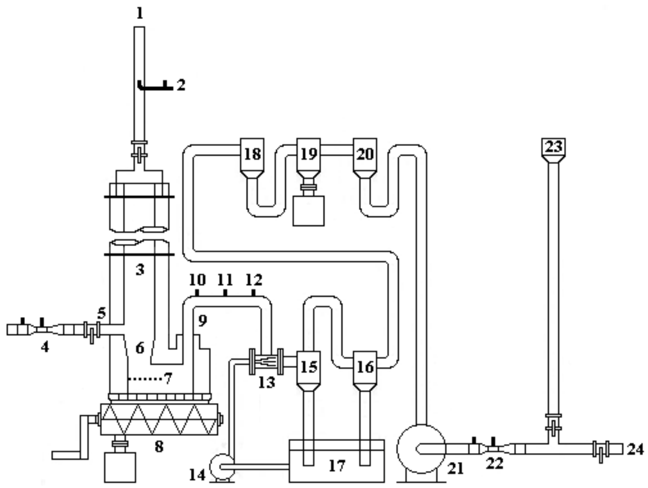
## 1. INTRODUCTION

Efforts all around the world has been undertaken seeking measures to reduce damage caused to the environment by the use of fossil fuels and renewable energy sources play an important rule on this matter. One promising resources for renewable energy is vegetable biomass since it has a renewal lifecycle of a few years. Furthermore, the use of vegetable biomass reduces the rate of emission of carbonaceous pollutants in the air, taking advantage of waste discarded as trash (such as waste wood, açai seed, cane bagasse, etc.), once the carbon found in the structure of the biomass comes from atmospheric $CO_2$ absorbed by vegetables through photosynthesis. A more efficient process and also able to wider solid biomass an application is its conversion from solid to gas phase: the gasification process. Such technology was used to move more than one million of vehicles in Europe during World War II, due to oil shortage (Reed, 1988). The bottleneck for such technology is the particulates and tar concentration in the gasifiers eluded gas. These two species are toxic, carcinogenic and have the potential to deteriorate mechanical equipments reducing their life time and increasing maintenance frequency. Ultimately, tar and particulate concentration defines gasifier quality. Therefore, this paper presents a performance study of an open-top and fixed bed downdraft gasifier located at the Gasification Laboratory of the School of Mechanical Engineering at Federal University of Pará. This type of gasifier is suitable for decentralized generation of electricity (<1000 kWt) in isolated communities or agricultural properties that have availability of biomass (Nogueira et al 2008; Coronado, 2006). Açaí seed (biomass available in the region) was used as fuel and an equipment locally developed named sampling line was used to separate tar and particulates from non condensable gases, allowing to identify and to quantify chemical species through chemical analysis and chromatography.

## 2. MATERIALS AND METHODOLOGY

"Figure 1" shows applied apparatus: gasifiers and gas cleaning system. The gasifier has a vertical cylindrical reactor with height of 1650 mm and internal diameter of 150 mm, built with steel plates 6 mm thick coated internally with a layer of 70 mm refractory concrete. Reactor lower end has a cast iron grate that sustains the biomass bed. Downstream the grate, there is a residue collector with a screw-worm where ash and charcoal residues are collected and removed. Following the reactor, the gasifier has a gas cleaning system to remove tar, particulate, moisture and protect a fan located after the cleaning system. Such fan has the function of reduce reactor and cleaning system pressure and impose gas flow. The fan is connected to an electric motor with variable speed to allow vary fan gas flow rate and therefore, the flow through the reactor. After the fan is locates a flare to burn all gases produced by the gasifier.

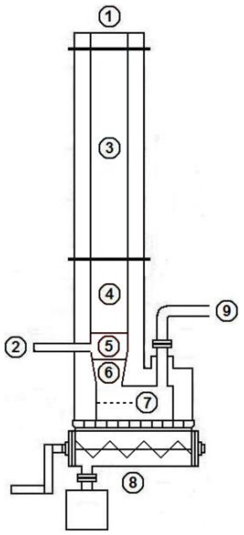
In this type of gasifier, open top, biomass and most of the air used to deliver oxygen to gasification process (between 60% and 70%) are inserted through reactor top. The remaining air is aspirated through a 25.4 mm ID tube located on the reactor side, slightly above the grate, promoting a combustion process and causing a local increasing on gas temperature in this region called combustion zone (region with highest temperature). Thus, biomass and gases move downward, biomass descends by gravity after being consumed through the thermal processes that occur inside the reactor and the gases by the action of the depression caused by downstream fan.



Subtitles:
1. Upper air inlet;
2. Pitot tube;
3. Gasifier reactor;
4. Venturi tube 1;
5. Lateral air inlet;
6. Reactor throat;
7. Grate;
8. Residue collector;
9. Reactor gas exit;
10. Gas sampling slot;
11. Pressure measurement slot;
12. Temperature measurement slot;
13. Water spray;
14. Water pump;
15. Cyclone;
16. Separator 1;
17. Water reservoir;
18. Filter fill with açai seed;
19. Separator 2;
20. Automotive filter;
21. Fan;
22. Venturi tube 2;
23. Flare;
24. Clean gas exit.

Figure 1. Applied gasifier scheme.

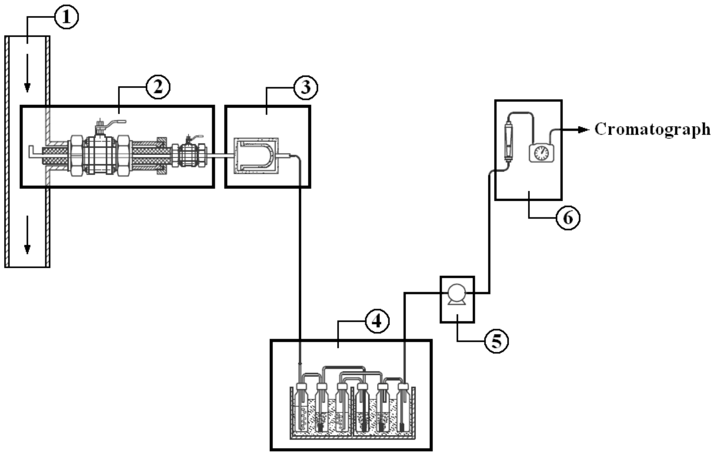
The gasification process, "Fig. 2", is done, basically, in four stages: drying, pyrolysis, combustion and reduction of carbonaceous residue. Drying is the process for moisture removal from biomass through heat addition: heat comes in and steam leaves açai seed. Once the drying process is completed, seed temperature goes up to initiate the pyrolysis process. It means that the dry biomass undergoes a continuous increasing on its temperature that has as consequence the breakup of its major components (hemi-cellulose, cellulose and lignin) turning into volatiles (small and long chain hydrocarbons species with tar included). Moisture from 3 and volatiles from 4 must go through the combustion zone 5. A fraction of the pyrolysis produced tar is destroyed when it flows through the combustion zone (region of highest temperature which provides heat to the dryer, pyrolysis and reduction processes). Below the combustion zone is found the reduction zone where carbonaceous residue, charcoal (formed after moisture and volatile matter depletion from initial biomass) reacts mainly with carbon dioxide and steam to produce carbon monoxide and hydrogen.



Subtitles:
1.Upper air and biomass inlet;
2. Lateral air inlet;
3. Drying zone;
4. Pyrolysis zone;
5. Combustion zone;
6. Carbonaceous residue reduction;
7. Grate;
8. Residue collector;
9. Reactor gas exit and cleaning system inlet.

Figure 2. Identification for applied gasifier process zone.

The operation starts with supply of 0.3 kg of ember charcoal on the reactor grate to ignite the biomass bed. Then, the reactor was filled with biomass (açai seed) and the exhaust fan speed is adjusted to promote depression, therefore, air flow rate into the combustion zone up to achieve gasification. The gas was collected during one hour using the sampling line, "Fig. 3", shortly after reactor gas exit (point 10-"Fig. 1") to measure the amount of tar and of particulates produced in the gasifier. The sampling line filters particulates and condenses tars in glass bottles containing isopropanol. These bottles are immersed in cold water at temperatures far smaller than tar condensation temperature and decreasing the output gas temperature. At the end of the sampling line, particulates, tar and non condensable gas are separated, allowing identification and quantification of chemical species through chemical analysis and chromatography. The sampling line was designed based on protocol developed by the European Community, known as Tar Protocol (2005).




Subtitles:
1. Row gas;
2. Gas pre-conditioning;
3. Filter;
4. System to remove particulates, tar and moisture from gas;
5. Vacuum pump;
6. Measurement station for pressure, temperature and volumetric flow rate.

Figure 3. Sampling line Scheme. (Adapted: Knoef et al, 2007).

## 2.1 Instrumentation

Pressure measurements were obtained with "U" manometer using water as manometric fluid. Temperature measurements were obtained with type K thermocouple connected to a digital thermometer (model: MT 520; manufacturer: Minipa) with range from -50° C to 700° C. Inlet air speed was measured with a Pitot tube at upper reactor entrance and a Venturi tube at the lateral entrance. Exit gas flow rate was measured using another Venturi tube located downstream of the exhaust fan. Species concentration present in the produced gases was measured using a portable gas chromatograph with thermal conductivity detector (TCD) (model: CP-4900 Micro GC; manufacturer: Varian) equipped with two columns to separate $H_2$, $O_2$, $N_2$, $CH_4$, CO e $CO_2$. Helium (with purity=99.995%) was used as carrier gas. Chromatograph concentration calibration was performed with a standard gas having the following composition: $H_2$=20%, $N_2$=45%, $CH_4$=3%, CO=20% e $CO_2$=12%.

## 2.2 Mathematical Equations

According Nogueira et al. (2008), to favor the gasification the equivalence ratio values "Eq. (1)", should be between 2<Φ<3 once the gasification process is very dependent on the amount of oxygen available for reactions. Excessive lack of oxygen leads to low temperatures what constraints all thermal process (dryer, pyrolysis and reduction). Excess of oxygen, the process enters in transition of gasification for combustion and the reaction will tend to form $CO_2$ and $H_2O$ what is not the gasification goal. According to simulations performed in the COMGAS software (program developed by the Group of Energy, Biomass & Environment (EBMA) of UFPA to evaluate gas composition on equilibrium after combustion or gasification), the point of maximum conversion efficiency of C into CO for açai seed gasification occurs around Φ = 2.2.

$$\Phi = \frac{\left( {}^{m_{fuel}}/_{m_{oxidant}} \right)_{real}}{\left( {}^{m_{fuel}}/_{m_{oxidant}} \right)_{stoichiometric}} \tag{1}$$

The produced gas thermal power, "Eq. (2)", was obtained timing the gas mass flow rate with its lower heating value (LHV) on dry basis. Energetic efficiency, "Eq. (3)", was calculated from the ratio between the amount of energy contained in the gases and the amount of energy supplied with fuel. The equation to obtain the carbon conversion efficiency is shown in the "Eq. (4)", where MW stands for species molecular weight.

$$Pow_{thermal,gas} = (\dot{m}_{gas}) * (LHV_{gas,dry\ basis}) \tag{2}$$

$$\eta_{energetical} = \frac{(\dot{m}_{gas})*(LHV_{gas,dry\ basis})}{(\dot{m}_{biomass})*(LHV_{biomass,dry\ basis})} \tag{3}$$

$$\eta_{conversion,C} = \left[ \frac{(MW_C/MW_{CH_4})*\dot{m}_{CH_4} + (MW_C/MW_{CO})*\dot{m}_{CO}}{\dot{m}_{C,biomass}} \right] * 100 \tag{4}$$

## 3. RESULTS

As previously mentioned, the gasifier was operated with açai seed (fuel biomass with diameter of 10 mm in average). Its energetic characterization is presented in "Tab. 1".

Table 1. Açai seed energetic characterization.

| Property | Açai Seed |
|---|---|
| **Proximate Analysis** | |
| Moisture (%, crude sample) | 16.53 |
| Volatiles (%,dry basis) | 71.95 |
| Ash (%,dry basis) | 0.87 |
| Fixed Carbon (%,dry basis) | 27.18 |
| **Ultimate Analysis (%, dry basis and ashless)** | |
| C | 47.00 |
| H | 6.58 |
| N | 1.07 |
| S | 0.85 |
| O | 43.63 |
| **Heating Value [kJ/kg]** | |
| HHV (calorimetric bomb) | 16795 |
| LHV | 15349 |

Source: Chemical Analysis Laboratory (UFSC).

Once biomass properties are known, it is possible to determine gasifier operating conditions and obtain figures that allow evaluating equipment performance. "Table 2" shows mass flow rate for air, biomass and of gas obtained during 7 different experiments as well as concentrations values for $H_2$, CO and $CH_4$ from these 7 experiments.

Table 2. Mass flows and concentrations obtained during 7 different experiments.

| Experiment | Φ | Air inlet [kg/h] | Biomass [kg/h] | Gas outlet [kg/h] | $H_2$ [%,vol.] | $CH_4$ [%,vol.] | CO [%,vol.] |
|---|---|---|---|---|---|---|---|
| 15 | 1.3 | 8.26 | 2.13 | 10.52 | 1.65 | 0.04 | 4.40 |
| 08 | 1.4 | 8.36 | 2.47 | 10.96 | 3.26 | 0.28 | 6.91 |
| 14 | 1.8 | 8.52 | 3.21 | 11.95 | 7.55 | 0.95 | 8.99 |
| 16 | 2.1 | 11.64 | 5.10 | 17.33 | 9.89 | 1.25 | 11.60 |
| 09 | 2.4 | 12.05 | 5.94 | 18.62 | 10.36 | 2.20 | 9.52 |
| 13 | 2.7 | 12.47 | 6.79 | 19.93 | 10.81 | 3.10 | 7.94 |
| 07 | 2.9 | 12.90 | 7.63 | 21.24 | 10.29 | 3.31 | 7.48 |

"Table 3" shows the thermal powers, energetic and carbon efficiencies obtained from 7 experiments data shown in the "Tab. 2".

Table 3. Thermal powers, energetical efficiencies and carbon conversion efficiencies obtained in the experiments.

| Experiment | Φ | $LHV_{gas,dry\ basis}$ [kJ/kg] | $Pow_{thermal,gas}$ [kW] | $\eta_{energetical}$ [%] | $\eta_{conversion,C}$ [%] |
|---|---|---|---|---|---|
| 15 | 1.3 | 185 | 0.46 | 6.10 | 23.68 |
| 08 | 1.4 | 352 | 0.92 | 10.45 | 35.28 |
| 14 | 1.8 | 707 | 2.02 | 17.70 | 42.34 |
| 16 | 2.1 | 1537 | 6.35 | 35.01 | 51.34 |
| 09 | 2.4 | 1774 | 8.04 | 38.01 | 44.52 |
| 13 | 2.7 | 2056 | 10.15 | 42.02 | 40.14 |
| 07 | 2.9 | 2266 | 12.09 | 44.52 | 38.87 |

"Table 4" shows mass balance for experiment 16, Φ=2.1, while "Tab. 5" shows comparison between results obtained in experiment 16 against results obtained from COMGAS software simulation with Φ=2.1. "Table 6" presents the average of the levels of particulates and tar obtained in the experiments.

Table 4. Mass balance for experiment 16.

| Input | Biomass (dry basis) [kg/h] | $H_2O$ (moisture) [kg/h] | Air [kg/h] | Total [kg/h] |
|---|---|---|---|---|
| | 4.26 | 0.84 | 11.64 | 16.74 |

| Output | $H_2O$ [kg/h] | $H_2$ [kg/h] | CO [kg/h] | $CH_4$ [kg/h] | $N_2$ [kg/h] | $SO_2$ [kg/h] | $CO_2$ [kg/h] | C [kg/h] | Ash [kg/h] | Total [kg/h] |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1.70 | 0.13 | 2.16 | 0.13 | 8.97 | 0.07 | 3.48 | 0.02 | 0.04 | 16.70 |

Table 5. Experiment 16 results compared against Congas equilibrium calculation.

| | Φ | $H_2$ [%,Vol.] | CO [%,Vol.] | $N_2$ [%,Vol.] | $CH_4$ [%,Vol.] | $SO_2$ [%,Vol.] | $CO_2$ [%,Vol.] | $\eta_{energetic}$ [%] |
|---|---|---|---|---|---|---|---|---|
| **Experimental** | 2.1 | 9.89 | 11.60 | 48.09 | 1.25 | 0.17 | 11.88 | 35.01 |
| **Simulation** | 2.1 | 14.05 | 12.56 | 47.67 | 0.41 | 0.17 | 12.05 | 40.13 |

Table 6. Tar and particulate concentration for experiment 16 obtained at position 10 in "Fig. 1".

| Property | Value [g/m$^3$] |
|---|---|
| (Tar e Particulate)$_{Filter}$ | 1.52 |
| (Tar)$_{Isopropanol}$ | 11.67 |
| (Particulate)$_{Hoses}$ | 0.10 |

## 4. CONCLUSIONS

Based on the experimental results, it is concluded that:

- The best gasification result was obtained in a range 2 <Φ <3, agreeing with literature information.
- Açai seed has low HHV (Higher Heating Value=16.795 MJ/kg) as compared with wood biomasses that has in average HHV about 20 MJ/kg.
- "Table. 2" shows that the maximum CO concentration (approximately 11.60%) was obtained in the experiment 16 with equivalence ratio of 2.1. Comparing the values from experiment 16 with the values obtained from COMGAS simulation, "Tab. 5", it is possible verify that the result obtained through chemical equilibrium (maximum possible value) is 12.56% of CO, demonstrating that the experiment 16 performed quite well as obtained 11.60% for such concentration. However, the amount of 14.05% of $H_2$ (obtained in from chemical equilibrium) is much greater than the amount of 9.89% of $H_2$ (obtained in the experiment 16). This indicates that part of the hydrogen atoms that would form $H_2$ was favored to form hydrocarbons or other species not identified by the chromatograph, since the amount of $CH_4$ (approximately 1.25%) obtained in the experiment 16 was greater that the amount obtained in the simulation (approximately 0.41%).
- "Table 3" shows that the gas LHV in dry basis increases with the increase of the equivalence ratio, occurring as result, increasing the thermal power and of the energetic efficiency. This increasing on LHV, thermal power and energetic efficiency, despite the decreasing on CO concentration in the experiments 09, 13 and 07, can be explained by the continuous growth of $CH_4$ concentration in such experiments as well as $H_2$ concentration raise on experiments 9 and 13. It happens because $CH_4$ and $H_2$ enthalpy of formation are smaller than the one for CO, increasing as consequence the gas heat of reaction.
- "Table 2" shows a slight excess in the values of mass flow of gas measured with the Venturi tube at fan outlet . Possible explanation for it is air leakage through gasifier connections since the gasifier works in these experiment ran on depression.
- If it were possible, for example, increase the biomass consumption capacity of the experiment 16, of 5.1 kg/h for 8 kg/h, the energetic efficiency of the experiment 16 would rise of 35.01% for 58.72%.
- "Table 6" shows that the sampling line locally developed performed quite well on quantifying tar and particulate concentration. Furthermore, despite the gas produced has attractive HHV, it is still unsuitable to be used in power equipments such as internal combustion engines, because these engines tolerates, in average, concentrations below 100 mg$_{tar}$/m$^3_{gas}$ and 50 mg$_{particulates}$/m$^3_{gas}$.

## 5. ACKNOWLEDGMENTS


- To CAPES by to finance for the scholarship for Bruno Almeida Pinheiro do Couto through the project “Biomassa Energética” [Procad/NF 2007/UFPA–ITA];
- To CNPq by to finance the project [578106/2008-6].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