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Simulation of tar reduction alternatives in the coffee stems gasification process

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Abstract. This work developed a simulation model able to compare three different secondary methods of tar retention that assess the energy consumption, investments and tar concentration of each alternative to clean the syngas produced in the gasification of coffee stems. The alternatives were the installation of a car filter (FC), a heat exchanger (IC) and activated carbon filtering media (FCA). The experiments were carried out in the Power Pallet GEK 20 kW downstream Gasifier and runs of 3, 6, 9, 12 and 24 hours of operation. The tar concentration was measured via VOC's direct detection equipment and showed values of 23, 18.7, y 222.3ppm for IC, FC and FCA respectively. Estimation errors obtained for the model developed in Aspen Plus[®] software for tar concentration were 16.75%, 14.63% and 0.02% for normal operation, FC and IC respectively. An Economic evaluation reported a value of 0.43, 4.06, 0.45 and 4.09\$/kW produced for normal operation, FC, IC and FCA respectively. Finally, the analysis of the internal combustion engine thermal efficiency exposed that IC and FC potentially increase the total energy production in 440kWh per year compared to normal operation.

1. Introduction

Gasification is a well-known process for over 200 years [1]. It was used in industrialized cities, where it found applications in internal combustion engines, motor vehicles and crafts. After World War II it was relegated due to the low costs of fossil fuels. Nowadays, biomass gasification has been established as a feasible and clean alternative technology in applications such as electrical, thermal and hydrogen production [2]. CENICAFÉ (Coffee investigation center) owns a downstream gasifier crafted by All Power Labs. Previous researches indicated that the gasifier optimal operational conditions generate electrical energy at rates between 1.14 and 1.47kg coffee stems per kWe produced and 2.11 to 2.48m³ of syngas per kg of coffee stems processed, respectively. Also, these findings showed a malfunction in the internal combustion engine and clogging, attributed to the tar present in the syngas. This mix of compounds was produced as a byproduct of the gasification reaction. The functioning of the GEK 20 gasifier starts with the introduction of feedstock into the hopper. After the hopper, the feedstock passes



through an auger and enters the gasifier. The feedstock fills the reactor and then passes through the stages needed for gasification: drying, pyrolysis, combustion, and reduction. The hot gas exits the reactor and passes through a cyclone to separate char particulates. The GEK utilizes the heat from the gas produced to dry the incoming feedstock through the Drying Bucket. After the Drying Bucket, the gas passes through the gas filter and gas drive systems to the engine where the combustion takes place and then to the energy production stage. The GEK Gasifier is able to produce three-phase electric energy, with outputs of 220 and 440V according to the configuration set and a nominal power of 20kW.

The scope of this paper aims to generate a simulation model that allows the evaluation of three alternatives to reduce the tar concentration in the syngas to a value less than 50ppm. These improvements will allow the optimal operational condition to produce electrical energy with no standstills due to the clogging of the engine or syngas transport pipelines. The reliability of the gasification process presents advantages such as: independency of the electrical grid and supply of electricity for non-interconnected regions (NIR), also it will contribute in the management of approximately 17 tons per hectare of coffee stems, produced in the renovation of the coffee tree present in 90000 hectares of coffee crops [3] and [4] The implementation of clean technologies to produce energy would positively influence the coffee growth process, through the technification and centralization of the wet processing methods, ensuring fair prices and payments directly to the coffee grower. Several investigations about biomass gasification have been discussed, but the biomass gasification of coffee stems is still an incipient topic.

2. Materials and methods

2.1. Tar measurement

The most accepted tar definition is given by the CEN/TC BT/TF 143 [5] tar measurement protocol in which tar is demarcated as any compound obtained via biomass gasification that has a molecular weight higher than benzene. This kind of compounds includes PAH (polycyclic aromatic compounds) containing one or more aromatic rings. According to the European Union's (EU) solvent emissions directive 1999/13/EC, VOC [6] (volatile organic compounds) are defined as compounds which show a vapor pressure equal to 0.01kPa or higher at a temperature of 20°C. Complementary, the directive EU 2004/42/EC [7] defines the VOC as any compound whose boiling point is less or equal to 250°C in atmospheric pressure conditions. Both definitions exclude compounds, which have molecular weight, are less than n-hexane. The comparison of these directives indicates that Tars and VOC share several characteristics, thus, for the purpose of the present work, tar concentration in syngas was obtained using a direct measurement VOC equipment MultiRAE Lite.

2.2. Operational conditions

The experiments consisted in 3, 6, 9, 12 and 24 hours of continuous running. The humidity of coffee stems was 12% mass fraction, in wet basis. Mass consumption was measured in weighing scale Vector® VI 101 showing average values of 15kg/h. An orifice plate flow meter installed after filtering stage measures the gas flow rate, showing typical values between 43 – 52m³/h. The composition analysis of the gas generated and the measurement of the low heating value (LHV) were made using a CMC Gasboard 3100P equipment. The gas composition values obtained were CO: 19.0%; H₂: 19.9%; CH₄: 3.0%; CO₂: 10.0%; O₂: 0.2%; LHV: 5669.3kJ/m³. The temperatures of the reactor in the oxidation (devolatilization and biomass drying, exothermic reactions, pyrolysis and tar generation) and reduction zones (endothermic reactions, syngas generation) were measured using thermocouples type K of 1/16" diameter and 24" length. Table 1 resumes the values obtained during the experimentation and the typical standard deviation.

Table 1. Experimental conditions through each test.

Test	T (°C)	σ (°C)	W (kg/h)	σ (kg/h)
3h	852.5	36.1618	14.69	2.5143
6h	717.3	13.2626	15.13	1.8156
9h	657.8	50.6870	14.53	3.7559
12h	717.0	14.6980	15.51	1.6065
24h	713.7	49.7318	14.97	6.2296
Total	731.6	72.1224	14.97	0.3868

2.3. Physicochemical characterization of coffee stems and biochar

Proximate and ultimate analysis of coffee stems and biochar generated during the gasification reaction were taken from literature [8]. Properties such as relative and particle densities and void fraction were measured according to ASTM D-854 [9] standard. Superficial area of coffee stems used in the filtering stage was measured through Digital Image Processing [10] showing an average value of $0.39556\text{m}^2/\text{kg}$. The particle size distribution (PSD) of coffee stems fed to the reactor was assumed as $10 - 40\text{mm}$ according to manufacturer recommendations, while the biochar PSD was measured using gradation test.

2.4. Characterization of retention alternatives

The alternatives evaluated in the present work were a car filter (FC) installed before the engine gas inlet within a tubing of $\frac{1}{2}$ " diameter arrangement. After each tests the gained mass was measured in the analytical balance Mettler Toledo PB 8001. The selected filtering media was a 3.5 inches custom oval conical air Filter. The main disadvantage of this method relies on the saturation time. Experiments concluded that after 3 hours of non-stop operation, the air filter reaches saturation state and no tar was caught further. The second alternative was the installation of a heat exchanger (IC) placed covering the cyclone. The aim of this retention method is to condensate the tar before the mix enters the engine. The cold fluid was water with a mass flow of 0.22kg/s . All the design specifications were calculated through Kern algorithm for concentric tube heat exchanger [11]. Finally, the third method consists in the replacement of the coffee stems used like filtering media with activated carbon (FCA) [12]. The filtering media was divided in two layers formed with coffee stems at the bottom of the filter with a length of 0.3m and PSD between $10 - 40\text{mm}$. The top layer was followed by activated carbon which PSD ranges between $5 - 12\text{mm}$. Several pressure drops were observed during the operation, obstructing the gas flow to the engine. The normal operation of gasifier with non-secondary methods used was assigned as coffee stems filtering media (FM).

2.5. Simulation model description

Figure 1 shows the simulation model, which describes the gasification of coffee stems. The wet wood (Non-conventional stream) inlets to the DRY-REAC block, where water vapor is generated and then separated in the FLASH block into two separate streams, STEAM and DRY-WOOD, the dried wood enters to DEVOL block, here an atomic balance takes place and generates the C, O₂, N₂, H₂, S and ASH-CHAR (Non-conventional stream) needed for the subsequent reactions. The atomic balances and yields (mass fraction) were estimated using Excel. The elements produced in the DEVOL block inlets to a separation unit in which three streams were obtained: First the byproducts of gasification such as biochar and ashes are contained in the CHAR stream. The second stream PRETAR is formed with C and H₂ required to generate tar in a proportion of 60% Benzene, 40% Toluene and 40% Naphthalene (mass fraction) [13]. According to the calculation and literature [14], 12% (d.b.) of the biomass turns into tar. And the final stream (PREDEV) is confirmed by the rest of C and H₂ and the other elements that will react in the gasification block GASIFICA. In this block, besides the compounds found in the PREDEV stream,

inlets the air needed for the combustion reaction in a proportion or equivalent ratio (ER, the ratio of the actual air/fuel ratio to the stoichiometric air/fuel ratio) equal to 0.3132. Lastly, the steam produced in the DRY-REAC block enters and the gasification reactions occurs. SYNGAS, TAR and CHAR are mixed after the gasification block and then inlets to the CYCLONE block in which the separation of solids (biochar and ashes) occurs. This cleaned up stream enters to the FILTER block and the first tar retention befalls. This block was defined using a user model that runs in Excel and allows the estimation of tar retained according to the Freundlich's isotherm algorithm [15]. The partially tar free syngas enters three blocks set that emulated the Otto Cycle and power generation. First of all, the syngas was mixed with air in an ER equal to 1.05, these mix inlets to the compression block ensuring an isentropic process and a compression ratio of 9.5, equivalent to the compression ratio of the engine. The compressed gas then suffers a combustion reaction in the BURST block, this block functions as a free Gibbs energy reactor and generates the corresponding combustion gases. Finally, the power generation stage takes places in the POWER block, here an isentropic expansion occurs, and the combustion gases exit the block to an atmospheric pressure.

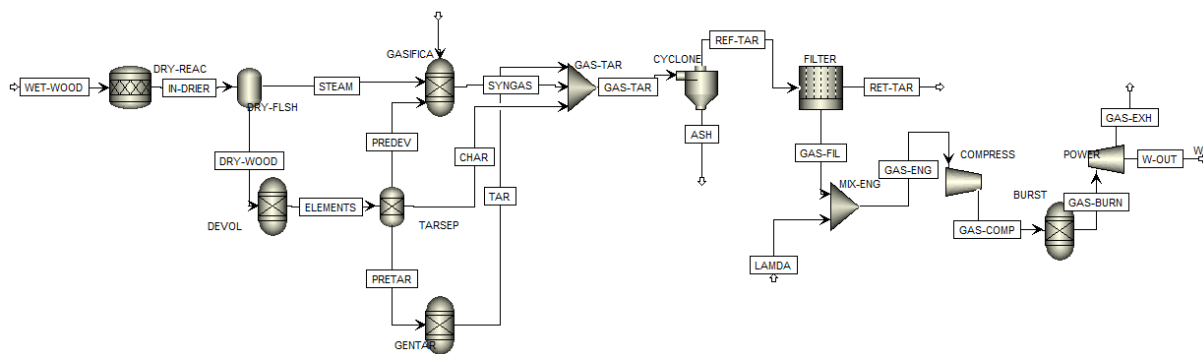


Figure 1. Simulation model process flows.

With the purpose of evaluating the alternatives two additional blocks were added to the simulation model. The HEATX block was placed after de cyclone to condensate tar with a FLASH block that ensures the separation of the liquid and vapor phases. Additionally, the FILCAR block emulates the FC alternative, consisting in a separator that takes the mix of tar in a proportion equal to 0.33ppm.

3. Results and discussion

3.1. Comparison of model and experimentation

The mass flow entered into the model and the one determined experimentally were 15kg/h. Figure 2 shows the estimated composition of the gas by the model and the composition determined experimentally. The calculated errors were 6.62, 1.57, 1.52, 1.15 and 2.64% for O₂, H₂, CO, CO₂ and CH₄ respectively. García *et al.* [16] found syngas composition from the gasification of coffee stems, which values are 17.5, 14.5, 11 and 3% for the components mentioned above. The model fits the experimental data properly with a tendency to overestimate the gas composition. The gasification reactor is a yield reactor. The final values programmed in the software were estimated through mass balance in Excel and assuming that all the water contained in the biomass enters the reactor as steam.

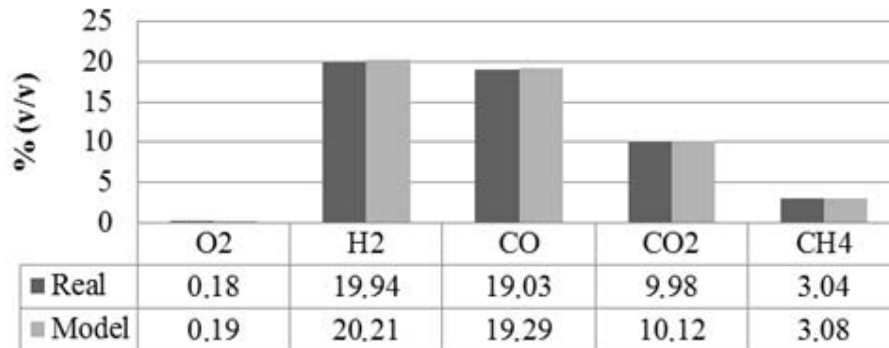


Figure 2. Syngas composition.

Another critical condition is the yield of tar conversion. A comparison between the real and the estimated values (Table 2) shows that ER presents an error of 4.4%, meanwhile the gas flow error is about 14.57%. It is also observed that the composition of tar exiting the filter and the heat exchanger had an error of 6.76 and 9.34% respectively.

Table 2. Gas flow. Estimated and real values.

Condition	Units	Exit FM	Exit IC
12 % tar (w.b.)	ppm [g/m ³]	19.964	18.697
	ER		0.31
	Gas flow [m ³ /h]		72.18
Experimental tar concentration	ppm [g/m ³]	18.700	17.100
	ER		0.3 (Theoretical)
	Gas flow [m ³ /h]		63.007

3.2. Evaluation of retention alternatives

The power generation was evaluated through the thermal efficiency that corresponds to the ratio of the power produced (as the low heating value of the syngas) and the power supplied (as the low heating value of coffee stems. 17493.3kJ/kg. Dimensionless). A sensibility analysis varying the temperatures exiting the filter (FM), heat exchanger (IC) and Separator (FC) in intervals between 100 – 300°C showed that the thermal efficiency decreases (η) with the increment of temperature (T), as seen in Figure 3.

The implementation of IC and FC alternatives generates 440kWh/year compared with FM, considering a biomass consumption of 15kg/h in a non-stop operation. This means that energy for 5 people can be delivered during a year given that the per capita energy consumption in Bogotá is about 77.57kWh [17]. Table 3 resumes the annual energy production for different alternatives estimated by the simulation model. The FCA alternative was not evaluated because a malfunction was observed and a consequent lack of experimental data.

According to Oliveros [18] the cost of energy generation using the GEK 20 is 0.43USD/kWh. This value includes the transportation and conditioning of coffee stems, the operative and maintenance associated costs. The values presented by Shafie *et al.* [19] are congruent with the value mentioned above, but a clarification of those is needed. The installed power is 1 to 900MW meanwhile the installed power of GEK is just 20kW. According to Thakur *et al.* [20] the costs of energy generation will decrease with the increase of the installed power. The cost associated to IC alternative includes the manufacturing, installation and operation of a heat exchanger, meanwhile the costs associated to FC includes the acquisition of 8 filters as a replacement during a 12 hours operation. Therefore, it means that saturation is

achieved after 3 hours or 4 filters per day. The remaining 4 filters will be used the next day meanwhile the used filters will be conditionate. For both alternatives (IC and FC) 10 years were considered as a depreation time. Table 4 resumes the tar concentration, thermal efficiency and cost per kW of each alternative.

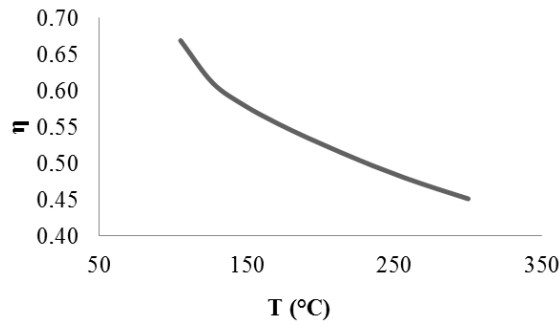


Figure 3. Effect of temperature (T) in thermal efficiency (η).

Table 3. Annual energy production.

Parameter	Value
Biomass consumption, kg/h	15
Operational time, h/año	4380
Consumed biomass, ton/año	65.7
Generated energy FM, MWh/año	27.76
Generated energy FM + IC, MWh/año	28.20
Generated energy FM + FC, MWh/año	28.12

Table 4. Alternatives energy production comparison.

Test	Tar concentration (ppm)	Thermal Efficiency	\$/kW
FM	17.1	0.0870	0.43
FM+FC	23.0	0.0878	4.06
FM+IC	18.7	0.0883	0.45
FM+FC+IC	18.3	0.0880	4.087
FCA	222.3	-	-

4. Conclusions

It was evidenced that none of the alternatives retained more tars than the original configuration of the equipment with the wood filter; this is because the gas which comes out of the cyclone contributes to the drying of the biomass. When refrigerated, the drying process of the biomass becomes less efficient, causing the temperature inside the reactor to decrease, favoring the formation of higher molecular weight tars [20]. According to this, it was concluded that the refrigeration of the gas must take place after the use of synthesis gas for drying. The thermal efficiency of the process through IC and FC was increased by 1.6% at a temperature of 170°C. For a continuous operation process, this increase of temperature or efficiency causes the energy production to increase up to 1MWh in a year due to the increase in the ratio of kWh/kg produced. The concentration of tars measured with the installation of the car filter (FC) has a higher concentration, because of the arrangement where it was installed. It condenses tars at the bottom, generating tar accumulation and the subsequent gas absorption. It is recommended to redesign the lower part of the assembly with a drainage system which prevents this phenomenon of accumulation to occur and subsequent dragging of tars.

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