International Review of Mechanical Engineering (I.RE.M.E.), Vol. 10, N. 4
ISSN 1970 - 8734 July 2016

Heat Losses Analysis Using Infrared Thermography on a Fixed Bed Downdraft Gasifier

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Abstract – *The continuous increase of energy consumption and the environmental effects of fossil fuel combustion are some of the causes promoting the development of alternative clean energy systems. This work aims to identify the total electric efficiency, and cold gas efficiency of a 10kWe commercial downdraft gasifier fed with Coconut Shells. Moreover, the scope is to establish the convection and radiation heat losses using thermography images and dimensionless parameters. An empirical relation to calculate the syngas composition based on the CO and CO_2 content was identified. Total electric efficiency was about 20% while cold gas efficiency around 53%. Radiation and convection heat losses from reactors surface were about 3% of total thermal energy employed. Coconut shells gasification is a feasible alternative for electricity generation for rural areas.*

***Keywords**: Coconut Shells, Downdraft, Gasification, Infrared Thermography, Syngas*

Nomenclature

ki	Air conduction constant
$m_{biomass}$	Biomass mass rate
Lc	Characteristic length
CGE	Cold gas efficiency
Q_{conv}	Convection heat losses
μ	Dynamic viscosity
Pe	Electrical power
A	External area
g	Gravitational acceleration
HHV	Higher heating value
β	Inverse average fluid temperature
LHV	Lower heating value
ε	Material´s emissivity
MW_i	Molar weight
Nu	Nusselt number
Pr	Prandtl number
Q_{rad}	Radiation heat losses
Ra	Rayleigh number
h	Specific convection heat coefficient
Cp	Specific heat capacity
σ	Stefan Boltzmann constant
T	Temperature
$\eta_{electric}$	Total electric efficiency
Q_{total}	Total heat losses
X_i	Weight fraction

I. Introduction

The continuous increase of energy consumption and the environmental effects of fossil fuel combustion are some of the causes promoting the development of alternative clean energy systems Biomass gasification is a helpful process for adding value to solid residues and agroindustrial waste which are not harnessed in some developing countries. In this way, this process becomes an alternative for either electricity generation or heating applications in rural places where the lack of these services encumbers the economic development.

This process implies the thermal partial oxidation of biomass to produce a more valuable gaseous fuel known as syngas which consists of a mixture of mainly CO and H_2 with CH_4 and CO_2 and other byproducts. The process conditions and final composition of the syngas vary depending on the reactor configuration and design. There are some new types of gasifier resulting from research and development, including the pressurized spout-fluid bed [1], the bubbling fluidized bed reactor [2], and the twin fluidized bed reactors [3] nevertheless.

The most common systems available in industrial scales are fluidized bed, updraft fixed bed, and downdraft fixed bed gasifier. In the fluidized bed gasifier, the gasification agent moves upwards with pressure enough to fluidize the fine biomass inside, enhancing the surface area and the efficiency [4]; nevertheless, this process requires advanced control system making it non-affordable for small and medium scale power plants. The updraft fixed bed gasifier has a similar behavior because biomass falls and gasification agent rises throughout the reactor, but herein biomass does not float and remains fixed in the equipment making it less expensive. This reactor is adequate where an external heating source is available because it needs to maintain the temperature profile. Finally, there is the downdraft fixed bed gasifier where biomass falls, and gasification agent moves through the system in the same direction.

The gasification agent is fed into a throat located between the hopper and the reactor promoting combustion reactions that release energy enough to

 DOI: 10.15866/ireme.v10i4.8935

maintain the process steady. Despite the results using pure oxygen, steam or CO_2 [5], air is still the most common gasification agent.

This process can be divided into four stages based on the changes of biomass chemical and physical properties.

The first stage occurs in the upper part of the reactor, where the temperature is lower than 150°C. Herein, the biomass gains energy and its humidity boil resulting on a dry solid. Later, the dry biomass moves downwards where the temperature is still higher, in the 200-550°C range; hence, pyrolysis reactions take place and volatile matter burns out of the solid producing a gaseous stream, made of volatile substances, and solid char.

Next, both currents, solid and gaseous, move to the throat of the reactor where they mix with the incoming gasification agent. In this zone oxidation reactions occur and release energy enough to maintain the process.

Afterward, there is the last zone where reduction reactions take place defining the final syngas composition. In this stage, there are simultaneous reactions taking place [6]. They are shown as follows:

Water –gas reaction:

$$C + H_2O \rightarrow CO + H_2 \quad (1)$$

Boudouard Reaction:

$$C + CO_2 \leftrightarrow 2CO \quad (2)$$

Shift reaction:

$$CO_2 + H_2 \leftrightarrow CO + H_2O \quad (3)$$

Methanation reaction:

$$C + 2H_2 \leftrightarrow CH_4 \quad (4)$$

Downdraft gasifiers have demonstrated to be feasible alternatives for generating electricity in rural areas where biomass is available. Therefore, more research has been done in this area varying biomass species.

Erlich and Fransson [7] analyzed the performance of a 20kWth pellet-fired downdraft gasifier when either wood pellets or bagasse respectively Empty Bunch Fruits were fed. Simone et al. [8] compared the feasibility and reliability of using wood pellets and sunflower seeds pellets into a 200kW downdraft gasifier. Prasad et al.[9] carried out an analysis of Pongomia de-oiled cake gasification. Roy et al.[10] simulated the behavior of a reactor using Wheat Straw, Rice Straw, and Coconut Shells and compared the performance when woody biomass was the feedstock They concluded that non-woody fuels led to fewer fuel costs than woody biomass showing the potential of these resources.

Most of the research available in the literature aims to either simulate the process or find the cold gas efficiency using prototype and small scale gasification power systems without analyzing the energy losses distribution.

This work aims to evaluate the performance of a commercial downdraft gasifier power system capable of generating electricity fuelled with Coconut shells.

Moreover, the scope of this work is to identify the total electrical efficiency of the system, and a methodology for calculating the losses due to the convection and radiation heat transfer mechanisms based on an exhaustive analysis using dimensionless coefficients and thermography results.

II. Methods and Materials

II.1. Downdraft Fixed Bed Gasifier Set Up

The tests were performed in the laboratory of Thermal Plants and Renewable Energies in the Universidad Nacional de Colombia (4.638°N -74.084°W, 2630m above sea level). Figure 1showsthe layout of the test setup. There is an AnkurWBG-20 Gasification power system, which consists of a WBG-20 downdraft fixed bed gasifier, the gas cleaning system, and a Prakash PNG15BG gas engine.

The gasifier has a hopper capable of containing 120kg biomass; although, the total capacity of the system varies depending upon the biomass density. Air goes into the system by two entrances located at side of the hopper. The air reacts with the pyrolyzed biomass in the throat, producing heat.

The hopper is located over the reactor; it consists of two welded cylindrical vessels made of stainless steel. The inner part contains the char produced after fast biomass combustion and has a ceramic cover inside aimed to decrease heat losses by conduction, convection and radiation to the outer vessel and the atmosphere. In this part, gasification reactions take place producing syngas and ashes.

This inner vessel has an ash removal system in the bottom; it takes out the ashes and disposes them into the lower part of the external vessel. Moreover, the syngas gets out from the inner to the outer vessel, which is attached to the cleaning system.

The first device of this system is a venturi tube, where the syngas mixes with cold water so rapidly, cooling the gas and condensing the tars. Afterwards, the mixture moves into the hydrocyclone, where the liquid stream, made of water and tars, goes downwards into a recovery vessel and the gaseous stream, wet syngas, moves towards the filters. The first one is a passive filter fed with sawdust; that dries the wet syngas and removes the remaining tars.

Next, there is a membrane security filter capable of retaining fine solid particles. After cleaning, the syngas can be burnt either in the chimney or the gas engine. During the start-up stage, the syngas goes into the chimney until the chemical composition reaches a stable state adequate for the gas engine.

The syngas composition is recorded by using an Emerson X-stream gas analyzer, which measures the CO, CO_2 content in syngas.

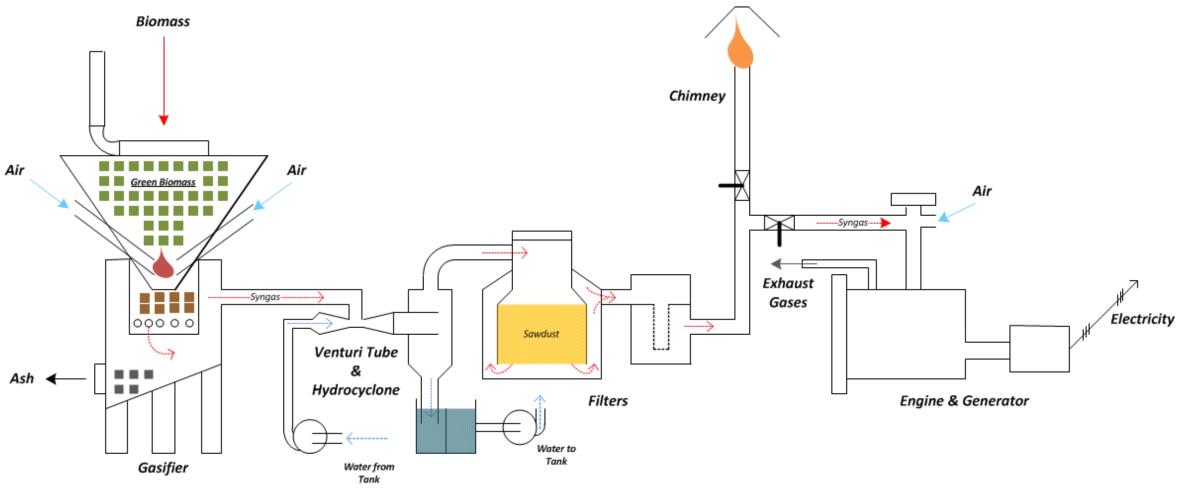

Fig. 1. Test set-up general layout

II.2. Biomass Characterization

Coconut shells were provided by Acquaire Ltda. They were ground and dried at ambient conditions. Proximate analysis was performed, and parameters like moisture, volatile matter, fixed carbon, and ash content were determined according to ASTM D3173, ASTM D3174, and ASTM D3175.

The ultimate analysis was assumed to the one presented on a previous work [14]. Higher and lower heating values were calculated using the results of proximate and ultimate analysis according to Obenberger and Thek [11]:

$$HHV = 0{,}3491X_c + 1{,}1783X_H + \\ +0{,}1005X_S - 0{,}0151X_N - 0{,}1034X_O + \\ -0{,}0211X_{ash} \quad (5)$$

$$LHV = HHV\left(1-\left(\frac{X_W}{100}\right)\right) - 2{,}447\left(\frac{X_W}{100}\right) + \\ -\left(\frac{X_H}{200}\right) \times 18{,}02 \times 2{,}447 \times \left(1-\left(\frac{X_H}{100}\right)\right) \quad (6)$$

where, HHV [MJkg^{-1}] corresponds to the higher heating value, and X_i is the content of C, H, S, N, O, and Ash in wt% (d.b) from the ultimate analysis.

Moreover, LHV [MJkg^{-1}] is the lower heating value, and X_W is the moisture content in wt% (wb).

II.3. Energy Efficiency Calculation

Two types of efficiency were analyzed. First, the total electric efficiency defined as the ratio between the electricity supplied to the thermal power provided by combustion of biomass. Secondly, the cold gas efficiency calculated as the ratio between the power available in the syngas and the thermal energy of biomass. The previous parameters were defined as follows:

$$\eta_{electric} = \frac{Pe}{\dot{m}_{biomass} \cdot LHV_{biomass}} \quad (7)$$

$$CGE = \frac{\dot{V}_{syngas} \cdot LHV_{syngas}}{\dot{m}_{Biomass} \cdot LHV_{biomass}} \quad (8)$$

where, $n_{electric}$ is the total electric efficiency, *Pe* [kW] relates the electrical power, $m_{biomass}$ [kgs^{-1}] is the biomass consumption, $LHV_{biomass}$ [kJkg^{-1}] is the biomass lower heating value. Moreover, CGE is the cold gas efficiency, V_{syngas} [Nm^{3}s^{-1}] means the syngas volumetric flow rate, and LHV_{syngas} [kJNm^{-3}] is the syngas lower heating value. The Power produced was calculated as the product of Voltage, Current, and the power factor for a three-phase electrical generator.

Biomass consumed was determined as the difference between the initial and final biomass load in the hopper divided by the time. As a result of the mass balance on the reactor, it is possible to establish the dry syngas mass flow rate, neglecting tars condensed into the water:

$$Coconut + a(O_2 + 3{,}76N_2) \rightarrow CO + CO_2 + \\ +H_2 + O_2 + CH_4 + 3{,}76aN_2 + tars + ash \quad (9)$$

$$C_{biomass} = C_{CO} + C_{CO_2} + C_{CH_4} \quad (10)$$

$$\frac{X_{C_{biomass}} \cdot \dot{m}_{d.biomass}}{MW_C} = \\ = \frac{\dot{m}_{syngas}}{MW_{syngas}} \cdot (X_{CO} + X_{CO_2} + X_{CH_4}) \quad (11)$$

where, $X_{Cbiomass}$ [wt%] is the carbon content in the biomass, $mb_{d.biomass}$ [kgs^{-1}] the dry biomass mass flow rate, MW_i[kgkmol^{-1}] the molar weight of C, CO, CO_2 and CH_4, $m_{d.syngas}$ [kgs^{-1}] the syngas mass flow rate, MW_{syngas}[kgkmol^{-1}] the molar weight of syngas.

The Syngas composition was established based on a comparison of data provided with the Emerson X-stream Gas Analyzer and results available in the literature.

Dry syngas molar weight results from the sum of the molar weight of each component times the molar fraction in the syngas. Syngas heating value is evaluated in accordance with Prasad et. al[9]. Table I exhibits the heating value of each substance embedded in the syngas:

$$LHV_{syngas} = (X_{CO} \cdot LHV_{CO}) + (X_{H_2} \cdot LHV_{H_2}) + \\ +(X_{CO_2} \cdot LHV_{CO_2}) \quad (12)$$

TABLE I
HEATING VALUE OF THE COMPOUNDS AVAILABLE CONTAINED SYNGAS

Compound	HV ($MJNm^{-3}$)
CO_2	0
CO	12,71
H_2	12,78
N2	0
CH4	39,76

II.4. Convection and Radiation Heat Losses

Heat losses by convection and radiation were calculated by Newton laws. The temperature profile was measured using a Fluke Ti10Infrared Thermal Imaging Camera, and compared with some data recorded with K-type thermocouple at five points throughout the reactor surface. Meanwhile, the ambient temperature and moisture were documented. The temperature was assumed constant at the same height around the reactor.

On that manner, the total heat losses were calculated as the sum of the flux at different sections:

$$Q_{total} = \sum_{n=1}^{5} \left(Q_{conv_{s_i}} + Q_{rad_{s_i}}\right) \quad (13)$$

$$Q_{conv} = h_i A (T_{xi} - T_{\infty i}) \quad (14)$$

$$Q_{rad} = \sigma \cdot \varepsilon \cdot A \cdot ({T_{xi}}^4 - {T_{\infty i}}^4) \quad (15)$$

where, Q_{convi} [kJs^{-1}] is the heat losses by convection at section i, h_i [$Wm^{-2}K^{-1}$] the specific convection heat coefficient, A [m^2] the external area, T_{xi} [K] the specific temperature in the surface, T_∞ [K] is the ambient temperature. Meanwhile, Q_{radsi} [kJs^{-1}] means the radiation heat losses at section i, σ is the Stefan-Boltzmann constant, ε the emissivity of the material [12].

Calculating the convective heat losses is a complex task when the specific convection heat coefficient is unknown. The area and temperatures could result from practical tests; whereas, the coefficient should be calculated as a function of Nusselt, Rayleigh and Prandtl dimensionless numbers assuming natural convection and a vertical plate [13]. Specific convection heat coefficient h_i, depends upon the convection heat loss Nusselt number Nu, the air conduction constant k_i [$Wm^{-1}K^{-1}$] and the characteristic length Lc [m]:

$$h_i = \frac{(k_i \cdot Nu)}{L_c} \quad (16)$$

$$Nu = \left(0{,}825 + \frac{0{,}387 Ra^{\frac{1}{5}}}{\left(1 + 0{,}492^{\frac{9}{16}}\right)^{\frac{8}{27}}}\right)^2 \quad (17)$$

$$Ra_L = \frac{g \cdot \beta_i \cdot (T_{xi} - T_\infty) \cdot Lc}{\nu^2} \cdot Pr \quad (18)$$

$$Pr = \frac{(\mu_i \cdot Cp_i)}{k_i} \quad (19)$$

$$\beta_i = \frac{1}{T_{fi}} \quad (20)$$

The equations above exhibit the procedure to evaluate Nusselt from Rayleigh and Prandtl Numbers. Where, g [ms^{-2}] corresponds to the gravitational constant, βi [K^{-1}] the inverse average fluid temperature and ν [m^2s^{-1}] is the ratio between the dynamic viscosity μ [Nsm^{-2}] against the air density ρ [kgm^{-3}]. Likewise, Prandtl depends on the specific heat capacity Cp [$Kkg^{-1}K^{-1}$] and air conductivity ki [$Wm^{-1}K^{-1}$]. Tfi [K] is the average temperature between the ambient and surface.

Fluid parameters such as air viscosity, density, conductivity, and specific heat constant slightly change due to temperature differences; hence, it is important to correlate these properties with the temperature.

Aspen Properties provides the values at different temperatures; afterwards, these values were plotted and their trend line determined:

$$\mu\ [\mathrm{Nsm^{-2}}] = 3{,}6425 \times 10^8 \times T + 1{,}8148 \times 10^5 \quad (21)$$

$$cp\ [\mathrm{Jkg^{-1}K^{-1}}] = 990{,}88 \times e^{0{,}0002T} \quad (22)$$

$$k_i [\mathrm{Wm^{-1}K^{-1}}] = 7{,}0744 \times 10^{-5} \times T + \\ +2{,}423 \times 10^{-2} \quad (23)$$

$$\rho = 1{,}165555 \times e^{-2{,}01578T} \quad (24)$$

III. Results

Coconut shells have a remarkable energy potential based on their proximate analysis. Moisture content was less than 11%, whereas fixed carbon and volatile matter comprehended about 85%wt.

Table II summarizes the results of the proximate analysis. Comparing the results with literature is possible to establish the importance of making this analysis beforehand because biomass characteristics varied due to parameters like source, or time stored.

In a previous work, we obtained 1,26% ash content and 12% moisture [14]. Likewise, Satnislav et al [15] gathered the composition of several biomass samples including Coconut shells; in this case, the ash content was 3,1%, but moisture content less than 4,5%.

TABLE II
PROXIMATE ANALYSIS OF COCONUT SHELLS

Parameter (%w.b)	Value
Moisture	10,46
Volatile Matter	67,67
Fixed Carbon	18,29
Ash Content	3,58
Sum	100

According to Van Krevelen diagram [16], coconut shells have an interesting potential and an increased heating value in comparison with traditional biomass like wood. The atomic H/C ratio is 0,11, and the O/C ratio equals to 0,84. Ultimate analysis and calculated heating value are presented in Table III.

The initial biomass load was 133,8kg Coconut shells; after finishing the tests, we recorded the final biomass load and determined that biomass consumption rate was 8,27kgh^{-1}. This meant a thermal power input of 38,62kWth and electrical efficiency of 20,71% with a maximum 8kWe electrical power output.

Cold Gas Efficiency depended on syngas volumetric flow and heating value. Syngas composition varied with time since the equipment started up until it reached its stable point. At this moment, the CO/CO_2 ratio was 0,94, and the maximum CO and CO_2 content in the syngas were13,2 and 14,1 respectively. To establish the composition of this gaseous fuel, we summarized different results available in the literature for downdraft fixed bed gasifiers with a wide variety of biomass and analyzed the relationship between the CO against CO/N_2, CO/H_2, and CO/CH_4 ratio. These results are shown in Table IV.

The results showed a remarkable behavior to obtain an approximate syngas composition based on the CO content without the installation of expensive gas analyzers. Useful for power systems installed in rural places where financial support is not an easy task. Polynomial trend-lines accurately describe the CO/CO_2, CO/N_2 against CO content in the syngas as presented in Fig. 2. The CO/CO_2 ratio is a remarkable manner for analyzing the equilibrium between these products in the syngas, based on the fact that the main objective of gasification is to transform biomass into a gaseous fuel with high heating values.

When CO content moves upwards the CO/CO_2 relationship should increase too because of equilibrium displacement in the water gas shift reaction [18] occurring in the final stage of the downdraft reactor.

There is not a simple relation between H_2 and CH_4 production against CO generation because several chemical reactions are occurring at the same time inside the reactor. Some of them are steam reforming of methane [18], water gas shift reaction, particle surface reactions like char combustion, and char reduction of CO_2, H_2 and H_2O[16]. Nevertheless, finding an approximate CH_4 and H_2 content based on CO is possible using a polynomial trend line of CH_4/CO_2 and H_2/CO_2 ratios (Fig. 3).

Despite the fact that these trends are not as accurate as the previous, they exhibited a good correlation with the results available in the literature.

TABLE III
ULTIMATE ANALYSIS, CALCULATED HIGHER AND LOWER HEATING VALUE FOR COCONUT SHELLS

C wt%	O wt%	H wt%	N wt%	S wt%	Sum	HHV MJkg^{-1}	LHV MJkg^{-1}
51,1	43,1	5,6	0,1	0,10	100	21,481	16,82

TABLE IV
PUBLISHED AND CALCULATED SYNGAS COMPOSITIONS RESULTING FROM BIOMASS GASIFICATION USING DOWNDRAFT GASIFIERS

Ref.		[7]		[8]	[17]	[18]	[19]	[10]	[9]	Calc.
N_2	50,4	53,3	55,0	49,5	55,83	47,7	64,45	53	71,44	61,2
CO	25,7	17,0	17,4	19,7	18,56	22,3	11,38	18,2	10,93	13,2
H_2	11,9	13,5	12,9	15,8	11,11	15,9	5,77	15,2	7,44	9,92
CH_4	2,6	1,9	1,5	2,30	2,15	3,1	1,93	5,9	1,02	1,56
CO_2	9,9	14,5	13,7	11,60	11,22	11	16,81	13,1	11,46	14,11
$\sum$	100,5	100,2	100,5	98,9	98,87	100	100,34	105,4	102,29	100,09
CO/CO_2	2,60	1,17	1,27	1,70	1,65	2,03	0,68	1,39	0,95	0,94
CO/N_2	0,51	0,32	0,32	0,40	0,33	0,47	0,18	0,34	0,15	0,22
H_2/CO_2	1,20	0,93	0,94	1,36	0,99	1,45	0,34	1,16	0,65	0,70
CH_4/CO_2	0,26	0,13	0,11	0,20	0,19	0,28	0,11	0,45	0,09	0,11

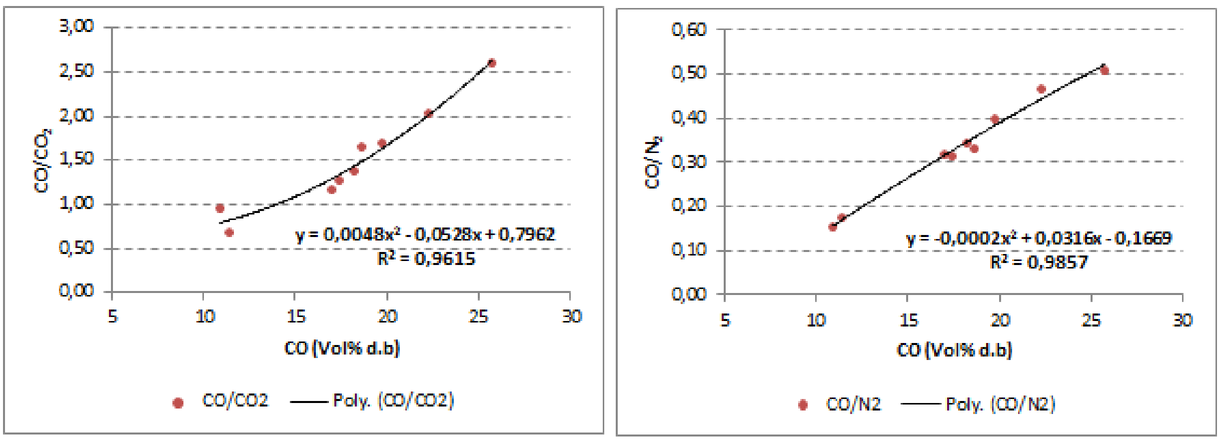

Fig. 2. Existing relationship between CO/CO_2 and CO/N_2 ratio as a function of CO content in syngas based on results published by various authors using downdraft gasifiers

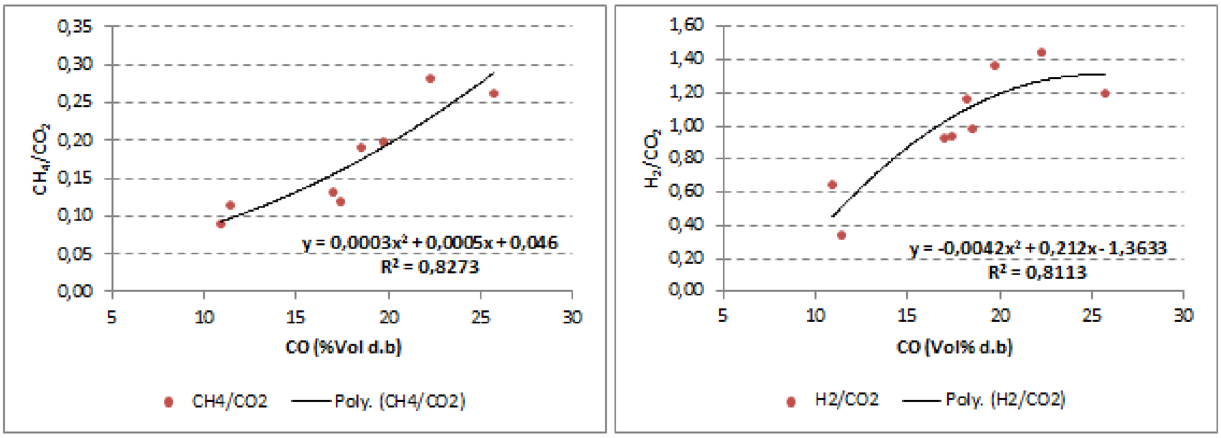

Fig. 3. Approximation of CH_4/CO_2 and H_2/CO_2 ratio as a function of CO content in syngas, using results available in literature for downdraft gasification systems

Based on the composition presented before, the syngas heating value was 3,57MJ/Nm^3. Thus, the cold gas efficiency in this system corresponded to 53,95%; Table V summarizes the energy analysis in the WBG-20 Biomass gasifier using coconut shells.

These parameters are typical for biomass gasification systems as summarized in literature [20].

The temperatures were constant after the system stabilization; although, they varied throughout the reactor height as presented in Figs. 4. Maximum temperature near the junction was about 160°C decreasing to 30°C at the bottom. The total area of the external surface was divided into five proportional zones and heat losses calculated for each one.

Convection heat losses calculation depended on air parameters like viscosity, heat capacity, density, and conductivity. However, the heat losses due to convection for each zone changed from 34 to 345,6 Wth while the temperature rose. Also, the radiation heat losses were 11Wth in the lowest zone and 116 Wth in the warmer zone. In both cases, the heat flux increased proportional to the surface temperature; although the same thermal gradient affects more the losses by convection than by radiation. Table VI exhibits the mean temperature along the reactor and their corresponding losses.

Moreover, the sum of the losses in each area is the total heat losses due to convection and radiation from the surface to the ambient. The total heat losses were 1,28 kWth meaning 3,32% of the total thermal energy released by biomass combustion. Convection heat flux was 2,52%; whereas, losses due to radiation was 0,80%.

TABLE V
PERFORMANCE OF THE WBG-20 DOWNDRAFT FIXED BED GASIFIER USING COCONUT SHELLS

Parameter		Unit
Mass consumption	8,27	kgh^{-1}
Thermal power input	38,62	kWth
Syngas flow rate	21,02	Nm^{3}h^{-1}
Syngas thermal power	20,84	kWth
Electrical power	8,00	kWe
Cold Gas Efficiency	53,95	%
Motor Efficiency	38,39	%
Total Electrical Efficiency	20,71	%

Figs. 4. (a)Temperature measurement placement along the reactor and (b) thermography of this vessel under stable conditions

TABLE VI
TEMPERATURE, DIMENSIONLESS COEFFICIENTS, CONVECTION, RADIATION AND TOTAL HEAT LOSSES ALONG THE REACTOR SURFACE

Position	*T* °C	*Pr*	*Ra*	*Nu*	Q_{conv} *W*	Q_{rad} *W*	Q_{area} *W*
T1	140,5	0,668	288002,37	27,80	345,65	116,41	462,06
T2	125,8	0,669	283782,30	27,66	296,71	96,60	392,31
T3	85,6	0,670	243737,56	26,28	167,01	49,35	216,36
T4	73	0,670	219191,49	25,37	128,69	37,71	166,40
T5	38	0,672	105325,98	19,91	34,64	11,43	46,07
∑					972,69	310,51	1283,20

IV. Conclusion

Coconut shells gasification showed an interesting performance for either syngas production or electricity generation.

The total electrical efficiency was about 20,7%, lower than conventional fossil-fired energy systems, but with the outstanding advantage of using a non-value and clean byproduct from agroindustrial systems. The downdraft fixed bed gasifier reached 54% cold gas efficiency, producing 21 Nm^{3}h^{-1}syngas which is in accordance with the rated gas production defined by the manufacturer. Based on the electrical power and syngas production, the efficiency of the internal combustion engine was about 38% in the range of gas-fired gensets. Empirical functions were defined to identify an accurate syngas composition based on the CO and CO_2 measurements relating these parameters with the CO/CO_2, CO/N_2 ratios in such a precise way. Moreover, H_2 and CH_4 could be approximated using the H_2/CO_2 and CH_4/CO_2 ratios.

Heat losses due to convection and radiation mechanisms from the surface of the reactor to the environment were calculated using an exhaustive method based on dimensionless numbers; they corresponded to 2,5 and 0,8% respectively of total thermal energy supply.

This meant that despite the temperatures reached, about 120°C, the losses in this section were not significant. Infrared thermography was employed to analyze the temperature distribution and some hot-spots along the reactor. Other heat losses, which may require further analysis, are the remaining calorific potential contained in the ashes, sensible heat lost during mixing of gas with water in the venturi tube, heat losses from the fin created in the junction between the hopper and the reactor, and tars produced which were neglected in this study.

Acknowledgements

The authors kindly acknowledge the financial support of COLCIENCIAS under the project code 1101-543-32104 and contract number 0464-2013.

References

[1] Deng, Zhongyi., Xiao, Rui., Jin, Baosheng., Huang, He., Shen, Liahong., Song, Qilei., Li, Qianjun. Computational Fluid Dynamics Modeling of Coal Gasification in a Pressurized Spout-Fluid Bed. *Energy & Fuels.* ACS, 2008. 22, 1560-1569 ISSN: 0887-0624. http://pubs.acs.org/doi/abs/10.1021/ef7007437

[2] Kaushal, Priyanka., Abedi, Jalal., Mahinpey, Nader. A comprehensive mathematical model for biomass gasification in a bubbling fluidized bed reactor. *Fuel,* Elsevier 2010. 89, 3650-3661. ISSN: 0016-2361. http://dx.doi.org/10.1016/j.fuel.2010.07.036

[3] Ruiz, J.A., Juárez, M.C., Morlaes, M.P., Muñoz, P., Meindívil, M.A. Biomass gasification for electricity generation: Review of current technology barriers. *Renewable and Sustainable Energy Reviews*, Elsevier, 2013. 18, 174-183. ISSN: 1364-0321. http://dx.doi.org/10.1016/j.rser.2012.10.021

[4] Alauddin, Zainal Alimuddin Bin Zainal., Lahijani, Pooya., Mohammadi, Maedeh., Mohamed, Abdul Rahman. Gasification of lignocellulosic biomass in fluidized beds for renewable energy development: A review. *Renewable and Sustainable Energy Reviews*, Elsevier, 2010. 14, 2852-2862. ISSN: 1364-0321. http://dx.doi.org/10.1016/j.rser.2010.07.026

[5] Wang, Lijun., Weller, Curtis L., Jones, David D., Hanna, Milford A. Contemporary issues in thermal gasification of biomass and its application to electricity and fuel production. *Biomass and Bioenergy*, Elsevier, 2008. 32, 573-581. ISSN: 0961-9534. http://dx.doi.org/10.1016/j.biombioe.2007.12.007

[6] Puig Arnavat, Maria., Bruno, Joan Carles., Coronas, Alberto. Review and analysis of biomass gasification models. *Renewable and Sustainable Energy Reviews,* Elsevier, 2010. 14, 2841-2851. ISSN: 1364-0321. http://dx.doi.org/10.1016/j.rser.2010.07.030

[7] Erlich, Catharina., Fransson, Torsten H. Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse: Experimental Study. *Applied Energy,* Elsevier, 2011. 88, 899-908. ISSN: 0306-2619. http://dx.doi.org/10.1016/j.apenergy.2010.08.028

[8] Simone, Marco., Barontini, Federica., Nicolella, Cristiano., Tognotti, Leonardo. Gasification of pelletized biomass in a pilot scale downdraft gasifier. *Bioresource Technology,* Elsevier, 2012. 116, 403-412. ISSN: 0960-8524. http://dx.doi.org/10.1016/j.biortech.2012.03.119

[9] Prasad, Lalta., Subbarao, P.M.V., Subrahmanyam, J.P. Pyrolysisi and gasification characteristics of Pongamia residue (de-oiled cake) using thermogravimetry and downdraft gasifier. *Applied Thermal Engineering*, Elsevier, 2014. 63, 379-386. ISSN: 1359-4311. http://dx.doi.org/10.1016/j.applthermaleng.2013.11.005

[10] Roy, P.C., Datta, A., Chakraborty, N. An assessment of different biomass feedstocks in a downdraft gasifier for engine application. *Fuel*, Elsevier 2013. 106, 864-868. ISSN: 0016-2361. http://dx.doi.org/10.1016/j.fuel.2012.12.053

[11] Obernberger, Ingwald., Thek, Gerold. Physical characterization and chemical composition of densified biomass fuels with regard to their combustion behavior.*Biomass and Bioenergy*, Elsevier, 2002. 27, 653-669. ISSN: 0961-9534. http://dx.doi.org/10.1016/j.biombioe.2003.07.006

[12] Perry, Robert H., Green, Don W. Perry´s chemical engineering handbook. McGraw Hill, 1999. ISBN: 0-07-049841-5.

[13] ASHRAE.*ASHRAE Fundamentals Handbook.* s.l. : AHRAE, Inc, 2009. ISBN: 978-1-61583-170-8.

[14] Forero Núñez, Carlos A., Castellanos Contreras, Jose U., Sierra Vargas, Fabio E. Control de una planta prototipo de gasificación de biomasa mediante redes neuronales. *Ingeniería Mecánica Tecnología y Desarrollo.* Sociedad Mexicana de Ingeniería Mecánica, 2013. 4, 161-168. ISSN: 1665-7381. http://revistasomim.net/revistas/4_5/vol4.5.2.pdf

[15] Vassilev, Stanislav V., Baxter, David., Andersen, Lars K., Vassileva, Christina. An overview of the chemical composition of biomass. *Fuel,* Elsevier 2010. 89, 913-933. ISSN: 0016-2361. http://dx.doi.org/10.1016/j.fuel.2009.10.022

[16] Janajreh, I., Al Sharah, M. Numerical and experimental investigation of downdraft gasification of wood chips. *Energy Conversion and Management*, Elsevier, 2013. 65, 783-792. ISSN: 0196-8904. http://dx.doi.org/10.1016/j.enconman.2012.03.009

[17] Dogru, M., Howarth, C.R., Akay, G., Keskinler, B., Malik, A.A. Gasification of hazelnut shells in a downdraft gasifier. *Energy,* Elsevier, 2002. 27, 415-427. ISSN: 0360-5442. http://dx.doi.org/10.1016/S0360-5442(01)00094-9

[18] Di Blasi, C., Branca, C. Modeling a stratified downdraft Wood gasififer with primary and secondary air entry. *Fuel,* Elsevier 2013. 104, 847-860. ISSN: 0016-2361. http://dx.doi.org/10.1016/j.fuel.2012.10.014

[19] Lenis, Yuhan A., Agudelo, Andres F., Pérez Juan F. Analysis of statistical repeatability of a fixed bed downdraft biomass gasification facility. *Applied Thermal Engineering,* Elsevier 2013. 51, 1006-1016. ISSN: 1359-4311. http://dx.doi.org/10.1016/j.applthermaleng.2012.09.046

[20] Ahrenfeldt, Jesper., Thomsen, Tobias P., Henriksen, Ulrik., Clausen, Lasse R. Biomass gasification cogeneration - review of state of the art technology and near future perspectives. *Applied Thermal Engineering*, Elsevier 2013. 50, 1407-1417. ISSN: 1359-4311. http://dx.doi.org/10.1016/j.applthermaleng.2011.12.040

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