CARBON CAPTURE AND STORAGE IN BIOMASS COMBUSTION PROCESS

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ABSTRACT

Biomass stores solar energy that man can convert into electricity, fuel or heat, resulting in cheap, clean energy with a negative carbon balance.

The use of biomass from agricultural secondary production as a potential energy source can improve soil quality and reduce greenhouse gas emissions in a complementary, non-competing way.

The paper presents a piece of combustion equipment performing the burning process by biomass gasification on the TLUD (Top-Lit UpDraft) principle, from which hot air and biochar are obtained.

The main function of this type of gas generator set on the TLUD principle is to generate a syngas flame which can be used as a heat source. The biochar obtained as a by-product is a sterile, active carbon with a large adsorption surface which is used as a soil amendment in environments with limited capacity for carbon sequestration and in soils depleted of resources.

Gasification on the TLUD principle occurs when the biomass layer is introduced into the reactor and rests on a grate through which the air flow for gasification passes from bottom to top. Priming of the gasification process is done by igniting the upper layer of biomass in the reactor. The oxidation front continuously descends consuming the biomass in the reactor. Due to the heat radiated by the oxidation front the biomass is heated, dried, and then it enters a fast pyrolysis process from which volatiles emerge and unconverted carbon remains there.

When the combustion front reached the grate, all the volatiles in the biomass were gasified and some of the carbon fixed was reduced; about 10 - 20% of the initial mass in the form of sterile charcoal, called biochar, remains on the grill.

Compared to wood direct combustion or gasification combustion processes, the TLUD gasification process is characterized by very low values of the superficial velocity of gas passing through the pyrolysis front. The slow process maintains superficial velocity of the generator gas produced at very low values, which ensures reduced carrying away of free ash of approximate size below PM2.5 and maxim values of 5 mg/MJbm when leaving the burner; such values are well below the target

imposed in the EU in 2015 for biomass combustion processes, which is below 25 mg/MJ.

The result of monitoring the gasification process can be used to automate and optimize the TLUD process in order to achieve green energy, for carbon sequestration in the obtained biochar and to reduce greenhouse gas emissions, thus contributing to achieving efficient protection of the environment and to ensuring sustainable energy development.

Keywords: *TLUD (Top-Lit UpDraft), biomass, gasification, biochar, heating*

INTRODUCTION

An exigence nowadays is the development and use of environmentally friendly and economical technologies for the production of clean energy, in sufficient quantities. The name "clean" refers in particular to the minimal impact that the energy production technology should have on the environment. There is a lot of discussion about excessive CO2 or (re)active gas emissions which can reduce the thickness of the protective ozone layer, characterizing human activity and existence, and implicitly the activity of energy production through conventional technologies. Lately, in many countries research efforts are being made with respect to unconventional energies (wind, solar, geothermal, hydroelectric, or biomass), which are an alternative to using fossil fuels.

Free combustion of agricultural biomass from residual production produces a large amount of pollutant emissions as well as a massive waste of thermal energy. Modern methods of biomass combustion are based on processes of densifying into pellets or briquettes and combustion in furnaces with high combustion air velocities, which results in high PM and CO2 emissions. Densifying of biomass consumes quite a large amount of energy, on average 5 ... 8% of the energy of non-densified biomass; it requires high electric power expensive facilities, and to the production cost one should add the cost of long-distance transport from the place of harvesting to the place of processing. It should be mentioned that pelletizing indirectly produces CO2 emission related to the electricity consumed in the process, but it has the advantage that the densified biomass can be burned in fully automated plants and it ensures a continuous and controllable production of thermal energy.

A solution for solving the problems of eco-efficient combustion of local, agricultural and forestry biomass is the use of thermochemical gasification on the TLUD principle (Top-Lit UpDraft) [1], which produces thermal energy with polluting emissions under the norms imposed for the year 2020, with conversion efficiency up to 85% and about 10..20% residual coal, not converted to gas, commonly referred to as biochar. This is a good amendment for agricultural soils and reduces the CO2 concentration in the environment by sequestering carbon in the soil for long periods.

MATERIAL AND METHODS

In order to produce thermal energy (hot air) from biomass and biochar, the thermochemical gasification of biomass on the TLUD (Top-Lit UpDraft) principle is considered. This process is efficient in low power applications; it is little demanding with respect to the quality of the biomass to be gasified, and the equipment has a simple and cheap structure.

Through thermochemical gasification, the biomass is oxidized in the reactor with 20-30% of the air required for stoichiometric combustion. The resulting gas, called “generator gas”, has a typical average composition: CO – 20%, H_2 – 18%, CO_2 – 10%, CH_4 – 4%, and remainings - N_2. The efficiency of conversion into thermal energy varies depending on the gasification process, the characteristics of the biomass used, and the level of insulation of the equipment, in the range of 75...85%. The calorific value of the gas produced is PCIgas □(4.5...5.5) MJ/Nm^3 depending on chemical composition and moisture content of the biomass. [2]

Table 1 presents the results obtained regarding the quality and quantity of the resulting generator gas and biochar. They differ both in the combustion mode and in the control of the gasification air in the TLUD reactor.

Table 1. Typical yields of biomass (dry basis) for different combustion modes [3]

Mode	Conditions	Liquid	Char	Gas
Fast	Moderate temperature ~ 500°C short vapor residence time ~ 1 s	75%	12%	13%
Moderate	moderate temperature ~ 500°C moderate vapor residence time ~ 10-20 s	50%	20%	30%
Slow	moderate temperature ~ 500°C very long vapor residence time ~ 5-30 min	30%	35%	35%
Gasification	high temperature > 750°C moderate vapor residence time ~ 10-20 s	5%	10%	85%

The operating principle of the TLUD type gas generator set is shown in figure 1. The gas generator set is composed of an up-draft gasifier coupled to a burner. The biomass is introduced into the reactor and rests on a grate through which the primary air for gasification passes from bottom to top. Ignition and initiation of the pyrolytic front is done at the top of the gas generator, and it advances into the biomass layer. The pyrolysis results in gas, tar and coal. The tar passes through the incandescent coal layer, is cracked and totally reduced due to the heat radiated by the pyrolysis front and by the flame at the top. The resulting gas is mixed with the secondary combustion air which is preheated by the reactor wall and is introduced into the combustion zone through the openings at the top of the reactor. The mixture with high turbulence burns with flame at temperatures of about 900ºC.

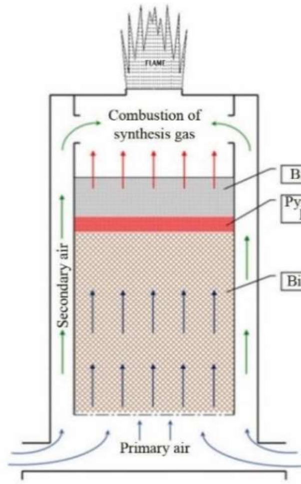

Fig.1. Functional diagram of the energy module type TLUD [4].

The biochar obtained as a by-product of gasification on the TLUD principle is a sterile charcoal obtained from pyrolysis of wood biomass in an oxygen-free environment or with a substoichiometric concentration. It has a carbon content of 75-90% and is characterized by high porosity with high adsorption capacity. The biochar can be used as an agricultural amendment to increase soil fertility, as well as a filter material for air, gas and water. Incorporated in the soil, it represents the most economical and ecological way to sequester atmospheric carbon for long periods of time.

Transformation of plant material into biochar has several advantages. The pieces of char can be the host for billions of microorganisms beneficial to the soil. Moreover, plant roots can grow between them and even in these pieces of biochar, feeding on nutrients stored in the porous char. It acts as a sponge that retains water and allows the roots to absorb it slowly in periods between rainfalls or irrigation. The biochar is not biologically active, does not degrade and does not return CO2 to the atmosphere.

Almost any form of organic natural (wood) material can be transformed into biochar. Therefore, the materials considered organic waste can be transformed into energy and biochar, helping to reduce greenhouse gas emissions and contributing to effective environmental protection and to ensuring sustainable energy development.

THEORY AND CALCULATION

From literature [4], [5], [6], [7], [8] it turns out that the gasification process is carried out at reduced feed rate of the pyrolytic front, with a specific hourly consumption of biomass of 80 - 150 kg/m²h, which results in reduced specific reactor powers of 250 - 350 kW / m². The slow process maintains the superficial velocity of gases in the reactor at very low values, $v \leq 0.06$ m / s, and does not allow carrying along of free ash particles larger than PM2.5, reaching up to 5 mg / MJbm when leaving the burner; this value is at least five times lower than the current standards required for solid fuel heat generators.

The stages of the gasification process (drying, pyrolysis, oxidation and reduction) take place simultaneously in different areas of the reactor.

Drying is necessary because the moisture content of biomass varies from 5 to 55%. At temperatures above 100° C, water is removed and turned into steam. During the drying process, the biomass does not suffer any decomposition.

Pyrolysis takes place in the temperature range of 150 - 700° C, and it consists of thermal decomposition of biomass in the absence of oxygen.

Oxidation takes place by the aid of the air introduced into the oxidation zone. The air contains oxygen, water vapours, inert gases, nitrogen and argon that do not react with the biomass components. Oxidation takes place at 700-2000° C.

In *reduction* several chemical reactions take place at a temperature of 800 - 1000° C and in the absence of oxygen.

The generator gas resulted is a mixture of combustible and non-combustible gases. The combustible gases are: carbon monoxide (15 - 30%), hydrogen (10 - 20%), methane (2 - 4%). The non-combustible gases are: nitrogen (45 - 60%), water vapours (6 - 8%), carbon dioxide (5 - 15%) [10].

If the specific power of the reactor is approx.300 kW /m², then for the power of 30 kW a reactor section of 30/300=0.100 m² results. For this section we start from a diameter of the reactor of 0.35m.

The calculation algorithm for the gas generator of 30 kW is [10]:

Diameter of the reactor: $D_r = 0.35\ m$ (1)

Biomass layer height (batch height): $H_{rbm} = 0.6\ m$ (2)

Section of the reactor: $S_r = \frac{\pi \cdot D_r^2}{4} = \frac{\pi \cdot 0.35^2}{4} = \frac{0.3847}{4} = 0.0961\ m^2$ (3)

Biomass volume in the reactor: $V_{rbm} = H_{rbm} \cdot S_r = 0.6 \cdot 0.0961 = 0.0577\ m^3$ (4)

Biomass layer density: 600 kg/m3 (for pellets)

Initial mass in the reactor: $M_{bm0} = 600 \cdot 0.05766 = 34.6\ kg$ (5)

The specific hourly consumption of gasified biomass is of 85 kg/m2 · h; therefore, for the surface of the reactor we will have a specific consumption of:

$C_{hbmg} = 85 \cdot 0.0961 = 8.17\ kg/h$ (6)

The running time will be: $t_g = \frac{34.6}{8.17} = 4.23\ h$ (7)

Energy from gasified biomass: $E_{gbm} = M_{bm0} \cdot P_{Cbm} = 34.6 \cdot 17 = 588.2\ MJ$ (8)

Thermal power of hot gases: $P_g = \frac{E_{gbm}}{t_g \cdot 3.6} \cdot \eta_{gTLUD} = \frac{588.2 \cdot 0.93}{4.23 \cdot 3.6} = 35.922\ kWth$ (9)

and burner thermal power, which takes into account the efficiency of combustion (comb) of the combustible gas ($\eta_{comb} = 0.95$) and the insulation (insul) efficiency (losses outward – $\eta_{insul} = 0.96$), will be:

$$P_{comb} = P_g \cdot \eta_{comb} \cdot \eta_{insul} = 35.922 \cdot 0.95 \cdot 0.96 = 32.76\ kWth \quad (10)$$

RESULTS

In a research and development department of INOE 2000-IHP Bucharest (www.ihp.ro), an experimental model of hot air generator on the TLUD principle with an induced draft system of 32 kW was designed and tested.

Operation of the experimental model of hot air generator on the TLUD principle (fig. 2) it is based on the following principle: gasification air (fig. 2b), driven by the fan 3, gets into the reactor 7 through the opening 9 and the holed bottom of the reactor, and the generator gas resulted from the pyrolysis process rises to the furnace and mixes with the combustion air which enters through the opening 8 and reaches the furnace 6 through the separator between the reactor and the combustion zone. The hot air draft from the burner washes the inside of the heat exchanger 1, and goes out through the funnel 4. Heated air (fig. 2a) from the outside of the heat exchanger 1 is driven by the fan 5, and gets out of the hot air generator through the opening 2.

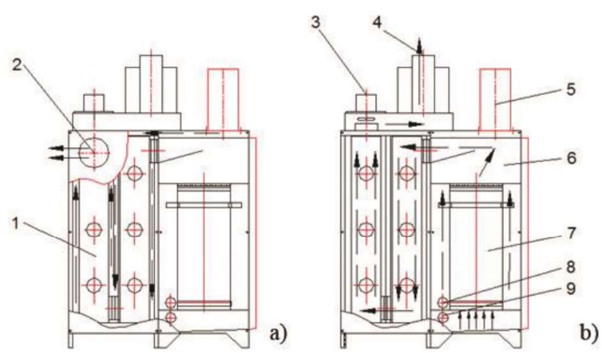

Fig.2. a) hot air path; b) exhaust gas path

The correct operation of the hot air generator involves maintaining a temperature of approx. 200°C in the funnel *4* to prevent condensation and deposition of tar. If the temperature is lower, the tar can be deposited on the exhaust path, and if higher the energy is wasted unnecessarily in the atmosphere. Maintaining the optimum temperature in the funnel is done by adjusting the air valves *8* and *9*.

During testing, opening of the valves for combustion air and inlet of gasification air was done manually by measuring the opening slot so that the air ratio established on the valves is Qc / Qg = 2.6, where Qc is combustion air flow and Qg is gasification air flow. Literature [9], [10] indicates that the flow rates ratio must be within the range 2.44 ... 3.3 to get the best results.

From the same sources [4], [5], [6], [7], [8] we know that the syngas superficial velocity is from 0.03 m/s to 0.04 m/s, well below the critical level of 0.1 m/s. On leaving the reactor, the combustion gas has a flow rate of 0.007 m^3/s and average temperature of 695° C.

In order to track the gasification process, the temperatures at the key points were monitored according to the test diagram (fig. 3) for:

- Ambient temperature

- Preheated air temperature around the exhaust funnel

- Supply air temperature in the inlet valves area

- Exhaust gas temperature

- Air temperature at the outlet of the air-to-air heat exchanger.

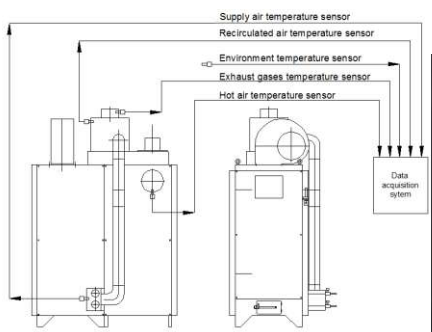

Fig. 3. Diagram of connections during testing

Fig. 4. The TLUD type furnace

The combustion of the generator gas mixture obtained from the biomass gasification gives a reddish-colored flame (fig. 4) in the burner. If the gasification process was completed and the pyrolytic front reached the bottom of the reactor the gasification process changes into Down Draft (the material advances towards the pyrolytic front); the char is gasified and the resulting gas combustion generates a blue flame.

The aim of the research is to obtain energy (hot air) and to sequester carbon in the biochar obtained as a by-product (char), so the combustion process will be stopped when the flame turns blue by turning off the induced draft fan 3 and opening the reactor.

An application developed in LabView was used to display and record the data. The application displays both numerically and graphically the temperature variation during combustion. When recording is stopped, the application allows saving the temperature values as a function of time in a text file. The data can be used and further processed.

The equipment was designed to suck air from the hot - exhaust gas - area, thus obtaining an energy recovery recorded at values of 10-30°C as the difference between the ambient temperature (blue graph) and the inlet air temperature in the air valves area (red graph).

As a result of data acquisition (fig. 5) throughout the operation until the flame turned blue and the hot air generator was turned off (the fans were turned off and the feeding door was opened) in order to obtain biochar, the following graph was obtained:

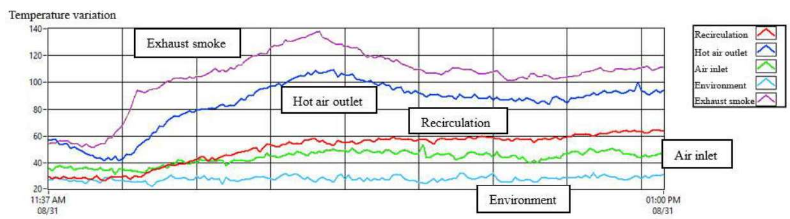

Fig. 5. Evolution of temperatures during the operation of the TLUD generator

The combustion process took 83 min. for a 15 kg bag of pellets; it was interrupted (fig. 6a) when the flame became blue (a sign that the pyrolytic front has reached the grid, the biomass gasification is completed and the burning of biochar begins). Thus, biochar was obtained (fig. 6b), approx. ¼ of the volume of the material initially introduced for combustion, and hot air from 90 to 110° C on leaving the exchanger (fig. 5).

The research will continue to determine the quality of the biochar obtained and to achieve process automation in order to optimize the functioning of the equipment.

a) b)

Fig. 6. a) Ceasing the process, b) Biochar.

CONCLUSIONS

Biochar is a steady form of carbon, chemically equivalent to charcoal, that can be used to improve soil in order to increase and maintain humidity, retain nutrients, as a habitat for beneficial microorganisms, as well to sequester carbon in soil for long periods.

The most important advantage that the gasifier based on the TLUD principle, designed and developed by INOE 2000, brings is that one can get clean energy compared to any of the other combustion modes. It also stores carbon in biochar, which is an important amendment to improve the quality of exhausted soils. The equipment is cheap, simple and reliable; it allows the use of a wide variety of biomass types and offers environmental protection solutions through particulate matter (PM) and CO2 emissions below the values required by law.

Based on this research and the data obtained, a simulation model can be developed and validated in order to control the combustion air and gasification air supply, so that the advantages of the TLUD principle to be exploited and a new technical solution of hot air generator with automation capabilities to occur, able to become the subject of a technology transfer to a production unit. One can also continue the research targeting the obtaining of high-quality biochar in order to bring maximum benefits to the soil in which it is integrated. This will bring a piece of innovative equipment to the market, able to satisfy the beneficiaries and to contribute to the promotion of sustainable energy development in harmony with the natural environment.

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