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COMBUSTION TEST EQUIPMENT IN LOW POWER TLUD GASIFIERS

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Abstract: The basic function of this type of gasifier on the TLUD principle is to make a flame from syngas that can be used as a heat source. Compared to other direct combustion or wood gasification processes, the TLUD gasification process is characterized by very low values of the surface velocity of gases passing through the pyrolytic front. The slow process maintains a surface speed of the gas produced at very low values, which ensures the reduction of free ash being dragged along to values below the 2015 norm imposed in the EU for biomass combustion processes. The article presents the TLUD combustion principle, TLUD gasifier sizing, a simulation of the automatic temperature control system, and a combustion test equipment in low power TLUD gasifiers.

Keywords: TLUD, pyrolysis, biochar, greenhouse, PI–controller, agricultural residues

1. INTRODUCTION

Gasifiers are essentially devices that allow the conversion of solid fuel into gaseous fuel through a thermochemical conversion process. This process involves a high (substoichiometric) temperature in the embers layer in order to obtain oxidation and reduction reactions between the solid fuel (biomass) and an oxidant, in our case the air. The construction is made so that the air and gas pass through the embers that advance into the fixed layer of biomass.

The TLUD gasifier is composed of a gasifier with ascending gasification air flow coupled to a gas fire *(Murad, E. et al., 2012)*. The biomass is introduced into the reactor and is supported on a grate through which the primary air for gasification passes from the bottom to the top *(Matache, G. et al., 2016)*. By thermochemical gasification, the biomass is oxidized in the reactor with 20 ... 30% of the air required for stoichiometric combustion. The result is a gas, called gasgen, which has a typical average composition: CO – 20%, H_2 – 18%, CO_2 – 10%, CH_4 – 4%, and the rest is N_2. The heat conversion efficiency varies depending on the construction of the equipment, the characteristics of the biomass used, as well as 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 the biomass chemical composition and humidity.

Ignition and initiation of the pyrolytic front are done at the top of the gas generator where a bed of embers is formed which advances into the biomass layer. Due to the heat radiated by the oxidation front, the biomass under the embers layer heats up, in the first phase it dries and then enters a process of rapid pyrolysis from which the volatiles are released and unreacted carbon remains. Pyrolysis results in gas, tar and coal. The tars pass through the layer of incandescent coal, are cracked and completely reduced due to the heat radiated by the pyrolysis front and the flame placed in the upper part. The resulting gas is mixed with the secondary combustion air at the top of the reactor. The high turbulence mixture *(Matache, G. et al., 2017)* burns with a flame at temperatures of about 900ºC. When the combustion front reached the grate all volatile gases in the biomass were gasified and part of the fixed carbon was reduced; about 10–20% of the initial mass remains on the grate in the form of sterile charcoal, called biochar *(Rădoi, R. et al., 2020)*.

The biochar obtained as a by–product is an active, sterile coal with a large adsorption surface, which can be used as a soil amendment in environments with low carbon sequestration capacity as well as a filter material for air, gas and water *(Drumea, P. et al., 2015)*.

To improve the gasification sustainability, researchers oriented towards the use of biochar product from gasification mainly as soil amendment. Up to 80% of biochar composition is unreacted carbon. It has increased capacity to hold water, and demonstrated the capacity to improve soil fertility, to reduce its acidity, and to mitigate the process of pesticides leaching to groundwater *(Patuzzi, F. et al., 2016; Fowles, M., 2008)*. Negative aspects related to gasification char are also encountered in terms of potential contaminant content, such as furans, heavy metals, dioxins, or PAH. Yet it has been demonstrated that higher pyrolysis time and temperature decrease PAH concentrations below the existing environmental quality standards *(Hale, S. et al., 2012)*. Having a highly porous structure, biochar can also be used to adsorb heavy metals or organic pollutants in filtering processes, such as for water and air filtration *(Shen, Y., 2015; Acharya, C. et al., 2013)*.

Heat production through biomass burning has however low efficiency and generates problems related to air quality, due to emissions of N_2O, CH_4, particulate matter (PM) and polycyclic aromatic hydrocarbons (PAH) *(Devesa–Rey, R. et al., 2011)*. Thermo–chemical biomass conversion through gasification is an alternative of higher efficiency. Gasification reactors demonstrated many benefits depending on their type, such as high carbon conversion, ability to scale–up, or low tar production. Apart from these advantages, they also pose disadvantages like sensitivity to biofuel moisture, complexity, low production of H_2 and CO, resilience, ash deposition on the reactor walls that leads to bed sintering, or maintenance costs *(Molino, A. et al., 2016; Iovane, P. et al., 2013; Wang, L. et al., 2008)*.

2. MATERIALS AND METHODS

— Sizing of the TLUD equipment

From the literature *(Pavel, I. et al., 2020; Maican, E. et al., 2017)* it results that the gasification process is done with low advance speed of the pyrolytic front, with a specific hourly biomass consumption of 80–150 kg/m²h, which results in low specific powers of 250–350 kW/m² for the reactor. The slow process keeps the surface velocity of the gases in the reactor at very low values, $v \leq 0.06$ m/s, and does not allow for free ash particles larger than PM2.5 to be dragged along, reaching a maximum of 5 mg/MJbm at the exit of 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. *(Pavel, I. et al., 2019)*. Drying is necessary because the moisture content of the biomass varies between 5 and 55%. At temperatures above 100°C, the water is removed and turned into steam. During the drying process, the biomass does not undergo any decomposition. Pyrolysis takes place in the temperature range of 150–700°C and consists in the thermal decomposition of biomass in the absence of oxygen. Oxidation takes place with the help of air introduced into the oxidation zone. The air contains oxygen, water vapours, inert gases, nitrogen and argon that do not react with biomass components. Oxidation takes place at 700–2000°C. During reduction, several chemical reactions take place at a temperature of 800–1000°C in the absence of oxygen.

The resulting syngas is a mixture of combustible and non–combustible gases. Combustible gases are carbon monoxide (15 – 30%), hydrogen (10 – 20%), methane (2 – 4%). Non–combustible gases are nitrogen (45 – 60%), water vapours (6 – 8%), carbon dioxide (5 – 15%).

— The calculation algorithm for a gasifier (Pavel, I. et al., 2019) of 3 KW and operating time of 3.5 h on the TLUD principle

If the specific power of the reactor is approx. 300 KW/m², then for the power of 3 KW a section of the reactor of 3/300=0.01 m² results. For this section, we start from the reactor diameter ($D_r = 0.1$ m) and the biomass layer height (loading height), $H_{rbm} = 0.5$ m.

Reactor section:

$$S_r = \frac{\pi \cdot D_r^2}{4} = \frac{\pi \cdot 0.10^2}{4} = \frac{0.03}{4} = 0.0078\ m^2 \tag{1}$$

Biomass volume in the reactor:

$$V_{rbm} = H_{rbm} \cdot S_r = 0.5 \cdot 0.0078 = 0.0039\ m^3 \tag{2}$$

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

Initial mass in the reactor:

$$M_{bm0} = 600 \cdot 0.0039 = 2.34\ kg. \tag{3}$$

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

$$C_{hbmg} = 85 \cdot 0.0078 = 0.66\ kg/h \tag{4}$$

The operating time will be:

$$T_f = \frac{2.34}{0.66} = 3.5\ h \tag{5}$$

Energy from gasified biomass:

$$E_{bmg} = M_{bmo} \cdot P_{Cibm} = 2.34 \cdot 17 = 39.78\ MJ \tag{6}$$

Thermal power of hot gases:

$$P_g = \frac{E_{bmg}}{T_f \cdot 3.6} \cdot \eta_{gTLUD} = \frac{39.78 \cdot 0.93}{3.5 \cdot 3.6} = 2.95\ kWth \tag{7}$$

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

$$P_{arz} = P_g \cdot \eta_{ard} \cdot \eta_{izol} = 2.95 \cdot 0.95 \cdot 0.96 = 2.69\ kWth \tag{8}$$

— The equations of combustion

For each fuel element the equation of the oxidation (combustion) process is: (Bălan, M., and Mădărăşan, T., 2013)

Combustion of carbon:

$$C + O_2 = CO_2 + Q_C$$

$$1\ kmole\ C + 1\ kmole\ O_2 = 1\ kmole\ CO_2 + 405800\ kJ$$

$$c\ kg\ C + c/12\ kmole\ O_2 = c/12\ kmole\ CO_2 + 405800\ kJ$$

If the combustion of carbon is incomplete, carbon monoxide (CO) is obtained as a combustion product:

$$C + \tfrac{1}{2} O_2 = CO + Q$$

Combustion of hydrogen in solid or liquid fuels:

$$H_2 + \frac{1}{2} O_2 = H_2O + Q_H$$

$$1 \text{ kmole } H_2 + 0.5 \text{ kmole } O_2 = 1 \text{ kmole } HO_2 + 240000 \text{ kJ}$$

$$h \text{ kg } H_2 + h/4 \text{ kmole } O_2 = h/2 \text{ kmole } H_2O + 240000 \text{ kJ}$$

Combustion of sulphur:

$$S + O_2 = SO_2 + Q_S$$

$$1 \text{ kmole } S + 1 \text{ kmole } O_2 = 1 \text{ kmole } SO_2 + 290200 \text{ kJ}$$

$$s \text{ kg } S_2 + s/32 \text{ kmole } O_2 = s/32 \text{ kmole } SO_2 + 290200 \text{ kJ}$$

Combustion of carbon monoxide:

$$CO + \frac{1}{2} O_2 = CO_2 + Q_{CO}$$

$$1 \text{ kmole } CO + 0.5 \text{ kmole } O_2 = 1 \text{ kmole } CO_2 + 283700 \text{ kJ}$$

$$(co)\ m^3_N\ CO + 0.5\ (co)\ m^3_N\ O_2 = (co)\ m^3_N\ CO_2 + 283700 \text{ kJ}$$

Combustion of hydrogen in gaseous fuels:

$$H_2 + \frac{1}{2} O_2 = H_2O + Q_H$$

$$1 \text{ kmole } H_2 + 0.5 \text{ kmole } O_2 = 1 \text{ kmole } HO_2 + 240000 \text{ kJ}$$

$$(h_2)\ m^3_N\ H_2 + 0.5\ (h_2)\ m^3_N\ O_2 = (h_2)\ m^3_N\ HO_2 + 240000 \text{ kJ}$$

Combustion of a hydrocarbon:

$$C_m H_n + \left(m + \frac{n}{4}\right) O_2 = mCO_2 + \frac{n}{2} H_2O + Q_{C_m H_n}$$

$$1 \text{ kmole } C_mH_n + (m + n/4) \text{ kmole } O_2 = m \text{ kmole } CO_2 + n/2 \text{ kmole } H_2O + Q_{CmHn}$$

$$(c_mh_n)\ m^3_N\ C_mH_n + (m+n/4)\ (c_mh_n)\ m^3_N\ O_2 = m\ (c_mh_n)\ m^3_N\ CO_2 + n/2(c_mh_n)\ m^3_N\ H_2O + Q_{CmHn}$$

If the combustion takes place in stoichiometric conditions, i.e., using the minimum air required for combustion (λ=1), then the minimum volume of flue gases will be obtained, with the equation:

$$V_g^{min} = V_{CO_2} + V_{H_2O} + V_{SO_2} + V_{N_2} \left[\frac{m_N^3}{kg_{cb}}\right] \tag{9}$$

The partial volumes of each element in the flue gas composition are calculated from the combustion equations of the combustible elements:

For CO_2:

$$V_{CO_2} = \frac{c}{12} \text{KmoleCO}_2 = \frac{22.414}{12} c = 1.867c \left[\frac{m_N^3}{kg_{cb}}\right] \tag{10}$$

For H_2O:

$$V_{H_2O} = 22.414 \left(\frac{h}{2} + \frac{w}{18}\right) + 1.61x = 1.245w + 1.61x \left[\frac{m_N^3}{kg_{cb}}\right] \tag{11}$$

For SO_2:

$$V_{SO_2} = \frac{22.414}{32} s = 0.7\ s \left[\frac{m_N^3}{kg_{cb}}\right] \tag{12}$$

The nitrogen volume, V_{N2}, contained by the minimum air required for combustion is calculated taking into account the volume participation of nitrogen in dry air:

$$V_{N_2} = 0.79\ L_{min} \left[\frac{m_N^3}{kg_{ch}}\right] \tag{13}$$

If the combustion takes place with excess air, the total volume of the flue gases is:

$$V_g^t = V_g^{min} + V_{aer}^{exces} = V_g^{min} + (\lambda - 1) L_{min} \left[\frac{m_N^3}{kg_{cb}}\right] \tag{14}$$

The volume of dry gases is obtained by subtracting from the total volume the volume of water vapours:

$$V_g^{us} = V_g^t - V_{H_2O} \left[\frac{m_N^3}{kg_{cb}}\right] \tag{15}$$

The volume of dry gases is very important in the control of combustion, because the composition of the dry gases is determined experimentally. The equipment used for combustion control, called gas analyzers, is provided with condensation systems for the water contained in the gas samples under analysis. Thus, only dry gases enter the process of chemical analysis of the flue gas composition.

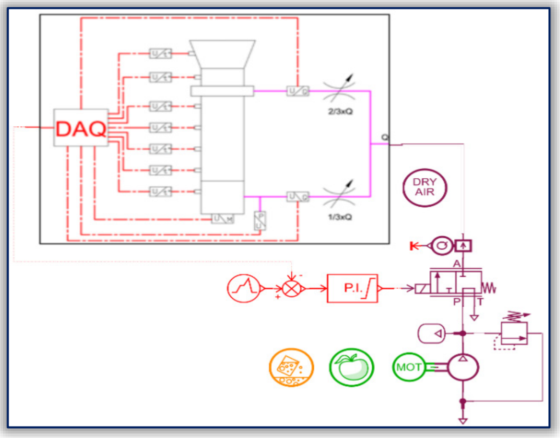

Figure 1 – Simulation network and parameters

Table 1. Simulation parameters and settings

Components / Submodels	Parameters
Work environments	Water and dry air
Electrical motor speed	1470 rev/min
Compressor displacement	68.05 cc/rev
Pneumatic chamber	100 L
Relief valve cracking pressure	6 bar
Pneumatic proportional directional control valve and pneumatic line	Dn 6
Proportional gain	150
Integral gain	2
Water tank capacity	5 L
Simulation settings	Simulation time: 4000 s Tolerance: 1 x 10^{-7} Sampling frequency: 100 Hz Print interval: 0.01 s

The numerical simulation network was made with Simcenter Amesim software. It includes mechanical, pneumatic and hydraulic components (water and dry air). Its role is to determine the maximum theoretical performance of the system and to analyze the control performance of the PI controller. The simulation lasts 4000 seconds; the print interval is 0.01 s, the sampling frequency is 100 Hz, and a tolerance of 1e–07.

The PI controller adjusts the air flow by means of the proportional control valve, which in turn adjusts the combustion temperature *(Tryner, J., 2016)*. The flame heats the water tank, and the water temperature is measured and transmitted to the PI controller comparator (feedback loop).

3. RESULTS

Presentation of the combustion test equipment solution in low power TLUD type gasifiers.

The equipment consists of a gas generator on the TLUD principle equipped with flow meters and air control throttles, seven temperature probes, four in the furnace area, one for the supply air, one in the flame area and one in the water tank for power testing. All these elements are placed on an electronic scale to establish the hourly biomass consumption. A pressure transducer is provided for measuring the gasification air pressure (necessary to cross the biomass layer). The data is acquired and processed in a controller that controls the control valve that provides flow to the two throttles adjusted in flow ratios, 1/3 for gasification and 2/3 for combustion. One of the objectives of the tests that will follow is to control and maintain the power of the gas generator at predetermined values.

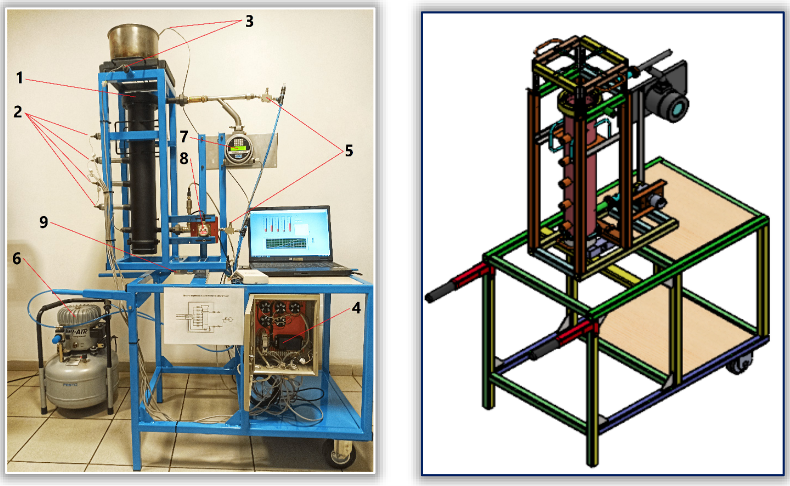

Figure 2 – Combustion test stand for a TLUD gasifier: 1– gasifier, 2– pyrolytic front temperature probes, 3– water and flame temperature probes, 4– electric panel, 5– pneumatic throttles, 6– compressor, 7– combustion air flowmeter, 8– pyrolysis air flowmeter, 9– electronic scale

With the combustion testing equipment in low power TLUD type gasifiers, data can be acquired that will be disseminated in further articles, relating to:

≡ Maximum and minimum power of the equipment
≡ Hourly biomass consumption
≡ Calorific value of different types of biomass
≡ Optimum temperature of the embers layer by varying the gasification air
≡ Combustion flame temperature
≡ Temperature variation in the water vessel
≡ Influence of gasification air temperature
≡ Combustion air and gasification air flows
≡ Influence of gasification air and combustion air flows

- ≡ Gasification air pressure for various biomass granulations
- ≡ Gasification air pressure for various height values of biomass in the gasifier
- ≡ Influence of the distance between the flame and the vessel to be heated
- ≡ Possibility to maintain a constant (adjustable) power by varying air flows.

Fuel consumption has been studied in other articles as well *(Murad, E. et al., 2012)* with a more complex pneumatic system, but at the presented stand it is done with an electronic scale that transmits the information during the testing to the acquisition board.

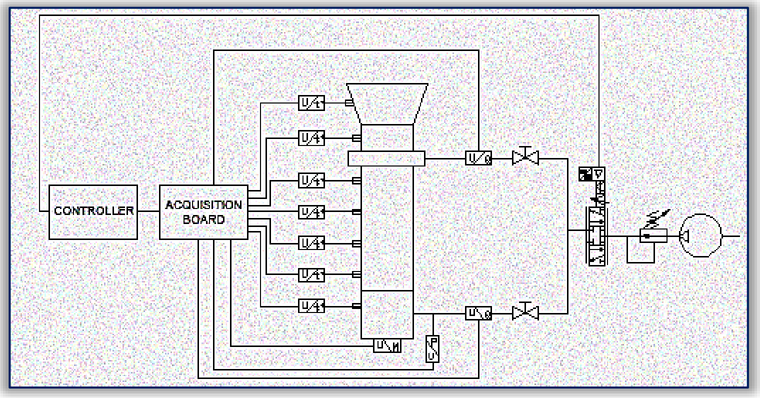

Figure 3 – Schematic diagram of the combustion test stand on the TLUD principle

4. SIMULATION RESULTS

In the figure 4 below, one can see the evolution over time of the compressor flow rate, in red color, which is constant throughout the simulation, pneumatic proportional control valve flow rate, in blue color, whose evolution is adjusted by the PI controller, and pressure drop due to the pellet layer, in yellow color. Pressure decreases because the pellet layer thickness decreases and an increasingly smaller resistance opposes the air flow. Transient phenomena occur because of pressure drop on the pneumatic proportional control valve.

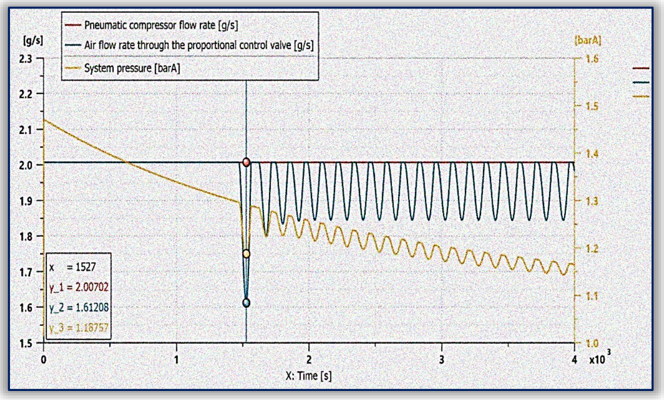

Figure 4 – Flow rates and pressure of the system

The figure below (figure 5) shows the evolution over time of the parameters of the PI controller, as well as the control signal that it sends to the pneumatic proportional control valve that adjusts the air flow.

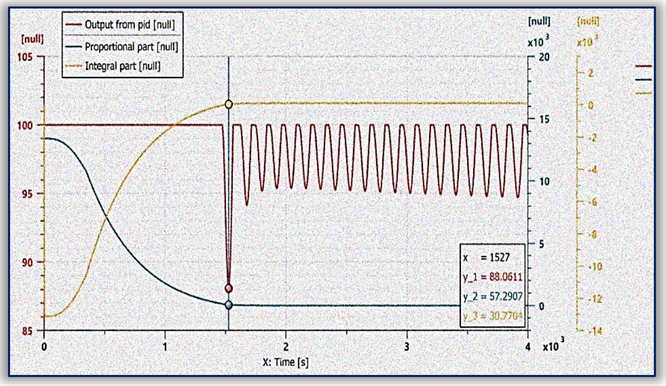

Figure 5 – Internal parameters of the PI controller and output signal

In the detail presented by the figure 6 above, one can see the evolution over time of the adjustment error. At first it is large, due to the thermal inertia of the system, and then it becomes very small (an amplitude of 0.4 ºC).

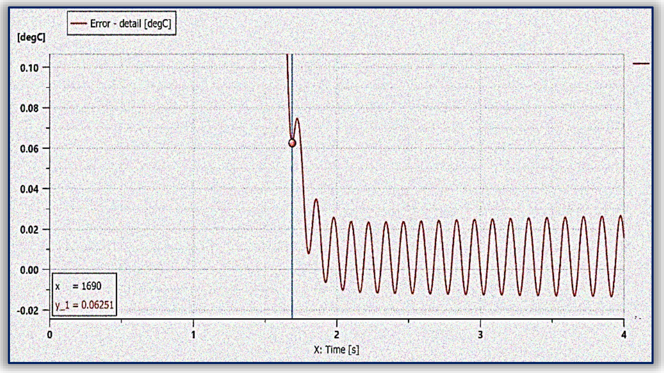

Figure 6 – Control error (detail)

The graph in the figure below shows the evolution over time of the following parameters:

- — The red curve shows the set point, which controls the system evolution over time of the desired temperature.
- — The blue curve shows the temperature of the combustion gases. In its evolution, one can see that after reaching the set temperature, it oscillates around a temperature of 189 ºC.
- — The yellow curve shows the temperature of the 5 liters of water; on this, one can notice that the temperature reaches 100 ºC in 1690 s (28.1(6) minutes).

5. CONCLUSIONS

By continuing the research with the combustion test equipment, presented as a physical achievement, suitable for low power TLUD type gasifiers, the study and control of combustion at TLUD type equipment can be deepened, which can transfer these devices from food preparation equipment category to automated heating equipment category similar to gasification boilers.

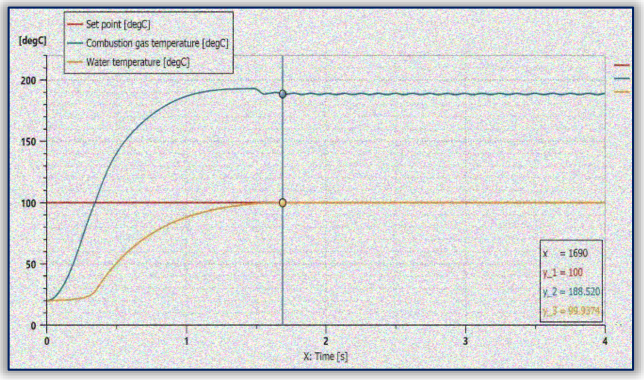

Figure 7 – Evolution over time of the process temperatures, time in s x 10^3

Almost any form of natural organic (wood) material can be transformed into biochar. Therefore, materials considered wood waste can be efficiently transformed into energy and biochar that can be used as main material for the amendment of degraded soils, and to sequester carbon in the soil for a long time, helping reduce greenhouse gas emissions, achieve effective environmental protection and ensure sustainable energy development.

Framing of the flame temperature in the range of 180–200 ºC is advantageous because the tar does not deposit and the equipment does not lose too much heat. Water temperature reaches 100 ºC in ~ 28 minutes.

Using only a PI–type controller in this case is appropriate because temperature exchange takes place slowly due to the high thermal inertia of masses. Even in this situation, the control performances are optimal.

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