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Equipment for Obtaining Thermal Energy by Using Biomass

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Abstract: *This paper presents the results obtained from testing a TLUD-type equipment, used to obtain biogas and biochar from biomass, developed and manufactured based on a patent elaborated under a research and development project by the staff of the Institute IHP. The paper presents solutions to increase the energy efficiency of burning boilers with gasification by recovering heat from the exhaust gases (which otherwise would be lost to the atmosphere) and reinserting it into the air circuit for gasification or combustion. The energy thus reintroduced into the combustion process can increase efficiency of gasification boilers by several percent, which means it saves large amounts of biomass and slows down global warming.*

Keywords: *Biomass, Combustion Processes, Gasifier, Thermal Energy, TLUD*

1. Introduction

An imperative of our times is the development and use of green and economic technologies in clean energy production, in a sufficient high amount. The clean attribute refers specifically to the minimal impact that the energy production technology should have with the environment.

The use of renewable energies is a characteristic of contemporary society, which is facing the decrease of classical resources, the rise in fuel prices and the pollution generated by their burning. However, the use of renewable resources to provide energy needs is still far from its full potential; this is also because of the lack of efficient conversion tools able to exploit various resources in mono-source or combined energy systems [1].

Increased efficiency in combustion processes is a goal proposed in all strategies of research and innovation, energy or environment. In the process of gasification, the inputs are biomass and air, while the outputs are fuel gas, biochar and ash, with a negative balance of carbon emissions due to carbon sequestration by biochar. The TLUD gasification principle (Figure 1) occurs when the biomass layer is introduced into a reactor and rests on a grid through which the air flow for gasification circulates from bottom to top. Gasification boilers operate under nominal conditions to maintain the temperature on the chimney at approx. 200° C to avoid condensation phenomenon (the formation of tar deposits).

2. General principles of biomass gasification

Priming gasification process is done by igniting the top layer of the biomass in the reactor. The combustion front descends continuously by consuming the biomass in the reactor. Due to the heat radiated from the oxidation front the biomass is heated, dried, and then it enters a fast pyrolysis process that releases volatiles and there remains unconverted carbon.

By the time the combustion front reaches the grill all the volatiles in the biomass were gasified and some of the fixed carbon was reduced; about 10 - 20% of the initial mass remained on the grill, in the form of sterile "green charcoal", called biochar.

The proportion of biochar, in which most of the ash from biomass is incorporated, depends both on the carbon stored in the biomass and on the temperature maintained in the carbon reduction reaction; a high temperature ensures the reduction of more carbon. If the supply with gasification air continues, we switch to an updraft gasification process in which a layer of incandescent charcoal is kept on the grill; of this, there results mainly CO and little CO_2, which passing through the hot charcoal layer enters the reduction reaction $C+CO_2 \Rightarrow 2CO$. This second phase is called charcoal gasification.

Compared to direct combustion or gasification processes of wood and pellets, the TLUD gasification process is characterized by very low values of the superficial gas velocity through the oxidation front, resulting in a very low content of atmospheric particulate matter (PM), PM < 5 mg/MJ, well below the required standard in the EU since 2015 for biomass combustion processes, which is 25 mg/MJ.

The gasification process is done with a reduced intensity with a specific hourly consumption of biomass of 80 – 150 kg/m^{2}h, which leads to reduced specific powers of 250 – 350 kW/m^2 of the reactor. The slow process maintains the superficial speed of the generator gas produced at very low values, $v_{sup} \leq 0.06$ m/s, which ensures reduced traction of free ash, and also at concentrations of $PM_{2.5}$ of maximum 5 mg/MJ_{bm} when leaving the burner; this value is at least five times lower than current standards required for solid fuel heat generators. [3, 4, 5, 6, 7]

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

Drying is necessary because the moisture content of the biomass is variable, ranging from 5 to 55%. At temperatures above 100° C, the 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, together with oxygen, water vapor, inert gases, nitrogen and argon that do not react with the biomass components. Oxidation takes place at 700-2000° C.

Reduction occurs in the reduction zone of the reactor. Here several chemical reactions take place at a temperature of 800 - 1000° C and in the absence of oxygen.

The generator gas 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 vapors (6 - 8%), carbon dioxide (5 - 15%) [8].

The fuel gas can be used for:

- burning in a specialized burner, resulting in high enthalpy combustion gases which contain very low concentrations of mechanical particles (MP) and CO, hot gases which are used in:
- the process of heating water, steam or air,
- external combustion engines to produce electric power

After filtering off the tar and MP contents, the fuel gas can be used in internal combustion engines to produce electric power.

Figure 1 is a block diagram of the procedure of energy recovery of biomass by thermo-chemical gasification.

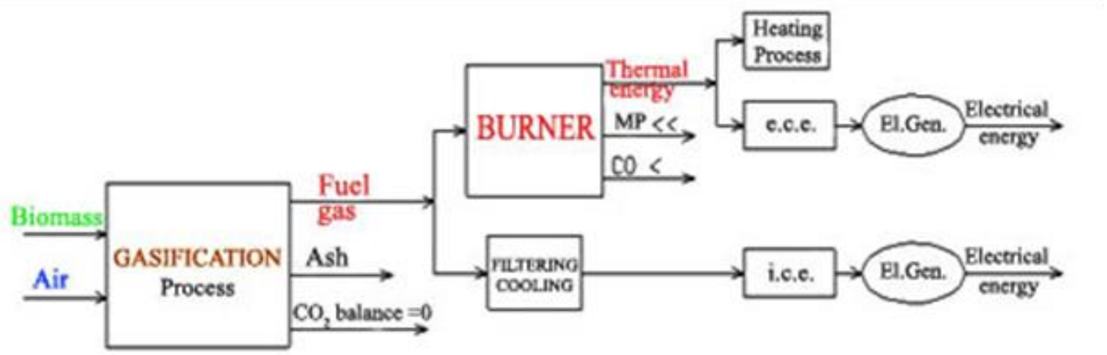

Fig. 1. The block diagram of energy recovery of biomass by gasification
MP mechanical particles; e.c.e. external combustion engine; i.c.e. internal combustion engine

3. Biomass gasification procedures

Two types of gasification procedures are currently being used: up-draft (counter-current) and down-draft (co-current).

The up-draft procedure

After this process works the simplest type of fixed bed gasifier. Biomass is fed from the top of the gasifier, and it slowly moves down as its conversion and ash removing take place. The insertion of the gasification agent (the air) is done through the bottom of the gasifier beneath a bar grill, or with a rotary grill, version which has the advantage of adjusting the evacuated ash flow rate, so the possibility to adjust also the speed at which the biomass moves down inside the gasifier. The gases produced pass through the gasifier from the bottom upwards, crossing through the layer of biomass, and they leave the gasifier in the top, sideways, at a level slightly lower than the one at which biomass is fed. In this way, biomass and gas flow is counter current, and the sequence of the reaction zones is as shown in Figure 2 (a) [2].

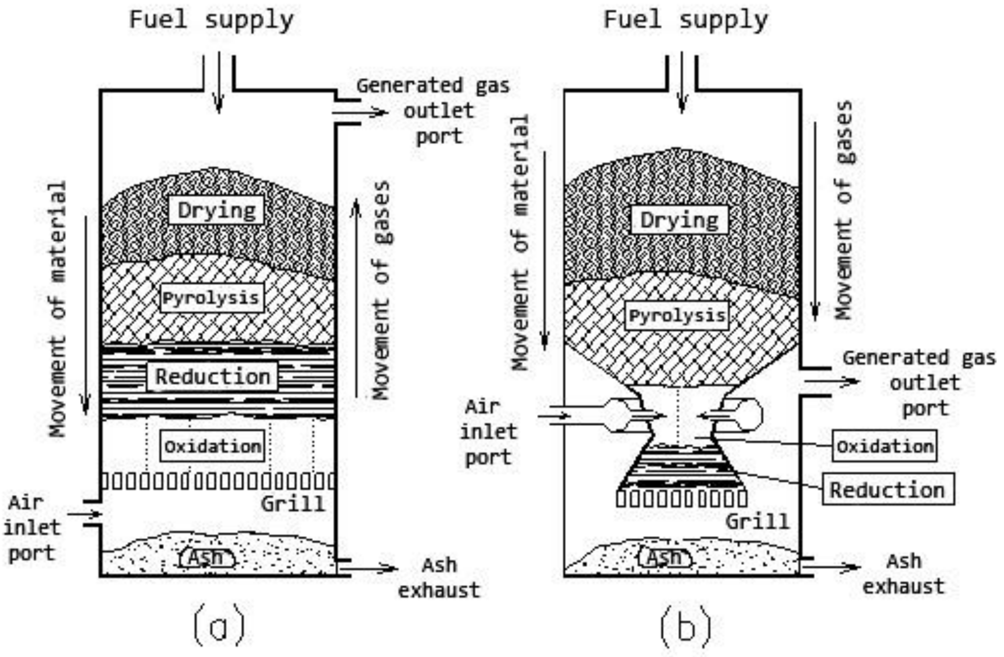

Fig. 2. Conventional gasification processes: up-draft (a) and down-draft (b) [8]

The most important advantage is simplicity, and also intense burning of charcoal and internal heat transfer from gas to biomass, which causes the gas temperature at the outlet to be relatively low and to achieve high efficiency of gasification. In this way, even a gas with a high moisture content (>50 %) could be used [8].

The most important disadvantage is the tar content in the gas, as well as the presence of moisture and pyrolysis gases, because they no longer cross the oxidation zone and are no longer burned, no longer cross the reduction zone and are no longer cracked. This is a minor drawback if we consider direct combustion of gas in regular furnaces. But if it is intended to use the gas for engines, then it is a must to clean the dust and tar off from the gas, otherwise they can cause serious problems.

The down-draft procedure

In this type of procedure, the biomass is inserted through the top, and the gasification agent (the air) can be inserted either through the top or laterally at a certain distance, somewhat lower. The gas produced exits the gasifier through its bottom, sideways, that is why it is said to be gasification in co-current, because especially in the reduction zone (the main gasification zone) the pyrolyzed biomass and gas have the same sense of movement, as one can see in Figure 2 (b).

Gases and vapors from the pyrolysis zone pass through the oxidation zone (high temperature zone) where they are more or less burned and / or cracked. Due to this reason, the crude final gas coming out of the gasifier has low tar content. In addition, moisture evaporates from biomass, also forced to go through the reduction zone, becomes gasification agent and reacts with carbon existing in the mangalized biomass, causing to appear CO and H_2 or even CH_4 (resulting from the reaction of carbon with hydrogen). This type of crude gas is much cleaner and can be used easily even for engines. However, in practice, a gas without tar is rarely obtained, because of the operating conditions of the gas-generating equipment [2].

However, due to the lower content of tar and organic compounds from the condensate, the down-draft gasifiers pose fewer problems, from the point of view of environmental protection, compared to up-draft gasifiers.

The disadvantages of down-draft gasification are the following:

- relatively high content of ash particles and dust of carbon material unreacted into gas;
- difficulty (often impossibility) to work with some types of biomass which has not been processed previously (materials with too small granulation or too low bulk density requiring briquetting or pelleting prior to insertion into the gasifier);
- high gas temperature at gasifier outlet port;
- biomass moisture must be less than 20-25 %, which requires in many cases the pre-drying of raw materials.

This biomass gasification technology is nevertheless the most flexible, and therefore the most advantageous, suited to be applied in most situations.

A variant of this gasification technology is represented by the open top gasifiers; they are also known in the literature under the denomination "open core". In these gasifiers the air is sucked over the whole section of the biomass layer, so that a more even distribution of oxygen is ensured. In this way, the oxygen will be consumed uniformly across the whole section and the oxidation wall temperature will be uniform, not appearing hot zones (areas of local extremes) in the oxidation zone, as seen in conventional gasifiers, because of poor internal heat transfer. Moreover, the air intake nozzles used in conventional gasifiers generate bubbles in the solid material layer and create obstacles that can affect the movement of the solid layer [9].

On the other hand, the air inlet to the top of the solid layer induces a downward flow of pyrolysis gas and carries the volatile products (tar) to the oxidation zone. In this way flow issues due to biomass pyrogenic reaction and caused by return and mixing are avoided.

In 1985 Thomas Reed proposes and implements a gasification process named 'inverted downdraft' – IDD, also known as TLUD – Top Lit Up Draft. It combines the characteristics of the technologies up and down draft and it is considered to be the best procedure for micro-gasification level because TLUD gasifiers are simple, reliable in operation and cheap.

4. Mathematical model

The CFD (Computational Fluid Dynamics) simulation of a heating station requires defining the main components and geometry presented in Figure 3.

The geometry mesh for a heating station was conducted unstructured with 456,222 tetrahedral elements, quality 0.8 with the Gambit v. 2.2.3 software. Meshing volumes obtained were optimized using ANSYS – Fluent v. 3.6.26 software.

Mathematical model required for CFD simulation is based on the equations of fluid flowing through the station and the energy equation for heat transfer. Differential equations of continuity and fluid flow are introduced into the calculation algorithm by the relations [10]:

$$\frac{d\rho}{dt} = -\rho(\nabla v) \tag{1}$$

$$\rho\frac{dv}{dt} = \eta\nabla^2 v - \nabla p + \rho g \tag{2}$$

where: ρ-fluid density; v-fluid velocity; η-fluid dynamic viscosity; p-pressure; g-gravity acceleration

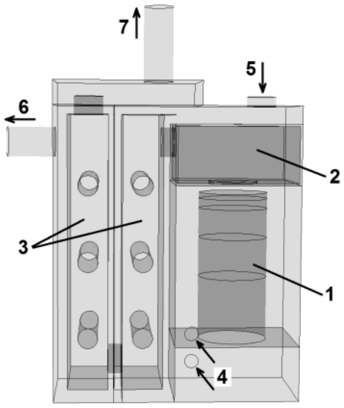

Fig. 3. Heating station geometry

1 – biomass burner;2 – furnace; 3 – heat exchanger; 4 – combustion air inlet port; 5 – outside air inlet port; 6 – hot air exhaust; 7 – combustion gases exhaust.

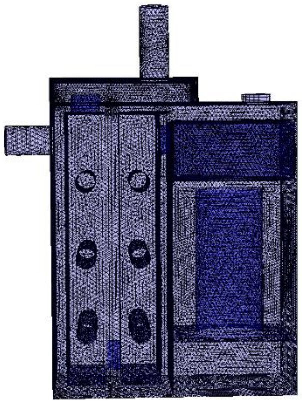

Fig. 4. Unstructured mesh of heating station geometry for CFD simulation

Differential energy equation for calculating heat transfer is introduced into the calculation algorithm by the relation:

$$\rho \frac{dU}{dt} = \frac{\partial Q}{\partial t} + K\nabla^2 T + \theta \tag{3}$$

where: *U*-internal energy; *Q*-heat flow; *K*-heat transfer global coefficient; *T*-temperature; *θ*-dissipation term.

If the fluid is considered incompressible and unsteady, three equations above shall be simplified accordingly. From the flow conditions according to the formula of Reynolds there has been determined turbulent flow in the heat exchanger. The standard *k-ε* model is the simplest turbulence model with two transport equations, which are added to the three previous equations, allowing independent assessment of the turbulent velocity and the turbulence length scale. Values of turbulent kinetic energy *k* and dissipation velocity *ε* are obtained from the system of transport equations:

$$\rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\mathrm{Pr}_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho\varepsilon - Y_M \tag{4}$$

$$\rho \frac{\mathrm{D}\varepsilon}{\mathrm{Dt}} = \frac{\partial}{\partial \mathrm{x_i}}\left[\left(\varpi + \frac{\mu_t}{\mathrm{Pr}_\varepsilon}\right)\frac{\partial \varepsilon}{\partial \mathrm{x_i}}\right] + \mathrm{C}_{1\varepsilon}\frac{\varepsilon}{\mathrm{k}}\left(\mathrm{G_k} + \mathrm{G}_{3\eta}\mathrm{C_b}\right) - \mathrm{C}_{2\varepsilon}\rho\frac{\varepsilon^2}{\mathrm{k}} \tag{5}$$

where: G_k-term for generation of turbulent kinetic energy; G_b-floatability term; Y_M -compressibility term; Pr_k and Pr_ε -turbulent Prandtl numbers for *k*, and respectively for ε.

Particularizing, the heat flow transmitted between the combustion gases and the air that has entered the heating station in the counter flow fluid-to-fluid heat exchanger, has the following equation:

$$Q = K \cdot S \cdot \Delta T_m \tag{6}$$

and capacity of the heating station shall be calculated using the next equation:

$$P = q_v \cdot \rho \cdot c_p \cdot \Delta T_m \tag{7}$$

where: *K*-global heat transfer coefficient, *S*- heat transfer area, q_V-volumetric flow rate, ρ- density; c_p -specific heat; ΔT_m- temperature difference inside the station.

5. Experimental modeling and testing

The paper presents a modern way of preparing and using the vegetal biomass for the ecological production of the cheap thermal energy required in the heating installations technology specific to the rural economy based on agricultural activities.

In a research project, an experimental model (Figure 5) was used which uses this procedure, which was tested in the laboratories of the institute. Thermal energy can be obtained by micro-gasification using the TLUD (Top-Lit UpDraft) process of vegetal biomass, which is characterized by high conversion efficiencies and very low CO and PM2.5 pollutant emissions. Applying the TLUD process it is possible to efficiently gasify biomass with relatively large variations of the chemical composition, humidity (under 20% water) and granulation properties (1-5 cm), aspect which provides a wide base of usable plant biomass sources [4].

The long-term acceptability of gasification technology and the CHAB concept as well as its introduction on the market depend on the technical performance, economic and environmental of gasification and biofuel plants, efficiency and safety of power plants that is using the gas fuel produced [6]

In order to achieve these goals, the system must have high operational safety and be reliable, environmentally friendly, economically viable and be exploited by a user with a minimum of professional training trained carefully through a monitored schooling system.

It is in the user and manufacturer's interest that the hot air generator is properly tested so as to achieve the desired performance. Therefore, a methodology has been developed for testing the hot air generator with the TLUD energy module, as well as calculation algorithms for the primary processing of experimental data.

Testing is carried out in four test steps:

1. Initial running test for system components **(IRT)**
2. Start test **(ST)** (sensory training, measurement and control instruments, data acquisition components (ST)
3. Operational test of the biomass gasification process **(LOT)**
4. The biochar discharge and off test **(BOT)**

The tests will be carried out in strict surveillance with the labor protection rules specific to hot combustion gases.

Following the mathematical modeling of the equipment, the project was improved resulting the Prototype, Figure 5.

The location of the heat exchanger and chimney fans is shown in fig. 6 and fig. 7.

The micro-gasification process is supplied with air from a variable speed ventilator. Biomass is introduced into the reactor and is based on a grid through which, from bottom to top, passes the air for gasification. Initialization process is done from the free upper layer biomass.

Thermal energy is obtained by burning hot gasogen, resulted during pyrolysis. It is mixed with preheated combustion air introduced into the combustion zone through holes located at the top of the reactor. Mixture with high turbulence burns with flame at the upper mouth of the generator with high temperature 900-1000°C. To adjust the heating power necessary, the air flow D_{ag} for gasification and D_{ard} for combustion are varied through two clacks, coupled mechanically or by varying ventilator speed. TLUD process is with fixed bed of biomass and therefore the generator operates in batch mode to recharging.

In order to put the prototype of the TLUD hot air generator into operation, the reactor was filled with 15 kg of pellets and the ignition with 4 pieces of fireplaces igniters was used. The draft fan and the hot air fan ware started. After a start-up period, the gasification process stabilized and a stable, slightly turbulent flame of orange color was obtained.

There was observed a high increase in air temperature at the outlet of the heat exchanger. After about 1 hour and 30 minutes, a total blue flame appeared at the burner, indicating the occurrence of gasification of the biochar. At that moment the blower stopped, the gasification and combustion air were closed. At the complete extinction of the blue flame, the reactor was extracted from the generator and the biochar was discharged.

Fig. 5. TLUD thermal generator prototype equipped with heat-resistant for temperature monitoring at points of interest

Fig. 6. Heat exchanger fan with a flow rate of 2000 m^3 / h

Fig. 7. Smoke chimney fan with a flow rate of 605 m^3 / h

In order to increase the technical performances of the TLUD hot air generator, compared to the Experimental Model, a number of modifications have been made to the prototype achievement:
- supplying the heat exchanger with a fan with a flow rate of 2000 m^3 / h, to reduce the temperature of the air conditioning (the air introduced into the greenhouse);
- mounting on a chimney of a special construction fan with a flow rate of 605 m^3 / h;
-mounting of thermo-resistors (temperature probes) in the main monitoring points of the process of biomass gasification and gasification of gas from gas producing, fig. 8: probe 1-in ambient environment; probe 2 on the heat exchanger fan air supply duct; probe 3 on the flue gas exhaust manifold (coil), a fan that assures the unfolding of the biomass pyrolysis process by suctioning the bottom reactor air and passing it through the biomass; probe 4 on the hot air transport pipe to the greenhouse.

Probe 2 Probe 3 Probe 4

Fig. 8. Mounting points for thermo-resistors

- the generator with the electric panel, fig. 9, which has been introduced: a programmable controller, which together with an external console allows real-time monitoring of recorded

temperature of thermo-resistors; a frequency converter that allows wide-ranging adjustment of fan speed installed on the chimney;
-developing the software to enable the process of gasification and the monitoring of the working parameters.

Fig. 9. Electric panel of the heat generator; programming the monitoring system for working parameters and data acquisition

Densified solid biofuels used in experiments were pellets obtained from softwood species with a thermal efficiency of 5 kWh / kg, maximum length 45 mm, diameter 6 mm, humidity ≤ 10%, resulting ash content ≤ 0,7%.
The pellets are introduced into the cylindrical reactor, fig. 10, which at the bottom is provided with a grill; after ignition of the pellets, by starting the fans, the primary air for gasification is determined to pass through the grill, passing through the ascending pellet mass. The pyrolysis process is triggered at a short time from the start of the fans, being sensed by the fact that at the top of the reactor, through the holes practiced in the circular sheath of the cover, intense burning of the gas from gas producing takes place, Fig. 11.

Fig. 10. The TLUD heat generator reactor

Fig. 11. Referring to the moment of initiation of the pyrolysis process

The pyrolysis process results in gas from gas producing, tar and biochar. Tars pass through the incandescent charcoal layer, are cracked and totally reduced due to the heat radiated by the pyrolysis front and the upper flame. The resulting gas is mixed with the secondary combustion air, preheated by the reactor wall, introduced into the combustion zone through the oriffices disposed at the top of the reactor. The mixture with high turbulence burns with flame at temperatures of about 900°C. The adjustment of the thermal power is made by the variation of the primary and secondary air flows.

The experiments took place in two stages:

- Stage I, which involved temperature monitoring at points of interest over a work cycle over time 12^{42}-13^{49}; the control elements during the working cycle were the gasification and combustion air intake valves; the reactor was fed with 7.9 kilograms of pellets;
- Stage II, which involved temperature monitoring at points of interest over a work cycle over time 14^{04}-14^{52}; the adjustment elements during the working cycle were the gasification and combustion air intake valves, respectively the fan speed mounted on the chimney; the reactor was fed with 7 kg of pellets;

Measured temperature values of heat-resistant are recorded at intervals of 30 s.

The difference between the ambient temperature and the heat exchanger temperature is due to the fact that a mixture of ambient air and some of the air in the reactor enclosure takes place in the main fan pipe (heat exchanger fan). The Δt difference reflects the degree of heat recovery in the combustion gases, contributing to the increase in the efficiency of the heat generator.

The graphical representation of the temperature values recorded during the two cycles of operation of the thermal generator is shown in the diagram of Fig. 12.

The main objective of the experimentation of the equipment under actual operating conditions was that by the control elements (gasification and combustion clacks, frequency converter for regulating the speed of the gasification gas and the exhaust of the combustion gases), the temperature values should be maintained in Designed limits: Climate air temperature value to be maintained around 150°C, combustion gas temperature around 200°C, Δt value - the difference between the heat exchanger temperature and the ambient temperature to be as high as possible to increase the efficiency heat generator.

In the case of the first operating cycle, only the burner clack at 13.14.49 was inserted in the direction of closing it, resulting in a limitation of the air temperature of the air at 177.5°C and of the combustion air temperature at 254°C. It is found that only by adjusting the aperture of the clacks the values of said temperatures can not be maintained at the projected values.

In the second operation cycle, the gasification air flow rate was adjusted by changing the fan speed by means of the frequency converter. It is noted that the temperature of the air conditioning temperature was kept below 155.6°C, and the value of the combustion gases below 192°C.

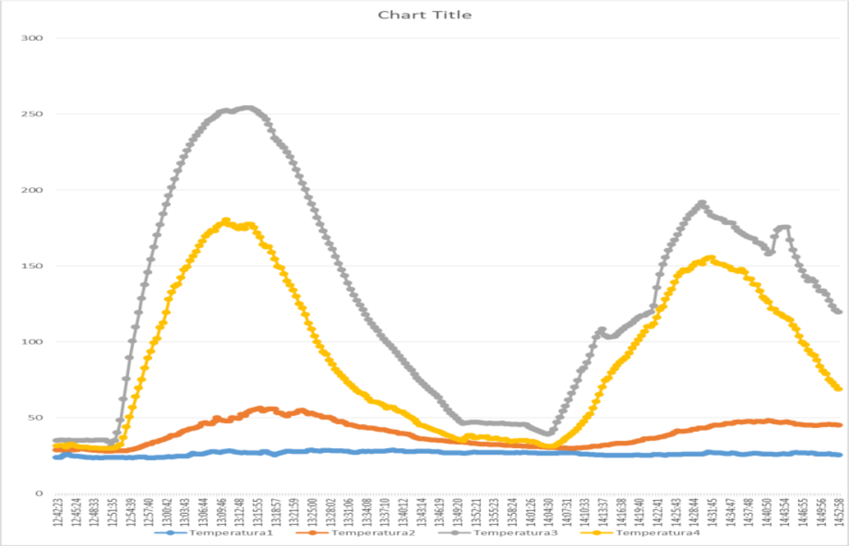

Fig. 12. Graphic representation of recorded temperature values during the two operating cycles of the heat generator

6. Conclusions

The prototype of the TLUD thermal generator, after removing the technical-functional deficiencies and the nonconformities found in the Experimental Model Test, meets the project objectives, works on the TLUD principle in different power regimes, achieves the projected values of the temperature at the points of interest and can be introduced into the fabrication delivered to the market.
Adjustment elements (gasification and combustion clacks, frequency converter for regulating the gasification fan flow rate and flue gas exhaust) allow the temperature to be adjusted and maintained within the projected limits;
To increase the efficiency of the heat generator, Δt - the difference between the temperature of the heat exchanger and the ambient temperature is higher;
The value of the air temperature introduced into the greenhouse tubing can be brought to the desired value by mixing air conditioning with fresh air from the outside of the greenhouse through a clack pipe.

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