Applied Research and Experimental Validation of a TLUD Industrial Solution

PhD. Eng. **Gabriela MATACHE[1],** Prof. PhD. Eng. **Edmond MAICAN[2],**
PhD. Stud. **Ioan PAVEL[1],** PhD. Eng. **Radu Iulian RADOI[1],**
Dipl. Eng. **Mihai-Alexandru HRISTEA[1]**

[1] INOE 2000-IHP Bucharest; fluidas@fluidas.ro

[2] UPB- ISB, e.maican@gmail.com

Abstract: *This paper presents the research carried out by the team of INOE 2000-IHP Institute in collaboration with UPB-ISB, on a hot air generating system to increase the energy independence of greenhouses and solariums aiming to extend the duration of their use by heating with local micro-gasified biomass in TLUD energy modules to increase production safety and reduce production costs. The target was the use of a hot air and forced circulation system equipped with rechargeable, simple, safe, efficient and environmentally friendly energy-saving TLUD modules in which the locally harvested, chopped and dried biomass is thermo-chemically gasified. From the micro-gasification of the biomass with the help of the TLUD type equipment, there resulted about 10% to 15% biochar, the part of carbon not converted into gas, which is a valuable agricultural amendment and contributes to the sequestration of carbon in the soil. These constructive and functional solutions can make an essential contribution to the stepping of agricultural farms from the semi-subsistence level to the commercial level, meaning a strong and stable growth of local crop production in the cold season.*
The paper deals with the research and experimentation of the gasification burning process on the TLUD principle and finalizes with a prototype of a hot air generator system that uses the secondary agricultural production as raw material and is mainly intended for the heating of the greenhouses.

Keywords: *TLUD gasification solutions, energy module*

1. Introduction

The heating systems for greenhouses can use water, steam or hot air as a heat source. The objective of these systems is to achieve a cheap, simple, safe heating that can be purchased by small manufacturers and to pay off quickly enough under limited usage for 3 to 4 months of use. As a result, the hot-air heating solution has been proposed, increasingly used for heating the greenhouses because:

- Ensures very good uniformity of temperature and humidity in the enclosure,
- Provides controlled ventilation that allows very good internal humidity control;
- By recirculation an increase in the energy efficiency of the heated tunnel solarium system is achieved.

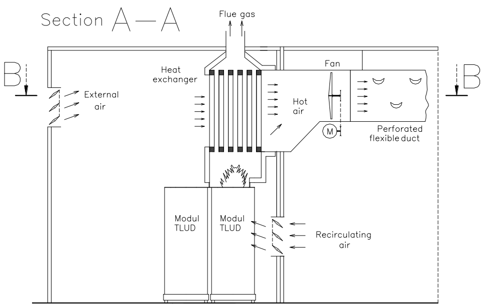


Fig. 1. Functional schematic diagram of a hot-air heated tunnel solarium

Figure 1 shows a functional diagram of a hot-air heated tunnel solarium. The solarium is heated by hot air through a flexible pipe that has slots for hot air distribution jets. A part of the indoor air is recirculated and mixed with the outside air needed for ventilation of the greenhouse. The mixture is heated with a flue gas $\Rightarrow$ air heat exchanger. This functional variant no longer implies periodic

ventilation that can be harmful if it is not well managed. In order to protect the plants from contact with too hot air, the maximum temperature of the jets is limited to 40°C, which implies the use of a constant flow rate for the air that heats the greenhouse. [1]
Figure 2 shows the block diagram of a tunnel solarium heated by a hot air system using two Biomass-Gasification-Module (BGM) thermal modules. The two modules are coupled to the inlet of the heat exchanger which operates at a constant flow of heated air and therefore has an average yield of 90% and a minimum yield of 85%. [2]

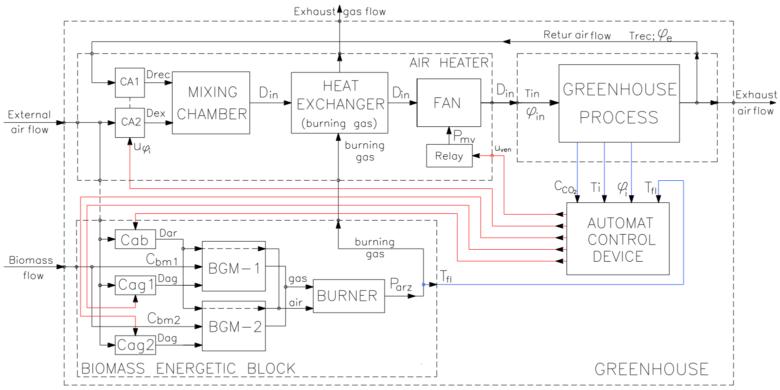


Fig. 2. Block diagram of solarium heated by a hot air system using two BGM thermal modules

2. Presentation of the chosen solution

The biomass is introduced into the reactor and rests on a grill through which the primary air for gasification passes from bottom to top. Rapid pyrolysis reaches a point of incandescence at the top and continues down into the biomass in the reactor. Rapid pyrolysis results in gas, tar and biochar. Tars pass through the incandescent charcoal layer, are cracked and completely 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 holes disposed at the top of the reactor. The mixture with high turbulence burns with flame at temperatures of about 900°C. The regulation of the thermal power is done by the variation of the primary and secondary air flows. The designed solution shown in Fig. 3 has been filed as Patent application No. A/00286/27.04.2015

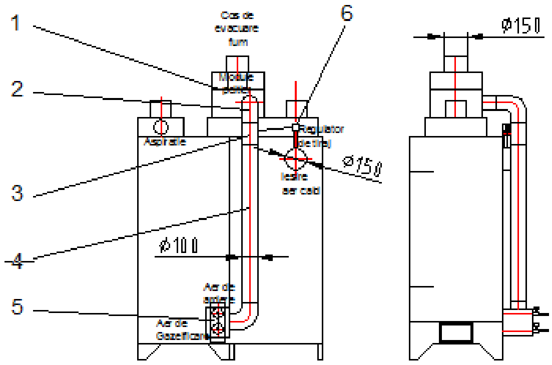


Fig. 3. The designed solution submitted for patenting

3. Numerical simulation of the experimental model

The CFD (Computational Fluid Dynamics) simulation has become a high efficiency technique used in the analysis and comprehension of biomass thermal conversion phenomena. Recovering the biomass and using it in heating stations may represent a cheap source of heating greenhouses and solariums in vegetable farming. This papers aims to develop a CFD simulation of a station which uses biomass in various working conditions, to obtain as good as possible heat transfer between the combustion gases and outside air used for heating greenhouses. The CFD simulation has been developed on a 3D model of a station, in which a number of technological parameters have been determined experimentally. Technical specifications of the station under simulation, using biomass (pellets) as a source of fuel are presented in Table 1. [3]

Table 1: Technical specifications of the heating station

Features	Specifications
Sizes	1.220 m (l) x 0.5 m (w) x 1.460 m (h)
Area of the heat exchanger	5.2 m^2
Fuel	biomass-pellets (density 200 kg/m^3, average size of pellets 0.025 m)
Combustion time	4 – 6 h

Mathematical model required for the 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:

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

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

where: ρ fluid density; v fluid velocity; η fluid dynamic viscosity; p pressure; g gravity acceleration.
Differential energy equation for calculating heat transfer is introduced into the calculation algorithm by the relation:

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

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 [5]:

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

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

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:

$$Q = K \cdot S \cdot \Delta T_m \qquad (6)$$

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

$$P = q_v \cdot \rho \cdot c_p \cdot \Delta T_m \qquad (7)$$

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.

A number of simplifying assumptions have been set so that the impact on the simulation results be minimal. It has been considered that the bed of biomass is a porous medium having a porosity of 0.3, it is homogeneous, constant height and its density does not change during the combustion process. Also, inlet temperature in the furnace is 1100 ºC, constant during combustion. Airflow and combustion gases flow through the heating station walls is considered as null. The condition imposed on combustion gases and hot air exhaust in the atmosphere is outflow, and overpressure is considered as null. Velocities of the combustion air and outside air inlet remain constant; they take values depending on the volumetric flow rate of technological operating parameters, according to Table 2.

Table 2: Technological operating parameters

q_v (m^3/h)	505	375	260
p (Pa)	200	300	400

Air inlet temperatures remain constant, with values of 15ºC for the air needed for combustion and 8ºC for the air brought in from outside with a view to heating inside the station. The volumetric mass and air viscosity have been considered constant for a given temperature.

The simulation results are presented as temperature and velocity fields, and respectively as the trajectory of pathlines in the simulation range of the heating station. The simulation has been developed for three different air flow rates with the ultimate aim to accurately determine the average output temperatures of hot air and combustion gases. The three-dimensional simulation of airflow and heat transfer provides the advantage of an overview very close to the real operation of a heating station when there are known the functional input parameters and temperature developed in the furnace by biomass (pellets) burning.

From numerical simulation there have been obtained the average output temperatures of hot air and resulted combustion gases, Table 3. Knowing the input and output parameters of the heating station, capacity of the heating station has been calculated by using the equation 7, air density and specific heat being considered constant.

Table 3: The values of parameters and heating station capabilities

q_v (m^3/h)	$T_{avg\ combustion\ gases}$ (˚C)	$T_{avg\ hot\ air}$ (˚C)	$T_{int\ outside\ air}$ (˚C)	$T_{int\ combustion\ air}$ (˚C)	P (W)
505	273	68	8	15	22260
375	253	63	8	15	15083
260	226	61.5	8	15	9876

Through the CFD simulation of the heating station, by introducing sequentially the three air supply flows, there results a capacity closed to the one proposed of 20 kW at a maximum flow rate of 505 m^3/h.

The analysis of airflow simulation and temperatures inside the heating station is performed for the maximum flow rate.

The temperature profile in the median plane for the heating station shows an ascending temperature gradient along the burner height, ranging from 80ºC at the bottom till a temperature of 1100ºC at the furnace entry point, (Figure 4).

If the input air required for combustion has the temperature of 15ºC, in the furnace the average temperature of combustion gases exceeds 900ºC. The temperature of combustion gases starts to decrease gradually in the heat exchanger, so that in the first section of the heat exchanger the average temperature is 600ºC, in the second section the gases reach an average temperature of 400ºC, while in the station chimney they are exhausted at the average temperature of 273ºC. The fresh air from the outside at a temperature of 15ºC takes some of the heat of combustion gases in the heat exchanger of the heating station, and it is discharged in order to produce heating at the average temperature of 68ºC.

The velocity profile in the median plane for the heating station shows minimum values near the walls and high values ranging from 3.5 m/s to 5 m/s at hot air and combustion gases output, Figure 5.

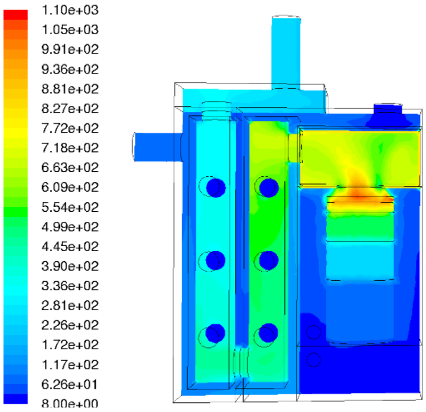


Fig. 4. The profile of temperature field in the median plane of the heating station T (˚C)

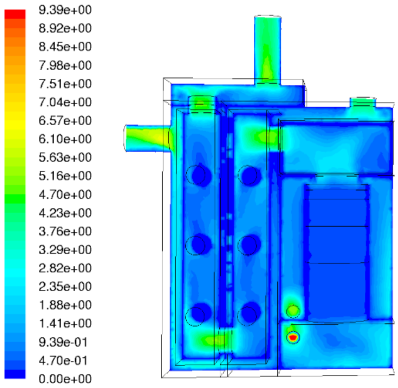


Fig. 5. The profile of velocity field in the median plane of the heating station v (m/s)

Moreover, average values of 4 m/s are recorded in the sections where the combustion gases pass from the furnace to the heat exchanger, from the heat exchanger to the exhaust air chimney, and also in the sections of the heat exchanger. Turbulence increases in these regions as a result of increased velocity and changes in direction, and the heat transfer intensifies. Turbulence level inside the station due to airflow and flow of combustion gases has been assessed by tracing the pathlines according to temperature (Figure 6) and velocity (Figure 7).

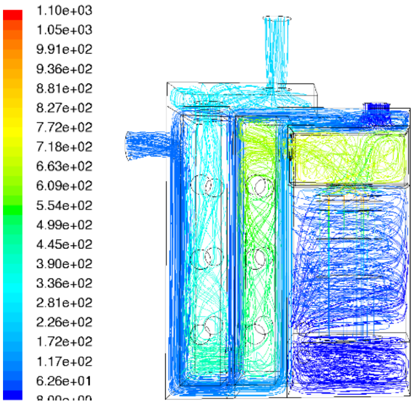


Fig. 6. Airflow and flow of combustion gases traced as path lines in the heating station (color bar - temperature TºC)

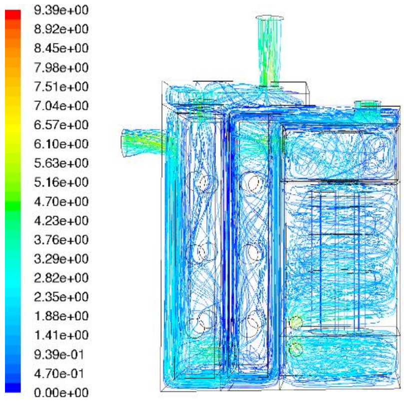


Fig. 7. Airflow and flow of combustion gases traced as path lines in the heating station (color bar - velocity v m/s)

4. Testing of the TLUD prototype

In testing, a 15 kilogram-bag of pellets per test has been used as combustion material. The reactor allows loading two bags of pellets.
The TLUD hot air generator prototype (Figure 8) has been tested in the low power and maximum power operation mode. Tests were conducted at INOE 2000-IHP premises.
Recording the temperature variation at different points of the hot air generator is done with the help of Pt1000 temperature probes. They are connected to a data acquisition board via 4 ... 20 mA amplifiers, the voltage conversion for the analog input of the acquisition board is made with the help of resistors (Figure 9). An application made in LabVIEW is used to display and record the data (Figure10). The application displays numerically and graphically the temperature variation during burning. When the recording stops, the application allows one to save the temperature values over time in a text file. These data can be processed later.

Fig. 8. The hot air generator prototype on the TLUD principle

The LabVIEW application (Figure 11) contains the following functional blocks: program loop with the possibility of setting the data acquisition range, data input block from the acquisition board in which the temperature - output signal scaling is done, numeric display, graph display, running time counter (seconds, minutes, hours), data entry in text file, graph deletion (when starting a new test), and a table display block.

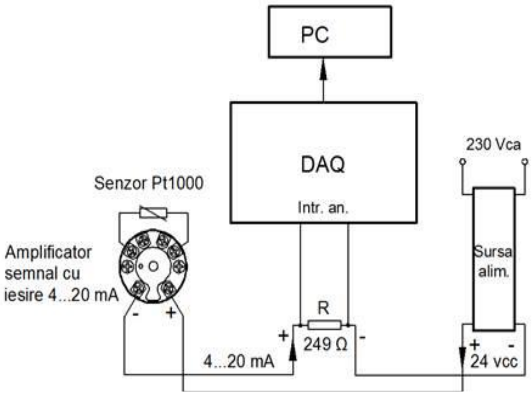


Fig. 9. Connection diagram of the data acquisition system

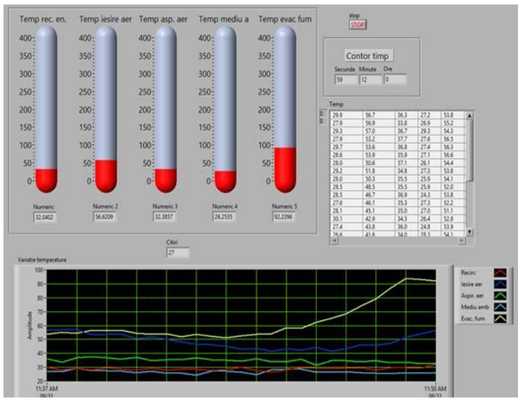


Fig. 10. Graphical interface of the data acquisition software

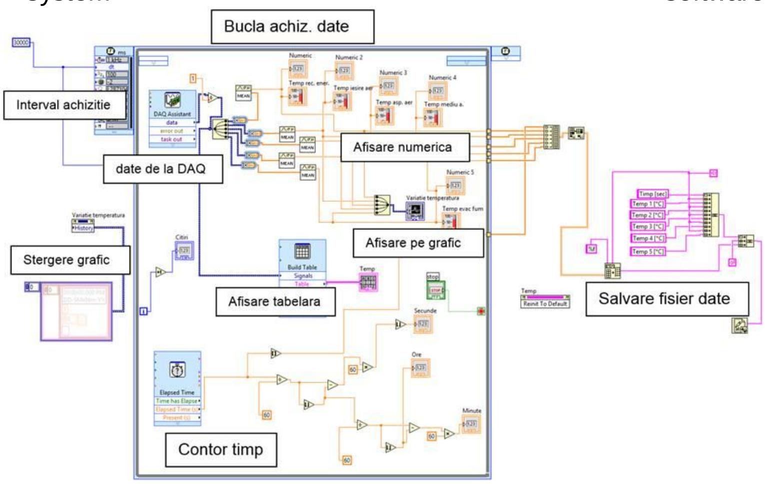
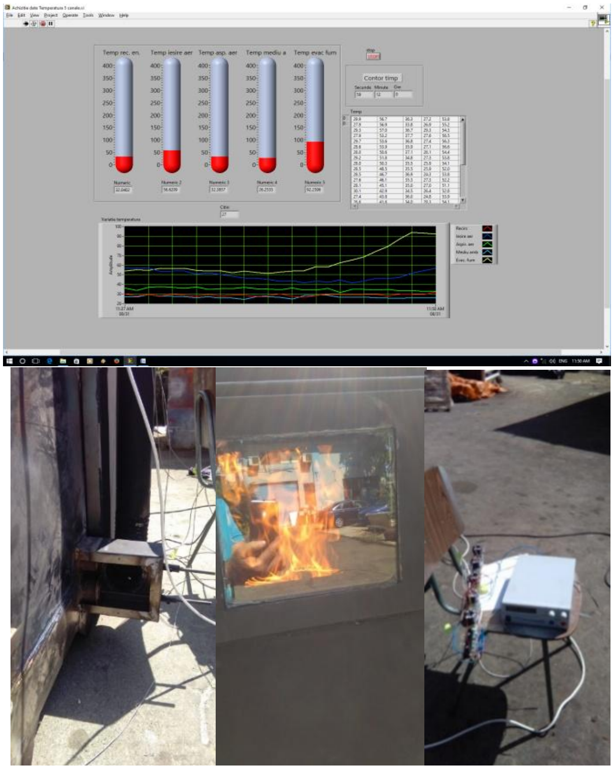


Fig. 11. Diagram in LabVIEW data acquisition software

Test 1 – The variant of gasification and obtaining biochar

The contents of a pellet bag were introduced into the reactor. Initiation of the combustion process was done at the top of the material in the reactor, with commercial fire ignition lighters and it took about 12 minutes from ignition to stabilized gasification mode according to the data acquisition (Figure 12).



a. b. c.

Fig. 12. Photos during tests (1)

After entering the gasification mode, the flame has moved from the combustion material in the reactor to the burner. The gas produced in the reactor was mixed with the combustion air and a flame similar to the flame from the stove was produced (Fig. 12.b). Several adjustments of the gasification and combustion air intake valves (Fig.12.a) have been made and the adjustability of the hot air generator power has been found. By opening them, the flame grows almost instantaneously. Thus, the correct operation of the TLUD type gasification principle (Top-Lit UpDraft) has been demonstrated.
As a result of the data acquisition (Fig. 12.c) for the entire duration of the operation until the flame is blue and the hot air generator stops (stopping of the fans and opening of the supply door) to get the biochar, the graph in Figure 13 has been achieved.

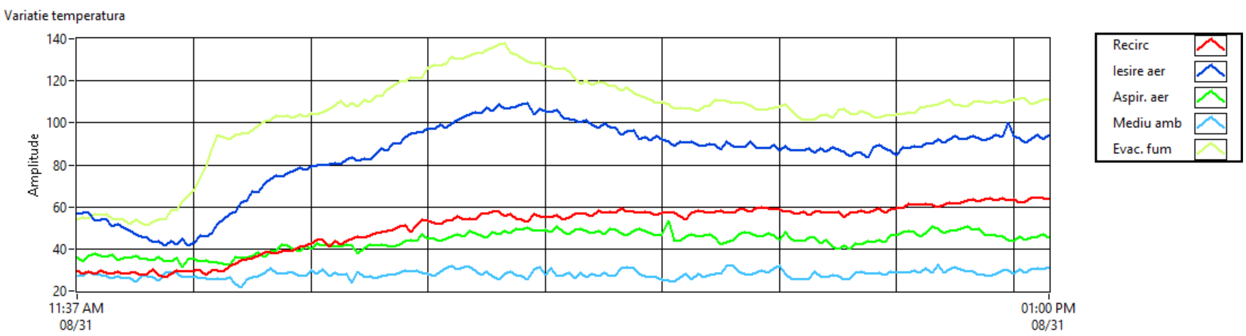


Fig. 13. Variation of temperature with biochar resulted

The burning process lasted 83 minutes for a 15 kg pellet bag under minimum power operating conditions and was interrupted when the flame was blue (signaling that the gasification of the material was complete and the gasification of the biochar is about to start). Thus, approximately ¼ of the volume of the material initially introduced for combustion resulted in biochar (Figure 14).

Fig. 14. Photos during tests (2) - biochar resulted

A good adjustment of power of the hot air generator was achieved by adjusting the combustion air and the gasification air. The temperature of the heating air at the generator outlet for the minimum operating conditions was stabilized at about 90°C and the chimney temperature was about 120°C. The air flaps have been adjusted to approximately 1-2 mm opening.
Under these conditions it can be said that the generator cannot work below the test values, so it has a minimum operating power of 3kW.

Test 2 - The variant of gasification without making biochar, with gasification of the latter
The contents of a pellet bag were introduced into the reactor. The initiation of the combustion process was done with commercial fire ignition lighters and it took about 12 minutes from the ignition to the stabilized operation mode according to the data acquisition (Figure 15).

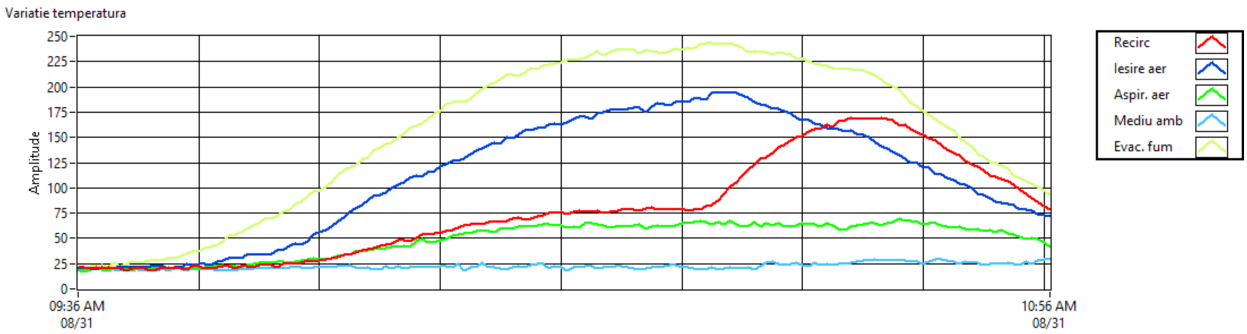


Fig. 15. Variation of temperature without biochar resulted

Under the test conditions at maximum power with combustion air flaps and gasification air flaps open at more than 10 mm, an average heating air temperature of 175°C was obtained and the chimney temperature was approximately 230°C according to the graph of data acquisition.

In Test 2, the burning process was no longer interrupted to obtain biochar (when the flame was blue), and this resulted in longer operating time and an energy amount higher by about ¼ compared to the variant when the reactor was shutted-down and biochar was obtained. The final

result of total burning, including biochar burning, was a very small amount of ash of about 50 g. The generator can work very well in both variants - with obtaining of biochar or burning it and getting energy. In both cases no emissions of smoke or unburned gas were found.
When the pyrolysis front reached near the bottom of the reactor and the thickness of the biochar layer decreased in the conditions of maintaining the flow of gasification air and the minimum resistance created by the material, the burning process accelerated for a short time (until all combustion material including the biochar has been consumed), and after that, although the burning process declined, the generator still supplied hot air for about 20 minutes due to thermal inertia.

5. Conclusions

The prototype tested meets the project objectives, works under different power modes, on the TLUD principle and it can enter into an industrial design process, after which it can be manufactured and delivered to the market.
It has been found that the smoke fan is large for operating conditions less than those obtained at test 1, but for operation at maximum power, as in test 2, it is well-sized. An improvement could be obtained if in the electronic control panel an electronic mount would be provided for the variation of the smoke fan speed. Thus, the hot air generator can be presented as operating from a minimum power of 3 kW up to a maximum power of 24 kW by adjusting the gasification air inlet flaps and combustion air inlet flaps.
If the aim is to introduce hot air into the greenhouse at a lower temperature than that provided by the generator, it is possible to resort to the solution of mixing hot air from the generator with fresh air from the atmosphere until the desired optimal temperature to enter the greenhouse is obtained.

Acknowledgements

Research presented in this paper has been developed with financial support of UEFISCDI (Executive Unit for Financing Higher Education, Research, Development and Innovation) under PCCA 2013 Programme, Financial Agreement no. 67/2014, Project title *Using renewable energy resources to increase the energy independence of mini greenhouses and solariums*, Project acronym *ENERGSER*.

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