HUNGARIAN UNIVERSITY OF
AGRICULTURE AND LIFE SCIENCES

ENERGY RELATIONS OF DECENTRALIZED CHP PYROLYSIS POWER PLANT

Doctoral (PhD) theseis

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1. BACKGROUND AND GOALS OF THE WORK

1.1. Background of the work

Nowadays, the utilization of renewable energy sources has become an extremely important task worldwide, thus increasing demand for energy use for various biomasses.

One of the biggest challenges of the 21st century is the management of climate change and energy dependence, which requires the transition to sustainable and decentralized energy production methods. Burning fossil energy carriers causes severe environmental loads, while increasing global energy demand urges new, innovative solutions. The development of combined heat and power generator (CHP) pyrolysis power plants, which are able to use the local bio-waste when based on the principles of a circular economy, offers an effective response to these problems.

The essence of CHP or associated heat and power generation is that the heat generated during the production of electricity is not released into the environment but is recovered. This heat can be used for, for example, for heating buildings, industrial processes, or hot water production. The efficiency of conventional power plants, which only generate only electricity plants can often achieve efficiency of up to 80% by utilizing CHP systems, ie the combined utilization of current and heat.

The utilization of renewable energy sources, and thus biomasses, not only relieves energy crisis, but also helps to reduce the impact of fossil fuels on the environment. Reducing emissions is also a key issue in the energy production of future energy, so this aspect should also be taken into account when developing new procedures.

The European Union's goal, in 2050, is to achieve climate and to increase the proportion of renewable energy to at least 42.5 %by 2030.

In this dissertation, the decentralized model is particularly emphasized, which allows for the optimal exploitation of local resources, compared to large central power plants. This approach reduces transport costs and logistics footprint while reinforcing local economies and energy security.

CHP pyrolysis power plants are capable of providing constant, basic energy against the fluctuating nature of solar and wind energy, thus complementing and stabilizing the energy network.

In addition, biosene, which is by-product, plays an important role in agriculture as a soil enhancer and carbon dioxide, contributing to the spread of negative carbon dioxide technologies.

Thus, with sustainable and environmentally conscious pyrolysis CHP (combined heat and electricity producer) systems, the energy produced can be utilized locally and, in the case of electricity surplus, can be fed to the utility network after proper synchronization.

The beneficial properties of biomasses can be used best when some natural waste material or by - products are used, as this can be obtained from the process instead of destroying.

1.2. Goals

The essence of decentralized CHP systems is to convert the raw materials locally into small or medium -sized units into heat and electricity, reducing energy losses and infrastructure.

Biomass pyrolysis is a very diverse and complex system that is influenced by many factors. The utilization of combined heat and electricity based on wood chips based on pyrolysis is an innovative technological approach that has many benefits, but also carries significant technical and engineering complexities.

In the framework of the research, I focused primarily on examining the preparation of biomass, the process of pyrolysis and the energy utilization of the resulting products, with particular reference to the efficiency, operational stability and environmental impact of the system. During the work, I used an interdisciplinary approach, combining mechanical, energy, material science and environmental considerations in order to ensure practical, sustainable technological solutions.

In my dissertation, I dealt with the energy utilization of softwood and hardwood chips, as well as forest chips as a biomass for energy purposes, in a decentralized environment. The abundant raw material is an excellent input for the production of combined electricity and heat.

I implemented the research by carried out my own laboratory measurements and the validation of a small power plant created by our research team (MATE-Pyrowatt Kft.) 100 kW of electric power plant.

So my goals were therefore during work:

- Getting to know existing domestic and very significant international literature
- Research for new technological opportunities for development
- Laboratory experiments perform pattern on fixed-bed-pyrolytic equipment
- Defining biomass raw materials and their properties that fit in decentralized energy supply
- Operating validation of 100 kW fixed -bed CHP system developed and executed by our research group (MATE - Pyrowatt Kft.)
- Finding and communicating new scientific results

2. MATERIAL AND METHOD

2.1. Tools and equipment used during the measurements

I started my measurements at the Laboratory of the Agricultural Mechanization Institute (MGI) and completed it at the Laboratory of the MATE Department of Building and Energy.

Moisture content **Heat of combustion**

Figure 1. METTLER TOLEDO moisture gauge, compression press, IKA-WERKE C2000 calorimeter (MGI lab)

Elemental composition of materials **Ash content, ash melting point**

Figure 2. ELEMENTAR VARIO X elemental composition testing device, Nabertherm combustion chamber, HESSE 154 heating microscope (MGI lab)

Gas composition

Figure 3. VISIT 03H gas analyzer (MGI lab)

2.2. Model experimental equipment

In order to achieve the set goals, I carried out several different experiments on laboratory sample units. The goal was to analyze the factors that can determine the quality and quantity of the product in the case of larger equipment. The small sample units were available in two versions.

The unit operating with inert gas (Figure 4) can analyze the progress of combustion, its propagation speed and individual stages of TGA analysis.

In the electrically heated (Figure 6) and completely closed system, the effects of introducing heated air in addition to TGA can be analyzed. The effect of air on the composition of the exhaust gas and the reduction of tar-type compounds.

The inner diameter of the insulated laboratory reactor is 110 mm. For each measurement, approximately 300-650 g of charge can be accommodated in the reactor space. The energy required for heating the system was provided by a 2.0 kW heating cartridge, which was controlled by the computer unit. The structure is illustrated in Figure 5.

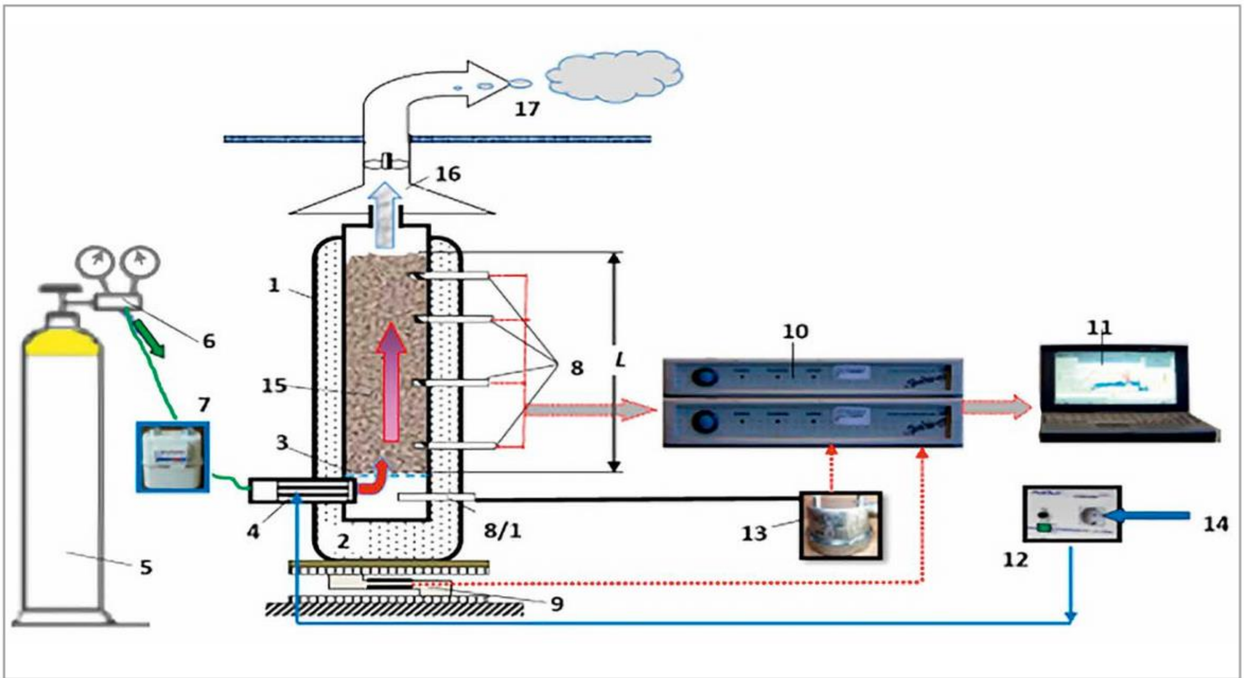


Figure 4. Nitrogen gas heated laboratory reactor measuring circuit (MATE lab)

1- generator body,
2- insulation,
3- material grid,
4- radiator,
5- N gas cylinder,
6- gas regulator,
7- gas meter,
8- temperature sensors,
8/1- temperature sensor (gas),
9- mass sensor (Hottinger),
10- data collector (multi-channel),
11- PC unit,
12- heating controller,
13- gas pressure sensor,
14- electric connector,
15- biomass,
16- gas collector,
17- gas outlet.

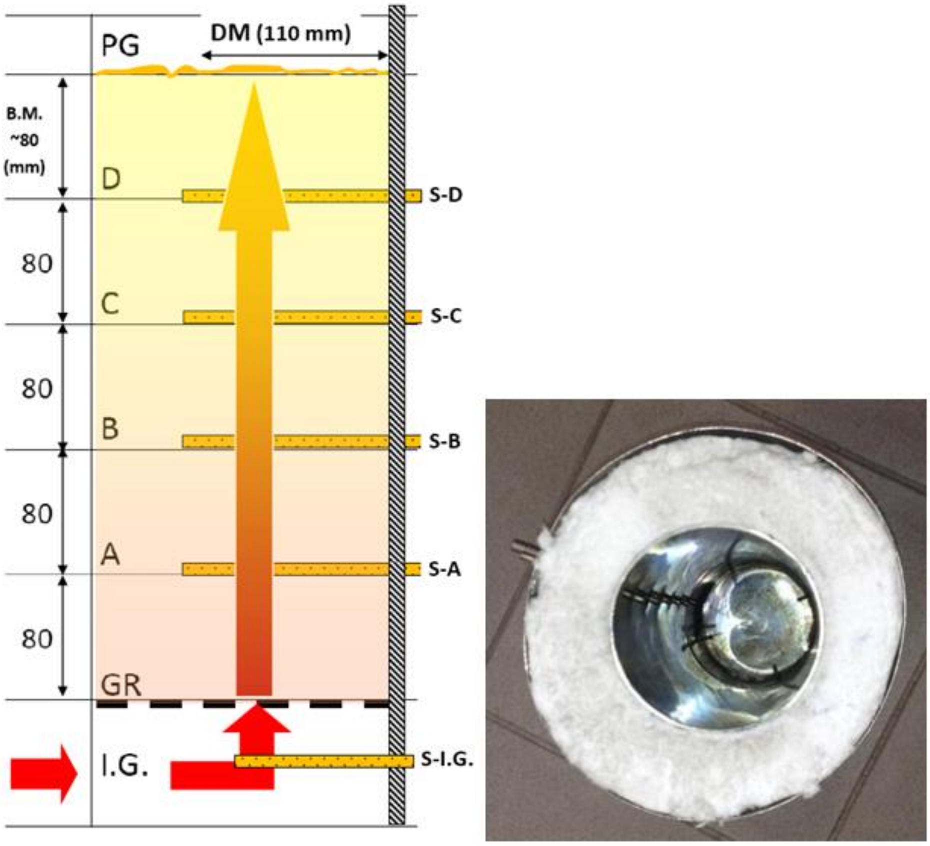


Figure 5. The main dimensions of the measuring unit, the location of the sensors, and the top view of the equipment (MATE lab)

Figure 6. Directly electrically heated, air-inlet laboratory reactor, maximum operating temperature: 1300 ºC (MATE lab)

3. RESULTS AND DISCUSSION

3.1. Effect of grain size on mass loss and gas composition change

During pyrolysis, the particle size of the starting material has a significant impact on the rate and extent of mass loss. Smaller particle sizes have a larger specific surface area, which results in faster heat transfer and more uniform decomposition, so the thermoconversion process occurs faster and more efficiently. In contrast, larger particles heat up more slowly inside, which delays pyrolysis.

During the measurement shown in Figure 7, I examined three types of particle sizes (and weights: 0.6g, 1.2g, 3.6g) of materials at two different treatment temperatures (600/1000 °C) in terms of mass change. In addition to temperature and mass, the starting parameter was the 100% state, and the measurement continued until it decreased slightly below 20%, where it was already visible how the decomposition stabilized.

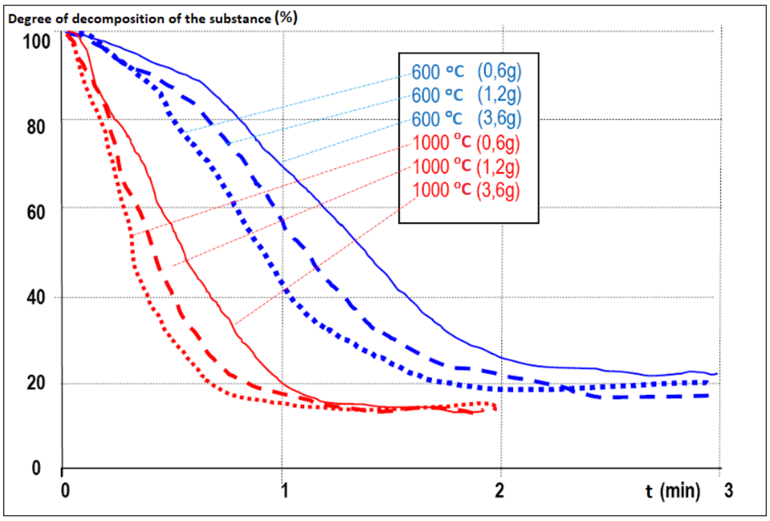


Figure 7. Weight loss for different particle sizes - G30 mixed wood chips (MGI lab)

Figure 8 shows the components of the resulting product gas at a treatment temperature of 800/1000 °C.

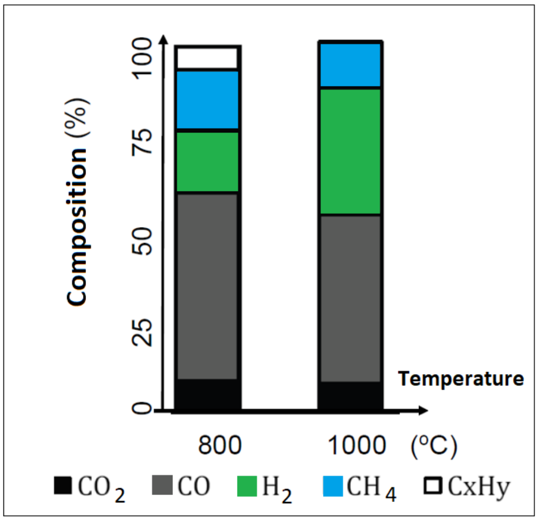


Figure 8. Gas composition change at 800/1000 °C, - G30 mixed wood chips (MGI lab)

3.2. Evolution of TG curves and pressure change in the reactor

Figure 9 illustrates the results of the test on the laboratory model reactor.

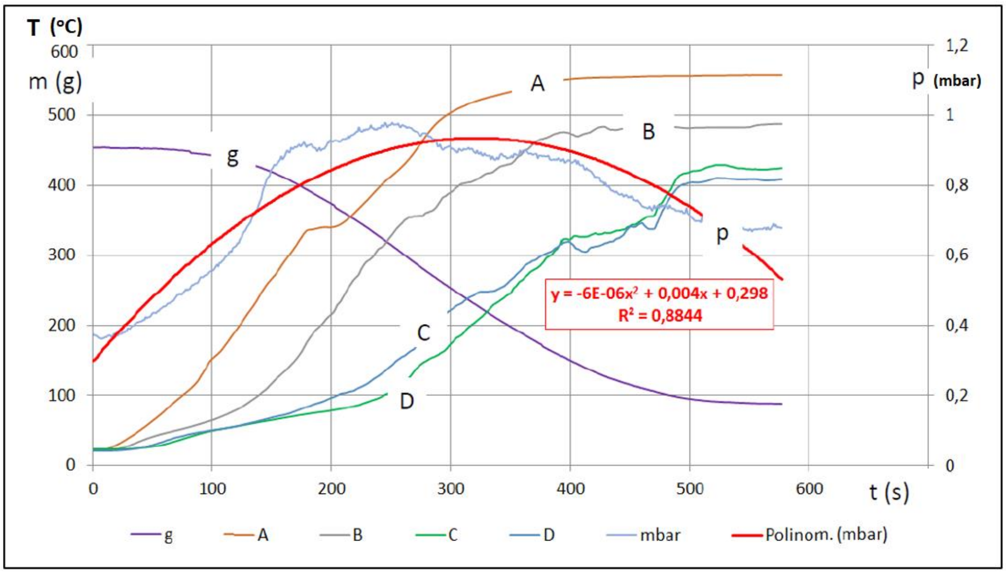


Figure 9. G30 decomposition of mixed wood chips (600 °C) (sampling density: 1,0 s)

g – mass, A – upper temperature sensor, B and C – intermediate sensor, D – bottom sensor, p – pressure change (MATE lab)

Figure 10 shows the pressure conditions of the pyrolysis process at different temperatures. In the case of a temperature of 400ºC, a linear progression (pressure increase) can be observed during the milky measurement, while in the case of a temperature of 600ºC, a parabolic progression can be observed. This is due to the collapse of the raw material at a given point, where the space between the grains becomes free and thus the resistance of the mass decreases and the pressure also starts to fall.

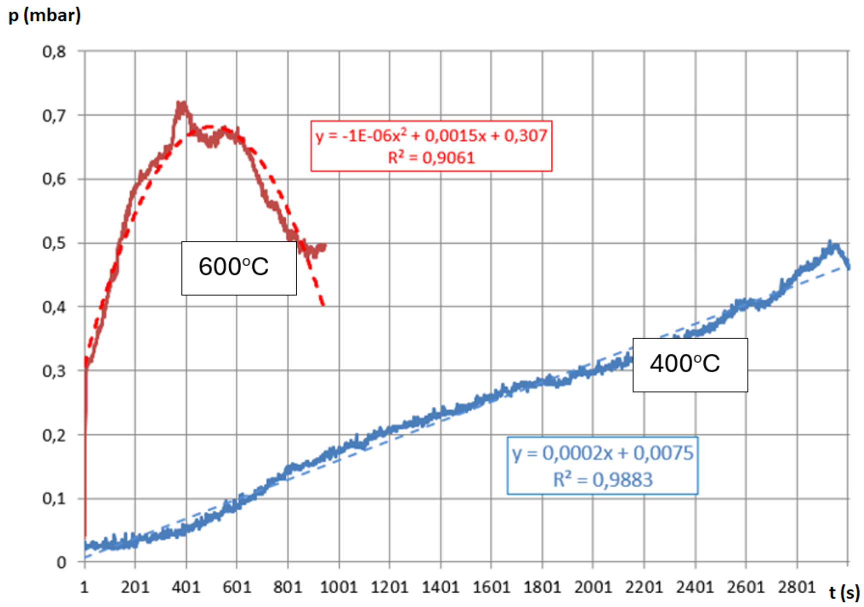


Figure 10. The change in pressure as a function of the intensity of decomposition - G30 mixed wood chips (MATE lab)

3.3. Geometric evolution of the temperature distribution and the double-walled system

I examined the development of the decomposition in the middle plane of the inert gas laboratory model reactor (Figure 11). I performed the measurement when the temperature at the second sensor of the material column also exceeded 350°C, meaning that pyrolization had begun or had already occurred. After that, I measured the distance from the wall at height H at which the material began to transform.

Radial distance (FT) and height (H) from one generator jacket

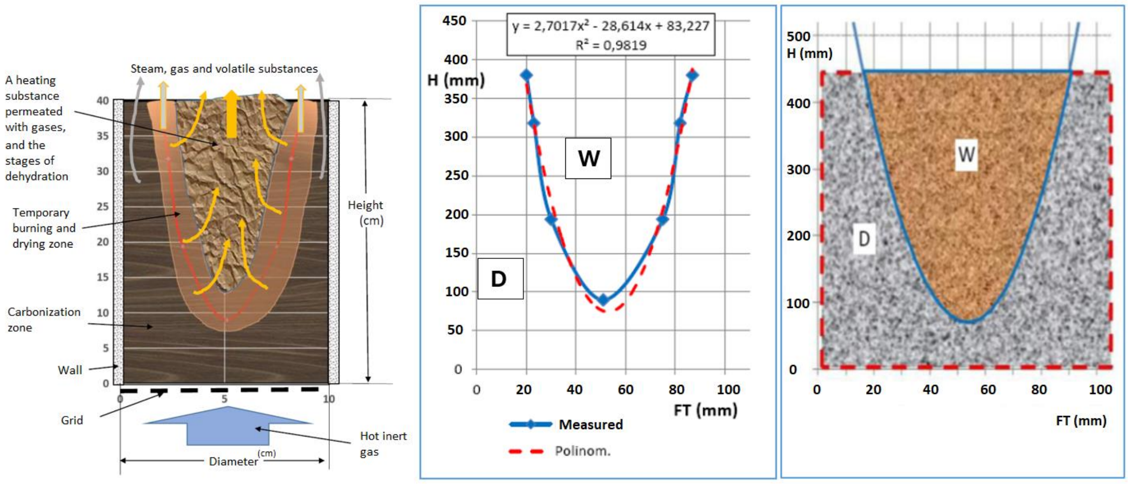


Figure 11. Geometric evolution of temperature distribution (own illustration)

I plotted the limits as a function, and then examined the function according to which the change occurs. The resulting parabola fits closely, (but I also examined the individual sides with an exponential function, and the result shows a fit with R2 > 0.9.) Thus, in the fixed-bed (zonal) reactor model, the progress of the material decomposition (Figure 11) takes place in the form of a downward-pointing parabolic cone. A top view is shown in Figure 12. The cross-sectional contour is described by the following function:

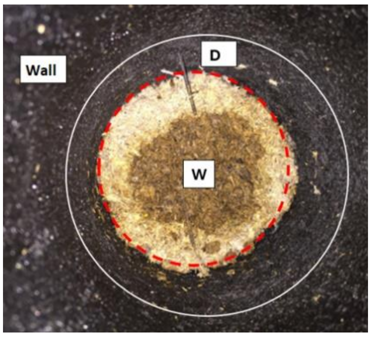


Figure 12. Top view image (own illustration)

$$y = 2,7017x^2 - 28,614x + 83,227$$
$$R^2 = 0,9819$$

x – diameter of the reactor (mm);

y – height of the reactor (mm)

1- biomass, 2- ash mixed with a little biochar
3- gas outlet to the cooler
4- preheated combustion air
5- slag (ash, residue, scraper shaft)
6- scraper 7- space between walls
A- Drying B- Pyrolysis C- Combustion
D-Cracking, cooling

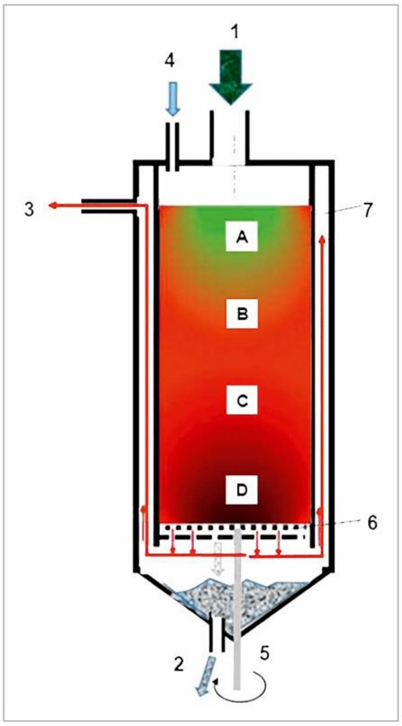


Fig. 13 Double-walled system

Figure 13 shows the operating solution resulting in the final design of the reactor, where the gas flowing out of the reactor heats the reactor wall thanks to the double jacket.

3.4. Connection of the system to the electrical network

The display (PLC) screenshot shown in Figure 14 below shows the electrical energy generation, as well as the connection of thermal energy, the incoming gas, and the display of real data from the turbocharger.

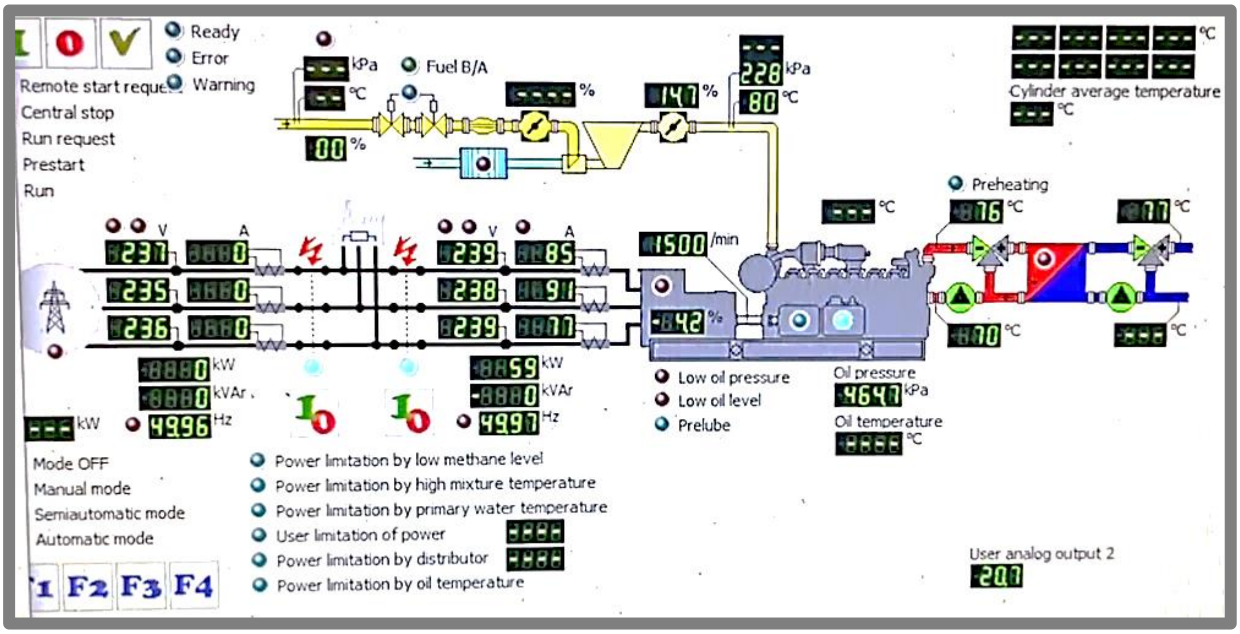


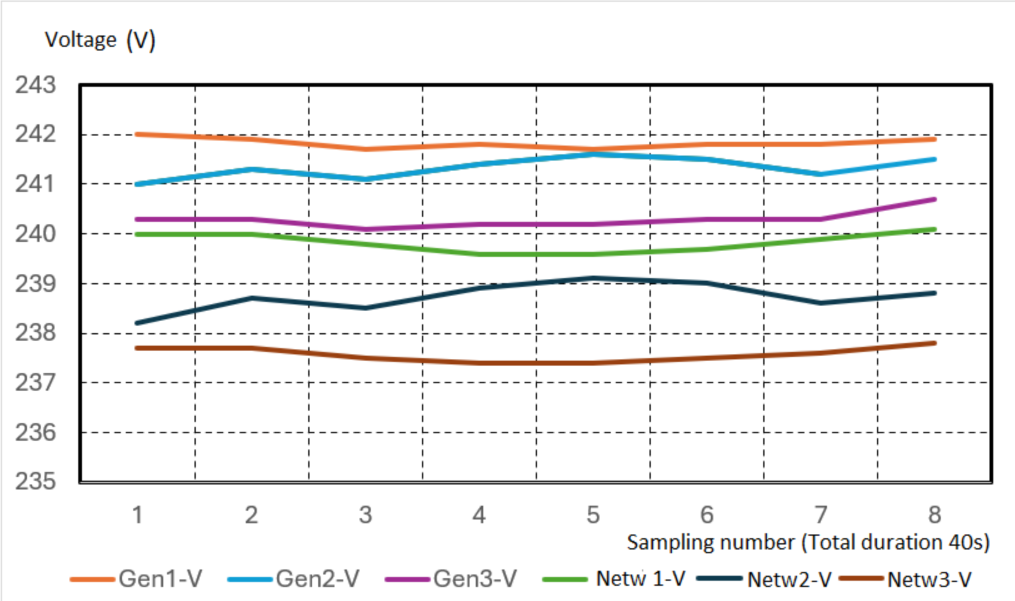
Figure 14. System connection to the electrical network, screenshot (own illustration)

Table 1. Operational measurements - presentation of a section of the connection

section	Gen.F [Hz]	Gen1 V. (V)	Gen2 V. (V)	Gen3 V. (V)	Power (kW)	Netw. F (Hz)	H1 V. (V)	H2 V. (V)	H3 V. (V)	Eng.sp. (min^{-1})
1	50.01	242	241	240.3	101.9	50.01	240	238.2	237.7	1501
2	50.01	241.9	241.3	240.3	101.7	50.02	240	238.7	237.7	1502
3	50	241.7	241.1	240.1	100.7	50.01	239.8	238.5	237.5	1501
4	50.02	241.8	241.4	240.2	99.7	50.02	239.6	238.9	237.4	1501
5	50.01	241.7	241.6	240.2	100.6	50.01	239.6	239.1	237.4	1502
6	50.02	241.8	241.5	240.3	101.2	50.03	239.7	239	237.5	1500
7	50.02	241.8	241.2	240.3	100.9	50.03	239.9	238.6	237.6	1502
8	50.01	241.9	241.5	240.7	101.2	50.02	240.1	238.8	237.8	1502

The results of one section of a longer operational measurement series are shown in Table 1, with continuous connection to the network, with a sampling frequency of 5 s. This measurement describes the operation of the system relatively well, the typical operating parameters, which were stable during the entire operation. Of course, the heating and the achievement of operating temperatures and performances do not occur immediately, this is a time-consuming process, typically 1-3 hours. Since the equipment is designed for continuous operation, the start-up procedure occurs only rarely.

Figure 15 below shows the voltage values of the generator and the grid based on the previous table 1. It can be observed that there is only minimal fluctuation in the system, both on the grid and the generator side, which indicates that the operation is undisturbed.



Fiugre 15. Evolution of generator and network voltages during operational measurements - sampling every 5 s (own figure)

Since the entire system is automated, intervention is rarely required, but professional supervision of operation is essential, which is facilitated by the PLC control display screen and remote access function. The system running together with the network is shown in Figure 16.

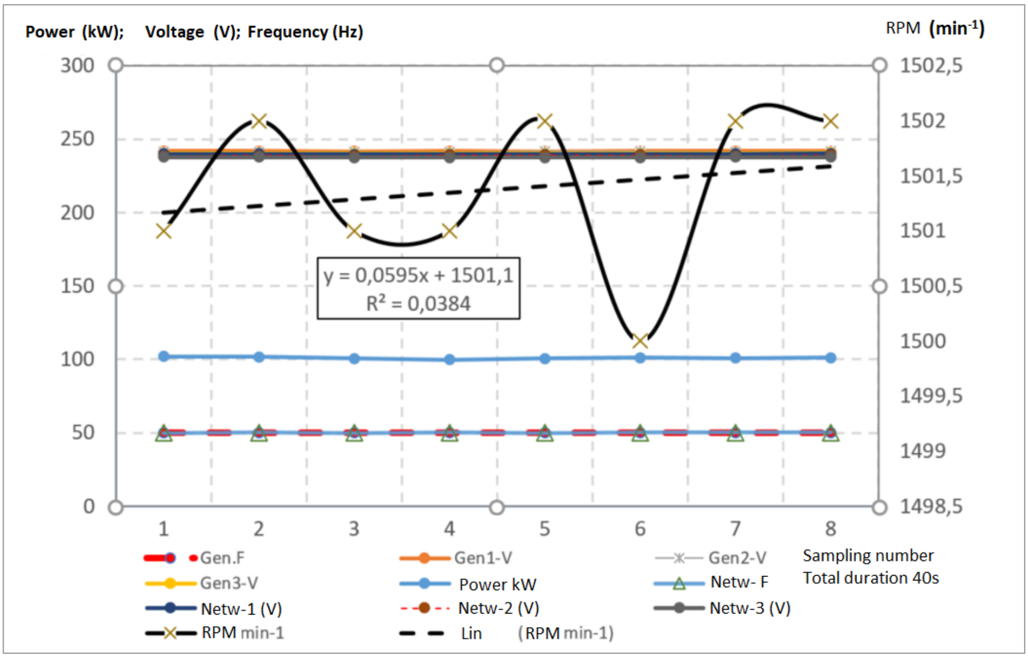


Figure 16. Running with the network - sampling every 5 s (own figure)

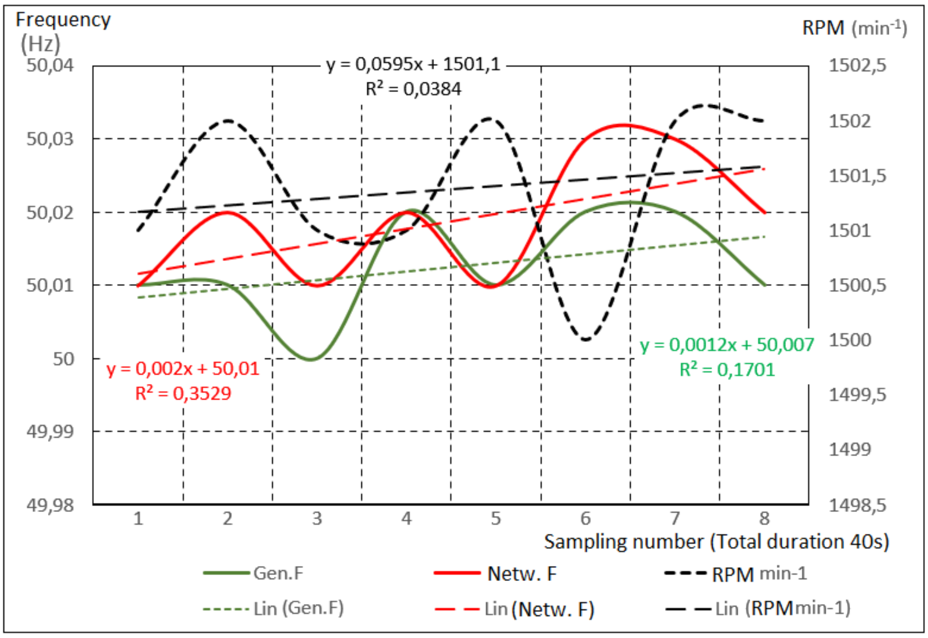


Figure 17. Revolution and frequency relationship - sampling every 5 s (own figure)

The rotational speed and frequency values are shown in figure 17, while the average phase voltages are shown in figure 18.

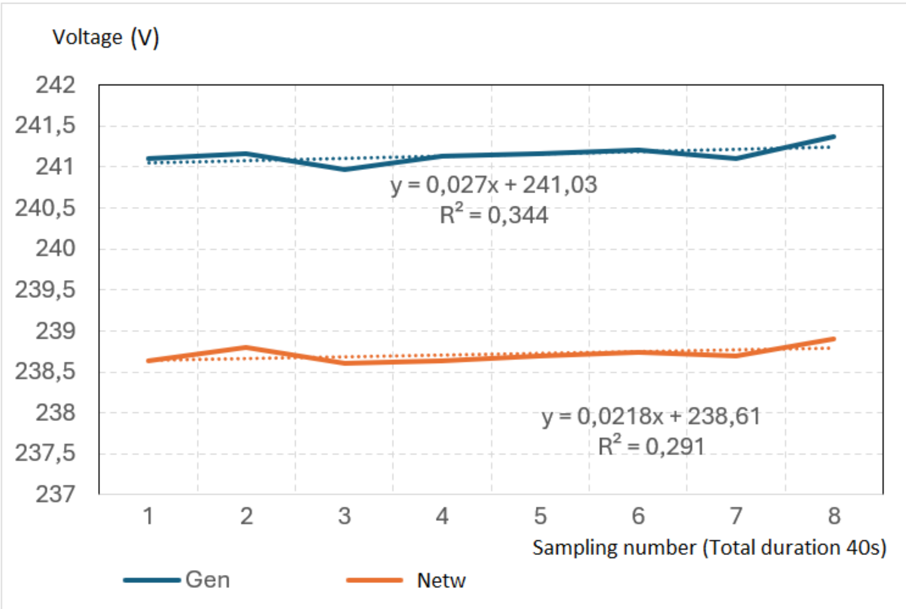


Figure 18. Generator and network phase voltages averaged - sampling every 5 s (own figure)

There is a small difference between the mains and generator voltages (within the permissible limits, according to the MSZ EN 50 160 standard), as the mains voltage constantly changes depending on the load.

The generator is able to maintain both frequency and mains voltages properly. The measurement data shows that the deviation of the values is very small, acceptable in practical operation, and complies with the relevant regulations.

4. CONCLUSIONS AND RECOMMENDATIONS

Based on laboratory measurements and international literature documents, almost all biomass materials are suitable for energy production and biochar production using pyrolysis techniques. A basic criterion is that the moisture content of the materials should be no more than 25%. The characteristics of the materials, e.g. particle size and moisture content, proved to be a basic requirement in the gravity-based model equipment used in the laboratory tests. The importance of the fineness was also confirmed by the pilot plant; if the material did not comply with the ÖNORM standard, the equipment was not able to operate without problems. The materials are not suitable for direct use even with a suitable moisture content if long stalk residues resulting from the nature of the grinding hinder the even flow in the reactor space.

Pyrolysis for energy purposes should be carried out at a high final temperature (>850°C), which increases the energy content of the gas and reduces the soot content. In such vertical gravity reactors, the decomposition zones (excluding transitions) must be known, as they can be used to determine the oxygen input required for the reaction and the appropriate mass flow rate of the material to be pyrolyzed. These factors determine the energy content of the resulting gas, but also the final efficiency with respect to the input energy content.

In order for the produced gas to operate a spark-ignition internal combustion engine and to set its speed to a constant level, it is necessary to produce high-purity generator gas with a minimum of soot and other solid particles, so that the direct-drive generator can constantly operate at the correct synchronous speed. The feedback received from the gas engine control unit and the turbocharger provides the necessary parameter modifications at the gas generator, the oxygen input and the flow of material to be pyrolyzed. The resulting gas contains a significant amount of solid impurities (powdery substances), therefore it must be filtered (using a dust separator) before being fed into the gas engine. Of the solutions tested in the experiments, the ceramic filter proved to be the most suitable, which can be cleaned periodically (even during operation) with counter-current flow.

Taking all of this into account, the appropriate synchronous speed can be achieved and the system can be connected to the public electricity network. Three control zones have been designed to achieve automatic safety:

- for the efficient operation of the gas generator,
- to ensure the correct speed of the spark-ignition engine, and
- to connect the electricity produced by the generator to the utility network.

In the plant-scale system developed by our research group and validated by me, the three control zones enabled secure network connection. With this, the system basically fulfilled the set goals, so the CHP system is able to operate independently, and does not require direct supervision if there is a sufficient material supply.

The energy efficiency achieved with the system is ~27% in terms of electricity, and if the heat energy is also used, a total of 68-77% can be achieved. When using the generated heat energy, priority is given to maintaining the moisture content of the biomass to be fed at the appropriate level. Therefore, it is necessary for the pre-storage systems to be equipped with thermo-fans. If drying is not required, the heat energy can be used for drying other crops or for communal purposes in the winter. The pyrolysis residue (3-4%) mainly contains ash and biochar. If the input material does not contain heavy metals, this residue can be used for agricultural purposes. The biochar contained therein represents the so-called “hard biochar”, which has a large internal surface area and therefore adsorption capacity, and does not decompose in the soil for decades.

Compared to traditional boiler-fired, steam turbine CHP systems, the implemented 100 kWe system has a more favorable efficiency and a smaller negative impact on the environment.

My laboratory measurements and the results of the validation of the equipment operating properly have proven that electrical and thermal energy can be produced with high efficiency from waste biomass, such as mixed wood chips.

5. NEW SCIENTIFIC RESULTS

My goal with the laboratory measurements was to determine the basic behavioral characteristics of the selected materials.

1. In the gas composition measurements performed at various treatment temperatures, I found that: at higher temperatures, the hydrogen content of the gas increases, which in turn reduces the carbon monoxide and methane content. The carbon dioxide content also decreased. In the sample device presenting the fixed-bed generator, the heating rate was higher in the (lower) parts closer to the heat source, while it was more moderate in the more distant material parts. The decomposition of the material followed the characteristic course of the (assumed theoretical) TGA well, the middle intensive section is characterized by the following linear function.

   At lower intensity of decomposition, at 400ºC: $y= -0.9x + 810.9$
   $R^2=\sim0.9$

   At higher intensity of decomposition, at 600ºC: $y= -0.2466x + 696.16$
   $R^2=\sim 0.9$

   Where (in both cases): x – period of time (s)
   y – mass of material in the reactor space (g)

2. The tests also pointed out that as a result of the decomposition, the air permeability of the set decreases due to the evaporating material, which must be taken into account when choosing the pump required for oxygen intake in the case of a reactor prepared for operational purposes.

   During decomposition at 600ºC, the material evaporates faster, while the pressure required for passage increases intensively (flow resistance increases), but after the transformation ceases, the space between the grains becomes free and the resistance of the set becomes lower. At slower decomposition (400 ºC), the evaporation occurs almost evenly throughout the entire process, and the resistance increases almost linearly.

   Change in pressure as a function of decomposition intensity
   At 600ºC, a resistance peak develops where the material collapses:

   $$y= -1E\text{-}06x^2+0.0015x+0.307$$
   $$R^2=0.9061$$

   At 400ºC, the increase in resistance with lower intensity decompisition lasts until the end of the process.:

   $$y= 0.0002x+0.0075$$
   $$R^2=0.9883$$

   Where (in both cases): x – period of time (s)
   y – change in pressure (mbar)

The amount of residue (ash and carbon) is less than when decomposed at higher temperatures, which also means that a greater amount of the material is converted into gas.

3. I examined the propagation of the decomposition of the introduced wood chips in the middle plane of the inert gas model reactor, during which I determined that the emerging geometric image is conical, the formation of which is also facilitated by the high-temperature steel wall. By modeling its cross-sectional contour, I obtained a quadratic function, the course of which depends largely on the relationship between the reactor diameter and height. The function obtained for the cross-sectional contour:

$$y = 2.7017x^2 - 28.614x + 83.227$$

$$R^2=0.9819$$

Where: x – the diameter of the reactor (mm)
y – height of the reactor (mm)

4. The cold efficiency of a gas generator is basically determined by the calorific value of the fuel input and the calorific value of the resulting generator gas. However, these values depend on the moisture content of the fuel and the composition of the combustible material of the resulting gas. From the point of view of the pyrolysis process, it can be said to be advantageous if the moisture content of the fuel is low (<25%) and the gasification temperature is high (>850ºC).

Cooling efficiency of the gas generator:

$$\eta_{HG} = \frac{H_{agáz} * q_{gáz}}{H_{atü} * q_{tü}} = \frac{5800 * 318}{18700 * 125} = 0.789\ (\sim 79\%)$$

Where:
$H_{agáz}$: Calorific value of generator gas [kJ/Nm^3]
$q_{gáz}$: Volume flow of generator gas [Nm^3/h]
$H_{atü}$: Calorific value of the average fuel consumed [kJ/kg]
$q_{tü}$: Fuel mass flow rate [kg/h]

5. The quality of the CHP system built with a pyrolysis generator is determined by the quality of the connection to the network. In order for the electricity produced by the system to be connected directly to the electricity network, it must meet the basic parameters of the network and the requirements of the relevant MSZ EN 50160 standard. The control unit of the system must monitor the electrical network and the connection can only be established if there is complete parameter matching. Continuous operation requires, in addition to the cooperation of the spark-ignition engine and the electric generator, reasonable control of the gas generator. The most basic indicator, the engine speed, determines the speed of the directly connected electric generator, and thus the frequency of the electric energy. The first and most important step is to reach (set) the appropriate values of the network and make the connection. After that, the generator must be adjusted to the network values by continuously monitoring the network. Since the system operates on a locally installed transformer station, its parameters depend significantly on the network load at the given

moment and on the nature of the load (the voltage of each phase and the load-dependent frequency of the entire system may also change). Therefore, the connection system must be network-following, otherwise the connection and continuous energy transfer may fail. During the validation of the CHP small power plant, I verify its proper operation with the following relationships.

Network frequency (Hz)	Generator frequency (Hz)
$y = 0.002x + 50.01$	$y = 0.0012x + 50.007$
$R^2 = 0.3529$	$R^2 = 0.1701$

Where (in both cases): y – frequency (Hz)
x – the measurement duration (s), in the range 0-40

Network phase voltage averaged:: (V)	Generator phase voltage averaged: (V)
$y = 0.0218x + 238.61$	$y = 0.027x + 241.03$
$R^2 = 0.291$	$R^2 = 0.344$

Where (in both cases): y – voltage (V)
x – the measurement duration (s), in the range 0-40

During this 40 s measurement period, the generator speed varied in the range of 1500-1502 min^{-1}, which can be considered adequate.

6. RELATED PUBLICATIONS OF THE AUTHOR

Peer-reviewed article in international language

1. Dhaundiyal, A., **Betovics, A.** M., Toth, L. (2025). Estimating a Non-Linear Economic Model for a Small-Scale Pyrolysis Unit. ENERGIES, 18(2),445. http://doi.org/10.3390/en18020445 **(Scopus: Q1, IF: 3,2)**

2. Madár, V., **Betovics, A.**, Tóth, L. (2023). PRODUCTION AND PRODUCTION-INCREASING FACTORS OF BIOCHAR. HUNGARIAN AGRICULTURAL ENGINEERING, (42), 14–25. http://doi.org/10.17676/HAE.2023.42.14

3. Madár V., **Betovics A.**, Schrempf, N., Tóth, L. (2023). Thermal decomposition of biomass, significance of biochar. MACHINES TECHNOLOGIES MATERIALS, 17(7), 267–269.

4. Madár V., Schrempf N., **Betovics A.**, Tóth L. (2021). GENERATING COLD ENERGY USING WASTE HEAT FROM A PYROLYSIS GENERATOR (CHP). HUNGARIAN AGRICULTURAL ENGINEERING, (40), 78–90. http://doi.org/10.17676/HAE.2021.40.78

Peer-reviewed article in Hungarian language

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