HUNGARIAN AGRICULTURAL ENGINEERING
No 40/2021 78-90
Published online: http://hae-journals.org/
HU ISSN 0864-7410 (Print)
HU ISSN 2415-9751(Online)
DOI: 10.17676/HAE.2021.40.78
Received: 05.12.2021 - Accepted: 22.12.2021

PERIODICAL
OF THE COMMITTEE OF AGRICULTURAL AND BIOSYSTEM ENGINEERING OF THE HUNGARIAN ACADEMY OF SCIENCES
and
HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES
INSTITUTE OF TECHNOLOGY

GENERATING COLD ENERGY USING WASTE HEAT FROM A PYROLYSIS GENERATOR (CHP)

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Abstract: Pyrolysis of wastes and agricultural by-products was addressed in the study. During the energetical utilization of biomasses, the pyrolysis power plant produces electricity and heat, so we examined the possibilities of using the generated waste heat. This waste heat can be used at the place of generation, to produce the so-called "cold energy", which can meet the energy demand of cold stores.

Keywords: biomass, pyrolysis, gas generator, waste heat, cold energy

1. Introduction

In this article, we present a special use of the energy obtained during the pyrolysis of biomass, which is less discussed and known among consumers. More research institutes and companies are involved in the pyrolysis of various wastes and agricultural main and by-products than in the exploitation for energy purposes, considering that in some respects, the so-called circular farming can take place. Throughout the process, heat and electricity are generated, but as an intermediate product from biomass, to improve the structure of agricultural soils, stable so-called biochar [1] can be produced, that has a positive effect. RAIL SAFE LTD. [2] and CSŐMONTAGE LTD. [3] have been engaged in the development, design and manufacture of pyrolysis generators for several years [4-9]. Small power plants with gas generators of 5, 30, 50 and 100 kW are already available. A number of authors and analysts have pointed out that these generators can be used economically if the obtained electricity and heat are used entirely. There are also many woody and cellulose-rich (Fig. 1 and 2) main and by-products [10] available in Hungary, which have an attractive carbon and energy content. Thereby, this solution can be applied to decentralized energy production as well, as there are legal possibilities for electricity feed-in, and thermal energy can be used in situ for several purposes.

Figure 1. Wood chips and pellets

Figure 2. Herbaceous material, e.g. straw pellets

We talk about a system that recycles waste heat at a higher temperature to produce “cold energy”, that allows fruits, vegetables and other foods to be stored permanently. These systems are able to provide the cold energy supply needed for cold stores with the waste heat of their operation.

2. Material and Method

2.1. Expectations to fuels

For the operation of the planned equipment, various biomasses arising in agriculture are suitable, but deteriorated rail sleepers are raw material as well.

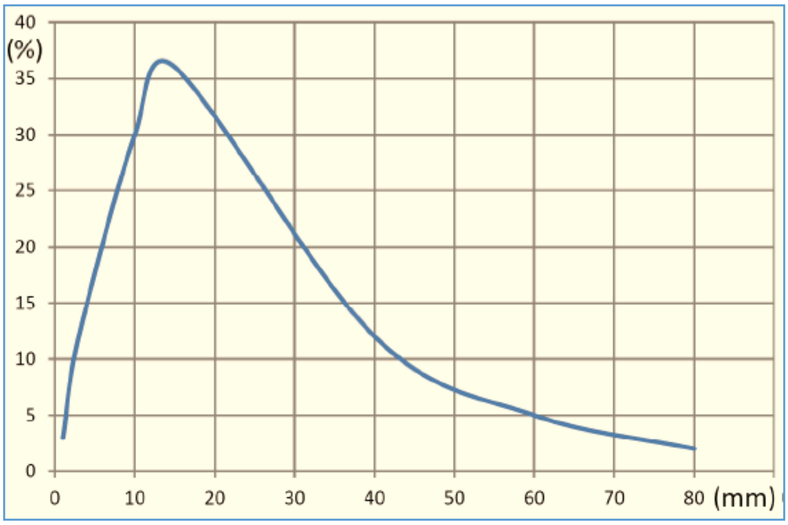
Important factors for proper operation [11]:

- degree of shooting of substances (Table 1, Fig. 3),
- moisture content and
- energy content but
- the amount of minerals may also be decisive.

Table 1. Wood chips according to size (according to ÖNORM M7133)

Wood chips	Dimensions allowed				Allowed extremes max.	
	max. 4%	max. 20%	60-100%	max. 20%		
Category	Chips’ size [mm]				Cross-section [cm^2]	Length [cm]
G30	<1,0	1-2,8	2,8-16	>16,0	3	8,5
G50	<1,0	1-5,6	5,6-31,5	>31,5	5	12
G100*	<1,0	1-11,2	11,2-63	>63,5	10	25

* - Not recommended.



Size ranges (mm)	<1	1 - 3	3-10	10-15	15-40	40-60	>80
Hardwood chips (%)	3	12	30	36	12	5	2

Figure 3. The distribution curve characteristic of hardwood chips

After delivery, substances must be dried to a moisture content of 18-20% before pyrolysis [12]. The equipment is suitable for this, as the heat demand of drying from heat demolition and energy conversion (gas engine electric generator), while heat is generated in exotherm processes. This is suitable and cheap for the high-temperature waste heat generated by the gas engine. It is more economical to get raw material with a low moisture content, and only the need for cutting to the right size can mean extra energy. The specifications of the test material are listed in Table 2.

Table 2 Characteristics of the test material

Denomination	Elemental composition					Moisture content	Calorific value (on dry matter basis)
	N	C	S	H	Cl		
	(%)						(MJ/kg)
Hardwood	0,10	42,83	0,07	6,29	0,00	12,73	16,86

If we decide to use herbaceous plants, it is best to pellet the materials, as pyrolysis is more efficient in a compressed form in a fixed bed system and the operation of the equipment is more problem-free.

2.1. The equipment established

The complete equipment can be placed in a separate plant hall (Fig. 4), which also contains the units required for pre-storage, drying and cutting. The material can be transferred directly from the storage and drying units to the equipment. The feed into the gas generator is provided by a pneumatical sluice. Controlling the sluice is important because decomposition requires a certain oxygen-poor environment.

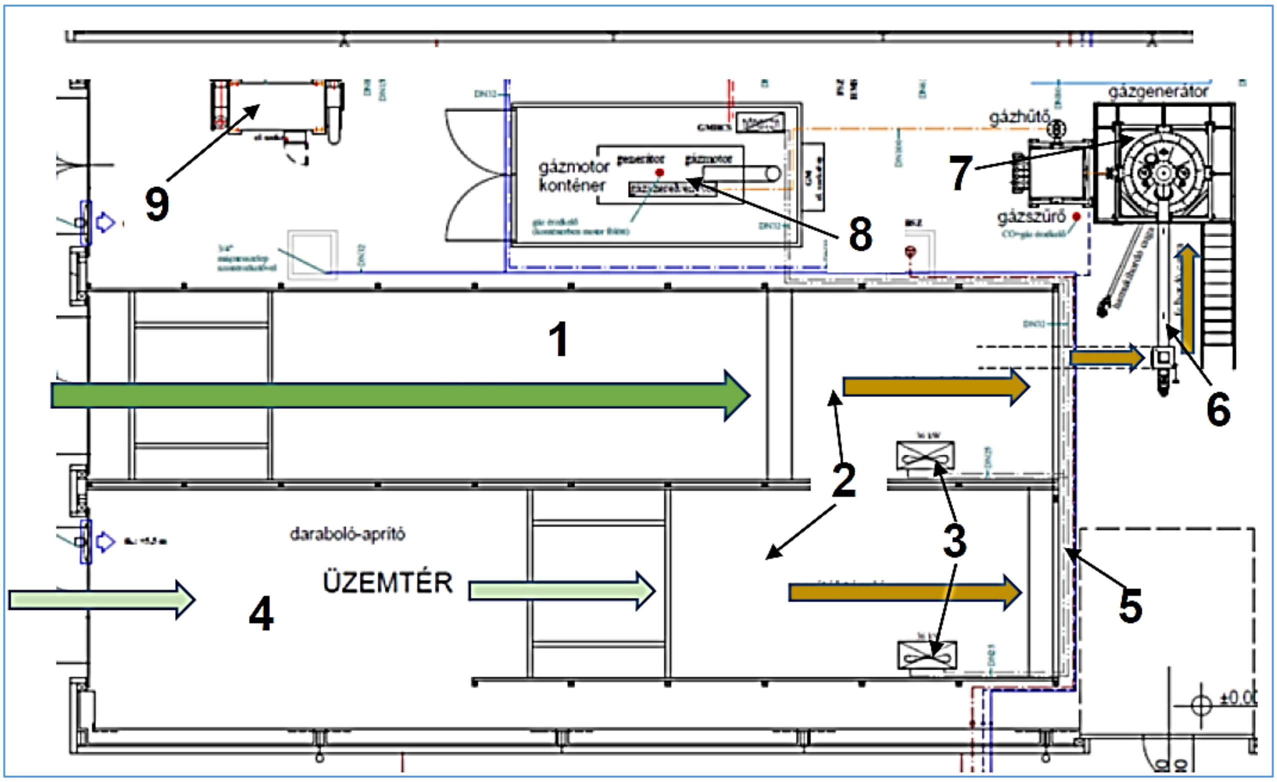


Figure 4. Layout of the complex facility in the building and the connection to the cooling system

Signs in fig. 4:

1. large storage (that can be folded by car)
2. drying areas
3. heaters
4. space reserved for cutting and shredding
5. transverse transport
6. delivery of the material to the reactor space
7. the reactor with its various components
8. motor and electric generator
9. absorption refrigeration equipment

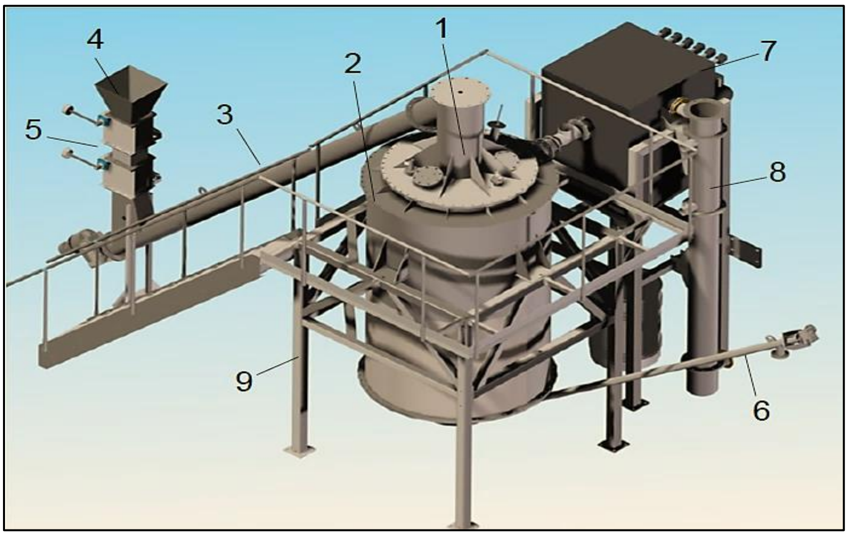


Figure 5. The generator body and the elements involved in the decomposition

Signs in fig. 5:

1. generator body with feed port
2. generator body and insulation
3. fuel delivery pipe
4. fuel inlet
5. sluice system
6. ash discharge and propulsion
7. gas filter and its units
8. heat exchanger
9. frame structure of the system

The generator (Fig. 5) belongs to the so-called fixed bed (Fig. 6) types [13], which represents a simple structure compared to screw or fluid bed designs. The material first enters the drying space, which ignites at the bottom and begins to glow at higher temperatures [14]. This and the next combustion chamber are also called oxidation zone, where gases and coal are produced by adding the optimal amount of air [15]. In the lower part of this layer, resp. in the next space is the reduction zone where the tar harmful to the gas engine decomposes (into combustible gases).

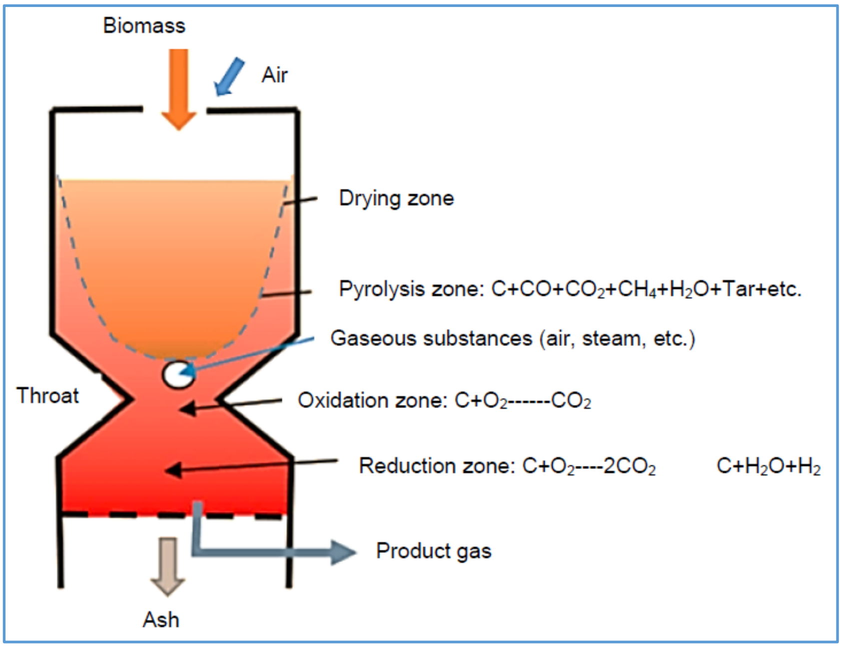


Figure 6. Theoretical operation of the bottom-drain fixed bed system

With the right temperature and air ratio, tar can be eliminated [16, 17]. Typically, the residual material contains 25-35% carbon and 1-2% minerals in the ash. The temperature of biomass stored outdoors is usually the same as the ambient temperature. It is higher in summer and lower in transition and winter time. Its moisture content is also variable, as it absorbs water from the air during the transition period.

The basic goal is the biomass entering the reactor to have a constant temperature and moisture content. We can only achieve this by fulfilling a pre-drying before the reactor. The heat generated in the reactor is used for this purpose: by passing the high temperature gas leaving the reactor into a heat exchanger.

The other side of this heat exchanger is supplied with drying air at a temperature suitable for the environment, which has been warmed up to 100-120°C in the heat exchanger. The temperature of the gas leaving the reactor is about 650-750°C. Due to the low temperature on the opposite side, the gas enters the second heat exchanger with a significant temperature loss, against which the air entering the reactor is preheated on its side (Fig. 7).

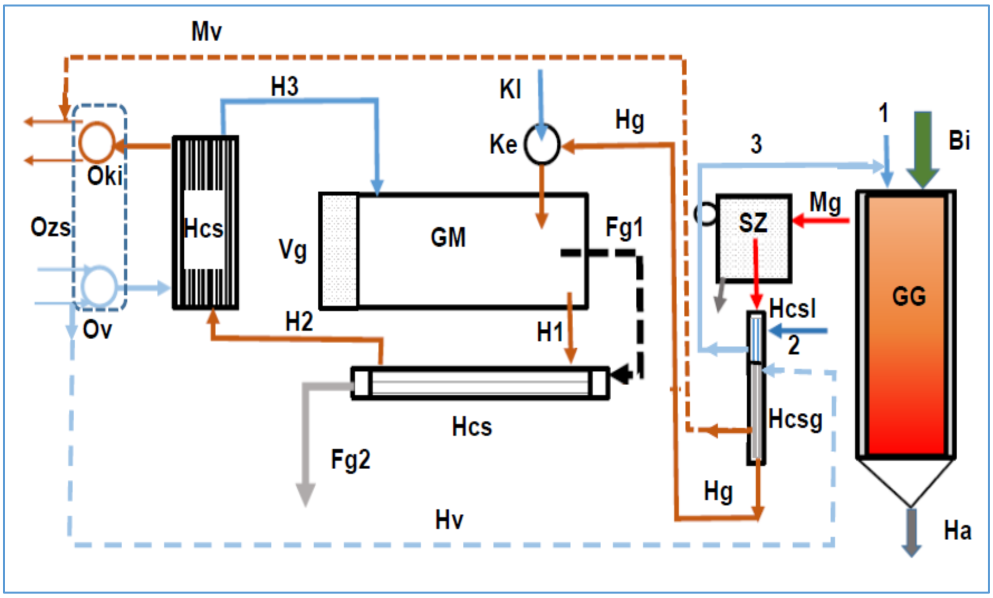


Figure 7. Schematic diagram of the system

Signs in the figure:

Sign	Denomination	Sign	Denomination
Bi	Biomass addition	Ke	Adding gas and air to the engine
KI	Ambient air	Fg1	Flue gas from the engine
GG	Gas generator	Hcs	Batch Heat Exchanger
Ha	Ash and residual coal	H1	Engine cover coolant
Mg	Hot gas	Kl	External combustion air
SZ	Filter house and filters	Fg2	Cooled flue gas
Hcsg	Gas / water heat exchanger cooler)	Vg	Electric generator
Mv	Hot water	H1	Engine outlet coolant
Hcsl	Gas / air heat exchanger	H2	Heated coolant
1	External air	H3	Cooled coolant
2	External air inlet	Hcs	Laminal exchanger
3	Warm added air	Osz	Output manifold connectors for dryer heater and absorption cooler
GM	Gas engine	Oki	Divider output
Hg	Cooled gas	Obe	Divider input

An important question is whether the material flows through the drying zone by gravity or vibration is required. When granular material is filled into the tank, the pressure at the bottom of the tank initially increases similarly to the hydrostatic pressure of liquids. However, with the amount of added material, the interaction between the sidewall and the grains increases, and the friction on the sidewall and between the grains as well. In addition to the gravity resulting from the height of the material column, the equilibrium of the set is determined by the compressive and frictional forces among particles. But due to irregular shape, tensions and entrapments can also occur.

In this case, the gas flowing between particles, which causes them to move, but the shredding knife at the bottom of the reduction space also plays a role in, which also has a force in the vertical direction (resulting in mechanical movement). In terms of static condition, a run-off occurs when the thrust is greater than the friction.

Model measurements with carbon particles (~ 1-8 mm) show that the drainage intensity is stable in the cone range of 40-60°, which is advantageous for the consistent operation of the system (Fig. 8).

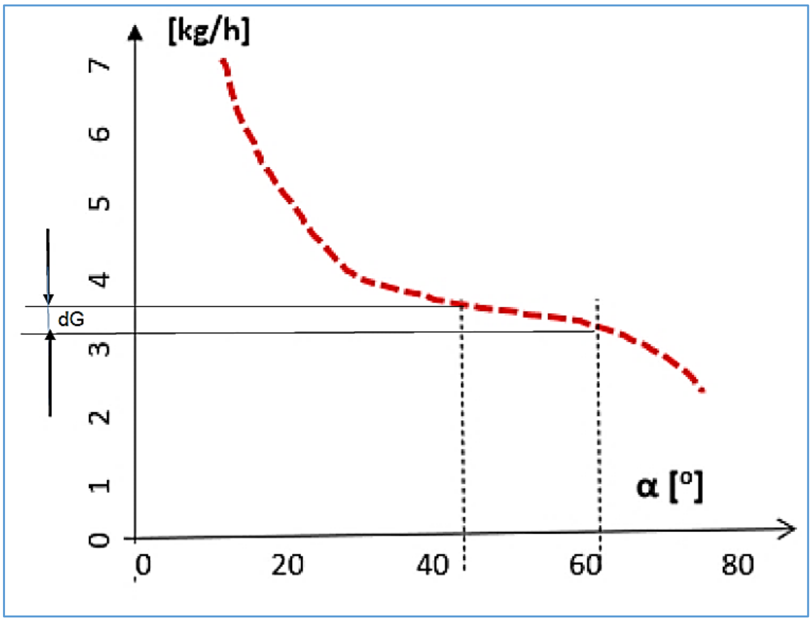


Figure 8. Mass flow as a function of α

If the value of α is smaller, the thrust will be larger, so the flow will be faster.

The scraper structure at the bottom of the reduction zone helps to remove ash and dust residues (it also prevents the lump residue from sticking together), but the gas also leaves the system on this surface and the perforated side wall. The gas flows to the dust separator and then to the bundle heat exchanger and then to the engine's mixing unit. So, the engine gets the right quality, dust and tar free gas, but the right mixture for ignition and combustion enters the engine by mixing air.

The filter unit is made of ceramic, which has excellent filtration properties, a long service life and can be easily cleaned by reverse flow air supply.

The amount of heat escaping through the exhaust of the engine heats a bundled heat exchanger [8], on the opposite side of which the engine outlet cooling water flows and further heats to the plate heat exchanger. There, the heat is released back into the engine compartment. On the outlet and inlet manifolds on the other side of this heat exchanger, a liquid of ~ 90°C supplies heat to the evaporator of the absorption cooler, and if necessary, to the heaters connected to the dryer. The intake air of the engine is heated by one part of a heat exchanger on the other side, which is a tubular but two-part heat exchanger, by warm gases. In the other part of the heat exchanger, the gas is further cooled, namely at the inlet of the plate heat exchanger, by the fluid of the return branch, which then opens into the outlet part of the manifold. The thermal energy content of the product gas is also used with these.

The spark-ignition gas engine (Fig. 9) drives the electric generator at synchronous speed, which supplies energy to the mains through a nearby transformer.

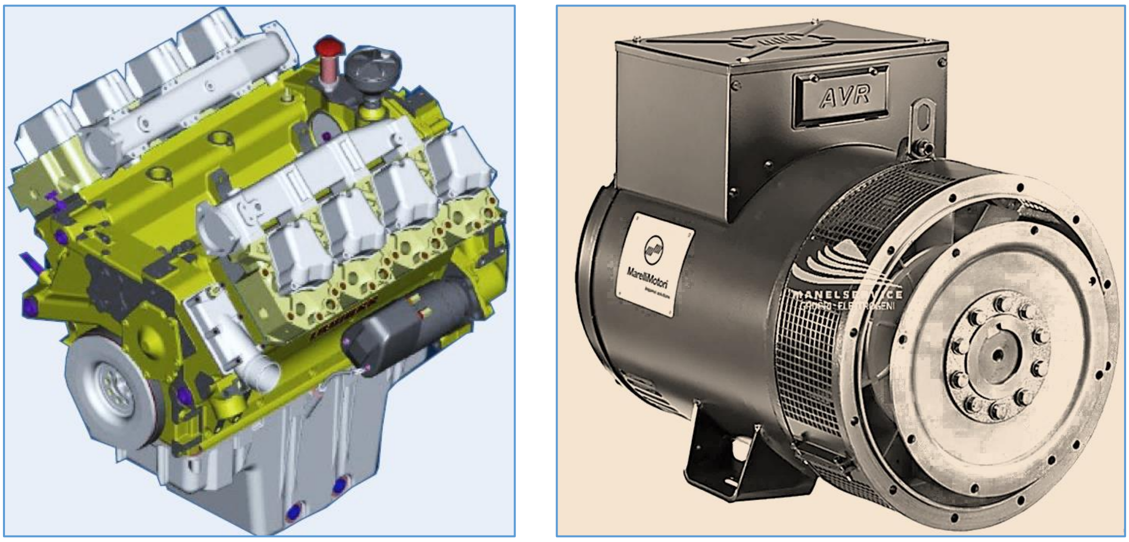


Figure 9. The spark-ignition 8-cylinder gas engine and the connected electric generator

After all, the waste heat of the system (55-60% of the total fed) can be used for cooling, or for drying fuel with a higher moisture content, for public utility purposes and for residential heat supply, depending on the needs and situations that arise.

An external air-based cooler is used to cool the absorber of the equipment.

The system can be considered a complicated assembly and the operation requires high accuracy, so the operation of the entire complex is automated.

The V1040 OPLC is a programmable logic controller with a built-in operator panel. The operator panel's 10.4" colour touch screen has function keys and a virtual alphanumeric keypad. The virtual keyboard will pop up automatically when required by the application, e.g. for data entry.

After all, control and management are made up of three systems. The **first unit** monitors and controls the pyrolysis equipment. This includes pre-drying, feedstock feed, air inlet, ash scraper operation, and temperature zone monitoring (Fig. 10).

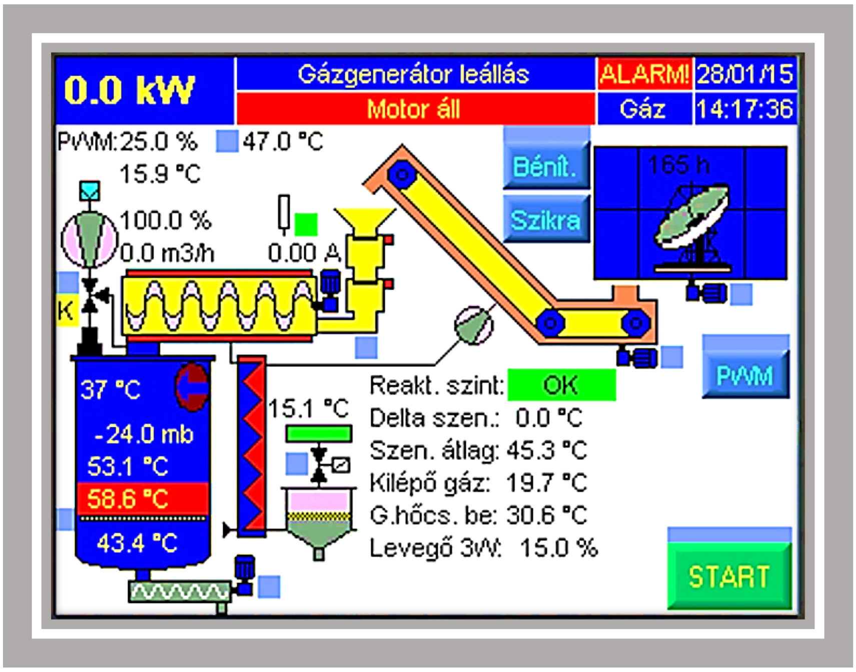

0.0 kW
Gázgenerátor leállás
Motor áll
ALARM!
Gáz
28/01/15
14:17:36
PWM:25.0 %
47.0 °C
15.9 °C
100.0 %
0.0 m3/h
0.00 A
165 h
37 °C
-24.0 mb
53.1 °C
58.6 °C
43.4 °C
15.1 °C
Reakt. szint: OK
Delta szen.: 0.0 °C
Szen. átlag: 45.3 °C
Kilépő gáz: 19.7 °C
G.hőcs. be: 30.6 °C
Levegő 3W: 15.0 %

Figure 10. The operation and the operating parameters of the gas generator interface for monitoring and control

It monitors the operating parameters, controls the gas generator and tracks all process-related temperatures as well as pressure values etc.

The second unit monitors the operation of the motor (Fig. 11) and the interaction with the electric generator. It adjusts the gas/air mixing ratio to get the engine running at its best efficiency.

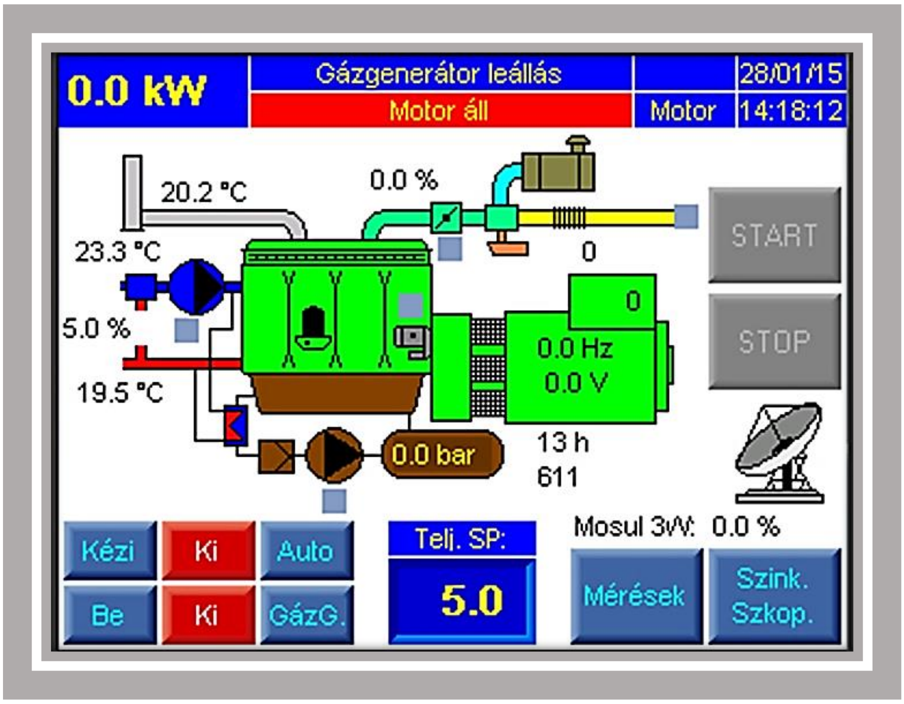


Figure 11. Operating characteristics of gas engine and electric generator

This screen shows the operation and operating parameters of the gas engine generator and the interfaces of the intervention options (touch buttons):

- The engine cannot be started until the gas generator parameters are correct.
- You can specify the desired power after start-up.
- Necessary controls for setting the motor mode.
- Engine speed, oil pressure and coolant temperature can be checked continuously.

The third system is based on the data and operational base of the two mentioned units, but it mainly cooperates with the electricity network, the base is provided by the network. After all, the system operates according to the strict needs of the network, subordinating the operation of the complex to it. If a malfunction detected by the controller, the main supply is cut off and the gas is burned by a logger placed outdoors. This eliminates the need to stop and restart the pyrolysis generator.

3. Result and Discussion

3.1. Characteristics of testing

Equipment designed for electrical power 100 kW_{max}

- Hardwood chips with a moisture content of 20%
- 13 MJ/kg calorific value

Table 3 shows the material used and the flow rate, table 4 describes the gas composition, table 5 introduces the characteristics of the energy produced and at last table 6 shows the occurring temperatures and other related characteristics.

Table 3. The material used

Fuel	Material flow (kg/h)
Wet wood	124
Moisture from the air	20
Air mass flow	239

Table 4. Gas composition

Gas composition	On wet basis (%)
CO	14.3
CO_2	11.6
CH_4	1.8
H_2	18.5

Table 5. Energy characteristics

Characteristics	Energy (kW)	Heat energy (%)
Heat energy (input)	477	100
Energy in charcoal (residual)	17.8	3.7
Heat loss	18	3.8

Table 6. Temperatures and other characteristics

Related characteristics	On wet basis
Fuel moisture content (%)	20
Initial temperature of fuel (°C)	25
Outside and inlet air temperature (°C)	25
Hot gas temperature (°C)	600
Gasification temperature (°C)	850
The energy content of the gas (MJ/Nm^3)	5.1
Cold gas efficiency (%)	70.1
Ash (%)	1.9

CHP performance characteristics:

- $\eta_e = 0.23\text{-}0.26$: 108-121 kWe
- Usable heat output: 350-365 kW
- 1 kWh of electricity can be produced from ~ 0.97-1.1 kg of wood chips.

The energy introduced into the wood but not utilized for drying and preheating the fuel, and includes the heat transferred by the components to the environment. These are: mainly with heat transfer and exhaust gas $\Sigma \sim 850$ MJ.

In this system, usable heat capacity is also used to produce cold energy for a cold store. In practice, it provides the input energy demand of the absorption chiller.

3.2. The absorption cooling system

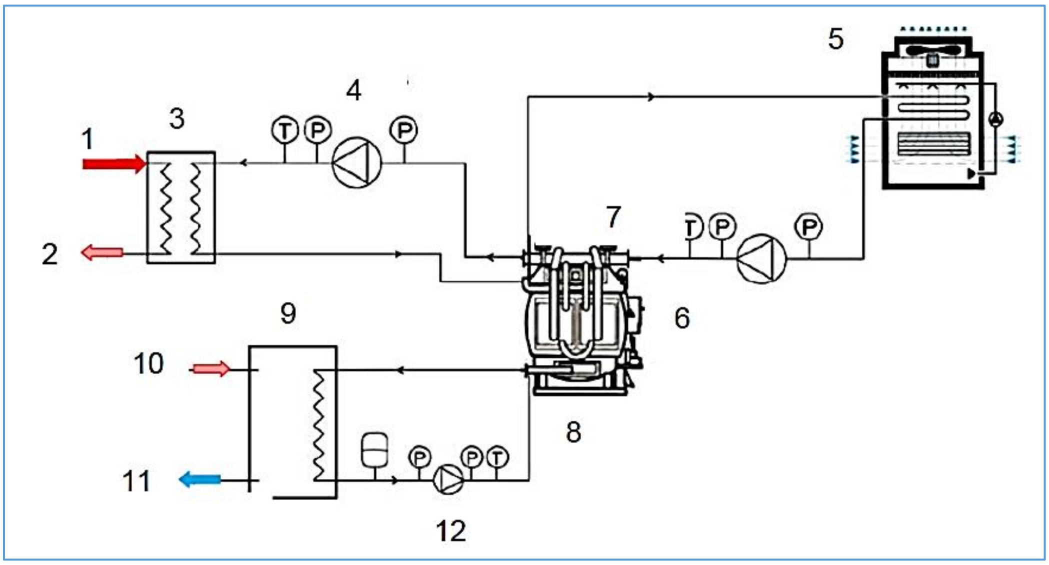


Figure 12. Cold power generation and system

Signs in fig. 12:

1. incoming heat energy to the distributor from a gas engine and a gas generator
2. return branch of divisor
3. plate heat exchanger
4. heating circuit elements
5. external air cooler to cool the absorber
6. absorption heat pump
7. cold energy circuit from the heat pump evaporator
8. cold energy circuit from the evaporator
9. heat exchanger of the cold store
10. return branch of the cold store
11. forward branch of the cold store
12. cooling circuit inlet fittings

The control of the CHP system described above is connected to the chiller, which is physically independent of its operation, namely it monitors the cold energy demand on the secondary side and intervenes according to its needs (Figure 12). If neither hot nor cold energy is needed, the thermal energy is released to the air through the air coolers.

In absorption refrigerators (Figure 13), instead of a compressor, in an absorption-desorption circuit, the working medium absorbs the vapor of the heat transfer medium at low pressure, increases the pressure of the solution to the upper pressure level, and then evaporates the heat transfer medium from the solution at the upper pressure level. So, they are also found in absorption machines: the evaporator, the condenser and the expansion valve. The mechanical compressor is replaced by a thermo-compressor (absorber + expeller) (Figure 13).

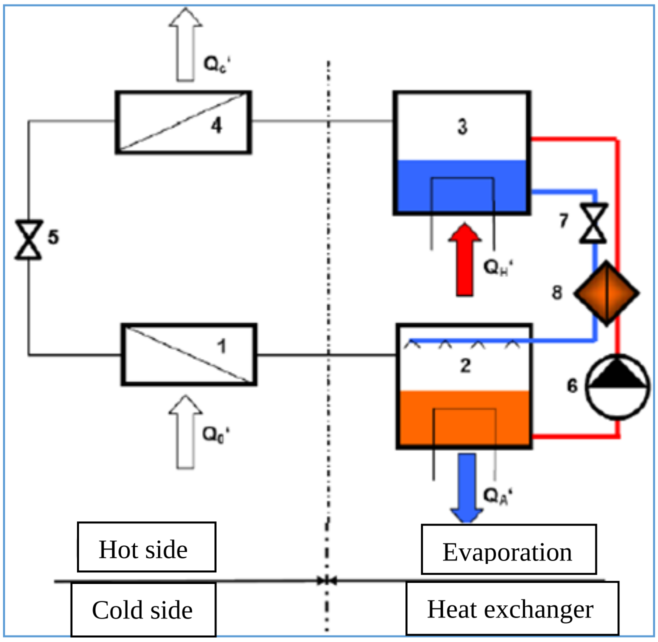


Figure 13. Schematic structure of the absorption refrigerator [8]

Signs in fig. 13:

1. evaporator
2. absorber
3. expulsive
4. condenser
5. expansion valve
6. pump
7. throttle
8. heat exchanger

From the generator the external heat causes the absorber steam to enter the condenser, where it becomes liquid under the influence of external cold energy, then evaporates through the choke when it draws heat from the hot material coming in the cooling circuit and liquefying. Upon entering the absorber, the poor solution returned from the generator is enriched and pumped back into the generator by the absorber pump. The intermediate heat exchanger improves efficiency by preheating the colder enriched medium, so less energy is required for re-expulsion.

Energy balance of the system:

$$Q_o' + Q_H' + P_P = Q_C' + Q_A' + Q_V' \qquad (1)$$

Where:

- Q_O’= cold energy capacity (cooling capacity)
- P_P = pump drive performance
- Q_A’= warm energy (absorber power)
- Q_H’= heat dissipation (heating)
- Q_C’= condensation power (heat absorption)
- Q_V’= losses

Cold energy performance:

$$Q_0' = \epsilon_h \left(Q_H' + P_p \right) \qquad (2)$$

Where COP: ϵ_H = 0,85-1,2.
In this case, the available heat output is 350 kW, the cold power output of the absorption machine is ~ 340-355kW (this has not been validated yet).

3.3. The implemented system consists of two parts (Figure 14)

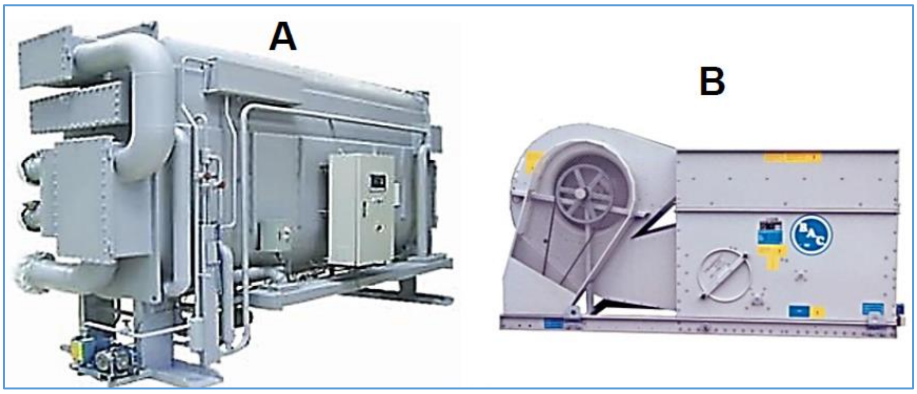


Figure 14. Chiller (A) and connected outdoor air cooler for absorber cooling (B)

The cooling unit:
The type of cooling unit is: 16JLH007. Manufacturer: Carrier CLK Corporation. Cold power output: 131 kW. Feed hot water: 90°C, mass flow: 7.5m^3/h. The returning water temperature is 70°C. Refrigerant LiBr: 55% aqueous dilution. Total power of internal pumps: 2.1 kW. The cold side: inlet 12°C, outlet 6°C, mass flow 21.1 m^3/h.
The external air cooler:

- Manufacturer: Baltimore Aircoil. Type VTL-E082-K.
- Drive motor: 7.5 kW, air delivery 10.6 m^3/s.

3.4. Cost calculation for refrigerated storage

(The cost of kWh is made of the cost of investment and fuel [18]. Due to simplification, it was performed only for the normally required cooling period of 8 months)

a) The 120kW system generates 660 000 kWh of electricity in 8 months (5 500 operating hours) to meet its own energy needs in other areas of the plant. Thus, at the current price of 10 € cent/kWh, it saves 119 459 €.
b) If 124 kg/h of quality wood waste (0.054 €/kg) is used during the operating period, 35 135 € will be issued.
c) The operating heat demand of the installed 131 kW absorption chiller 720 500 kWh over an 8-month period, which is waste heat, so it means no expense. If you buy electricity and the chiller works with 1.2 SPF, you will save 156 756 € (10 € cent/kWh electricity). With a good approximation, the energy requirement for storing one ton of fruit is ~ 100kWh (over 8 months). With this system, 7 200 tons can be stored at ~ 6°C.
d) Due to the operation of the system, an additional ~ 70 kW of waste heat is available, which, when used or sold, means a profit of 124 324 € (at a price of 8.6 €/GJ).
e) The investment cost of the system is 432 432 €.
f) With these values, calculated with a simple return: the investment pays off in 3.3 years, i.e. it is already profitable in the fourth year.

(It would be less favourable, if the cooling facilities were solved with an electric heat pump, which would require ~ 360MWh of main electricity (including 2.0-2.5 SPF) (excluding the unit's own electricity consumption), which is ~ 65 135 € expenditure (excluding depreciation of the system).

2. Summary

In our study, we presented an environmental-friendly, energy-efficient system for the use of primary- and waste biomass. Biomasses with significant energy and cellulose content are well suited for the system, but require some preparation. The fragmentation and water content of the materials must be adequate for the beneficial operation of the system.

In the case of the developed pyrolysis (so-called thermal decomposition [19]) equipment, 0.9-1.15 kg of wood (containing 15 - 20% moisture) is needed to produce 1.0 kWh of electricity. During its operation, it generates 1.1-1.3 times more thermal energy than electricity, which can be used in its entirety (can be recuperated). This heat energy comes from the cooling of the gas generated during pyrolysis and the waste heat generated by the operation of the gas engine. It can be used entirely for community purposes, e.g., for heating, or domestic hot water, etc.

In this research, they are used to produce cold energy, namely to drive an absorption chiller, which e.g. provides the cold energy demands of storing fruits.

The economic calculation shows that given current electricity and firewood prices, the application of the system is particularly economical and even suitable for profit generation. It is even more advantageous to have biomass as waste in the operating environment, or even to pay for its destruction. The system is environmental-friendly, part of the so-called “circular farming”, but its environmental benefits are also significant. The resulting high mineral content ash and residual biochar are returned to the soil, increasing its productivity and water storage capacity. Compared to the natural fermentation of biomass, methane emissions are reduced and this contributes to the reduction of methane produced in agriculture as a strong greenhouse gas, and ultimately to the reduction of environmental pollution.

Acknowledgement

Thanks to GINOP-2.1.2-8-1-4-16 “Development of a complex energy system for the implementation of about 95% efficient, circulating decentralized energy production” entitled research and development, the processing of which provided substantive assistance.

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