SZENT ISTVÁN UNIVERSITY

Increasing the efficiency of pyrolisys generator

PhD thesis
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CONTENTS

LIST OF SYMBOLS, ABBREVATIONS

C	carbon	[-]
CH_4	methane	[-]
CO_2	carbon dioxide	[-]
CO	carbon monxide	[-]
FG	fluegas	[-]
G	gas	[-]
HCS	heat exchanger	[-]
HMV	domestic hot water	[-]
H_2	hydrogen	[-]
H_2O	water	[-]
L	air	[-]
m	weight	[kg]
O_2	oxigen	[-]
P	performance	[kW]
p	pressure	[Pa]
Q	Volume flow	[m³/h]
t	time	[s]
T	temeprature	[°C]
V	water	[-]

1. INTRODUCTION AND OBJECTIVES

In the first chapter of my thesis, I draw up the importance of this topic and I describe the main objectives of my research.

1.1. Introduction

In the recent decades, it has become absolutely clear that the polluting and energy-wasting way of life of mankind can lead to the depletion of natural resources and ecological catastrophe in the long run.

Nowadays, besides the rapid development of technology, we must keep in mind not only the use of larger volumes of renewable energy sources (solar, wind, hydropower, geothermal) but also the use of waste and by-products, originated from various industrial processes, agriculture, food or human livelihoods. Various technologies have already been developed for the thermal recovery of these materials. They must be continuously developed and adapted to the respective areas of application and the physical/chemical properties of the available raw material. Gasification processes combine the benefits of incineration and thermal decomposition and minimize secondary environmental impacts. They can be considered as alternative methods of the future in the thermal treatment of solid waste as in opposition to incineration technology.

1.2. Objectives

The aim of my work is to immerse in the relevant, available literature and with the help of its research, to gain insight into the topic and its level of elaboration.

Following the experience gained, to make hypotheses and confirm or refute them in my practical research in order to further develop and fill in the missing parts that may have not been elaborated in enough details.

Research objectives related to the investigation of raw materials that can be subjected to the pyrolysis and its process:

After reviewing the literature, my goal was to determine what kind of technological design a CHP power plant requires.

To achieve this, prior to the implementation a laboratory-scale experimental reactor must be set up and preliminary process experiments must be performed with its help.

The physico-chemical characteristics of the charge and the intensity of the heating are expected to have a major influence on the processes in the reactor space.

I aimed to measure, record and analyse the thermal decomposition stages happening in the laboratory system

The aim of my research:

- Implementation of laboratory large-sample (500 - 1000 grams) experimental technology in such a way that the processes taking place in it can be transferred to the development of a semi-industrial level solution.

- Investigation of pyrolysis processes and data recording of biomass samples of different bulk densities, mainly woody stems as a function of time, with inert gas heating at different treatment temperatures.

- As the treatment temperature increases, the rate of the thermal decomposition process is expected to increase, leading to more intense degassing. My goal:

- Recording and analysis of the parameters of pyrolysis processes completed at two different treatment temperatures - 400 °C, 600 °C.

- Recording the time-dependent characteristics of the reaction zone also within the load

- Investigation of the reaction intensity of charges with different bulk densities (porosity)

- In addition to the different physical, chemical and geometrical properties of the raw materials (bulk density, bulk density, porosity, energy content, etc.), the basic objective is to improve the final efficiency of the fixed bed system in relation to the obtained "energy / raw material mass" (J/kg).

- After the investigation of the literature and the laboratory research, I can conclude what type of technological solution is necessary to further develop the known ones, in order to obtain the gas with the lowest possible tar content, which ensures a longer run time of the CHP small power plant.

- Establishment of plant-scale equipment in accordance with the experience of laboratory tests and thus perform validation tests.

- The high temperature process (600 °C to 800 °C) and the cracking of the tar in the charge can ensure high purity product gas.

- In fact, the efficiency can be checked with the semi-operational experimental reactor, whose unique geometrical dimensions (oxidation/reduction cone characteristics) also contribute to the production of high purity, more efficient gas, which can be further enhanced by the combined gas path and expected multi-point feed air

- In carrying out this research task, my goal is to develop control methods that are suitable for the optimal operation of solar energy utilization systems.

To achieve this, I set the following objectives:

- development of models suitable for describing time-varying heat and material flow processes in a solar energy system;
- development of computer measuring, data collection and monitoring procedures suitable for the energetic measurement of solar thermal energy utilization systems; and their implementation;
- performing energy measurements to verify the developed models;
- development of control algorithms;
- evaluation of different control strategies based on a verified model;
- physical realization of the developed control methods.

2. MATERIAL AND METHOD

In this chapter of my dissertation, I present the experimental methods, tools and the samples used to achieve my research goals.

2.1. Examined materials

In order for an efficient pyrolysis (thermal decomposition) equipment to be properly designed and manufactured and then used, it is necessary to know the available materials.

Design can also be site-specific if there are large quantities of continuously available materials in the area.

The relevant materials from the technology point of view, I will test are the following:

- acacia wood chips,
- poplar wood chips,
- agricultural by-products

2.2. Instruments and devices used for the tests

It is extremely important to know the parameters to be tested, not only in the light of the performance of laboratory experiments, but also in the design and setting of operating parameters of semi-industrial scale (5 kWe) technology.

Characteristics currently tested and instruments used

- moisture content (thermo-gravimetric balance),
- heat of combustion, calorific value (adiabatic bomb calorimeter),
- ash content (incinerator, laboratory balance),
- elemental composition (elemental composition analyser),
- ash melting point (ash melting point microscope)
- gas composition (gas analyser).

The test methods for the parameters are set out in national and international standards, which are included in the list of areas of application of the Laboratory in accordance with the standard marked ISO/IEC 17225: 2018.

2.3. Laboratory large sample pyrolysis reactor

Following the raw material tests, I carried out gasification tests in the laboratory of the Institute, on my own initiative with a large-scale laboratory pyrolysis reactor designed and constructed jointly with an industrial partner (Fig. 1. and 2).

The wall of the reactor consists of a hardened steel tube (1) with a diameter of 110 mm, carefully insulated around with rock wool and resting on a precision

torsion balance cell (9). The charge (15) can be placed in the reactor tube. its weight varies between 400 and 1500 grams depending on the mass density of the raw material. The heat energy required for gasification is provided by the 2000 W heating cartridge (4), which is controlled by a separate, self-developed unit (12). The heat energy required for gasification is provided by the 2000 W heating cartridge (4), which is controlled by a separate, self-developed unit (12). Five K-type thermocouples were placed on the longitudinal axis of the reactor (8). The lowest is directly in front of the heating cartridge (8), which provides feedback to the controller to bring the heating according to the program.
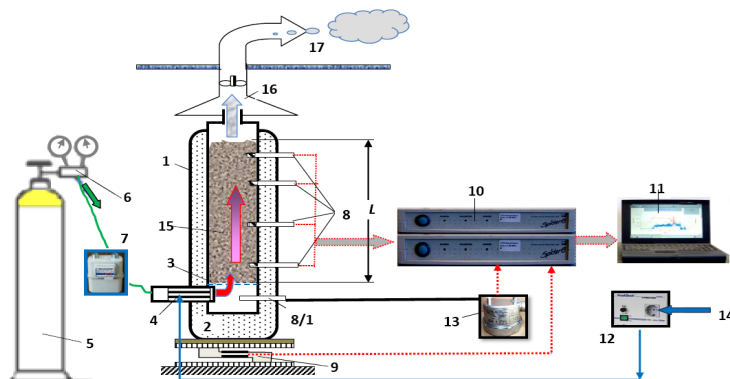

Fig. 1. Schematic diagram of a pyrolysis reactor and its measuring system

Going vertically upwards, four more thermocouples were placed at equal distances (80 mm) to examine the degassing temperatures as a function of time and weight loss.

Nitrogen (4.5 purity) gas (5.6 and 7.) is introduced into the reactor space through the heating cartridge using a pressure regulator, providing an inert atmosphere to avoid unwanted oxidation.

The large amount of gas flowing through and the high mass charge have a strong cooling effect on the system.

Therefore, we have chosen a heating cartridge with a higher capacity than theoretically necessary and the excess of the power can be used to compensate the process characteristics (rate of heat change, desired temperature) to the desired value.

The 600 °C required for complete decomposition and the same gas temperature were also reached. The resulting product gas was removed after measurement and then flaring (16th and 17th).
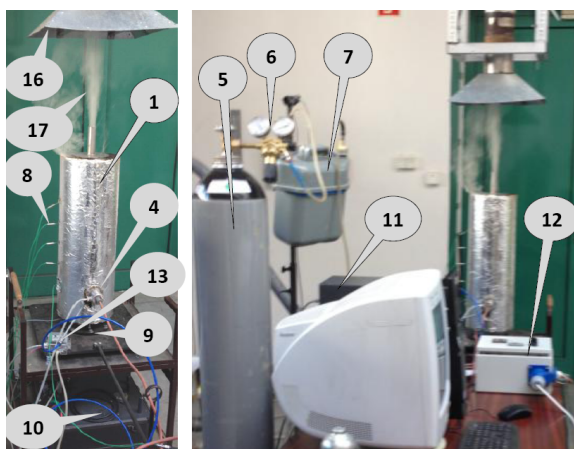
Fig. 2. Pyrolysis reactor and its measuring system

1- generator body,
2- insulation,
3- material grid,
4- radiators,
5- N tank,
6- gas regulator,
7- gas meter,
8- temperature sensors,
temperature sensor (gas),

9- mass measuring sensor (e. Tensom.),
10- data logger (multi-channel),
11- PC,
12- heating controller,
13- gas pressure sensor,
14- electric connectors,
15- biomass,
16- gas collector,
17- gas outlet.

3. RESULTS

In this chapter of my dissertation, I present the new scientific results of my research, which contribute to the increase of the efficiency of solid biomass gasification reactors and to the optimal operation of the technology.

3.1. Intensity of mass change in relation to time

The selected raw material (hardwood chips) was first treated at 400 and then at 600 °C in an inert gas (4.5 nitrogen) environment to avoid oxidation.

The experiments were performed until mass stability was established. The recorded parameters as a function of time were as follows:

- temperature in the material set at four different heights, as shown in Fig. 1, from bottom to top: A, B, C, and D (See symbols in Fig. 3. and 4).
- weight loss (g),
- pressure change at the bottom of the charge (p).

The tests were performed on 7 types of materials, of which I present the hardwood chips as an example.

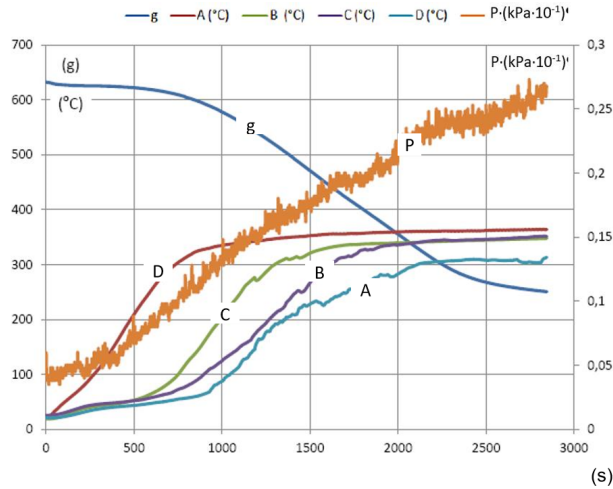Diagrams made from its data series are illustrated in Fig. 3. and 4.

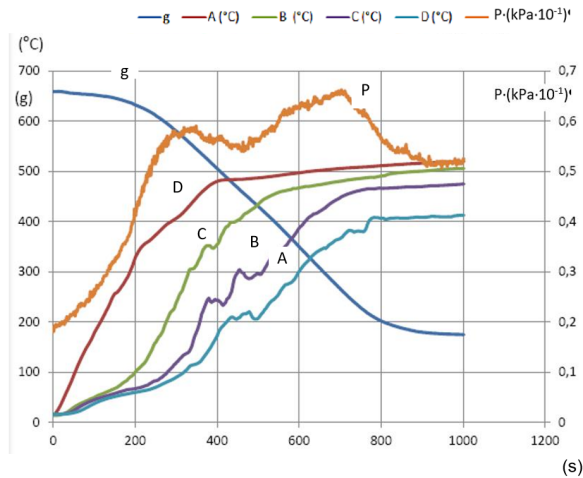Fig. 3. Pyrolysis of hardwood chips at a treatment temperature of 400 °C

Fig. 4. Pyrolysis of hardwood chips at a treatment temperature of 600 °C

I measured the propagation of temperatures in the material in relation to time (A, B, C and D curves).

Nitrogen gas enters the reactor space through the heating cartridge by means of a pressure regulator, which provides an inert atmosphere. The resulting product gas was led to a composition analyser and then to the flare. The time series mass change of the material was registered with a precision balance built under the gasifier. Despite the seemingly oxygen-free environment, carbon was reduced by 11/3 of the mass values obtained in the elementary measurements. At higher temperatures, the decomposition of carbon was aided by the oxygen formed during the dissociation of water in the material. The temperature change at the higher temperature is very fast, at 600 °C the change in the upper temperature shows almost the same tendency as at 400 °C the lowest point where the heated inert gas was introduced (Fig. 5).
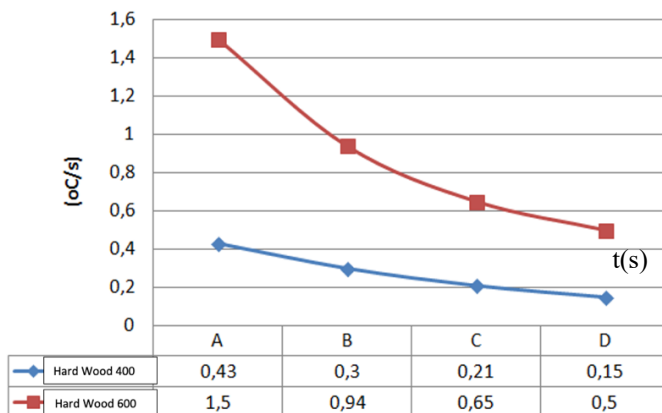

	A	B	C	D
Hard Wood 400	0,43	0,3	0,21	0,15
Hard Wood 600	1,5	0,94	0,65	0,5

Fig. 5. Intensity of temperature change (°C/s) for the same wood chips

In the same measurement, the weight changes of the measured materials in relation to time are shown in Fig. 6.
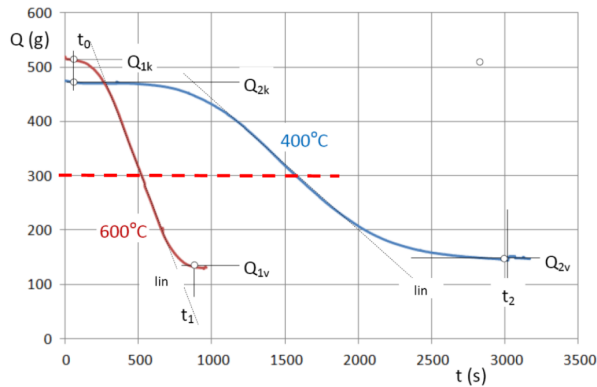

Fig. 6. Coalification in inert gas at 400 and 600 °C, change (decomposition) of mass as a function of time

Depending on the temperature, the goal can be dual: to produce biochar (> 400° C) or propellant (<600 °C). Generally, at the two temperatures, the weight loss is twice as intense compared to the linear sections.

At higher temperatures, the residue (C-D) is ca. 10% less.

In the entire decomposition processes, the further decomposition of carbon is already due to oxidation and reduction.

In the experiments, I found that the characteristics of the weight loss properties of the charge are very similar at both treatment temperatures.

The characteristics of the diagrams constructed from the data collected by the temperature sensors placed at different heights in the material column are also very similar at both treatment temperatures.

The change in pressure ratio showed a significant difference between the 400 and 600 °C treatment.

This is due to the fact that higher treatment temperatures cause faster degassing, which affects the "collapse" of the material set as well as the clustering of particles.

This is due to the marked difference between the pressure values of the flowing gas at a treatment temperature of 400 and 600 °C (Fig. 7).
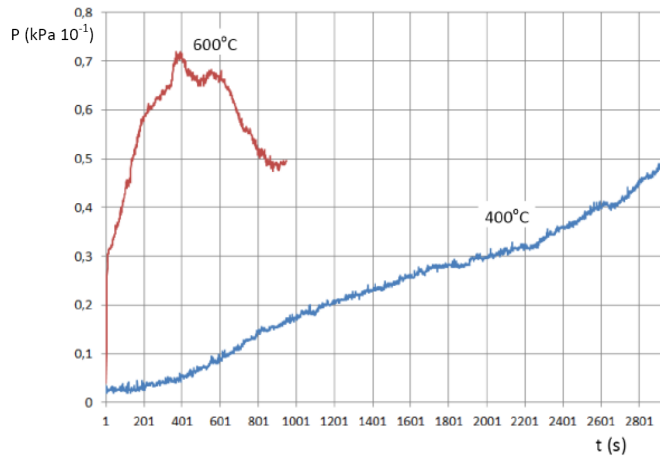
Fig. 7. Pressure required for gas flow during carbonization

3.2. The effect of the fluid resistance of a set of materials on the reaction process

When designing the laboratory experiments, the fraction size of the available raw materials, the density of each particle, and the bulk density of the total charge (as a unit) had to be taken into account. The gas permeability and porosity of the charge affect the entire pyrolysis process, as well as the quantity and quality of the recoverable product gas and biochar. During the measurements, the porosity and the gas permeability of the charge could be monitored with a pressure measuring sensor placed at the bottom of the reactor. Fig. 3. and 4. are based on data from charring hardwood chips. Fig. 7 shows the inert gas pressure values as a function of time. From the high-pressure nitrogen cylinder, the gas enters the space beneath the heating unit, at a constant pressure and mass flow. The sensor placed there measures its changed values over the entire carbonization cycle in relation to time. In case of the various types of materials, the difference in the initial state was a few hundred kPa (0.03-0.05). In case of higher temperature heating, the pressure increased to 0.03 kPa in a few seconds and it continuously changed to 0.07 kPa, the duration of which was ~ 400 s.

By this time, the temperature of the total volume of material had become higher than 100 °C, so steam and gas formation had begun in each layer (active pyrolysis).

Layers A and B were intensely carbonized and the smaller particles of the material continued to shrink, the layer thickness decreased and thus the internal flow resistance was reduced.

This resulted in a decrease in pressure, which eventually stopped at 0.05 kPa. By this time, the entire mass had charred and "collapsed," causing a slight increase in pressure.

The trends were the same for both hard and soft wood, but to a greater extent for softwood due to the looser structure (Fig. 8)

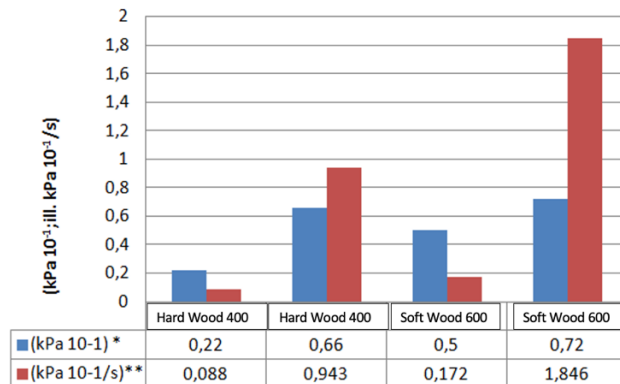|	Hard Wood 400	Hard Wood 400	Soft Wood 600	Soft Wood 600
$\blacksquare$ (kPa 10-1) *	0,22	0,66	0,5	0,72
$\blacksquare$ (kPa 10-1/s)**	0,088	0,943	0,172	1,846

Fig. 8. Pressure required for gas flow * and intensity of pressure change ** during charring

At 400 °C there was a steady increase in pressure until complete carbonization, at which time the increase stopped at 0.05 kPa as before (this process may be typical for the production of coal) These phenomena are very important for fixed-bed, vertical, top-fed and bottom-air generators, especially if the goal is to produce heat and electricity instead of coal. The primary air is introduced at the bottom, its amount is also very important due to the maintenance of the combustion temperature and the reduction of the resulting tar. Utilization of the results in the semi-industrial system

During the system design, we used the results of the available source work, the experiences and suggestions gained by the authors, and the results of the research carried out in the laboratory.

Nevertheless, I also refer to previous results of the design and measurements a few times in order to shed light on the specific reasons for the given solution.

After all, the planned system differs in many details from the so-called from upper feed and lower gas discharge solutions, mainly due to simplifications.

System description:

The incoming biomass is transferred from the on-site (yard) storage space to the pre-storage in front of the equipment, where it is dried to the desired moisture content as required. The heat required for this is provided by the energy obtained from the hot gas by means of a gas-air heat exchanger (in Fig. 9. the direction of the processes is indicated by the arrows). The air entering

the oxidation space is also preheated by air flowing through the mentioned heat exchanger. So, on the other side of this heat exchanger, the air is preheated and then the water is injected into this air stream as well. This takes place already in the reactor.

The entire space of the reactor (from the gas outlet side) is below the atmospheric pressure (with the help of a connected vacuum pump), which also derives the direction of gas flow. The gas discharged from the bottom of the generator is cooled by heat exchange and the already colder gas enters the dust filter, where the dust is roughly separated, but from there it is sent to another safety filter to get completely tar-free gas into the connected system. This protects the combustion chamber of the engine from the formation of deposits. The waste heat generated in the engine is recovered via the two water/water heat exchangers. The heat exchangers are used to preheat the domestic hot water. The final temperature of the domestic hot water is practically carried out by the high-temperature flue gas, escaping from the engine. As a result, clean and low-temperature flue gas is released into the environment.

In this way we achieve the best efficiency of the complex system. I will present later the detailed description of the other functional elements of the system.
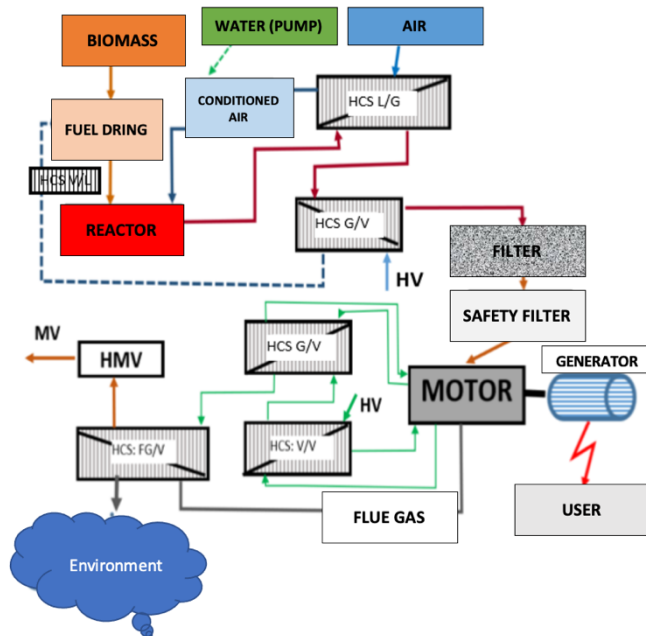

Fig. 9. Functional diagram of the system (HCS - heat exchanger, L - air, V - water, G - gas, FG - flue gas, HMV - domestic hot water)

According to the literature, besides maintaining the temperature, the introduction of water and air in the oxidation and reduction space changes the composition of the gas and reduces the tar content.

As a result of water injection, the water (water vapor) flowing into the open pores of the carbon particles dissociates into hydrogen and carbon monoxide. This also changes the composition, flammability and energy content of the gas. To control this, different amounts of water were injected into the system through injectors through the adjustability of the mentioned vibrating valves.

At the measurements we added water to the incoming flowing air which feeds the pyrloysis. A significant part of the water and water vapor/air water mixture went directly to the oxidation and reduction space. The effect on the temperature of the system is essential, since the temperature of the reduction chamber must be kept at an appropriate level even when water and air (methane oxygen or CO_2) are introduced. This requires the correct choice of the transition and orifice of the reduction funnel under the oxidation space so that the right amount of material flows through. Thus, the mass flow of the flow can be matched to the feed. The experiments were performed at a constant value of the power delivered.

As a result of the amount of water introduced, the temperature of the reduction chamber decreased (Table 1, Fig. 10-13).

Table 1. Data measured by condensate injection

Performance (kW)	Intake air (m³/h)	Time (sec)	Oxidation temp (°C)	Condensate mass flow (kg/h)
5	11,25	83,2	1165	0,43
5	10,5	69,2	1150	0,52
5	10	55,4	1140	0,65
5	9,75	43,4	1136	0,83
5	9,25	35,6	1128	1,01
5	8,75	30,6	1116	1,18
5	8,5	26,8	1080	1,34
5	8,5	23,8	1048	1,51
5	8,5	21,2	1021	1,70
5	8,25	19,2	1010	1,88
5	8,125	17,8	1000	2,02
5	8,25	16,8	1000	2,14

We can see from the results that in the case of the present device it is not advisable to add more than 1.5 kg/h of water so that the temperature of the reduction chamber does not fall below 950-1000 °C. The introduction of air also affects the temperature of the reduction chamber. Given that a larger amount of oxygen is also introduced with the air, this improves combustion, so it has an increasing effect on temperature. With the present equipment, the introduction of more than 9.0-9.5 m3/h air volume is not justified, as it would already reduce the temperature of the reduction chamber. It comes from the two correlations that the correlation between water and air dosing is exponentially decreasing (nearly linear). This result in the following, when increasing the air, it is justified to reduce the amount of water.
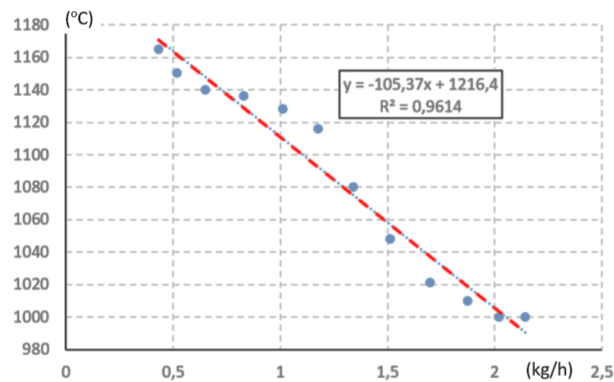

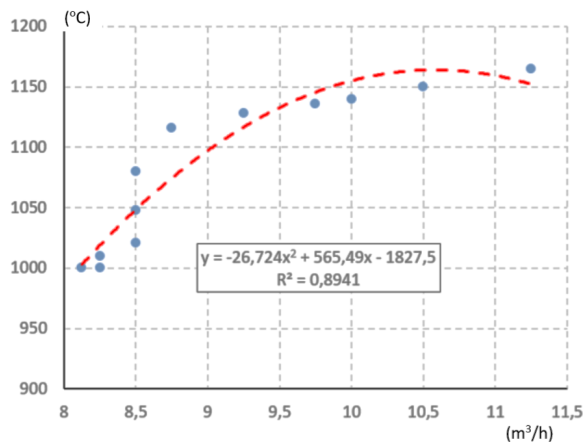Fig. 10. Effect of water intake on the temperature of the reduction chamber

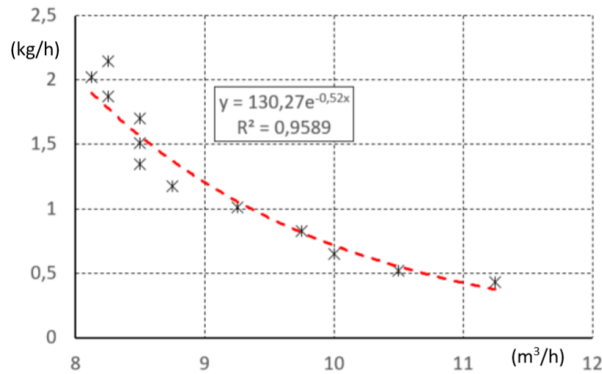Fig. 11. Effect of air intake on the temperature of the reduction chamber
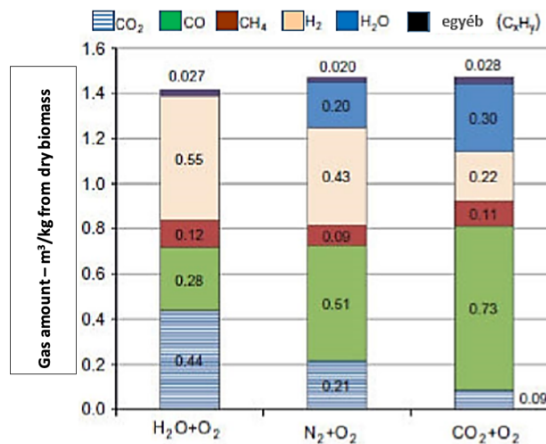
Fig. 12. Relationship between air and water intake

Fig. 13. Intake of H_2O, O_2 and CO_2 into the oxidation-reduction zone, their effect on the gas composition

After all, H_2O, O_2 (CO_2) have a significant beneficial effect in the process of pyrolysis of biomass and in catalytic gasification. Due to their dosage, the proportion of tar compounds in the conversion to gaseous compounds is reduced. In gasification reactions above 850-900 °C, all effects prevail. According to literature sources, the highest cold gas efficiency can be achieved with a carbon dioxide-containing atmosphere. The effect of any of its dosing reduces the tar content below the limit required for engines. Literature sources also point out that the rate of degradation can be increased by water intake. My experiments in the laboratory have shown that this is true for medium-sized hardwood biomass chips.

4. NEW SCIENTIFIC RESULTS

1. Development of a laboratory measuring unit and test principle

In order to increase the efficiency of the pyrolysis generator, I developed a laboratory measuring unit and its measuring principle, which I also built. It was also possible to determine the degree of mass change (gas formation) of biomass materials with different structures and energy contents, the intensity of changes per unit time, the pressure demand of the flowing gas, the temperature distribution within the material and the effect of material properties. Based on the vertical temperature differences, the change of the reaction zones as a function of time can be well followed. In the equipment, the heat dissipation is more intense along the walls with good thermal conductivity and in the material, which affects the decomposition processes of the material. This phenomenon must be taken into account in the constructions (compensated by counter-heat removal, the energy obtained from it can be used for drying the materials). Such a model measuring unit was not known in the literature.

2. Effect of pyrolysis temperature on reaction rate and product gas

Using the experimental model equipment I designed, I recorded the time-series mass change of the material with a precision balance built under the gasifier. As a result of the higher intensity heat transfer, the decomposition process, the gas formation is faster, the volume is more, but the amount of residual solids (coal and ash) is less. At higher treatment temperatures, the decomposition of the material is aided by the oxygen formed during the dissociation of the water in it. For the same substances, it is faster in the intensive phase (t_{lin}) of the mass change (gas formation) at the higher temperature (600 °C, ~ 0.9 g/s, while at 400 °C it is ~ 0.3 g/s, almost three times).

3. The effect of the physical attributes of the charge on the degassing reaction

I proved that the density of the biomass materials to be pyrolyzed and the bulk density of the set of materials consisting of them significantly influence the pyrolysis process.

I examined the total charge as a unit. The density and thus the porosity changes during decomposition, which changes the intensity of gas extraction.

With an initial moisture content of 15% and the same shredding characteristics, the change in density was as follows:

- 31.4% for hardwood chips,
- 61.4% for pine wood chips,
- for hardwood pellets 58.4% and a
- 64.1% for pine shavings,

The intensity of gas extraction changes the least during decomposition, in the case of hardwood chips that better retain their structure. It is the similar case with pelleted materials.

4. Effects of the air and steam to the temperature and the degradation velocity

By operating and using the semi-industrial experimental unit, I proved that the temperature of the reduction space required to reduce the tar content decreased as a result of the amount of water introduced into the oxidation space (confirmed by the change in the colour of the flame). It can be shown that the boundary case is determined by the temperature of the reduction chamber, the temperature of which must not fall below 950-1000 °C.

I proved by my semi-operational test measurements that (under certain conditions) the temperature of the reduction chamber decreases above the specific value of 1.4-1.8 m^3/kWhe of air.

$$y= 105,37x +1216,4,$$

(where y = °C; x = kg/h air; R^2 = 0,9614)

Increasing the air intake reduces the water intake demand. The obtained correlation:

$$y = 130,27 \ e^{0,57x}.$$

(R^2 = 0,9589; the values of y and x correspond to the above)

I proved that in the case of the fixed bed, semi-operating, experimental equipment designed for the CHP (5.0 kW) system, the efficiency of conversion to electricity (kWhe / kg material) with low moisture content and thus higher calorific value compared to wetter materials (significant evaporation of water due to energy demand), even higher than the more favourable values (~ 12-16%).

5. Correlation between charge porosity and particle displacement

When designing specific equipment, it is necessary to know whether the air intake causes grain movement.

In a separate laboratory unit prepared for this purpose, I investigated the air permeability of granular carbon (remaining after pellets and chips) in the oxidation and reduction zones at material thicknesses of 25 and 50 cm (at a density of ~ 220 kg/m^3).

I determined at what driving force (N) the air flow required for the displacement of the particles is created.

For a 25 cm layer of carbon:

$$P_{gv} = 5.66 \, Q_s$$

(limit value $P_{gv} = 96{,}1$ N; a $Q_s = 17{,}4$ m^3/h)

For a 50 cm layer of carbon:

$$P_{gv} = 7{,}94 \, Q_s$$

(limit value $P_{gv} = 135{,}98$ N; a $Q_s = 16{,}36$ m^3/h)

$$(R^2 = 0{,}8941)$$

These measurements continued until the particles moved. I proved with my measurements that material movement can be created with the introduction of air, but its limit case is when the mass flow in the oxidation and reduction spaces is already unfavourable for transformations (decompositions). Then mechanical movement becomes necessary. The need for movement is also affected by the size of the angle of the oxidation cone. The force in the direction of movement (downwards) must be greater than the frictional force due to the conicity and then the vaulting of the material is more moderate.

5. CONCLUSIONS AND SUGGESTIONS

During my research work, I dealt with the pyrolysis of solid biomass by-products of various origins under laboratory and semi-industrial conditions.

Relying on laboratory tests, an innovative small power plant capable of producing heat and electricity (CHP) with a capacity of 5 kWe has been implemented, which is able to produce product gas with better efficiency and better quality than the previous

One of the aims of my research was to enable the thermochemical equipment developed by me, my colleagues and my partners, to work efficiently with by-products whose quality parameters do not correspond to the operation of equipment created for the thermal utilization of classical biomass.

Together with my partners and professional conductors, we designed and implemented a unique, large-sample laboratory equipment and a measuring system that can handle 500–1500 grams of test charge, record temperature, pressure and mass change data over time.

Studies have shown that the pyrolysis process is greatly influenced by the size of the particles forming the charge as well as the density of the individual particles, as the porosity of the whole and part of the material is closely related to the active surface involved in the process.

The degassing process also increased with increasing temperature, which is an expected result, but for materials of different origins and porosities, several conclusions could be drawn from the pressure change detected at the bottom of the charge.

The results obtained during the laboratory tests are suitable for the technological development of residential, semi-industrial and industrial scale because the size of the experimental set (500-1500 grams) can be extrapolated to a larger scale, since the behaviour of the set is very similar to that of the charge fed to said larger-scale equipment.

With the help of the implemented 5 kWe power equipment, I proved that the technological implementation designed by us is able to process the materials with unfavourable energy parameters examined during the laboratory tests.

In addition, it has been proved during operational measurements that the appropriate amount of air and water spray fed to the pyrolysis and reduction zone has a positive effect on the processes in the reactor and on the quality of the product gas, especially the gas tar content.

6. SUMMARY

The aim of my research was to determine and present the energy parameters of those raw materials produced in large quantities in Hungary and Europe, - poor quality softwood and hardwood chips, corn stalk, biogas stable sludge, separated manure- whose recycle and usage is cumbersome. Upon completion of the analytical studies, I performed examinations, using the model equipment of the semi-industrial technology to be developed. However, this also required the design of the laboratory reactor itself and its measurement system. The device has been able to accommodate large samples (500–1500 grams) compared to laboratory sizes, which depend on the particle size of the loaded sample and its density.

The compliance to domestic and international measurement standards was ensured with the involvement of an accredited calibration laboratory. In this way the sensors installed in the experimental equipment (K-type thermocouples, pressure gauge, balance cell, gas meter) and the values measured by them are traceable. Thus, the data recorded during the measurements are real and reliable. It is important to note that I have not found any publication about this type of laboratory large sample in either the domestic or international literature.

In the next step, based on the experience from the data of the experimental measurements, it was possible to start the design of the small power plant with a capacity of 5 kWe.

Laboratory experiments were essential because the ca. The behaviour of a 1-1.5 kg load can be extended to a much larger size, thus optimizing both sizing and cost. When designing the semi-industrial equipment, the goal was to achieve the highest possible efficiency and to produce product gas with the highest possible energy content, but at the same time with the lowest possible tar content. To be able to achieve these results was due to the unique design of the reactor zone, the way the product gas was discharged, and to the air and water fed into the system at the right place and in the right amount.

Compared to the product gas produced by conventional pyrolysis, the higher calorific value was due to the hydrogen released from the injected water, the lower tar content is provided by extraction through the reduction zone, since the long-chain compounds in the gas are fragmented and bound by the formation of a high-porosity, high-temperature activated carbon layer.

The new scientific results derived from my work can help practicing engineers in the optimal design and construction of such and similar equipment capable of pyrolyzing solid biomass. It also contributes to environmentally conscious, carbon-neutral heat and electricity production.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign languages

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