UNIVERSITY „POLITEHNICA” of BUCHAREST
FACULTY OF POWER ENGINEERING

SUMMARY OF PhD THESIS

Studiul proceselor termice de conversie optimă a biomasei prin maximizarea eficienței energetice globale

Study of optimal thermal conversion processes of biomass by maximizing global energy efficiency

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SUMMARY

Key words: biomass, gasification, combustible gas, gas turbine, combustion, steam turbine, electricity production, emissions, green energy.

CHAPTER I

1. CONTEXT AND MOTIVATION

In the energy sector, there have been major changes over the last 30 years in Romania, both in terms of production, total consumption and electricity consumption per capita, as well as electricity price and production structure in terms of primary energy sources used [1, 2, 3]. If in 1989 fossil fuels provided 90% of the electricity produced [5], in 2017 only 42% of the energy produced in Romania used fossil fuels as a primary source of energy [6]. This has reduced carbon dioxide emissions by almost two-thirds [3, 7]. However, under current conditions, greenhouse gas emissions must be drastically reduced to minimize pollution and to maintain a favorable atmosphere for life on Earth [8]. This can be achieved by producing electricity using non-polluting primary sources of energy, such as renewable sources.

Biomass is the only renewable energy source that has similar properties to those of fossil fuels: high concentration, storage possibilities, can be transported over long distances and converted to other energy types - thermal, mechanical, electrical; it can also be used to produce biofuels [14, 27]. Bioenergy is also the only renewable energy source that can be co-processed with fossil fuels in current energy conversion systems (oil refineries, coal gasification plants) to ensure a gradual transition of energy production from renewable sources [16].

CHAPTER II

2. CURRENT STATUS OF BIOMASS TO ENERGY CONVERSION SOLUTIONS BY THERMOCHEMICAL PROCESSES - COMBUSTION AND GASIFICATION

2.1. ENERGY POTENTIAL OF BIOMASS

In 2001, the European Parliament and the Council of the European Union defined the term "biomass" in Directive 2001/77/EC as follows: "*biomass shall mean the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste*" [24].

Thus, biomass sources are multiple and diversified, covering a wide range of products, sub-products and waste from forestry industry, agriculture, including livestock, municipal and industrial waste as well as energy crops [16, 23, 26, 27]. The advantage of energy crops lies in the fact that they do not require quality soil and too much care, water and fertilizers. This is due to the fact that the quantity and not the quality of the crops are important.

Vegetal residues from agriculture has the most important biomass potential in Romania (63% of the total), followed by forestry residues accounting for 16% of the total [31]. The biomass sources in Romania are shown in Figure 2.1.

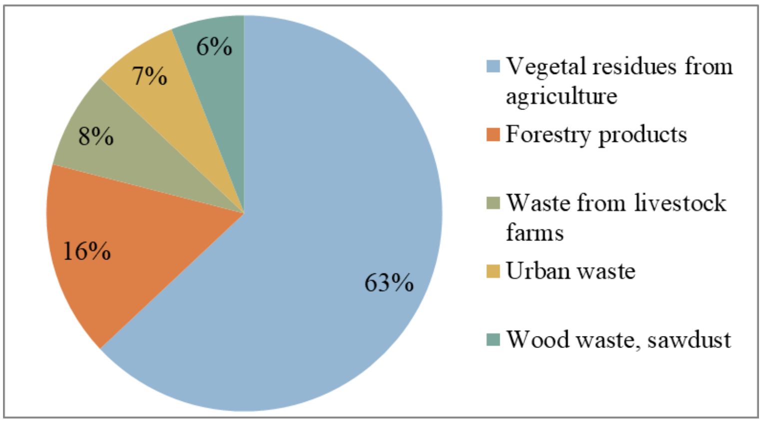


Figure 2.1.Biomass sources potential in Romania [31]

2.1.1. Potential of forest resources

In Romania, the total area of forests represents 6.9 million hectares, of which less than half, about 3.1 million hectares, are owned by the state, being managed by the National Forest Administration – Romsilva [33, 34]. The volume of wood that can be harvested from forests is regulated by the forestry arrangements, and is about 9 million m^3/year [33]. If forests not owned by the state are taken into account, the forest exploitation potential in Romania could reach an annual quota of 16-17 million cubic meters of wood [35]. Under these conditions, the annual energy potential of wood can reach 115,200 TJ [36-38].

2.1.2. Potential of agricultural resources

All crop and wood residues from cleaning of vineyards, orchards and meadows can be used to produce green energy. The average quantity of grains, straw (which can be used for energy production) as well as multi-crop ratios together with the calorific value, the area cultivated in Romania and the energy potential of the residues are presented in Table 2.1.

Table 2.1: Average yield of grains and residues for main agricultural crops in Romania [4, 30, 39, 40]

		Wheat	Other cereal	Corn	Sunflower	rapeseed	Soy
Average amount of grain	t/ha	6.5		6.8	2.5	3.5	3.5
Average amount of straw	t/ha	5.2	4	8.9	10.2	10.1	2.3
Grain-straw ratio	-	1:0.8		1:1.3	1:1.4	1:2.9	1:0.6
Heating value	kJ/kg	17,208	14,000	~ 17,620	15,804	17,100	13,680
Cultivated area	thous. ha	~ 2.109	~ 775	~ 2.497	1.011,5	367,9	128,1
Annual residues quantity	Mill tons	10.97	3.1	22.22	10.32	3.72	0.29
Energy potential	TJ	188,717	43,400	391,575	163,055	63,540	4,030

Some crops can be used for energy or derived fuels production, corn and sugar beet can be used for ethanol production [41-44], rapeseed oil can be used for biodiesel production [45, 46], but oil is used in food industry, so it is a priority for another industries. The same applies to some of the agricultural residues, which are directed for animal feed and shelter, as well as for soil fertility maintaining [47], so they cannot be entirely devoted to the energy sector. Thus, only a part of their energy potential can be valued in installations for electricity or derived fuels production.

2.1.3. Potential of energy crops

Energy crops are defined in agronomy as crops grown almost exclusively for energy production, including: industrial rapeseed, reed, energy grass, and various wood species such as acacia, poplar and willow [48]. In the same category are included the plants whose cultivation and maintenance are made at low costs and do not require certain climate conditions, and can be used for biofuels production or can be directly exploited due to their energy content (electricity and thermal energy production) [49]. Rape, acacia and poplar are the most important energy crops in Romania. Paulownia, Mischantus and Switchgrass are also part of the energy crops category, but they are mainly cultivated in areas with different climate from that of Romania.

2.2. THERMOCHEMICAL CONVERSION PROCESSES FOR BIOMASS

Biomass can be converted into different energy forms, electric and/or thermal energy, as well as derived fuels [14]. Depending on the treatment or conversion type to which biomass is submitted different products result, which may be used in different thermodynamic cycles to produce energy or may be subjected to chemical treatments to produce transportation fuels or added-value chemical compounds. Biomass can be transformed into various forms of energy through thermo-chemical, bio-chemical or physicochemical conversion processes [14, 16, 66, 67]. The conversion process is chosen depending on the type of biomass and the available flow, as well as the desired useful effect.

Combustion and gasification are two similar thermo-chemical processes in many ways. However, the most notable difference between these two is that in the gasification process the energy is integrated into chemical bonds in the produced gas, while in the case of combustion these chemical bonds are broken to release energy [19].

Both the gasification and the combustion process can be divided into several process stages, which are not clearly delimited in time and space within the reactor, these stages overlapping according to the type of installation [9, 19, 23, 66, 67, 69, 70]. Gasification and combustion stages are:

Combustion

- Drying;
- Pyrolysis;
- Ignition;
- Volatile matter combustion;
- Char combustion.

Gasification

- Drying;
- Pyrolysis;
- Combustion of some gases, vapors and char;
- Char gasification.

2.3. VARIABLES AFFECTING THE BIOMASS CONVERSION PROCESSES

The biomass composition, as well as some physical and thermodynamic properties of it, influence the conversion processes [68, 70]. Also, the physicochemical and thermodynamic biomass properties vary widely, and these variations may even occur between two samples belonging to the same source according to its location source, especially in the case of waste. For this reason, knowing the value of a single biomass property is not sufficient to characterize a process or to design a thermochemical conversion installation [68].

Among the physicochemical and thermodynamic properties affecting thermal conversion processes, the most important are: permeability, density, specific surface area, porosity, reactivity, thermal conductivity, specific heat, heat of formation, heat of reaction, calorific value, ignition temperature, to which are added the process parameters: temperature, pressure, stoichiometry [19, 68, 70, 71]. Fuel composition is important in terms of emissions and greenhouse gases, mainly emissions from complete combustion and ash-related problems [70].

Table 2.2: Variables affecting the biomass conversion processes [9, 16, 17, 19, 67, 68, 70, 71, 173]

Variable	Effect/influence
Fuel moisture content	- process temperature decrease - residence time increase - occurrence of incomplete combustion emissions - flame stability - system efficiency decrease - storage period - low heating value - conversion installation choices - energy consumption for drying
Volatile matter	- fuel reactivity. Biomass is more reactive (can be easily converted into gas) than coal, due to high volatile matter content - thermal decomposition - combustion behavior
Fixed carbon content	- influence the size of reactor and the process duration
Ash content and ash composition	- process temperature - dust emission - ash handling - ash use/disposal - conversion installation type - safety in operation - deposits formation - process system control - alkali and phosphorus – slagging and fouling, ash using, deposits formation - potassium (and silicon) – ash low melting point, cracking, corrosion, aerosol formation, ash uses - fluorine –HF emissions, corrosion - sodium – ash melting, corrosion, aerosol formation, use of ash - magnesium, calcium – increases ash melting point, its use, deposits formation - trace elements, heavy metals - emissions, use of ash, aerosol formation
Elemental analysis	- Carbon – heating value, possible CO emission from incomplete combustion - Hydrogen – heating value - Oxygen – heating value (negative impact) - Nitrogen – emissions of NO, NO_2, N_2O and NH_3 - Sulphur –SO_x emissions, corrosion, CO_2 additional emissions, impact on downstream gas conditioning and fuel synthesis operations - Chlorine – corrosion and pollution – HCl and PCDD/F emissions, catalyst poisoning, ash low melting point
Heating value	- fuel use - installation type
Density	- feedstock handling - rates and efficiencies of the conversion process - combustion chamber volume to energy input ratio - combustion behavior

	- thermal conductivity - segregation - thermal decomposition
Bulk density	- logistics - storage, transport, handling
Dimension	- feedstock handling - rates and efficiencies of the conversion process - residence time - aerodynamic properties - active surface area
Porosity	- fine particle formation - reactivity (weight loss in time unit) - devolatilization behavior - heat and mass transfer - conversion
Homogeneity	- process control
Contact area surface	- reactivity
Electrical conductivity	- microwave processing, particle cleaning by electrostatic precipitation - fine particles evacuation
Hygroscopicity	- logistics - storage, transport, handling
Shape and particle size (distribution)	- storage space (bridging in bunkers, self-ignition) - transport features (transport) - heat and mass transfer behavior - type of conversion installation - safety in operation - drying - dust formation
Thermal conductivity	- physicochemical processing (heat transfer)
Fine parts (wood pressing)	- deposit volume - transport losses - dust formation
Resistance to abrasion (wood pressing)	- quality change - segregation - fine particles
Heat exchangers	- heat exchange with surrounding or heating water
Air station and distribution (combustion)	- incomplete combustion emissions - NO_x emissions - process temperature
Fuel distribution	- reactivity
Heat transfer mechanism	- incomplete combustion emissions - thermal efficiency
Insulation	- incomplete combustion emissions - process temperature
Air preheating	- temperature
Process stoichiometry and type of oxidant used (gasification)	- process temperature - flue gas volume (combustion) - composition and heating value of produced gas (gasification) - conversion efficiency - specific investment - low oxygen steam ratio – H_2 and CH_4 concentrations increase - high oxygen steam ratio – CO and CO_2 concentrations increase

Pressure	- high pressure – reducing the compression energy and plant size (gasification); favors the production of ammonia; decreases coke reactivity - composition and heating value of produced gas (gasification) - CO_2 and CH_4 concentrations increase with pressure increase - CO and H_2 concentrations decrease with pressure increase - Conversion efficiency
Temperature	- high temperature – increases oxygen consumption and decreases the overall process efficiency (gasification), the occurrence of NO_x emissions - CO_2 and CH_4 concentrations decrease at temperature increase - CO and H_2 concentrations increase at temperature increase

2.4. BIOMASS TO ENERGY CONVERSION TECHNOLOGIES

Both biomass combustion plants and biomass gasification reactors are based on fossil fuel conversion technologies with adjustments imposed by biomass characteristics.

2.4.1. Biomass combustion technologies

Biomass combustion plants, also called boilers or furnaces, are classified according to the flow conditions inside the plant as follows [16, 177]:

- Fixed bed combustion installations (grate firing systems);
- Fluidized bed combustion installations;
- Entrained flow combustion installations.

In order to choose a combustion system type, the fuel properties and the amount of steam to be produced must be taken into account. Also, one type of combustion plant cannot be developed at any scale, there is a power range characteristic for each type of plant. Fixed bed combustion plants are typically used for smaller power plants (2.5-175 MWt); fluidized bed combustion plants are specific to medium power plants (<750 MWt); entrained flow combustion reactors are used in high power plants (<2500 MWt) [16, 69]. Figure 2.2 shows the output ranges for different types of combustion plants.

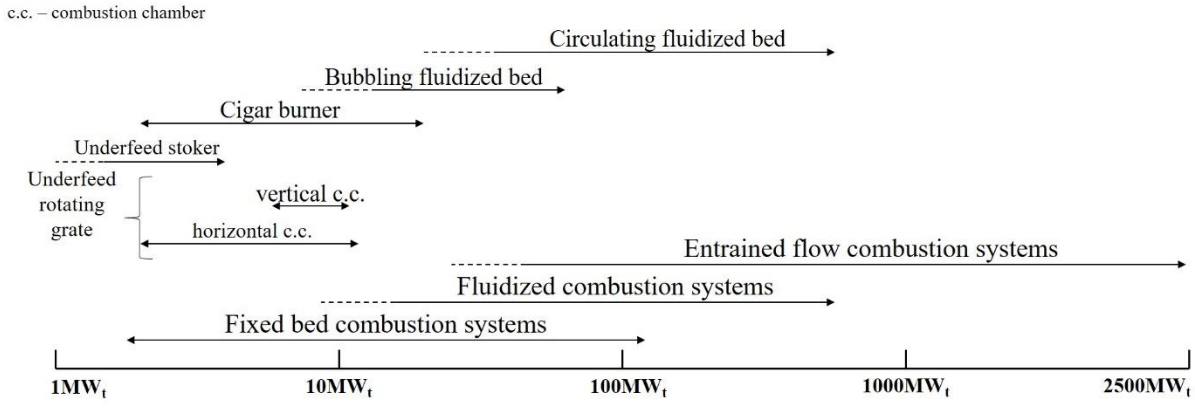


Figure 2.2. Combustion installations and their output ranges [16, 69, 70]

2.4.2. Biomass gasification technologies

The gasification reactor or gasifier is the installation where the gasification process takes place. Nowadays there are hundreds of constructive variants of it, which are divided into several categories depending on the heat source, the oxidant used, the transport of fuel in the reactor, the pressure and the contact between the solid and the gaseous phases. Thus, the following types of reactors depending on the fuel transport in the reactor are encountered [16, 17, 19, 23, 66, 67, 178-180]:

- Fixed bed gasifier;
- Fluidized bed gasifier;
- Entrained flow gasifier.

Only one type of gasifier cannot be developed at any scale, there is a power range related for each type of gasification reactor. Fixed bed gasification reactors are typically used on low power (<10 MW_t); fluidized bed gasification reactors are specific to medium power plants (5-100 MW_t); entrained bed gasification reactors are used in high power plants (> 50 MW_t) [16, 19, 69]. Figure 2.3 shows the power ranges for each type of reactor.

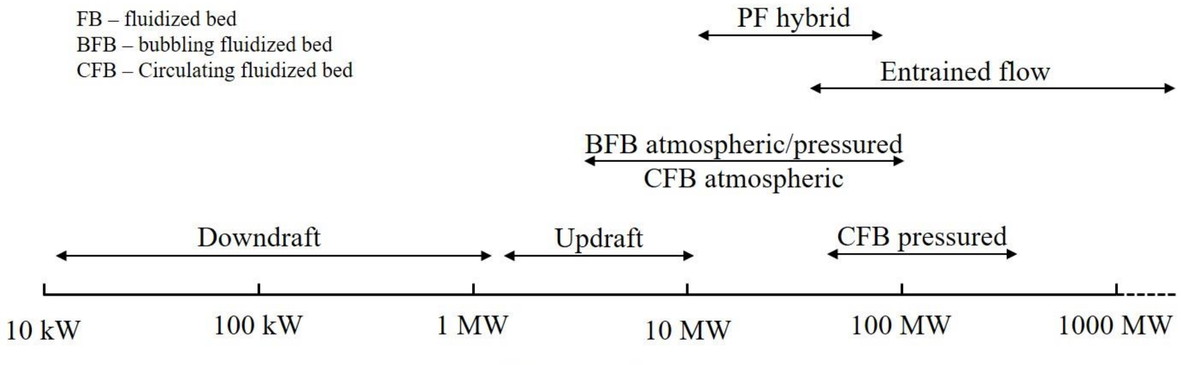


Figure 2.3. Gasification reactors and their output ranges [16, 19, 69]

Table 2.3 presents the comparison of fixed bed, fluidized bed and entrained flow gasification reactors, depending on their parameters and features.

Table 2.3: Comparative analysis of gasification reactor types [17, 19, 67, 68, 71, 173, 175]

Parameter / feature	**Reactor type**		
	Fixed/moving bed	**Fluidized bed**	**Entrained flow**
Fuel size	< 51 mm	< 6 mm	< 0,15 mm
Fine particle tolerance	Limited	Good	Excellent
Abrasion tolerance	Very good	Good	Poor
Exhaust gas temperature	425 – 650℃	800 – 1050℃	1250 – 1600℃
Accepted fuel	Low rank coal, biomass. Fuel with a moisture content of less than 20% for downdraft reactors.	Low rank coal, excellent for biomass	Any type of coal, including with agglutinate tendency, not suitable for biomass
Oxidant requirements	Low	Moderate	High
Reaction zone temperature	1090℃	800 – 1000℃	> 1990℃
Steam requirements	High	Moderate	Low
Ash	Dry. Depending on the fuel type, slag may be formed in updraft reactors.	Dry	Slag
CGE	Relatively high, however, if tar is not taken into account as a useful product, then efficiency decreases. Generally, cold-gas efficiency is 70% for air-reactors using air as an oxidant, but can also reach 80%	Moderate for atmospheric installations using air as an oxidant. Efficiency values are between 60% for atmospheric reactors using air and 70% for oxygen pressurized reactors, but efficiency values of 89.2% may also been reached	80%
HGE	High (~ 80%)	Moderate (60%) to high (85%). Maximum values are obtained in pressurized reactors.	
Applications	Small units (10 kW – 10 MW)	Medium size units (5 – 500 MW)	High capacities (50 – over 1000 MW)
Problem areas	Tar production and utilization of fines	Carbon conversion	Gas cooling
Strengths and Weaknesses	Downdraft: lower calorific value, moderate dust, low tar Updraft: higher calorific value, moderate dust, high tar	Higher capacity than fixed bed reactors, improved heat and mass transfer from improved fuel, higher calorific value, higher efficiency	Can gasify all types of coal, high sensible heat of gas, large capacities, imply ash slagging

	Crossdraft: lower calorific value, moderate dust, high tar		
Sensitive to:			
Fuel specification	- Downdraft: specific - Updraft: moderate - Cross-draft: moderate	- Bubbling: flexible - Circulant: flexible	
Fuel size	- Downdraft: good - Updraft: very good - Cross-draft: good	- Bubbling: acceptable - Circulant: acceptable	
Moisture content	- Downdraft: acceptable - Updraft: very good - Cross-draft: good	- Bubbling: good - Circulant: good	
Ash content	- Downdraft: low - Updraft: low - Cross-draft: low	- Bubbling: very good - Circulant: very good	
Reaction temperature	- Downdraft: 1000°C - Updraft: 1000°C - Cross-draft: 900°C	- Bubbling: 850°C - Circulant: 850°C	
Fuel mixing	- Downdraft: low - Updraft: low - Cross-draft: low	- Bubbling: very good - Circulant: excellent	
Exhaust gas temperature	- Downdraft: 800°C - Updraft: 250°C - Cross-draft: 900°C	- Bubbling: 800°C - Circulant: 850°C	
Tar content in gas	- Downdraft: very low (~ 1,000 mg/Nm^3) - Updraft: very high (~ 50,000 mg/Nm^3) - Cross-draft: very high	- Bubbling: moderate (1-15 g/Nm^3) - Circulant: low (~ 10,000 mg/Nm^3)	Due to the high temperatures almost all the tar is destroyed, resulting in a gas with low concentrations of CH_4 or other light hydrocarbons.
Dust content in gas	- Downdraft: moderate (0.1-0.2 g/Nm^3) - Updraft: good (0.1-1 g/Nm^3) - Cross-draft: high	- Bubbling: very high (2-20 g/Nm^3) - Circulant: very high (10-35 g/Nm^3)	
Char content in gas	- Downdraft: 9.3-30 g/Nm^3	- Bubbling: 1.04-43.61 g/Nm^3	

		- Circulant: 1.7-13.1 g/Nm^3	
Turndown ratio	- Downdraft: acceptable - Updraft: good - Cross-draft: good Moderate, approximative 2/1	- Bubbling: very good - Circulant: good High, about 4/1. Higher values can also be obtained for large installations where the bed can be divided into sections.	
Scale up potential	- Downdraft: low - Updraft: good - Cross-draft: low	- Bubbling: good - Circulant: very good	
Start up speed	- Downdraft: low - Updraft: low - Cross-draft: low	- Bubbling: good - Circulant: good	
Control	- Downdraft: acceptable; difficulties in maintaining a uniform temperature profile Updraft: acceptable; high response time - Cross-draft: acceptable	- Bubbling: very good - Circulant: very good Short response time, a few minutes, for a wide range of plant dimensions.	
Carbon conversion	- Downdraft: very good - Updraft: very good - Cross-draft: low In fixed bed reactors, high carbon conversion efficiency can be achieved with minimal effort.	- Bubbling: acceptable - Circulant: very good A 95% carbon conversion efficiency is difficult to achieve due to compromises between gas quality and fluidization. This efficiency is even lower for reactors that use air instead of oxygen. The residence time is higher than for fixed bed reactors, to achieve the same conversion efficiency, a solution would be pressurization.	High
Thermal efficiency	- Downdraft: very good - Updraft: excellent - Cross-draft: good	- Bubbling: good - Circulant: very good	

Low high heating value of gas	- Downdraft: low - Updraft: low - Cross-draft: low	- Bubbling: low - Circulant: acceptable	Moderate
Usual number of phases involved	One gas phase and one phase for each solid involved. As a rule, gasification reactors involve one solid, two phases.	Two gaseous phases (gas emulsion and bubbling) plus one phase for each solid involved.	
Superficial gas velocity	Relatively low or below the minimum fluidization limit.	Above the minimum fluidization limit and up to the limit of pneumatic transport.	
Pressure drop in bed	Higher with superficial speed increase	Remain constant in the fluidization range	
Operating risks	Moderate, largely due to the possibility of interruption caused by blockages due to high temperatures in the combustion zone which may exceed the melting / softening temperature of the ash, and the tar acting as a bond between the particles in the devolatilization area, mostly for the small size particles or for fibrous fuel.	Moderate to low. There may be problems in bed due to high temperatures that exceed the softening temperature of the ashes.	
Polluting emissions level	High and difficult to avoid	Low and easy to control. The main reason is the possibility of adding a solid absorbing pollutants to the bed. It mixes very well with other solids and maintains good contact with the gaseous phase. Relatively low temperatures minimize NO_x production.	
Investment cost	Moderate. Particular attention should be paid to the ash removal system and material close to the combustion zone	Low because of the relatively low and uniform bedding temperature.	

CHAPTER III
3. BIOMASS VALORISATION BY GASIFICATION IN GT THERMODYNAMIC CYCLE

3.1. EXPERIMENTAL STUDY

3.1.1. Gasification process – transitory regimes

Experimental simulations of the gasification process were carried out in a batch tubular reactor, from the Renewable Energy Sources Laboratory of the Politehnica University of Bucharest. The original designed tubular reactor uses as heating platform NABERTHERM tubular electric oven, model RO 60/750/13. The experimental setup allows gasification process simulations with external energy input, using air, oxygen or water as process agent. This allows the gasification process to be carried out in a batch mode, its configuration leading to mass and energy balance determination, resulting by-products properties determination and the optimum process parameters according to the pursued conditions establishment. Design of the gasification process in the batch tubular reactor is shown in Figure 3.1.

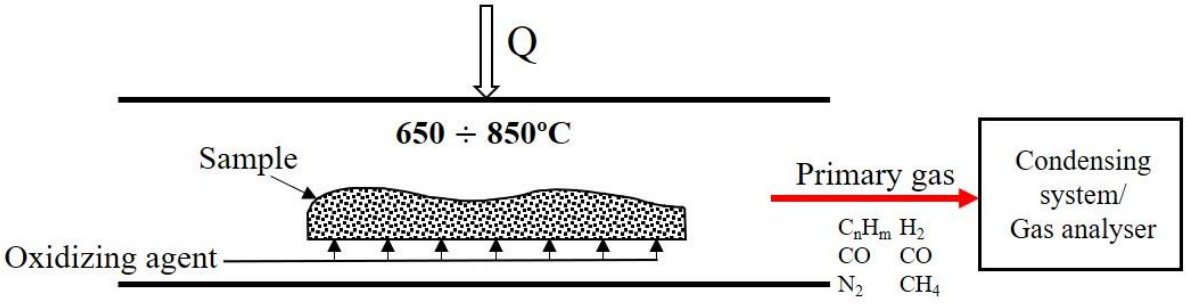


Figure 3.1. Design of the gasification process

For air-gasification processes, air was introduced in the reactor with an air compressor, the air flow being controlled by a flowmeter. For steam gasification processes, the water was introduced in the reactor with an automatic syringe injection pump at a constant and controlled flow rate. Depending on the oxidant flow rate and the its required amount to be introduced in the process, resulted the gasification process duration, shown in the corresponding tables for each set of measurements.

For the analysis of the produced gas and to observe the transitory regime of the gasification process, the Testo 350 XL gas analyzer probe was inserted into the exhaust pipe of the gas condensing system. Concentrations of gaseous species can be analyzed in real time during the process, so the transitory regime of the gasification process can be observed.

With the measured data, variation curves of instantaneous gaseous species concentrations can be plotted in time depended charts, these being necessary for the analysis of the gasification process initiation stage and for the optimal process parameters establishment.

By analyzing the transitory regime of a gasification process, the gasification steps can be delimited in time approximately, the composition of the gas produced at each stage can be determined, and the material conversion efficiency and process efficiency can be determined according to the studied parameters.

The results of batch gasification experiments - transitory regime - do not reveal the final composition of syngas, but only an primary composition, as the process is not complete - as in the case of a continuous gasification process. However, the proposed approach reveals the initiation stage of gasification processes and serves as a starting point for obtaining the optimal process parameters necessary to initiate the gasification of various materials studied, under the proposed conditions.

The three materials studied were poplar wood, rapeseed residues and food court waste. The process temperature varied between 650°C and 850°C, and the equivalent air ratio varied between 0.25 and 0.40. For each set of measurements conducted, different process parameters were established and calculated, these being presented in the tables.

3.1.1.1. Air gasification of poplar wood

Poplar has been studied over time, proving its ability to be used as a feedstock in gasification processes [183-185]. The gas obtained from wood gasification has good combustion properties and can be successfully used for electricity production [186, 187]. The transitory regime for poplar was determined to serve as a comparison for the transitory regimes of two other materials that have not yet been studied as potential feedstocks in gasification processes and to establish optimal process parameters according to the conditions pursued.

Table 3.1: Process parameters for air gasification of poplar wood

Temperature	°C	650			750 °C			850 °C		
ER	-	0.25	0.30	0.35	0.25	0.30	0.35	0.25	0.30	0.35
Sample weight	gr	10	10	10	10	10	10	10	10	10
Amount of air	l	10.49	12.59	14.68	10.49	12.59	14.68	10.49	12.59	14.68
Air flow rate	l/min	1	1	1	1	1	1	1	1	1
Pressure	bar	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013
Process	min	10:30	12:30	14:40	10:30	12:30	14:40	10:30	12:30	14:40

Figures 3.2-3.4 presents the transitory regimes of poplar wood air gasification processes at 650°C and ER of 0.25, 0.30 and 0.35. In Figure 3.2 gasification process stages are delimited in time. The gasification process stages vary from one process to another depending on process temperature, the gasification agent and the material used, and in some cases the ER value.

Analyzing the three graphs below it can be seen that the ER value influences the duration of the gasification stages. As a larger amount of air is required as ER increases, and because the sample weight and the air flow rate are kept constant, then the air supply time in the reactor (the total duration of the process) is longer. As a result, the char gasification stage will be increased, as this phase starts about four and a half minutes since process starts and continues in all three cases until it is complete.

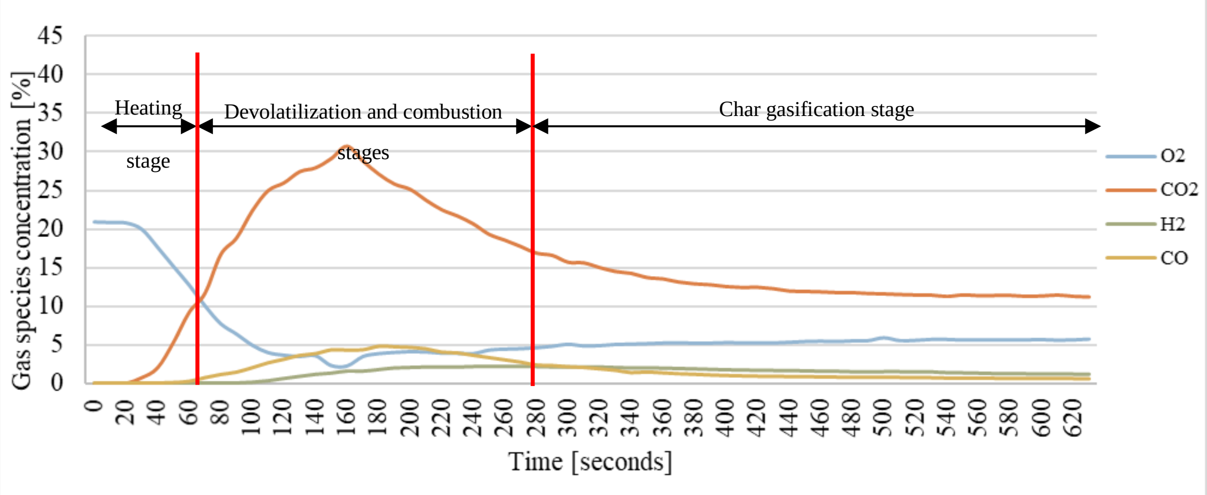


Figure 3.2. Poplar wood air gasification process – transitory regime – 650°C; ER = 0.25

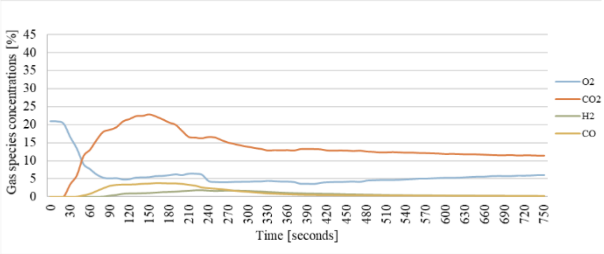


Figure 3.3. Poplar wood air gasification process – transitory regime – 650°C; ER = 0.30

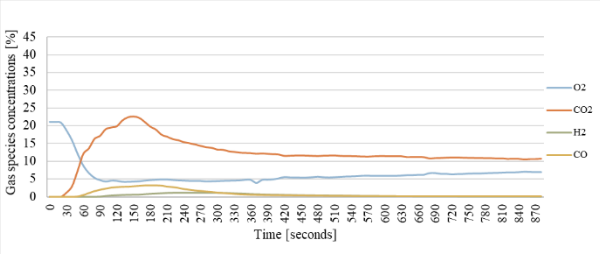


Figure 3.4. Poplar wood air gasification process – transitory regime – 650°C; ER = 0.25

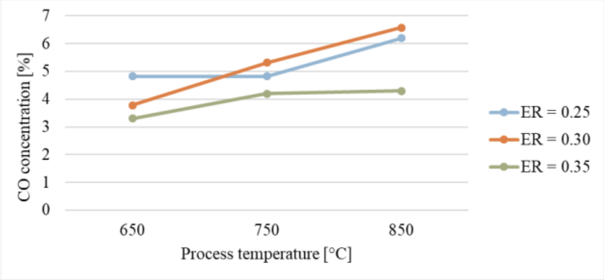


Figure 3.5. Variation of carbon monoxide concentration – air gasification of poplar wood

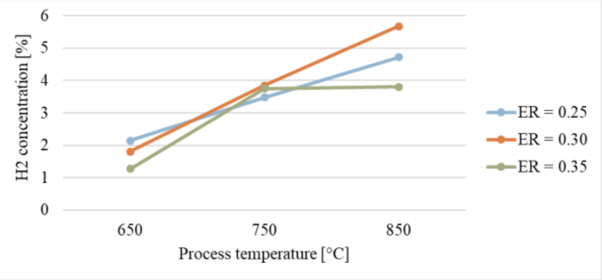


Figure 3.6. Variation of hydrogen concentration – air gasification of poplar wood

Analyzing the two charts above, optimal process parameters for air gasification of poplar wood can be established, namely: to maximize the CO and H_2 concentrations in the produced gas, the optimal process parameters are process temperature 750-850ºC and ER 0.25-0.30.

3.1.1.2. Air gasification of rapeseed straws and residues

Rape is a plant cultivated annually in Romania on quite large surfaces, with a considerable amount of residue being generated annually. Rape straws generated annually have an energy potential of about 63540 TJ. So far, rape straws have not been used as feedstock in gasification processes, but have been studied for bio-ethanol [189] and bio-oil production [114]. As far as their gasification is concerned, only simulations [190] or pretreatment studies such as torrefaction [191] for further use in gasification processes have been carried out.

Samples of rape straws used in this experiments are plant straws cut manually from the field prior to harvest, and straw residue samples are represented by residues obtained by harvesting rape straws with agricultural machinery.

Table 3.2: Process parameters for air gasification of rapeseed straws and residues

Material type Process parameter	U.M.	Rapeseed straws	Rapeseed straw residues
Temperature	ºC	650 / 750 / 850	650 / 750 / 850
ER	-	0.25 / 0.30	0.25 / 0.30
Sample weight	gr	12 / 10	12 / 10
Amount of air	l	12.51	11.07
Air flow rate	l/min	1	1
Pressure	bar	1.013	1.013
Process duration	min	12:30	11:04

In Figure 3.7 and Figure 3.8 transitory regimes of air gasification of rapeseed straws, respectively rapeseed straw residues, at 650°C and an ER of 0.25 are presented.

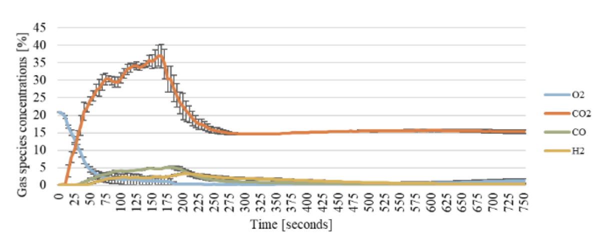


Figure 3.7. Rapeseed straw air gasification process – transitory regime – 650°C, ER = 0.25

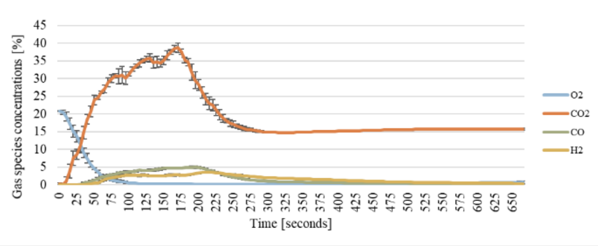


Figure 3.8. Rapeseed straw residues air gasification process – transitory regime – 650°C, ER = 0.25

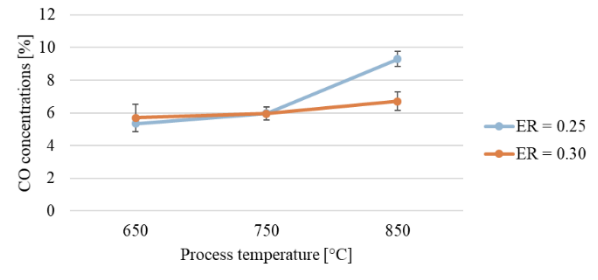


Figure 3.9. Variation of carbon monoxide concentration – air gasification of rapeseed straws

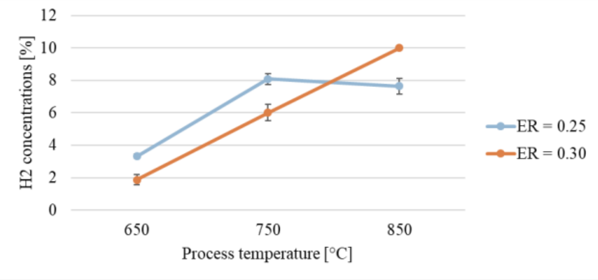


Figure 3.10. Variation of hydrogen concentration – air gasification of rapeseed straws

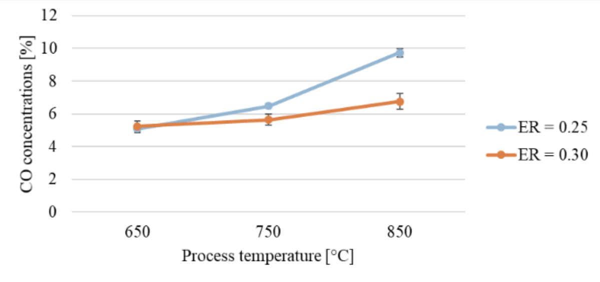


Figure 3.11. Variation of carbon monoxide concentration – air gasification of rapeseed straw residues

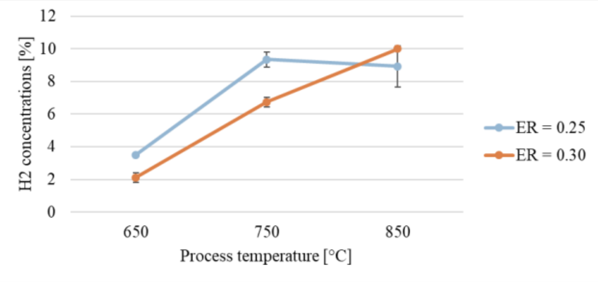


Figure 3.12. Variation of hydrogen concentration – air gasification of rapeseed straw residues

Depending on the gaseous species concentration that is intended to be maximized in the produced gas, in case of air gasification of straws or the rape straw residues, two sets of optimal process parameters can be defined. Thus we have:

- If maximization of carbon monoxide concentration in the produced gas is desirable, optimal process parameters are: 850°C and ER = 0.25;
- If maximization of hydrogen concentration in the produced gas is desirable, optimal process parameters are: 850°C and ER = 0.30.

Analyzing the results obtained for the two types of materials, rape straw and rape straw residues, it can be observed that they do not differ greatly regarding to their behavior in gasification processes. Thus, the method of harvesting does not considerably influence the use of rape straw in gasification processes.

3.1.1.3. Air gasification of rapeseed straw with different moisture content

In this section the rapeseed straw with different moisture content (M) were studied, in comparison with the dry material. The influence of samples moisture content on gasification process and hydrogen production was investigated. Moisture content of samples was 5%, respectively 10%. This values were chosen since immediately after harvesting the moisture content of rapeseed straw was 4.93% (approximately 5%), and after almost three months in which the samples were grounded and stored in the laboratory (place with quite high humidity), the moisture content of samples was about 9.31% (approximately 10%).

Table 3.3: Process parameters for air gasification of rapeseed straw with different moisture content

Process parameter	U.M.	M = 0%	M = 5%	M = 10%
Temperature	ºC	650 / 750 / 850	650 / 750 / 850	650 / 750 / 850
Pressure	bar	1.013	1.013	1.013
Sample weight	gr	10	10	10
ER	-	0.30	0.30	0.30
Amount of air	l	12.51	11.89	11.26
Air flow rate	l/min	1	1	1
Process duration	min	12:30	11:55	11:15

In Figures 3.13-3.15 transitory regimes of air gasification processes of rapeseed straws with different moisture content at 850°C and ER of 0.30 are presented. The analysis of the three graphs shows that the variation in gas species concentrations is not influenced by the moisture content of the material.

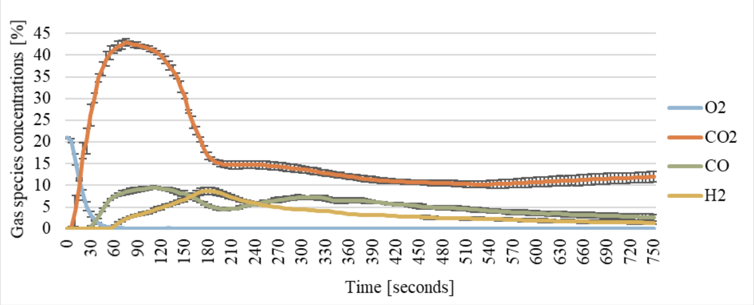


Figure 3.13. Dry rapeseed straw air gasification process - transitory regime - 850°C, ER = 0.30

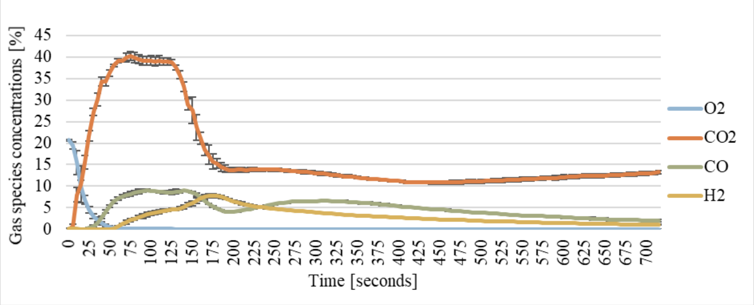


Figure 3.14. Rapeseed straw (5% moisture content) air gasification process - transitory regime - 850°C, ER = 0.30

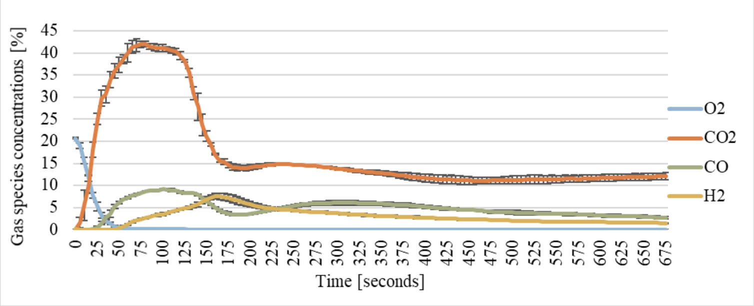


Figure 3.15. Rapeseed straw (10% moisture content) air gasification process - transitory regime - 850°C, ER = 0.30

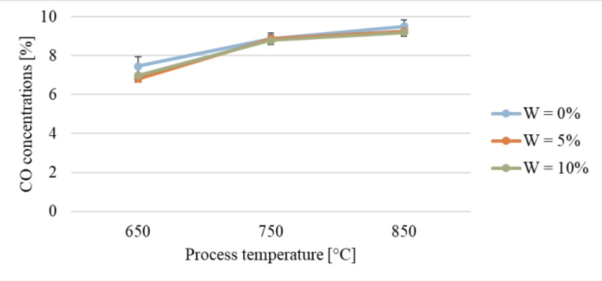


Figure 3.16. Variation of carbon monoxide concentration – air gasification of rapeseed straws with different moisture content

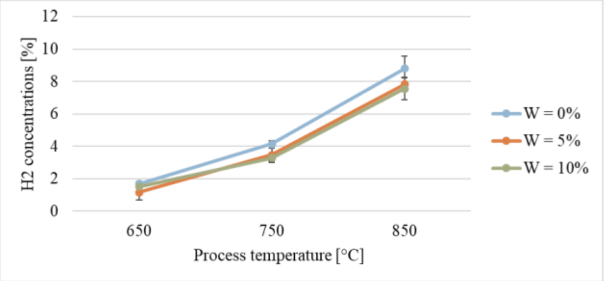


Figure 3.17. Variation of hydrogen concentration – air gasification of rapeseed straws with different moisture content

By analyzing the two graphs above, optimal process parameters can be established for air gasification process of rape straws with different moisture content. To maximize the concentrations of combustible gas species (CO and H_2) at this air equivalent ratio of 0.30, the optimal process temperature is 850°C. It can be concluded that at this level of moisture content it is not necessary to dry the rape straws for their use in the gasification processes, since their moisture content does not considerably influence the combustible gases concentration.

3.1.1.4. Steam gasification of rapeseed straw

Using steam as an oxidizing agent aims the hydrogen concentration in the produced gas to increase. In order to observe the influence of hydrogen production in the gas produced according to the type of gasification agent used, gasification experiments of rape straws (dry matter) at 750 and 850°C were repeated, keeping all the process parameters constant, except the type of oxidant. The amount of oxygen introduced in the process with air (ER = 0.30) was taken into account, the same amount of oxygen being introduced in the process with water.

Table 3.4. Process parameters for steam gasification of rapeseed straw

Process parameter	U.M.	Value
Temperature	°C	750 / 850
Pressure	bar	1.013
Sample weight	gr	10
Equivalent ER	-	0.30
Amount of water	ml	4.16
Water flow rate	ml/min	0.33
Process duration	min	12:30

Comparing the transitory regimes of rape straws steam gasification process at 750°C (Figure 3.18) and 850°C (Figure 3.19), with those of rape straws air gasification process at same process temperatures, it can be seen that instantaneous concentrations of carbon monoxide and hydrogen in char gasification stage maintains at a higher level. Thus, except for the first minutes of the process, when hydrogen begins to form, the hydrogen concentration is approximately constant throughout the process.

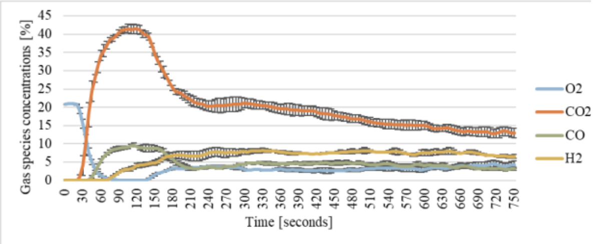


Figure 3.18. Rapeseed straw steam gasification process - transitory regime - 750°C

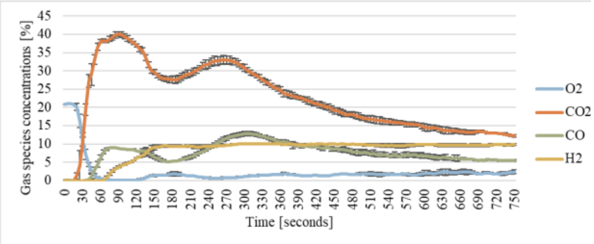


Figure 3.19. Rapeseed straw steam gasification process - transitory regime - 850°C

Comparing the values from Figure 3.20 with those from Figure 3.16, can be observed that when using steam as an oxidizing agent in the gasification process of dried rape straws, the maximum instantaneous concentration of CO reached is higher by 2÷3 percentage points, compared to air gasification process. For H_2, the maximum instantaneous concentration at 850°C cannot be determined since the gas analyzer cannot measure and display a H_2 concentration higher than 9.99%, but it is certainly higher than 10%. An increase in instantaneous H_2 concentration is observed when process temperature increases from 750°C to 850°C. Comparing the data in Figure 3.20 and Figure 3.17, an increase in the maximum instantaneous H_2 concentration by 5 percentage points and, respectively, a minimum of 1 percentage point in the use of steam as an oxidant in the gasification process at 750°C, respectively, 850°C is observed.

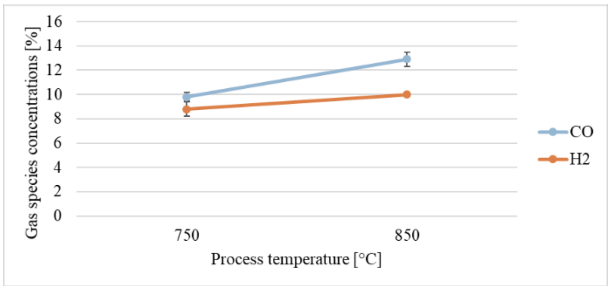


Figure 3.20. Variation of CO and H_2 concentrations - steam gasification of rapeseed straws

According to the results obtained for rapeseed straws gasification processes, optimal process parameters are: steam as a gasifying agent and a process temperature of 850°C. However, if steam cannot be used as an oxidizing agent, the optimum process parameters for the gasification of rape straws are: 850°C and ER = 0.30.

3.1.1.5. Air gasification of food court waste

Food court waste (FCW) is a waste generated in shopping centers in food court zone. Usually, it contains the following: paper, cardboard, plastic, organic residues, wood, metal and glass. Paper, cardboard and plastic are packing waste as well as disposable cutlery and dishes. Organic wastes are food debris. The wood is found in small quantities. Metal, or more precisely aluminum, and glass are also packaging waste, in which beverages were bottled.

Depending on the type of restaurants in the food court area of the shopping centers, the season, the day of the week and even the time of the day, the composition of this waste can vary widely. For example, waste from some shopping centers may not contain metal or glass in its composition. Also, organic waste represented by leftovers, differs greatly depending on the type of restaurants present in each location, with Romanian, Asian, Italian, fast food, etc. specific.

The five main components of waste - paper, cardboard, plastic, organic waste and wood - have been studied individually as well as in various mixtures over time as a feedstock for thermo-chemical conversion processes. Researchers results have shown that these five materials treated individually can be successfully used in gasification processes.

Table 3.5: Process parameters for air gasification of food court waste

Process parameter	U.M.	ER = 0.25	ER = 0.40
Temperature	ºC	650 / 750 / 850	650 / 750 / 850
Pressure	bar	1.013	1.013
Sample weight	gr	10	6.25
Amount of air	l	15.88	15.88
Air flow rate	l/min	1	1
Process duration	min	15:53	15:53

In Figure 3.21 and Figure 3.22 the transitory regimes of FCW air gasification processes at 750ºC and different value of ER values are presented. The value of the air equivalent ratio does not influence the duration of the heating and combustion and devolatilization stages. These two stages are influenced in turn by the process temperature. Increasing the air equivalent ratio value negatively influences the maximum instantaneous concentration of gaseous species formed, carbon dioxide, carbon monoxide and hydrogen, as in previously cases.

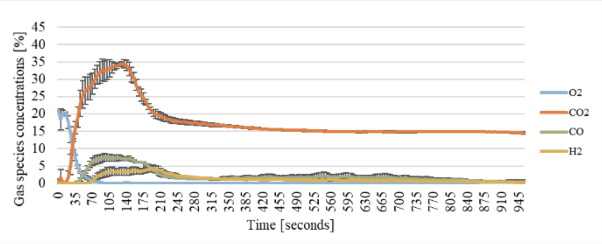


Figure 3.21. Food court waste air gasification process - transitory regime - 750°C, ER = 0.25

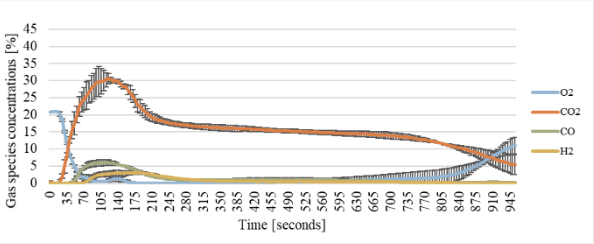


Figure 3.22. Food court waste air gasification process - transitory regime - 750°C, ER = 0.40

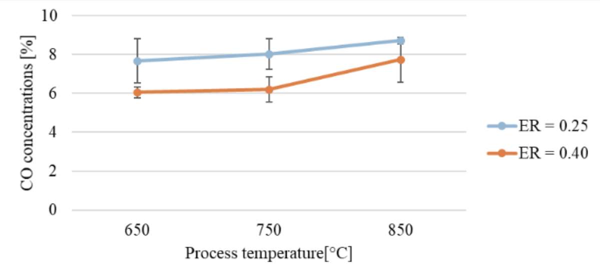


Figure 3.23. Variation of carbon monoxide concentration - air gasification of food court waste

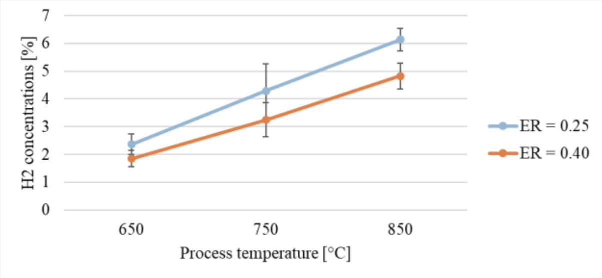


Figure 3.24. Variation of hydrogen concentration - air gasification of food court waste

Taking into account the results obtained in this subsection and presented in the above graphs it can be stated that the optimal process parameters for FCW air gasification are ER = 0.25 and a process temperature of 850°C.

3.1.1.6. Air/steam gasification of food court waste

In order to observe the influence of hydrogen production in the produced gas according to the gasifying agent used (air or steam), food court gasification experiments at 750 and 850°C and ER = 0.30 (in the case of steam gasification processes the equivalent amount of oxygen introduced in the process in the case of an ER of 0.30) were conducted. Both processes were performed at same process parameters, including the amount of oxygen introduced into the process, the only difference being represented by the oxidizing agent. The air requirement for an air gasification process of 10 grams of FCW was calculated and the oxygen contained in the specific amount of air. Then, the amount of steam required to be introduced in the process was calculated to provide the same amount of oxygen in the reactor. Process parameters chosen and calculated are presented in Table 3.6.

Table 3.6: Process parameters for air/steam gasification of food court waste

Oxidizing agent	Air	Steam
Temperature	750ºC / 850ºC	750ºC / 850ºC
Pressure	1.013 bar	1.013 bar
Sample weight	10gr	10gr
ER	0.3	-
Amount of air/steam	19.05 l	6.3384 ml
Air/steam flow rate	1 l/min	0.3336 ml/min
Process duration	19 min	19 min

In Figure 3.25 and Figure 3.26 the transitory regimes of air and steam gasification processes of food court waste at 850°C, are presented. In the case of steam gasification processes, compared to those using air as a gasifying agent, the oxygen concentration decreases at the beginning of the process, then rise and remains at a fairly high level until the end of the process. Considering that reactions between water vapor and solid carbon are considerably slower than those between air (O_2) and carbon, the residence time may be too short for the steam gasification process. Oxygen has no time to react with the sample in the char gasification stage and is evicted from the reactor unreacted.

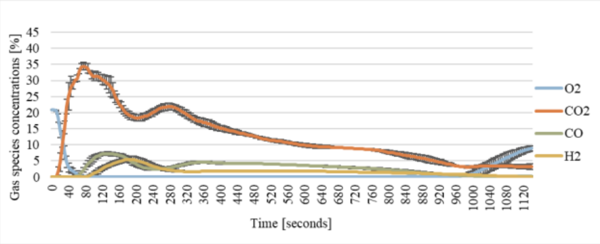


Figure 3.25. Food court waste air gasification process - transitory regime - 850°C, ER = 0.30

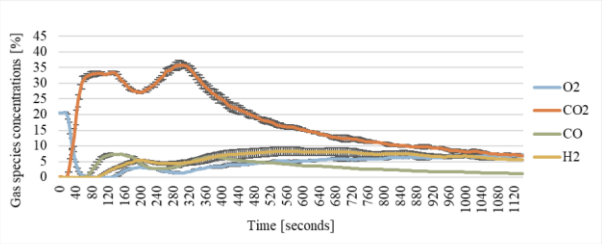


Figure 3.26. Food court waste steam gasification process - transitory regime - 850°C

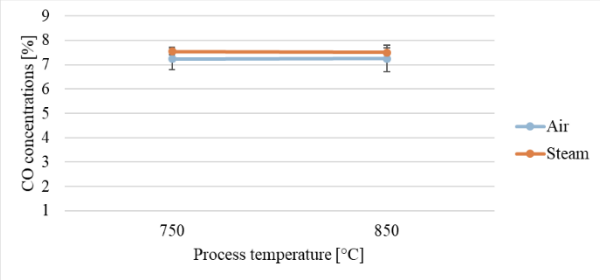


Figure 3.27. Variation of carbon monoxide concentration - air and steam gasification of food court waste

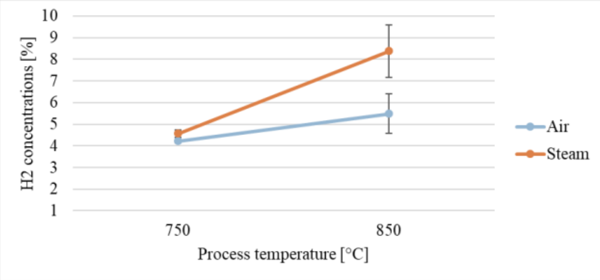


Figure 3.28. Variation of hydrogen concentration - air and steam gasification of food court waste

From the graphics above, optimal process parameters can be determined in the case of food court gasification process at an equivalent oxygen rate of 0.30, thus: process temperature of 850°C and the steam as an oxidizer.

3.1.1.7.Conclusions

Within this subchapter the transitory regimes of air/steam gasification processes of three categories of materials under different process conditions were studied. The materials analyzed were poplar wood, rape stalks and residues and food court waste. Process temperatures varied between 650°C, 750°C and 850°C, and the air equivalent ratio ranged from 0.25 to 0.4, with a step of 0.05. The process pressure was, in all studied cases, atmospheric pressure, and the oxidizing agent used was air or steam. The amount of steam introduced into the process (SBR) was not typical for a continuous gasification process (SBR = 1:1 ÷ 5:1), this being calculated so that the amount of oxygen introduced in the steam process is equivalent to the amount of oxygen introduced into the air process. Thus, in the case of gasification processes comparison, the only difference was the type of oxidizing agent used.

The transitory regime of a gasification process helps studying and understanding the phenomena that occur during a gasification process, to characterize and compare the gasification processes under different conditions, to determine the primary gas composition and the optimal process parameters to initiate the gasification process of various materials studied under the proposed conditions.

For these experiments, poplar wood was chosen as a comparison term for the other two studied materials. Poplar wood has proven its ability to be used as a feedstock in gasification processes. Thus, the transitory wood regime has served as a reference model for newly studied materials. Air equivalent ratio and temperature values were chosen from the most common values used in wood air gasification.

Rape straws and residues, as well as food court waste, have been studied in order to determine the possibility of using them as primary energy source in thermo-chemical conversion processes. The results have shown that these agricultural and municipal waste can be successfully used to produce a good combustible gas. The physicochemical properties of agricultural and municipal wastes studied (high content of volatile substances, relatively low ash content, wood-like chemical composition) favor them in gasification processes, moreover their transitory regimes are similar to those of a wood (poplar). Also, the maximum instantaneous concentrations of combustible gases obtained from gasification of rape straws and residues and of FCW were higher, compared to those obtained for poplar wood. Consequently, we can say that the primary gas obtained from the gasification processes of the two new categories of materials studied has better combustion properties compared to that obtained for poplar wood, which is already used as feedstock to obtain the syngas.

According to the results obtained from the gasification experiments, the optimal process parameters for gasification of the rape straws are temperature of 850°C, ER equivalent of 0.30, and using steam as the gasifying agent. At these process parameters the highest values of the instantaneous concentration of carbon monoxide and hydrogen are obtained. Also, hydrogen is produced almost the entire process, not only in the combustion and pyrolysis stages, so the amount of hydrogen in the gas produced will be higher.

Regarding to food court waste gasification processes - transitory regime - best results were obtained at 850°C, ER equivalent of 0.30 and steam as oxidant. If steam cannot be used in gasification processes, the optimal process parameters for the FCW gasification processes are: 850°C and ER = 0.25.

3.2. GASIFICATION PROCESS EFFICIENCY

The gasification process can be evaluated regarding to the quality of the gas obtained, the conversion efficiency and the energy efficiency of the process. To assess the gasification process in terms of gas quality, the gas composition and its lower calorific value are analyzed. The produced gas composition is influenced by a variety of process features and parameters, including: the feedstock composition, the type of gasification agent used, the ratio of oxidant to fuel, process temperature and pressure, residence time, reactor type [17, 19, 67].

To assess the gasification process in terms of conversion efficiency and energy efficiency, three factors can be calculated [17, 19, 67, 173]:

- Carbon conversion efficiency – CCE
- Cold-gas efficiency – CGE
- Hot-gas efficiency – HGE

Carbon conversion efficiency is the carbon percentage in the fuel which is converted into gas products through the gasification process and can be expressed as follows [19, 67]:

$$\mathrm{CCE} = \frac{\text{Carbon in gasification products [kmol]}}{\text{Carbon in fuel [kmol]}} * 100 \tag{3.1}$$

or if the unburn carbon in ash is taken into account [16, 17]:

$$\mathrm{CCE} = \left(1 - \frac{\text{Carbon in gasification ash [kmol]}}{\text{Carbon in fuel [kmol]}}\right) * 100 \tag{3.2}$$

In order to determine the CCE, a series of data must be determined, including: the composition of the produced gas, the amount of gas produced, the amount of carbon contained in the gas, etc. The amount of gas produced can be determined by two methods:

- Method 1: Knowing the amount of gas produced (determined from the mass balance), expressed in mass units, and the molar mass of the gas;
- Method 2: Knowing the amount of nitrogen introduced in the gasification process and the concentration of nitrogen in the gas produced.

To determine the CCE the amount of substance (produced gas) expressed in moles it is necessary to know. Depending on the method of calculation chosen to determine the amount of substance, two values resulted, therefore the CCE value was calculated using both values.

Cold-gas efficiency (CCE) is the ratio of the chemical energy of the gas produced and the chemical energy of the gasified material, being expressed thus [16, 17, 19, 67, 173]:

$$\mathrm{CGE} = \frac{\mathrm{LHV_{gas}} * \mathrm{M_{gas}}}{\mathrm{LHV_{fuel}} * \mathrm{M_{fuel}}} * 100 \tag{3.3}$$

where $\mathrm{LHV_{gas}}$ is the calorific value of the product gas, $\mathrm{LHV_{fuel}}$ is the calorific value of the fuel used, $\mathrm{M_{gas}}$ represents the mass of gas produced from the gasification of $\mathrm{M_{fuel}}$ kilograms of fuel.

Due to high temperatures at which the gasification process takes place, the gas produced by most types of reactors has a very high outlet temperature with an important sensitive energy content. In applications where this sensitive energy can be used (in an oven or boiler), the hot-gas efficiency (HGE) can be defined, taking into account both the chemical and the sensitive energy of the gas produced, so we have [19, 67, 173]:

$$\mathrm{HGE} = \frac{\mathrm{LHV_{gas}} * \mathrm{M_{gas}} + \mathrm{M_{gas}} * \mathrm{c_{p_{gas}}} * (\mathrm{T_{gas}} - \mathrm{T_{fuel}})}{\mathrm{LHV_{fuel}} * \mathrm{M_{fuel}}} \tag{3.4}$$

where $c_{p_{gas}}$ is the specific heat of the product gas, $\mathrm{T_{gas}}$ represents the gas temperature at the gasification reactor outlet, and $\mathrm{T_{fuel}}$ represents the fuel temperature entering the gasification reactor.

Although the experiments do not simulate a complete gasification process, the process efficiencies can be calculated. Their values differ greatly from the values obtained for a typical gasification process but these can be used to characterize the gasification processes and to observe the influence of parameters on process run.

3.2.1. Biomass conversion efficiency and energy efficiencies of air gasification processes of poplar wood

Within this subsection, the carbon conversion efficiency and the energy efficiencies of air gasification processes of poplar wood were calculated at different process temperatures and at different air equivalent rates.

Figure 3.29 and Figure 3.30 show the variation of carbon conversion efficiency, calculated by two methods, in poplar wood gasification processes, according to process parameters.

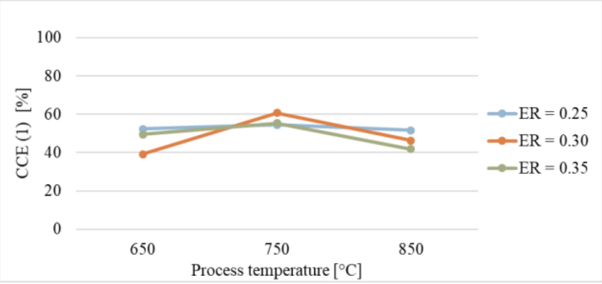


Figure 3.29. Carbon conversion efficiencies (1) - air gasification processes of poplar wood

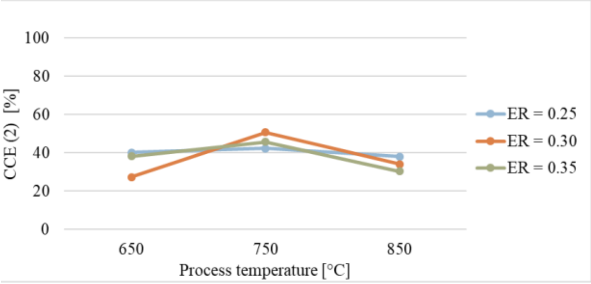


Figure 3.30. Carbon conversion efficiencies (2) - air gasification processes of poplar wood

From the above figures it can be seen that regardless of the calculation method chosen, the highest CCE value is obtained for the air gasification process at 750°C and ER = 0.30. Irrespective of the calculation method of substance quantity chosen and of the air equivalent ratio, CCE is maximized at a process temperature of 750°C.

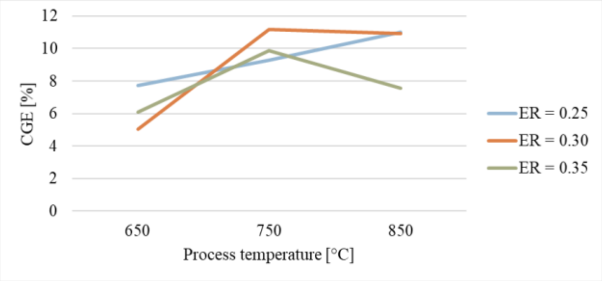


Figure 3.31. Cold-gas efficiency - air gasification of poplar wood

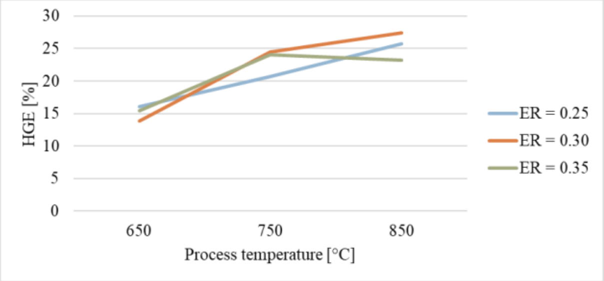


Figure 3.32. Hot-gas efficiency - air gasification of poplar wood

The highest values of CGE are obtained for the air-gasifying processes of poplar wood at 750°C and ER = 0.30 and at 850°C and ER = 0.25/0.30. In the case of HGE, the highest values are obtained for the gasification processes conducted at 850°C and ER = 0.25/0.30.

3.2.2. Biomass conversion efficiency and energy efficiencies of air gasification processes of rapeseed straws and straw residues

Within this subsection, the carbon conversion efficiency and the energy efficiencies of air gasification processes of rapeseed straws and straw residues were calculated at different process temperatures and at different air equivalent rates.

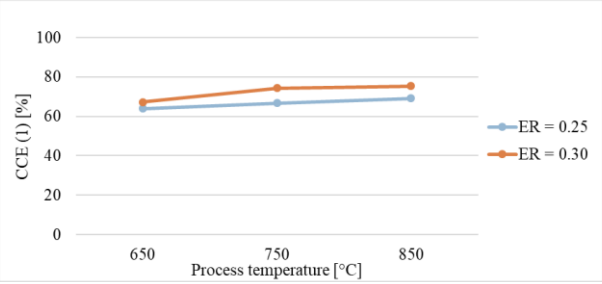


Figure 3.33. Carbon conversion efficiencies (1) - air gasification processes of rapeseed straws

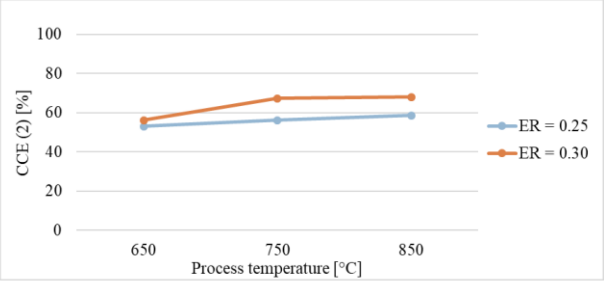


Figure 3.34. Carbon conversion efficiencies (2) - air gasification processes of rapeseed straws

Irrespective of the calculation method chosen, the CCE maximizes at 850°C and ER = 0.30 in the case of air-gasification processes of rape straws. Carbon conversion efficiency increases at temperature rise for each ER value, and for ER increase.

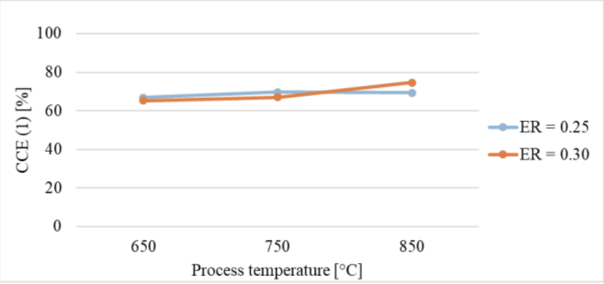


Figure 3.35. Carbon conversion efficiencies (1) - air gasification processes of rapeseed straw residues

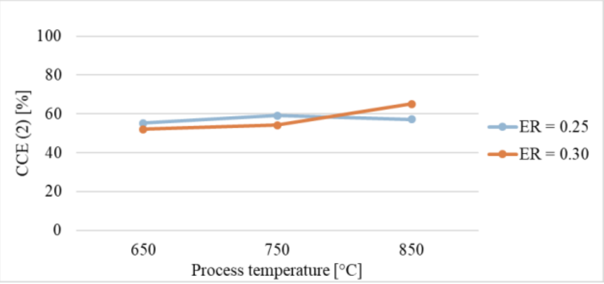


Figure 3.36. Carbon conversion efficiencies (2) - air gasification processes of rapeseed straw residues

In figures above, the variation of the CCE value in air gasification processes of the rapeseed straw residues depending on the process parameters, is presented. The CCE value is calculated using the two previously methods presented. In both cases CECs are maximized at 750ºC and ER of 0.25, and at 850ºC and ER of 0.30.

For both rape straws and straw residues, the CCE values obtained by the first calculation method are in the range of 60-80% and the CCE values obtained using the second calculation method are between about 55 and 75%. Irrespective of the calculation method chosen to determine the amount of gas produced, the carbon conversion efficiency is maximized at ER = 0.30 and a process temperature of 850°C for both materials.

Figure 3.37 and Figure 3.38 show the cold-gas and the hot gas efficiencies in the air-gasifying processes of the rapeseed straws.

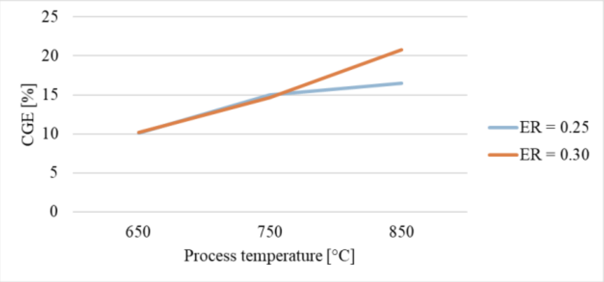


Figure 3.37. Cold-gas efficiencies - air gasification processes of rapeseed straws

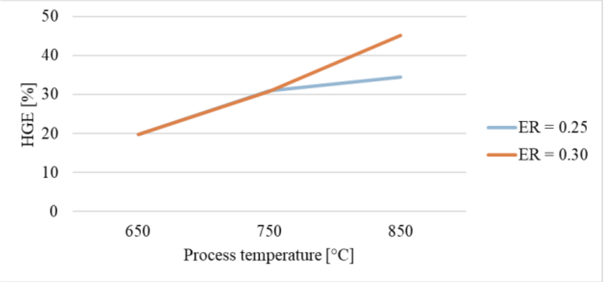


Figure 3.38. Hot-gas efficiencies - air gasification processes of rapeseed straws

At lower process temperatures, 650-750ºC, both the CGE values and the HGE values are not influenced by the air equivalent ratio value. The highest energy efficiencies values are obtained at 850°C and ER = 0.30.

In the figures below, the variation of CGE and HGE according to process parameters in the air gasification of rape straw residues, is presented.

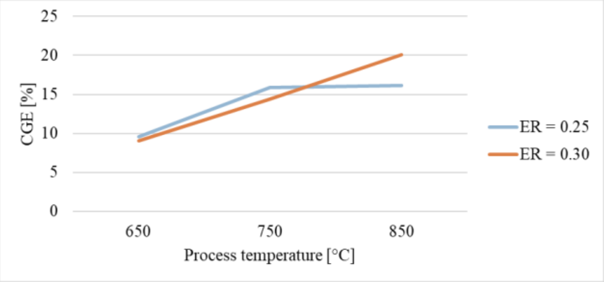


Figure 3.39. Cold-gas efficiencies - air gasification processes of rapeseed straw residues

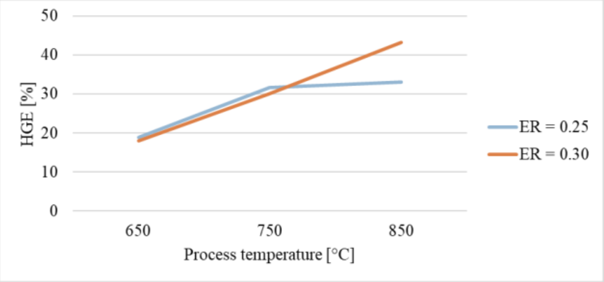


Figure 3.40. Hot-gas efficiencies - air gasification processes of rapeseed straw residues

The highest values of CGE and HGE are obtained for the air-gasification process of rape straw residues at 850ºC and ER = 0.30.

3.2.3. Biomass conversion efficiency and energy efficiencies of air gasification processes of rapeseed straws with different moisture content

Within this subsection, the mass balance, the carbon conversion efficiency and the energy efficiencies of air gasification processes of rapeseed straws with different moisture content at different process temperatures were calculated.

Figure 3.41 and Figure 3.42 show the influence of process temperature and sample moisture content on the CCE - two calculation methods.

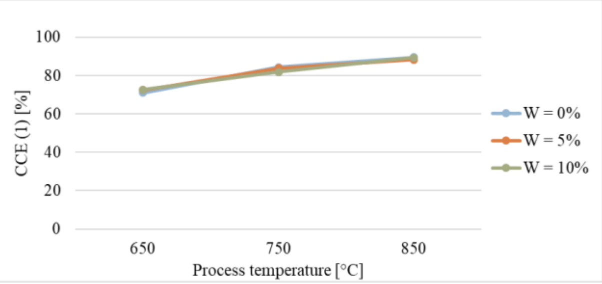


Figure 3.41. Carbon conversion efficiencies (1) - air gasification processes of rapeseed straws with different moisture content

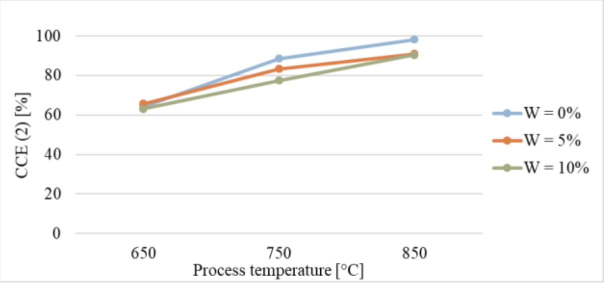


Figure 3.42. Carbon conversion efficiencies (2) - air gasification processes of rapeseed straws with different moisture content

Using the first calculation method of the CCE, it can be noticed that the carbon conversion efficiency is not influenced by the moisture content of the sample at all, but only by temperature increase. From the second graph above, it can be seen that CCE is negatively influenced by increasing the samples moisture content, and positively by temperature increase, when CCE is calculated by the second method. The moisture content of the sample influences even with 8-9 percentage points the value of carbon conversion efficiency in gasification processes at 850ºC.

From the graphs below, it can be seen that both the CGE and HGE variation depending on temperature is approximately linear. Both energy efficiencies calculated increase with the process temperature increase, and their values are not influenced by the moisture content of the sample.

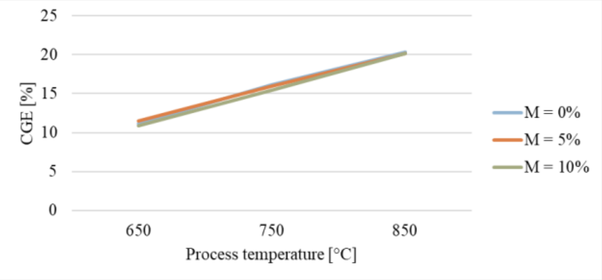


Figure 3.43. Cold-gas efficiencies - air gasification processes of rapeseed straws with different moisture content

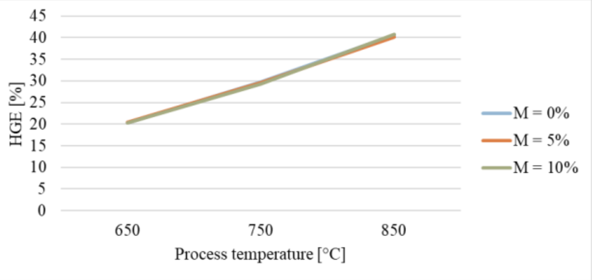


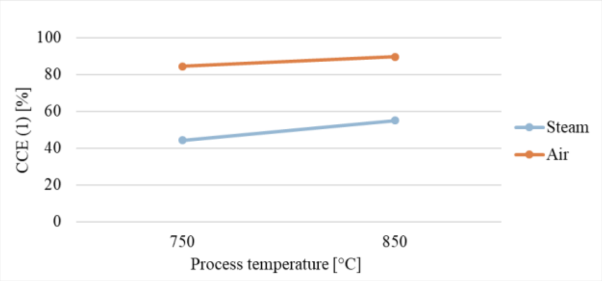
Figure 3.44. Hot-gas efficiencies - air gasification processes of rapeseed straws with different moisture content

The highest values of CGE are obtained for gasification processes at 850°C, which exceeds by at least 20%. In the case of HGE, the highest values are obtained for the gasification process at 850°C, which is around 40.5%.

3.2.4. Biomass conversion efficiency and energy efficiencies of steam gasification processes of rapeseed straws

Within this subsection the mass balance, the carbon conversion efficiency and the energy efficiencies of the steam gasification processes of dried rape straws at different process temperatures were determined.

Figure 3.45 and Figure 3.46 show the variation in carbon conversion efficiency in steam gasification processes of dried rape straws at different temperatures compared to air gasification processes at the same process parameters.



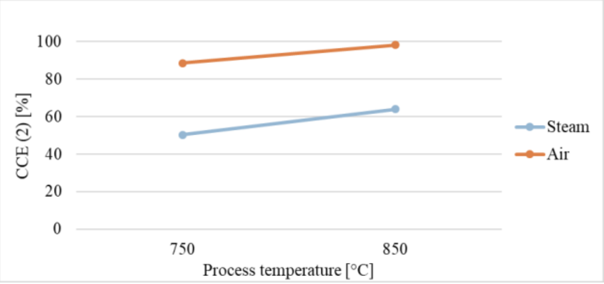
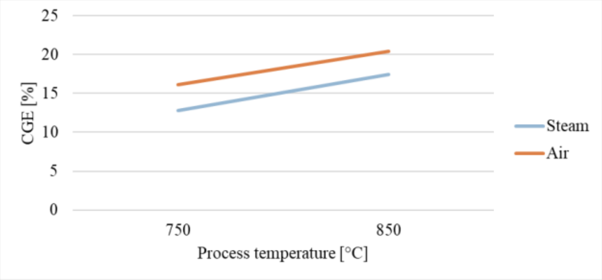


Figure 3.45. Carbon conversion efficiencies (1) - steam gasification processes of rapeseed straw

Figure 3.46. Carbon conversion efficiencies (2) - steam gasification processes of rapeseed straw

CCE increases at process temperature increase in steam gasification processes, but its values are considerably lower compared to the values obtained for the same process parameters in the case of air gasification. This is due to the too short residence time for steam gasification processes.

In the figures below the variations of CGE and HGE in the air and steam gasification processes of dried rape straws at ER (ER equivalent) = 0.30 and the process temperature of 750 and 850°C, are shown. The two energy efficiencies increase at process temperature increase, regardless of the oxidant used, but lower CGE and HGE values are obtained when steam is used.



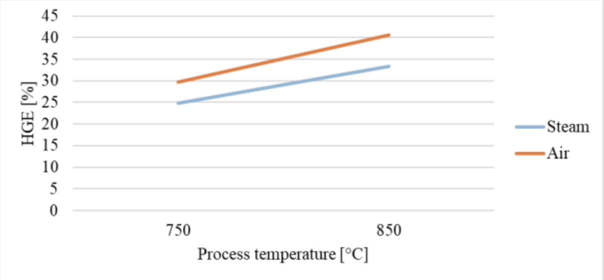


Figure 3.47. Cold-gas efficiencies - steam gasification processes of rapeseed straws

Figure 3.48. Hot-gas efficiencies - steam gasification processes of rapeseed straws

The use of steam as an oxidizing agent in gasification processes of dried rape straws leads to a decrease of CGE and HGE by about 3, and respectively 7, percentage points, compared to the values obtained for the air gasification process of rape straws.

3.2.5. Biomass conversion efficiency and energy efficiencies of air gasification processes of food court waste

Within this subsection the mass balance, the carbon conversion efficiency and the energy efficiencies of the air gasification processes of food court waste at different process temperatures and different values of ER were determined.

In Figure 3.49 and Figure 3.50, the CCE variation with temperature and ER in the FCW air gasification processes are presented. Regardless of the calculation method of the CCE, an increase with temperature increase is observed. For the gasification process at 850°C and ER = 0.40 the difference between the CCE values obtained using both calculation methods is 16 percentage points.

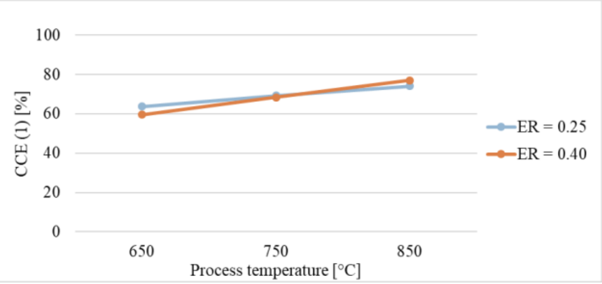


Figure 3.49. Carbon conversion efficiencies (1) - air gasification processes of food court waste

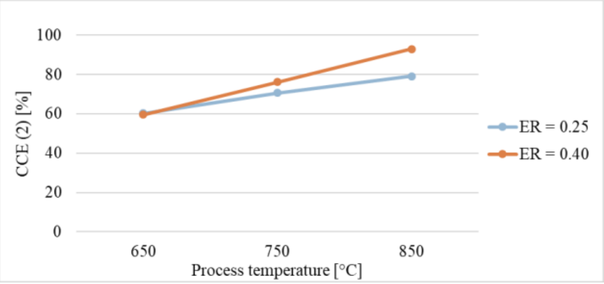


Figure 3.50. Carbon conversion efficiencies (2) - air gasification processes of food court waste

Figure 3.51 and Figure 3.52 show the variation of CGE and HGE, depending on the process temperature and ER for food court waste gasification processes. The energy efficiency of the gasification process, increases with process temperature and ER increase.

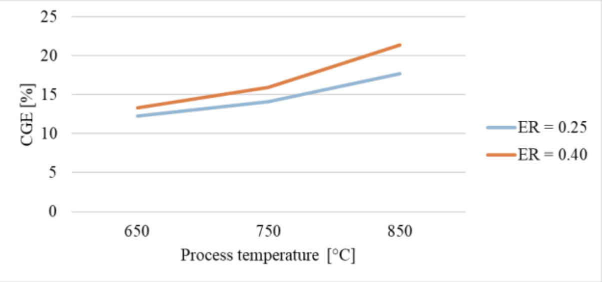


Figure 3.51. Cold-gas efficiencies - air gasification processes of food court waste

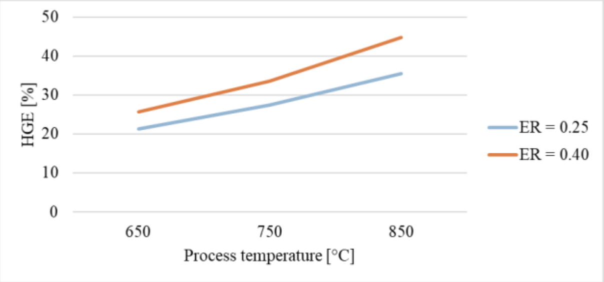


Figure 3.52. Hot-gas efficiencies - air gasification processes of food court waste

Increasing the ER value leads to an increase in CGE and HE values, at the same process temperature by up to about 4 and 9 percentage points. Increasing the process temperature from 650°C to 850°C leads to an increase in CGE and HGE of approximately 5-8 and 14-19 percentage points, respectively. Highest efficiency values are obtained at 850°C and ER of 0.40.

3.2.6. Biomass conversion efficiency and energy efficiencies of air/steam gasification processes of food court waste

Within this subsection the mass balance, the carbon conversion efficiency and the energy efficiencies of the air/steam gasification processes of food court waste at different process temperatures were determined.

Figure 3.53 and Figure 3.54 show the variations in carbon conversion efficiency, calculated in both ways, for food court gasification processes according to the process temperature and the oxidant used.

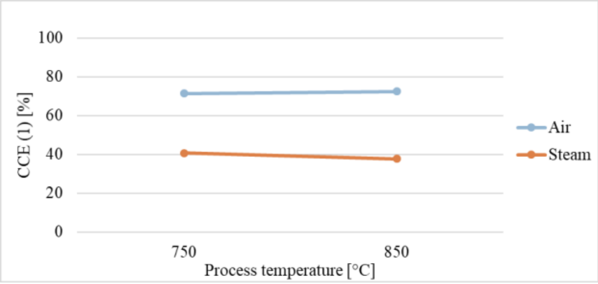


Figure 3.53. Carbon conversion efficiencies (1) – air vs. steam gasification processes of food court waste

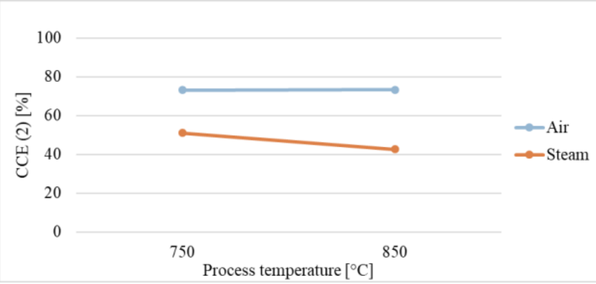


Figure 3.54. Carbon conversion efficiencies (2) – air vs. steam gasification processes of food court waste

Carbon conversion efficiency is greater in the case of air gasification processes of FCW, and increases slightly with temperature rise. CCE records much lower values for steam gasification processes, decreasing with temperature increase within the studied range.

The figures below show the variations in energy efficiencies of air/steam gasification processes of food court waste at different process temperatures. Both CGE and HGE are influenced by the process temperature and the oxidant used. Energy efficiency increases with process temperature increases in both cases, but the values obtained for steam gasification processes are much lower compared to those obtained for air gasification processes within the analyzed temperature range.

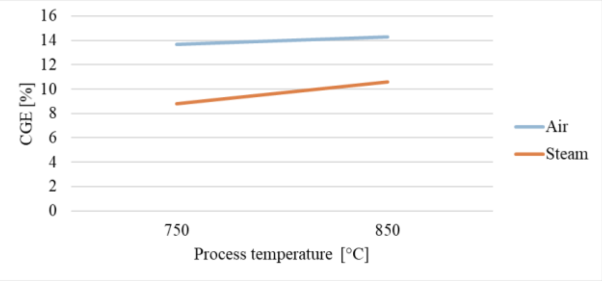


Figure 3.55. Cold-gas efficiencies - air vs. steam gasification processes of food court waste

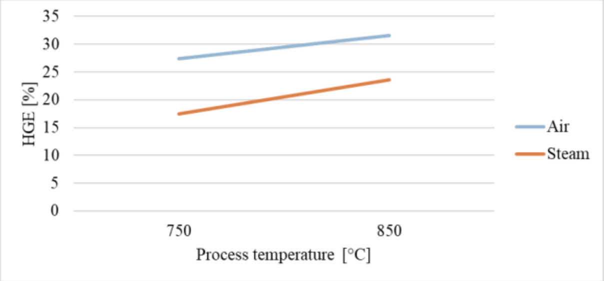


Figure 3.56. Hot-gas efficiencies - air vs. steam gasification processes of food court waste

CGE decreases by approximately 3-5 percentage points and HGE decreases by 8-10 percentage points when steam is used in the process, while the temperature increase by 100°C leads to an increase of CGE and HGE of maximum two, and about 6-8 percentage points, respectively.

3.2.7. Conclusions

In the case of air gasification processes analyzed, gas production exceeds 94%, somewhat expected, given that the main product obtained from gasification processes is gas. Gas production is largely influenced by the process temperature, increasing with temperature rise. At higher process temperatures, the conversion efficiency of solid material into the gas increases. For steam gasification processes, gas production is less than 90% in some cases. This is due to the process duration (residence time). Due to a lower reaction rate of steam with solid carbon in char, compared with the oxygen from air reaction with carbon, the material was converted to a lesser extent, thus resulting in lower gas production. When using steam as an oxidizing agent in gasification processes, the residence time should be increased to ensure the time needed for reactions to take place.

Carbon conversion efficiency was determined using two calculation methods. One method takes into account the amount of gas produced, determined by mass balance. The other calculation method takes into account the amount of gas produced determined by calculation based on the amount of nitrogen introduced into the process and the concentration of nitrogen in the product gas. Depending on the gasification experiment under consideration, better CCE values can be obtained either by applying one method or the other.

Carbon conversion efficiency tends to increase with temperature and air equivalence ratio increase, in the studied cases. Higher process temperatures provide a higher reaction rate and a greater amount of air introduced in the process provides more oxygen available in the reactor for carbon oxidation reactions. The use of steam as an oxidizing agent leads to the decrease of CCE under studied conditions. As mentioned above, for better conversion efficiency in gasification processes, both for conversion efficiency of the feedstock, as well as for carbon conversion efficiency, the use of steam as an oxidant in the process requires a longer duration of the process to improve the results.

The values obtained are small compared to the CGE and HGE values of standard gasification processes, due to the type of experiments performed. As mentioned above, a complete gasification process does not take place in the laboratory reactor used. Thus, the energy efficiencies values are calculated on the basis of intermediate gas compositions, representing the efficiencies of some gasification process stages, not the whole process. However, calculated energy efficiencies values can be used to characterize gasification processes and to observe the influence of process parameters on the gas obtained.

Usually, the difference between CGE and HGE in a typical gasification process is about 10-20 percentage points. If we analyze the results obtained under this subsection, one can observe that the same trend is observed here between the CGE and HGE values.

According to the results obtained for process energy efficiencies, optimum process parameters are:

- Air gasification of poplar wood: temperature 850ºC, ER = 0.30;
- Air gasification of rapeseed straws: temperature 850ºC, ER = 0.30;
- Air gasification of rapeseed straw residues: temperature 850ºC, ER = 0.30:
- Air gasification of rapeseed straws with different moisture content: temperature 850ºC;
- Steam gasification of rapeseed straws: temperature 850ºC;
- Air gasification of food court waste: temperature 850ºC, ER = 0.40;
- Air/steam gasification of food court waste: temperature 850ºC, air as an oxidizing agent.

3.3. BURNING OF FUELS PRODUCED THROUGH GASIFICATION

The main product obtained from the gasification process is, as mentioned in the previous chapters, the synthesis gas. It can be valued energetically by combustion in plants equipped with internal combustion engines or with gas turbines.

As in the case of combustion of solid fuels, a combustion calculation is required to determine the combustion air demand, but also to determine the volumes of combustion gases produced. The calculation of combustion of gaseous fuels is based on the gas fuel composition given in percentage volumes and the stoichiometric reactions of combustible fractions [205].

Combustion process calculation was performed for the following three types of gases: methane gas, Syngas 1 (gas obtained from air gasification of dry poplar wood) and Syngas 2 (gas obtained from air gasification of poplar wood with 30% moisture content).

Table 3.7: Gas compositions

		Methane	Syngas 1	Syngas 2
CO	[%]		25	22.4
CO_2	[%]		20	13.8
CH_4	[%]	100	2	2.8
H_2	[%]		11	16.2
N_2	[%]		42	44.8
LHV	kJ/kg	49896	4022.20	4852.10

From the combustion process calculation for the gaseous fuels presented in the table above, the volume of humid air required for complete combustion and the volumes of flue gases was determined for each fuel.

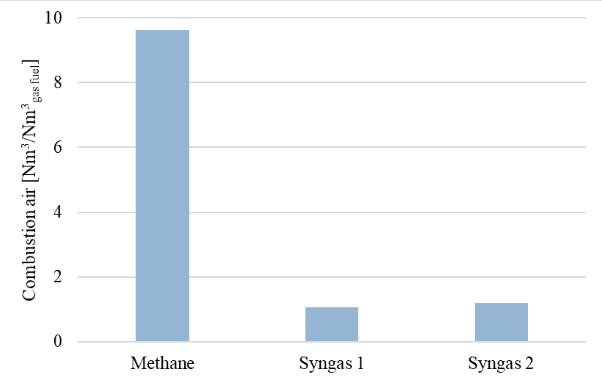


Figure 3.57. Real volume of humid air required for gas fuels combustion

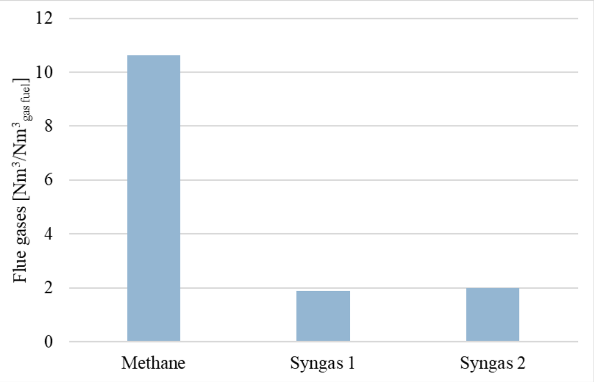


Figure 3.58. Real volume of flue gas from gas fuels combustion

Figure 3.57 shows the volume of humid air required for combustion of the three gaseous fuels. Analyzing the values presented in the graph we can see that in the case of Syngas 1 combustion the air requirement represents only 11% of the humid air requirement for methane combustion, and in the case of Syngas 2 combustion the air requirement represents only 12.45% of the humid air requirement for methane combustion. This is due to the different compositions of the three types of gas. In the two types of syngas compositions, methane (CH_4) is found to be very low, 2 and 2.8%, respectively, and the non-combustible gases are in a proportion of 62 and 58.6%, respectively. With such a high content of non-combustible gases it is expected that the volume of humid air required for complete combustion to be much lower for the syngas compared to methane. Also, the two types of syngas have in their composition carbon monoxide and hydrogen. For the combustion of one volume unit of carbon monoxide or hydrogen, the combustion air demand is four times lower than the combustion air required to burn one volume unit of methane.

Figure 3.58 shows the total real volume of flue gases resulted from the combustion of one volume unit of methane or syngas. After burning one volume unit of Syngas 1 or Syngas 2, the flue gases volume is about 5.50 times smaller compared to methane burning. This was to be expected because the combustion air demand is higher in the case of methane combustion and the mass balance must be respected.

3.4. GASEOUS FUELS CONVERSION IN GAS TURBINES INSTALLATIONS

To produce energy from the syngas, the Solar Mercury 50 heat recovery gas turbine (GT) with a unitary power of 4.6 MW was chosen [207]. The power level has been chosen in correlation with the energy potential specific to a source of wood or agricultural biomass. In general, energy applications that use biomass as fuel (excluding solid waste assimilated to it) are limited by available biomass on site at power levels up to 20MW. Typically, biomass power plants have an installed power of 3 to 10 MW_{el}.

Within this subchapter, the net electricity produced and the consumption of gas compressor were calculated in the case of different gas types uses. Four assumptions are proposed: methane feed at 2 bar, methane feed at 4 bar, feeding with Syngas 1 and feeding with Syngas 2, to observe the turbine behavior under different conditions. The combustion chamber and internal heat recovery efficiencies, the compressor internal efficiency and turbine internal efficiency are considered constant regardless the type of gas used, and their values are presented in the table below, as well as the other calculation assumptions.

Table 3.8: Calculation assumptions

Parameter	U.M.	Methane		Syngas	
				1	2
Gas temperature	ºC	10	10	45	45
Gas pressure	bar	2	4	1	1
Combustion chamber efficiency	%	99	99	99	99
Internal heat recovery efficiency	%	99	99	99	99
Compressor internal efficiency	%	85	85	85	85
Turbine internal efficiency	%	85	85	85	85
Extreme absolute temperature ratio	-	4.83	4.83	4.83	4.83
Internal heat recovery thermal efficiency	%	87.5	87.5	87.5	87.5

The natural gas temperature and pressure have been chosen depending on the plant's site conditions. Thus, appropriate parameters were chosen according to the parameters of the natural gas transportation and distribution network. The syngas temperature and pressure feed are specific to syngas conversion installation (gasification reactor).

For the calculation of the gas turbine installation, it was considered to be supplied with methane gas and the power at the generator terminals is 4600 kW. Thus, the necessary fuel and combustion air flows, as well as the mass flow of flue gases, the net electrical power produced and the gas compressor consumption, were determined.

In order to determine the gas compressor consumption and implicitly the net electrical power produced in the case of syngas gas turbine supply, it is considered that the volume occupied by the flue gases in the combustion chamber is equal to the volume occupied by the flue gases released from natural gas combustion. Thus, the combustion gas flow is first determined, then the efficiencies and the power at the generator terminals are recalculated, in the case of syngas feed.

Figure 3.59 shows the input and output mass flows into and from the gas turbine installation in the four cases studied. The input mass flows are represented by the fuel and combustion air flows, and the output flow is represented by the flue gas flow. The methane gas flow rate is 0.24 kg/s, but the syngas flow is up to about 13 times. This is due to the low calorific value of the syngas, compared to natural gas. In order to ensure the same thermal power inside the combustion chamber, it is necessary to increase the fuel flow rate.

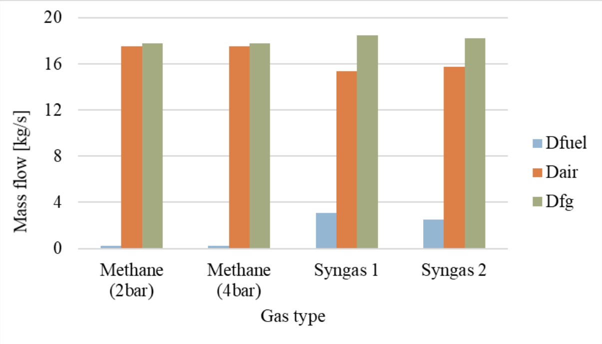


Figure 3.59. Mass flows in/out GT

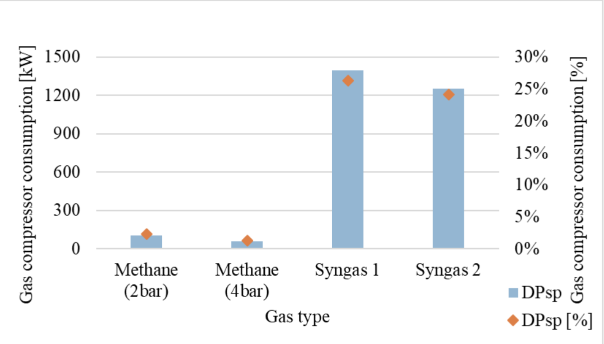


Figure 3.60. Gas compressor consumption

The demand for combustion air is lower in the case of syngas combustion, since it has in its composition non-combustible elements in quite large proportions. The air flow rate in syngas GT-fueled represents approximately 87-90% of the airflow required for a methane-fueled plant. Because of the much higher fuel requirement, in the case of a syngas-fed GT, compared to methane-fueled GT, the flue gas flow is higher. This is 18.48 kg/s if the plant is powered by Syngas 1 and 18.22 kg/s if the plant is powered by Syngas 2 compared to methane-fueled plants whose flue gas flow is 17.78 kg/s.

Figure 3.60 shows the gas compressor consumption in the four studied cases. The gas compressor consumption is reduced by approximately 40% in the case of methane supply at 4 bar compared to the first case analyzed - methane 2 bar. However, when using methane gas, the gas compressor consumption is very low, resulting in very good net efficiencies. In the case of syngas turbine supply due to the high fuel flow, the gas compressor consumption is very high, 1397 and 1255 kW, respectively. Since much of the energy generated by the generator is lost with the gas compressor supply, the net electricity produced and, implicitly, the net plant efficiency are lower in the case of syngas use compared to the use of methane gas.

When the turbine is supplied with methane at 2 bar and methane at 4 bar, the compressor consumption represents 2.34% and 1.35%, respectively, of the power at the generator terminals. In the case of the plant supplied with Syngas 1 and Syngas 2, the compressor consumption represents 26.36% and 24.21%, respectively, of the power at the generator terminals. In conclusion, the use of syngas in GT increases the consumption of the compressor by over 20 percentage points compared to the use of natural gas. This is due to the higher syngas flows required.

Figure 3.61 shows gross and net GT efficiencies using different gaseous fuels. Efficiencies were calculated both with respect to (η_{gross} and η_{net}), and without taking into account the physical heat of the fuel (η_{gross}^* and η_{net}^*). In the case of methane gas, it can be noticed that irrespective of fuel feed pressure, the gross efficiency is 38.5%. Net efficiency is lower, 37.6% and 37.98% respectively, when methane supply pressure is 2 bar and 4 bar respectively. For Syngas 1 and Syngas 2, the gross efficiency is 38.43% and 38.63%, respectively, and the net efficiency decreases considerably to 28.30% and 29.29%, respectively.

There is a close link between net efficiency and gas compressor consumption. Thus, the higher the consumption of the gas compressor, the net output of the plant will decrease. At the same time, as the fuel flow increases, the compressor consumption increases and the net efficiency decreases.

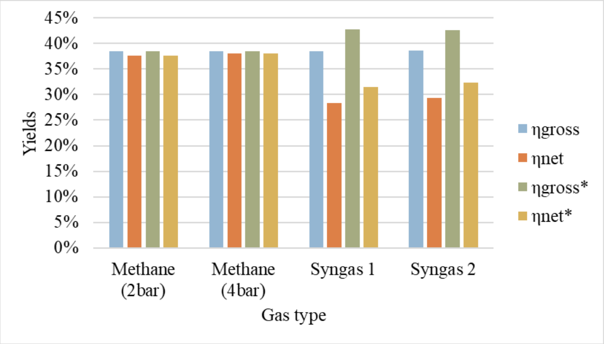


Figure 3.61. Gross and net efficiencies

If the physical heat of the fuel is not taken into account, we note that the recalculated installation efficiencies do not change when using methane. However, when using a syngas fuel, efficiency increase. Thus, for Syngas 1, the gross efficiency is 42.70% and the net efficiency is 31.45%, increasing by more than 4 and 3 percentage points, respectively. In the case of Syngas 2, both gross and net efficiencies increase by about 10% if the physical heat of the fuel is not taken into account in their calculation. Also, from the figure above it can be noticed that in the case of Syngas 2 higher electric efficiencies are obtained, compared with the use of Syngas 1 in GT.

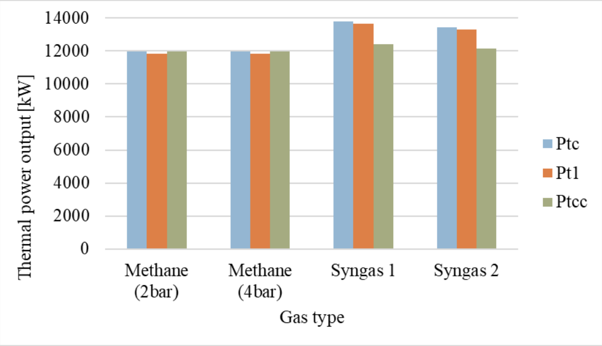


Figure 3.62. Thermal power output in GT installation

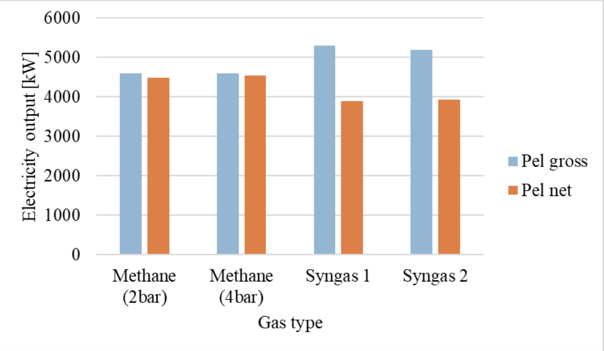


Figure 3.63. Electrical power output in GT installation

Figure 3.62 shows the thermal power released by combustion of fuel at combustion chamber (P_{tc}), the thermal power received by the cycle from the combustion chamber (P_{t1}) and the chemical heat of the fuel (P_{tcc}) in the four studied cases. In the case of methane supply of GT, it can be seen that the three calculated thermal powers have close values, around 11900 kW. The thermal power developed by fuel burning in the combustion chamber is equal to the chemical heat of the fuel, which means that in this case the physical heat of the fuel is negligible. When using syngas in the gas turbine power plant, there is a notable difference between P_{tc} and P_{tcc}, which means that in the case of syngas feed of GT, the physical heat of the fuel is not negligible. Also, the thermal power developed by burning fuel in the combustion chamber is higher when using syngas as fuel compared to the use of methane gas.

Figure 3.63 shows the power at the generator terminals ($P_{el\ gross}$) and the net electrical power ($P_{el\ net}$) produced in the GT in the four studied cases. In case of syngas use in the gas turbine system, the power at the generator terminals is higher than in the case of methane gas use, but the net electrical power is lower. This is due to the high energy consumption of the gas compressor when using syngas as a fuel.

In the case of Syngas 2, the power at the generator's terminals is slightly lower than in the case of Syngas 1 (5183 kW versus 5299 kW), but the net electricity output is higher (3928 kW versus 3902 kW). This is due to the lower consumption of the gas compressor in the case of the gas turbine unit supply with Syngas 2 (Figure 3.59).

3.5. GASIFICATION CONVERSION SOLUTION FOR SMALL POWER INSTALLATIONS

In order to determine what is the optimal solution for biomass to electricity conversion, a number of factors need to be taken into account, including biomass requirements, fuel transportation from source to point of consumption, and energy consumed in the preparation/pre-treatment biomass processing.

When using Syngas 1, synthesis gas obtained from air gasification process of dried poplar wood, net power output is 3902 kW. The biomass feed rate in this case is 3.0852 kg/s. In the case of Syngas 2 (gas obtained from air gasification process of wet poplar wood) use in the gas turbine installation, the electrical power output is 3928 kW at a biomass feed rate of 2.5056 kg/s. Thus, to produce about 3.9MW of net electricity, woody biomass consumption decreases by about 20% if Syngas 2 is used.

Wet biomass flow rate required for Syngas 2 production is slightly lower than the dry biomass flow required to obtain Syngas 1. However, it should be borne in mind that in order to obtain Syngas 1, poplar must be dried beforehand. Thus, in order to obtain the required flow of Syngas 1, the wood biomass demand is 1.98 kg/s, 46% higher than the biomass flow required for Syngas 2.

Net power produced in GT when using Syngas 2 is slightly higher than in the case of Syngas 1. Syngas 1 gas production involves the drying of biomass (additional energy consumption), since all biomass sources have a certain moisture content, no matter where and when it is collected. Therefore, the optimal solution for electricity production from biomass through gasification is the gasification of wet poplar wood and to valuable the gas in a gas turbine.

CHAPTER IV

4. BIOMASS VALORISATION BY COMBUSTION IN ST TERMODYNAMIC CYCLES

4.1. BIOMASS COMBUSTION

In order to determine the combustion process components (combustion air volume and flue gas volumes), it is necessary to know the chemical composition in percentage by weight of analyzed fuel (4.1) [14, 210].

$$C^i + H^i + O^i + N^i + S_c^i + A^i + W_t^i = 100\% \tag{4.1}$$

In Chapter III two types of syngas were used, both obtained by gasification of poplar wood. The raw materials for obtaining the syngas were dry poplar wood and poplar wood with 30% moisture content. In this chapter the electricity produced by the use of the two types of wood in steam turbine installations will be determined.

In order to determine the amount of air needed for complete combustion as well as the flue gas volumes released from poplar wood burning, account is taken of its gravimetric chemical composition and the reactions of solid fuel combustion process. The results of the combustion process calculation of poplar wood, both dried and with 30% moisture content are presented in the following.

Figure 4.1 and Figure 4.2 show carbon dioxide, water vapors and nitrogen volumes and masses released from one mass unit of biomass (poplar wood) combustion. It is noted that both volumetric and mass, the quantities of carbon dioxide and nitrogen released from combustion of one mass unit of dry poplar are higher. However, in the case of poplar wood with 30% moisture content combustion, the volume of water vapor released is over 10 times higher compared to the volume of water vapor released from combustion of dry wood.

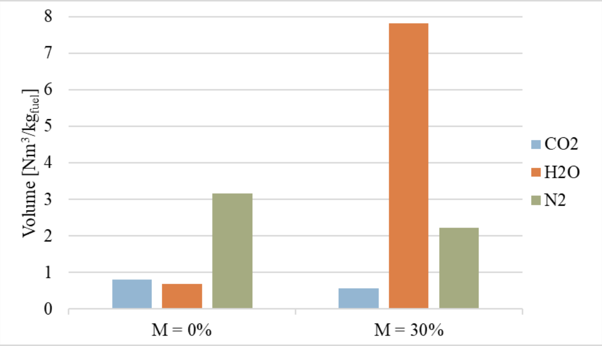


Figure 4.1. Flue gas volumes - poplar wood combustion

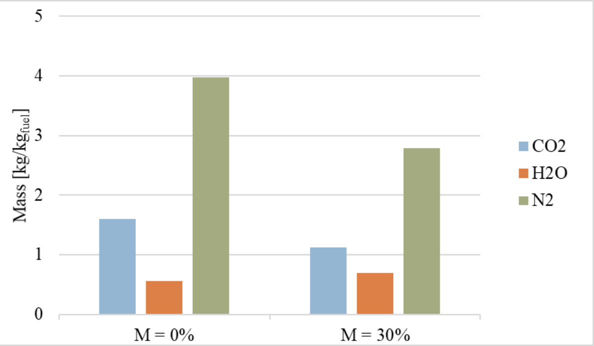


Figure 4.2. Flue gas masses - poplar wood combustion

Figure 4.3 and Figure 4.4 show the total flue gases volume and mass released from combustion of one mass unit of dry poplar versus poplar with 30% moisture content.

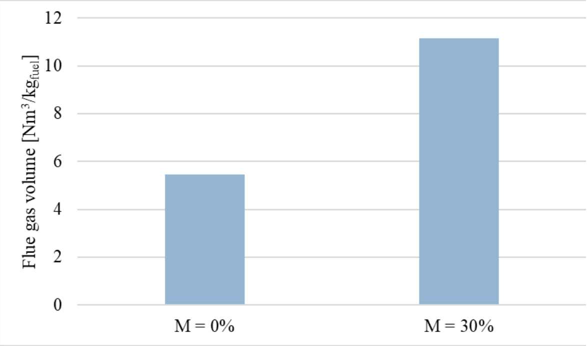


Figure 4.3. Total flue gas volume - poplar wood combustion

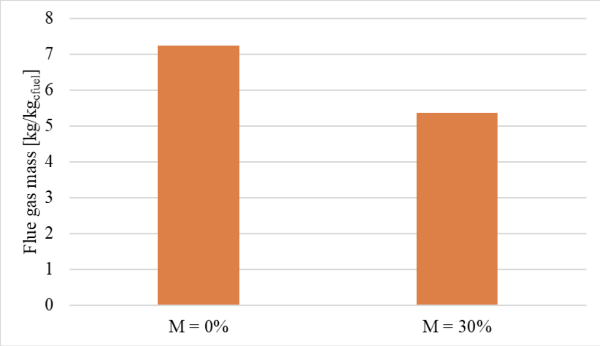


Figure 4.4. Total flue gas mass - poplar wood combustion

From the two graphs it can be noticed that the flue gas volume is lower and the flue gas mass is higher in the case of dry poplar wood combustion, compared to combustion of poplar wood with 30% moisture content. This is due to the high content of water vapor in the flue gases released from wet fuel combustion.

4.2. COMPUTATION OF THERMO-MECHANIC SCHEMA

The energy utilization of wood biomass using combustion as the thermal-chemical conversion process takes place in steam turbine installations (ST) operating after the Rankine cycle. The basic scheme of such an installation includes: boiler or steam generator, steam turbine, electric generator, condenser and feed pump. Biomass is burned in a boiler - a combustion reactor. The heat produced by biomass combustion turns water into steam, which is then expanded in the turbine, producing mechanical work. The electric generator has the role of converting mechanical energy into electricity, and the condenser provides condensation of steam from the steam turbine. To increase the performance of such an installation, one more regenerative preheater are added to the initial scheme. Their purpose is to preheat the supply water.

Depending on biomass source availability and type the calculation of the thermo-mechanic circuit takes into account, among other things, the source flow and its physicochemical properties. Thus, the electrical power produced by burning the available biomass can be determined. Available biomass considered is: 1.39 kg/s dry poplar wood and 1.36 kg/s, wet poplar wood. These dry or wet wood flows are need to produce Syngas 1 and Syngas 2, respectively. To determine the optimum biomass-power conversion solution, in this chapter was determined the electrical power produced in a steam turbine installation, taking into account the amount of available biomass and its properties. Thus, two biomass - gasification - GTI and biomass - combustion - STI conversion chains can be compared from the electricity production as a function of available biomass point of view.

Calculation of the thermo-mechanical circuit involves calculation of condenser pressure, determination of mass and energy balances on each equipment, as well as turbine steam expansion, and the determination of overall efficiency.

The chosen steam turbine model is Siemens SST-060, the turbine catalog technical specifications being presented in Table 4.1.

Table 4.1: Steam turbine technical specifications [211]

Parameter	U.M.	Value
Power output	MW	≤ 6
Speed	rpm	10500 ÷ 23000
Main steam parameters: - Temperature - Pressure	 ºC bar	 ≤ 530 ≤ 131
Exhaust steam parameters: - Condensing - Back-pressure	 bar	 vacuum ≤ 29

In order to initiate the calculation and to determine the electricity produced from two types of wood presented above as primary energy source, the main steam parameters were selected as follows: temperature (t_0) 520ºC and pressure (p_0) 100 bar. The average annual temperature of cold water was 14°C, and the cooling water temperature increase in condenser (Δt_{cd}) was of 9°C. The minimum temperature difference in the condenser ($\delta t_{min\ cd}$) was chosen from the load curve, 4.5°C, resulting a condensation temperature (t_{cd}) of 27.5°C. The condensation pressure (p_{cd}) was determined from water/steam thermodynamic properties tables based on the steam saturation temperature at the condenser (p_{cd} (t_{cd})). Table 4.2 presents the initial data considered for initiation of the thermo-mechanic schema calculation.

Table 4.2: Input data

Variable/Parameter	Notation	U.M.	Dry poplar	Wet poplar
Main steam parameters: - Pressure - Temperature	 p_0 t_0	 bar ºC	 100 520	
Cooling water temperature (annual average)	$t_{râu}$	ºC	14	
Cooling water heating in the condenser	Δt_{cd}	ºC	9	
Minimum temperature difference in the condenser	$\delta t_{min\ cd}$	ºC	4.5	
Condenser parameters - Pressure - Temperature	 p_{cd} t_{cd}	 bar ºC	 0.03674 27.50	
Thermal power released by fuel combustion in the combustion chamber	P_{tc}	kW	22381	14295
Boiler efficiency	η_{GA}	%	85	
Number of preheating stages	z	-	6	

As mentioned above, the first step in computation the thermo-mechanic schema is the choice of condenser pressure. The next step is to achieve the thermal circuit scheme that involves choosing the position of the degasser in the regenerative preheating line and determining the water parameters at the preheaters and the steam pressures at equipment and steam outlets. Modeling of steam expansion in the turbine involves calculating the average pressure pipe modeling between the steam generator and the steam turbine, and the high-medium (intermediate) pressure (HIP) and low pressure (LP) stage processes. Calculation of the thermo-mechanic schema also involves the calculation of the specific mechanical work and the representation of the steam turbine process in the enthalpy-entropy (h-s) diagram. After the calculation of the thermo-mechanic schema, the performance indicators of the steam turbine installation are also determined. Thermo-mechanic schema diagram is shown in Figure 4.7.

Figure 4.5 shows the thermal power released by wood combustion in the steam generator, the thermal input entered into the conversion cycle, the internal power developed in the steam turbine, the mechanical power at the turbine coupling, the power at the generator terminals and the semi-net electrical power, determined for the two materials used, dry poplar and wet poplar. When the wet material is used, there is a decrease in the plant power output. This is due to the wet fuel lower quality (LHV of 10.54 MJ/kg versus 16.13 MJ/kg for dry wood), as the fuel flow is approximately equal, 1.36 kg/s of wet wood and 1.39 kg/s of dry wood.

According to the results obtained, a 30% moisture content of the material leads to a decrease of about 36% of the thermal power released by fuel combustion and to a decrease by about 40% of the semi-net electrical power output. The semi-net electrical power produced from dry poplar wood is about 7 MW, and in the case of wet poplar wood is about 4.2 MW.

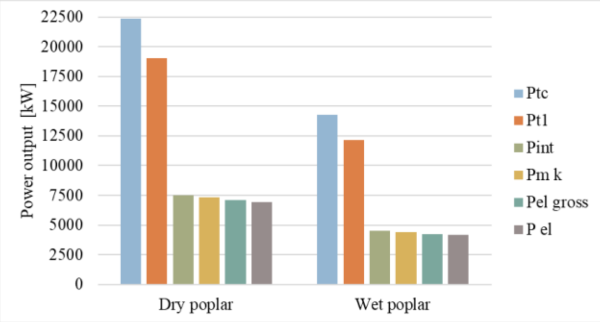


Figure 4.5. Power outputs in the STI

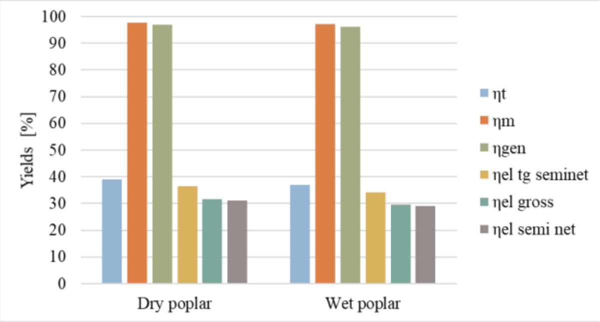
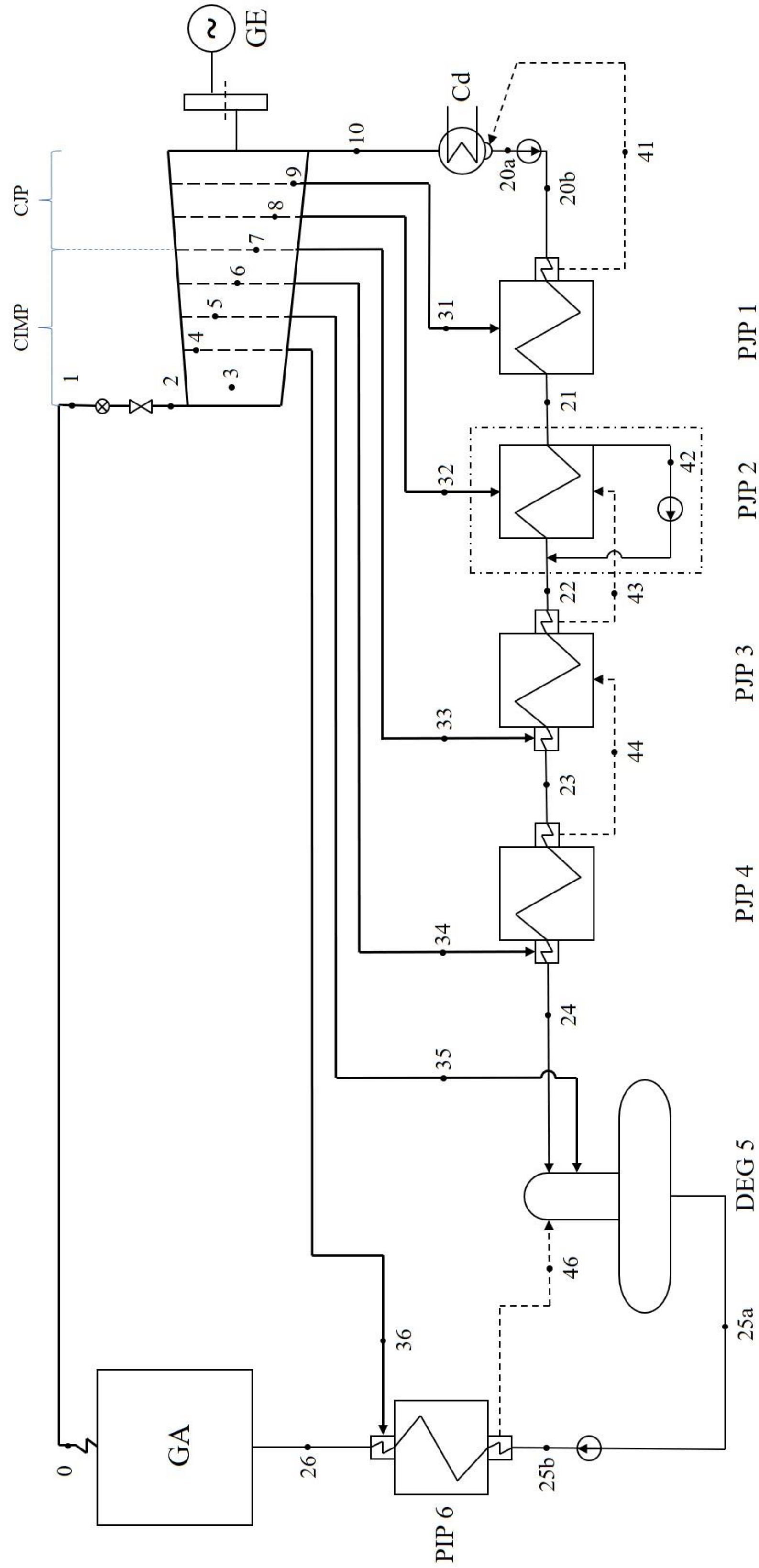


Figure 4.6. Efficiencies of STI

Figure 4.6 shows the thermal cycle efficiency, mechanical efficiency, generator efficiency, semi-net turbo-generator group efficiency, gross electrical efficiency and semi-net electrical efficiency, depending on the biomass type the plant is fed to. It can be seen from the graph that the mechanical efficiency and generator efficiency are not strongly influenced by the moisture content of the sample. However, the thermal cycle efficiency, semi-net turbo-generator group efficiency, gross electrical efficiency and semi-net electrical efficiency, decrease by about two percentage points, in case of a moisture content of 30% of the sample.



GA – *steam generator*; CIMP/CIP – *high-medium/low pressure stage processes*; GE – *generator*; Cd – *condenser*; PJP – *low pressure preheaters*; DEG – *thermal degasser*; PIP – *high pressure preheater*.

Figure 4.7. Diagram of the thermo-mechanic schema

4.3. FUEL QUALITY INFLUENCE ON ENERGY CONVERSION SYSTEM

Moisture content has a major impact on fuel quality, much of fuels energy being consumed for drying. In order to determine the influence of fuel quality on the energy conversion system, the initial biomass flow (with a moisture content of 30%) of 1.98 kg/s was considered. This represents wet biomass (with a moisture content of 30%) needed to obtain 1.39 kg/s of dry poplar wood required to supply the gasification reactor to produce Syngas 1. For this biomass flow (1.98 kg/s) the semi-net electrical power output in the steam turbine installation shown in the previous subchapter was determined. The results are compared with the results obtained for ST fed with 1.39 kg/s dry poplar wood, which represents the dry mass of the same amount of raw biomass.

The same input parameters were considered for the calculation (Table 4.2), but the thermal output released by fuel combustion is in this case 20868 kW.

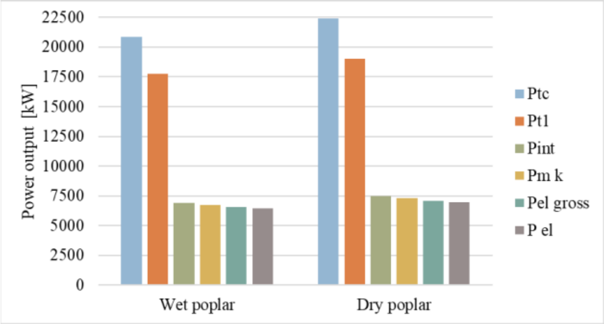


Figure 4.8. Power outputs in the STI

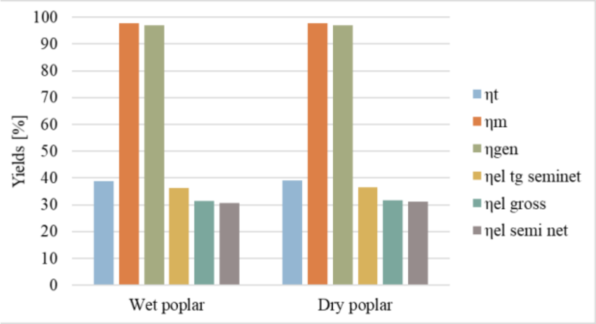


Figure 4.9. Efficiencies of STI

From figures above, it can be seen that the use of wet wood (30% moisture content), compared to the use of dry mass of the initial quantity available, in steam turbine installations, leads to a slight decrease in the power produced by the plant. The semi-net electrical power output is lower by about 500 kW.

4.4. CONVERSION SOLUTION FOR SMALL POWER INSTALLATIONS

In this chapter the semi-net power output in a steam turbine system equipped with the Siemens SST-060 steam turbine was determined. Electric power produced was calculated according to three biomass flows:

- The demand of dry biomass (1.39 kg/s) to produce the Syngas 1 flow required to supply the GT;
- The demand of wet biomass (1.36 kg/s) to produce the Syngas 2 flow required to supply the GT;
- The demand of wet biomass (1.98 kg/s) to ensure a dry biomass flow of 1.39 kg/s.

Biomass considered was poplar wood whose lower calorific value is 16128 kJ/kg (dry material). When using dry biomass in the steam turbine plant, semi-net electricity output is 6953 kW, and the semi-net electrical efficiency is 31.07%. When using a wet poplar wood flow of 1.36 kg/s, the semi-net electricity output is 4163 kW, the efficiency of the plant being in this case 29.12%. In the third case, the wet biomass flow rate of 1.98kg/s (dry mass = 1.39 kg/s) efficiencies in the STI a 6547 kW semi-net electric power output and an electrical efficiency of the plant of 30.80%.

According to the results obtained, the most advantageous solution would be the use of 1.98 kg/s wet biomass flow in the STI for electricity production. Although the best results are obtained when using dry biomass, this solution involves the complete drying of the biomass, which implies additional energy consumption, that can exceed 500 kW.

CHAPTER V
5. COMPARATIVE STUDY ON POLLUTION EMISSIONS FOR BIOMASS TO ENERGY CONVERSION SYSTEM

5.1. IDENTIFYING AND ESTIMATING THE POTENTIAL POLLUTANTS

Biomass combustion has an environmental impact due to atmospheric emissions. Depending on the type of emission, its influence may be local - particulate incomplete combustion emissions, regional emissions - NO_x and SO_2 emissions or other emissions that cause acid precipitation, or global emissions - greenhouse gas emissions or emissions that have the effect of depleting the ozone layer [70].

The synthesis gas from the gasification reactor contains various contaminants, such as particles, tar, sulfur or chlorine compounds, which must be removed from the gas stream for it further use either as chemical feedstock or alternative fuel [17, 71].

Due to the contaminants present in the synthesis gas and the impossibility to use the gas as it exits the reactor, the gasification reactor and the gas cleaning installations are usually considered as an integrated system [68]. Figure 5.1 presents schematically the biomass-power conversion chain using gasification as the thermo-chemical conversion process. Thus, by analyzing the scheme below, the pollutants present in the syngas at it exits from the gasification reactor can be observed: tar, ash or solid particles of large size, sulfur or chlorine derived compounds and fine particles. For each type of pollutant it is necessary to apply another method of retention.

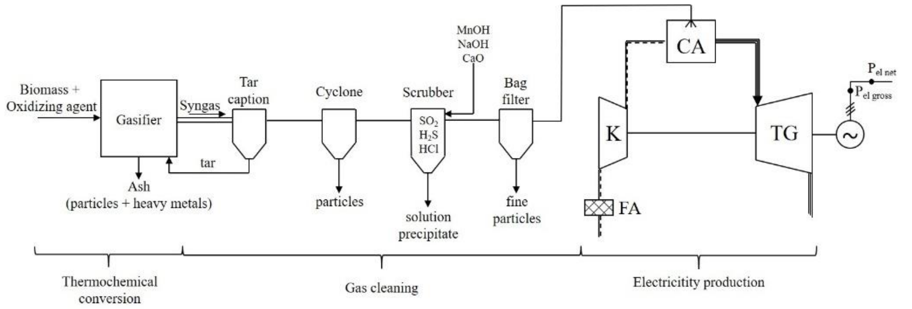


Figure 5.1. Biomass to energy conversion chain via gasification

K – *compressor*; CA – *combustion chamber*; TG – *gas turbine*; FA – *air filter*; TA – *steam turbine*; PA – *feedwater pump*; GE – *generator*.

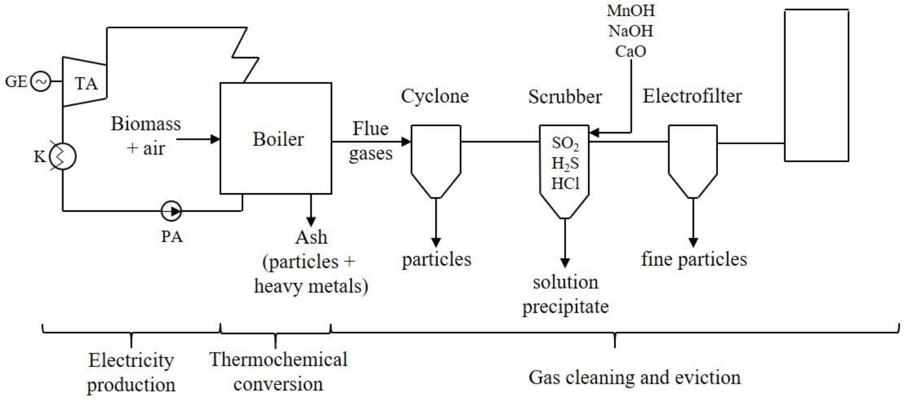


Figure 5.2. Biomass to energy conversion chain via combustion

Figure 5.2 shows the biomass-to-energy conversion chain via combustion, and the emission reduction measures applied.

By comparing the figure above with Figure 5.1 we can see that some of the installations used for synthesis gas cleaning (cyclone filter, scrubber, electro filter/sack filter) are also used to reduce emissions from biomass combustion [16]. The combustion process differs from that of gasification by the total oxidation of the combustible elements contained in the converted material. Which means that in the flue gas stream we should not encounter tar or other combustible elements. For this reason, flue-gas cleaning installations do not include tar-cleaning/removal equipment in the gas stream.

5.2. POLLUTANTS CONCENTRATIONS IN PROCESS FLOWS

As stated in the previous chapters, there are a number of factors that influence biomass conversion. Thus, depending on the biomass type and it features, the conversion plant type, the process parameters etc., the pollutants concentrations in the process streams differ widely. Thus, depending on the biomass properties, an optimal conversion system can be chosen, coupled with optimal process parameters, in order to minimize the pollutant emissions.

5.3. EMISSION FACTORS

The emission factor is a criterion for comparison fuels or energy units in terms of pollutant emissions.

By definition, the emission factor is the ratio between the amount of pollutants emitted and the amount of energy produced. It can also be expressed as the ratio of the noxious flow to the produced power [217].

Taking into account that neither solid nor gaseous fuels studied in this paper does not contain Sulphur or Chlorine, sulfur or chlorine compounds will not occur in the gas stream (syngas or flue gas), therefore only the carbon dioxide emission factor can be computed.

Figure 5.3 shows the carbon dioxide emission factors reported to primary energy of the studied gaseous fuels. According to the results presented in the graph there is a correlation between the calorific value of the gas and the emission factor. Thus, as the calorific value of the gas increases, the CO_2 emission factor decreases. The CO_2 emission factor reported to primary energy of Syngas 1, the gas with the lowest LHV, is nearly six times higher than the methane emission factor.

Due to the source from which the analyzed synthesis gas (wood biomass) was produced, CO_2 emissions from syngas combustion are not considered as a source of pollution. Biomass is considered carbon neutral, as it is believed to have absorbed the amount of carbon dioxide from the atmosphere during the growth is equivalent to the amount released by combustion.

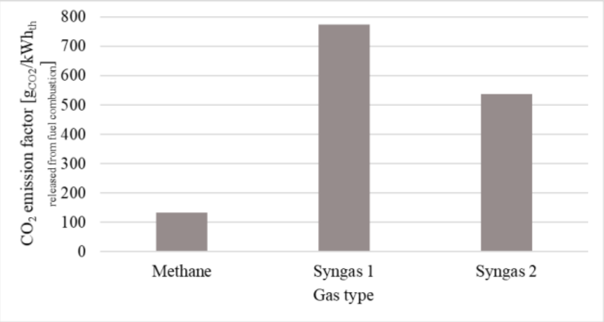


Figure 5.3. CO_2 emission factors reported to primary energy – gas fuels

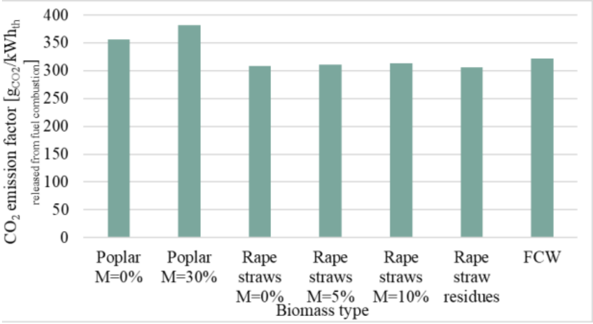


Figure 5.4. CO_2 emission factors reported to primary energy – solid fuels

Figure 5.4 shows the carbon dioxide emission factors reported to primary energy for all solid fuels studied in this paper. As mentioned above, primary emission factors are a feature of the fuel, thus fuels can be compared to each other in terms of emissions.

Analyzing the results presented in the graph we can see that in the case of poplar wood the increase of the moisture content from 0 to 30% has a negative influence on the carbon dioxide emissions. The CO_2 emission factor reported to primary energy for poplar increases by more than 7% with the increase of fuel moisture content by 30%. In the case of rape straws, the carbon dioxide emission factor reported to primary energy increases by about 1% and 2% respectively, with straws moisture content increase by 5% and 10%, respectively, compared to dry material. The carbon dioxide emission factor for rapeseed straw residues is roughly equal to that of dried rape straws. This was to be expected, since the two materials are the same part of the rapeseed plant, only the harvesting method was different. The CO_2 emission factor reported to primary energy for food court waste is lower than that of the wood but slightly higher than that of the agricultural waste.

Among the analyzed fuels, both solid and gaseous, the smallest CO_2 emission factor is that of natural gas. The highest carbon dioxide emissions are recorded for syngas fuels.

Figure 5.5 shows the carbon dioxide emission factors reported to net energy for the four gas turbines analyzed.

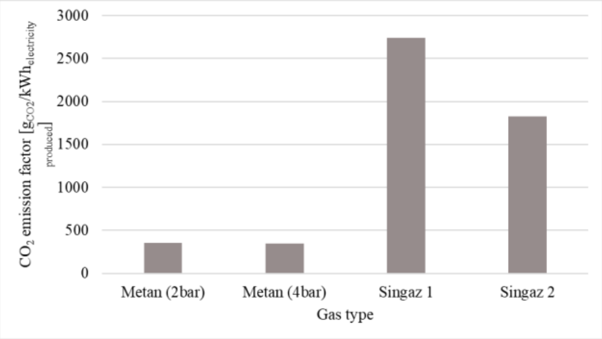


Figure 5.5. CO_2 emission factors reported to net energy output – GT installations

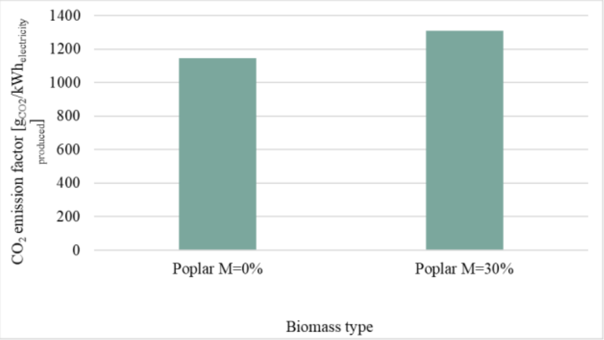


Figure 5.6. CO_2 emission factors reported to net energy output – ST plant

For methane-fueled plants, CO_2 emission factors are approximately equal (about 350 $g_{CO2}/kWh_{electricity\ produced.}$) and considerably lower compared to the emission factors of syngas powered GTs. For Syngas 1 and Syngas 2, the emission factor is approximately 8 and 5 times higher compared to methane combustion in the gas turbine installation. However, as mentioned earlier, syngas is considered CO_2 neutral, this factor being calculated for purely informative purposes.

Figure 5.6 shows carbon dioxide emission factors reported to net energy for dry and 30% moisture content poplar wood supplied in the steam turbine installation. From the graph above, it can be seen that in the case of wet poplar wood, the CO_2 emission factor is higher by about 14% compared to the CO_2 emission factor for the ST fed with dry poplar wood. This is due to the lower quality of wet fuel compared to dry fuel. Part of the energy produced by wood burning is consumed to dry it.

5.4. BIOMASS TO OPTIMAL ENERGY CONVERSION SOLUTION

Following the comparison of the two biomass-fueled STs with the two syngas powered GTs, it can be seen that the lowest CO_2 emission factor reported to net energy is obtained in the case of dry biomass-fired STs. The use of gas turbine installations for electricity production involves higher carbon dioxide emissions compared to biomass direct combustion. Thus, from the point of view of carbon dioxide emissions, the optimal solution for electricity producing from biomass is the combustion of dry biomass in a steam turbine installation.

CAPITOLUL VI
6. CONCLUSIONS AND RESEARCH PERSPECTIVES

6.1. GENERAL CONCLUSIONS

The mankind's dependence on electricity has to be correlated with the importance of pollution reduction to maintain optimal living conditions on Earth. The solution to meet the previously exposed is to abandon fossil fuel power plants and to use clean energy sources, such as biomass, which has a very important global energy potential through the variety of forms it can be found.

In Romania the most important biomass sources are vegetal residues from agriculture and forestry products, which account for about 80% of the annual energy potential of biomass sources. The annual energy potential of forest products amounts to 115,200 TJ/year, while the vegetal waste from agriculture amounts to 850,000 TJ/year. To optimize these resources and maximize power generation in Rankine-Hirn or Brayton thermodynamic cycles, all variables that affect conversion processes and their effect on the reaction products must be studied in detail. Current combustion and biomass gasification plants are based on solid fuel conversion technologies. Only one type of combustion/gasification system cannot be developed at any scale, there is a power range characteristic of each plant type.

By analysis of the experimental results, the optimum process parameters for each material and the influence of the process parameters on the quality of the primary gas product were determined. For poplar wood, the concentrations of carbon monoxide and hydrogen in the product gas maximize at ER = 0.30 and the process temperature of 850°C. The quality of the produced gas is largely influenced by the type of oxidizing agent, thus the optimal process parameters for the rapeseed straws are steam as oxidant (SBR 0.416:1) and the process temperature of 850°C. In the case of the food court waste, two sets of optimal process parameters were obtained: if maximizing the production of carbon monoxide in the gas produced is desired, the optimal parameters are air gasifying agent, ER = 0.25 and a process temperature of 850°C; if maximizing the hydrogen concentration in the gas produced is desired, the optimal parameters are: steam as gasifying agent (SBR = 0.634:1) and a process temperature of 850°C. Primary gas obtained from the rape straw gasification process (transitory regime) at 850°C shows the best properties, with the maximum instantaneous CO and H_2 concentrations recorded being 12.90% and above 10%, respectively. The increase in the process temperature has a positive influence on the formation of the gaseous species, regardless of the material used, but the amount of oxidant introduced into the process has to be optimized, since its over increase leads to the increase of the carbon dioxide content in the produced gas.

For batch gasification experiments, conversion efficiencies and energy efficiencies were also calculated. The experiments performed do not simulate a complete gasification process, so the values of carbon conversion efficiency, cold-gas efficiency and hot-gas efficiency obtained, do not reflect the actual values of a real gasification process. However, the values obtained help to characterize the processes, to determine optimal process parameters and to observe the influence of process parameters. The highest carbon conversion efficiency was obtained for the air-gasification process of dry rape straws, ER = 0.30 and 850°C, this being 98.20/89.53% depending on the calculation method chosen to determine the amount of gas produced. The highest value of the cold-gas efficiency (21.35%) was obtained for the air gasification process of food court waste at ER = 0.40 and 850°C. The highest value of hot-gas efficiency (45.20%) was obtained for the air gasification of rape straws at ER = 0.30 and 850°C. The use of steam as an oxidizing agent has a negative effect on process efficiency as it is less reactive than air (oxygen). To increase the efficiency of steam gasification processes, the residence time needs to be increased compared to air-gasification processes.

In order to observe the effects of the syngas use in gas turbine installations on its performance, two types of syngas (Syngas 1 and Syngas 2) were chosen. Syngas 1 (obtained from air gasification of dry poplar wood) has a calorific value of 4022.20 kJ/kg, and Syngas 2 (obtained from air gasification of wet poplar wood M = 30%) has a calorific value of 4852.10 kJ/kg. Both gases have considerably lower calorific values than natural gas. The use of syngas in GT, compared to methane, leads to increased fuel consumption and, implicitly, gas compressor consumption up to 13 times. The increase in gas compressor consumption is felt by lowering the net electricity efficiency by up to 25% and the net power output by 14%. In the case of Syngas 1 use in GT, the net electricity efficiency is 28.30% and the net electrical power output is 3902 kW. When using Syngas 2, the net electricity efficiency is 29.29%, and the electric power produced slightly increases to 3928 kW. The use of syngas to produce electricity in the gas turbine system has a negative effect on its performance and electricity production compared to the use of methane gas. However, syngas has the advantage of being a non-polluting source of energy because it was produced as a result of biomass gasification. The optimal solution for power supply is Syngas 2, as the production of energy is higher and the gas is obtained from the process of gasification of wet poplar wood, so it is not necessary to consume additional energy for biomass drying.

The biomass used to produce Syngas 1 (1.39 kg/s of dry poplar wood) and Syngas 2 (1.36 kg/s of wet poplar wood, M = 30%) can be used in steam turbine installations to produce energy. Thermal circuit scheme is provided with six regenerative preheating stages to optimize the process and increase the plant efficiency. The six stages of regenerative preheating are as follows: four low pressure preheaters, a thermal degasser and a high pressure preheater. In order to determine the electric power produced in STI depending on the amount of biomass available, the thermo-mechanical circuit calculation was performed. Thus, the semi-net electrical power output in the STI powered by dry poplar is 6953 kW, the semi-net electrical efficiency being 31.07%. In the case of STI supplied with wet poplar wood, the semi-net power output is 4163 kW and the semi-net electric efficiency is 29.12%.

In order to observe the influence of fuel quality on the plant performances, the electrical power produced in STI supplied with 1.98 kg/s of poplar wood with 30% moisture content was also estimated (this represents the required biomass to obtain 1.39 kg/s poplar dry wood). The net electrical power output in STI in this case was 6428 kW, at a semi-net electrical efficiency of the installation of 30.80%. Thus, the drying of biomass leads to an increase of the electricity production by only 525 kW and to an increase of the efficiency by 0.27 percentage points. These increases in power and efficiency are insignificant compared to the energy consumption needed to dry biomass.

Even though biomass is considered a renewable energy source, a non-polluting source, through its thermo-chemical conversion, pollutants occur in process streams. The types of pollutants present in the two studied processes, combustion and gasification, have been identified, and the gas cleaning technologies for each process are presented.

Even though the electricity production solutions proposed in this paper are considered carbon neutral, this does not mean that CO_2 emission should not be considered. Thus, the carbon dioxide emission factors reported for primary energy, for each type of fuel studied, and the carbon dioxide emission factors reported for the useful energy for each electricity generation plant presented were calculated. Regarding the fuels studied, the lowest carbon dioxide emissions are recorded for rapeseed straw residues (306.00 g_{CO2} / $kWh_{th\ released\ by\ fuel\ comb}$), the highest emissions being for Syngas 1 (774.87 g_{CO2} / $kWh_{th\ released\ by\ fuel\ comb}$). The emission factor relative to the useful energy for gas turbines powered by syngas is approximately double compared to solid biomass-fired STI. The lowest CO_2 emissions are recorded for ST fueled with dry poplar wood, 1146.77 $g_{CO2}/kWh_{electricity\ production}$.

6.2. PERSONAL CONTRIBUTIONS

The bibliographic study consisted in an analysis of all variables that influence the conversion processes, their effects on process and reaction products, and a detailed comparative analysis of the types of existing biomass gasification reactors.

Regarding the experimental study is concerned, this paper give a particular importance to the study of the transitory regimes of the gasification processes. With the help of these, the stages of the gasification process can be delimited in time, so the gaseous species produced at each moment of the process can be quantified. Although the synthesis gas composition cannot be determined for continuous operation, this approach reveals the initiation stage of gasification processes serving as a starting point for obtaining the optimum process parameters necessary to initiate the gasification process of a certain type of material as well as the process instabilities during partial load periods (changes in continuous operation). Also, the transitory regime of a gasification process provides all the data necessary for the mass and energy balances and process efficiencies calculation. Thus, the influence of process parameters on the process energy performance can be observed.

According to the literature, rape straws and food court waste have not previously been used as feedstock in gasification processes. This thesis provides experimental data to convert these products. After analyzing the experimental results, these two materials studied have better properties compared to poplar wood, thus being considered as a primary energy source for gasification processes.

In Chapter III the effect of gases produced by biomass gasification use on the performance of gas turbine installations (case study - GT Solar Mercury 50) was studied.

It has also been used as a reference for comparing the possible electrical power to be produced by using biomass, a steam turbine installation for which the electrical power produced according to the availability of the biomass source has been estimated.

6.3. RESEARCH PERSPECTIVES

The main research prospects to be studied later are:

1. The study of other product mixtures gasification. Biomass sources are typically characterized by a discontinuous flow, for example vegetal agricultural residues. They are usually produced once a year and in different regions of the country. In order to have as much as possible and to ensure continuity in the plant's supply, they must be collected and stored in one place. Using them in mixtures with other waste or forest products could make it possible to use them in several locations.
2. Effect of modifying the food court waste composition on the performance of the gasification process. As mentioned in paragraph 3.1.1.6, the recipe of the food court waste varies also within the same location by hour. The results obtained in this paper are strictly valid for a waste composition, composition that we may no longer find depending on where the waste is generated. For this reason I consider it interesting to follow the effect of the waste recipe on the composition of the produced gas.
3. Creating a logical scheme for choosing the optimal gasification reactor type according to the properties and availability of the biomass source to maximize the electricity production. In Chapter II were presented the effects of the variables that influence the gasification process and the comparative analysis of the gasification reactors. Thus, in order

to maximize the useful effect of the available biomass, the optimal conversion reactor and the optimal process parameters must be chosen.

SELECTIVE BIBLIOGRAPHY

[1]. Pedraza, Jorge Morales. *Electrical energy generation in Europe: the current and future role of conventional energy sources in the regional generation of electricity*. Springer, 2014.

[2]. IndexMundi - Country Facts - https://www.indexmundi.com/, accessed 05.03.2019, 12:00

[3]. World Bank Open Data - https://data.worldbank.org/, accessed 05.03.2019, 12:00

[4]. EUROSTAT https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Main_Page**,** accessed 25.06.2018, 18:24

[5]. Smith, Elliott C., et al. *East European energy. Romania's energy needs persist*. No. GAO/NSIAD--92-257. General Accounting Office, 1992.

[9]. Miller, Bruce G., and David Tillman. *Combustion engineering issues for solid fuel systems*. Academic Press, 2008
[10]. Juntunen, Jouni K., and Sampsa Hyysalo. "Renewable micro-generation of heat and electricity—Review on common and missing socio-technical configurations." *Renewable and Sustainable Energy Reviews* 49 (2015): 857-870.

[11]. Kelly, Nick, et al. "Impact of microgeneration systems on the low-voltage electricity grid." (2014).

[14]. Badea, Adrian Alexandru, Victor Cenușă, and Mihaela-Cristina Ciobanu. *Surse regenerabile de energie*. AGIR, 2013.

[15]. *Beneficiile energiei regenerabile,* Comisia Europeana, 2011 – EC2011

[16]. De Jong, Wiebren, and J. Ruud van Ommen. *Biomass as a sustainable energy source for the future: Fundamentals of conversion processes*. John Wiley & Sons, 2014.

[17]. Higman, and M. van der Burgt, *Gasification*, Gulf Professional Publishing, 2008

[18]. Demirbas, M. Fatih, Mustafa Balat, and Havva Balat. "Potential contribution of biomass to the sustainable energy development." *Energy Conversion and Management* 50.7 (2009): 1746-1760.

[19]. Basu, Prabir. *Biomass gasification, pyrolysis and torrefaction: practical design and theory*. Academic press, 2013.

[23]. Heidenreich, Steffen, Michael Müller, and Pier Ugo Foscolo. *Advanced biomass gasification: New concepts for efficiency increase and product flexibility*. Academic Press, 2016.

[35]. CEONU pentru Europa, Comisia Economică ONU, and Ministerul Ecologiei şi resurselor Naturale. "Raport informativ privind politicile naționale în domeniul eficienței energetice şi surselor regenerabile de energie.", Iunie 2009

[41]. Schwietzke, Stefan, et al. "Ethanol production from maize." *Molecular Genetic Approaches to Maize Improvement*. Springer, Berlin, Heidelberg, 2009. 347-364.;

[42]. Oleskowicz-Popiel, Piotr, et al. "Ethanol production from maize silage as lignocellulosic biomass in anaerobically digested and wet-oxidized manure." *Bioresource technology* 99.13 (2008): 5327-5334.;

[43]. Vučurović, Damjan G., et al. "Process model and economic analysis of ethanol production from sugar beet raw juice as part of the cleaner production concept." *Bioresource technology* 104 (2012): 367-372.;

[44]. İçöz, Erkan, et al. "Research on ethanol production and use from sugar beet in Turkey." *Biomass and bioenergy* 33.1 (2009): 1-7.

[45]. Saka, Shiro, and Dadan Kusdiana. "Biodiesel fuel from rapeseed oil as prepared in supercritical methanol." *Fuel* 80.2 (2001): 225-231.;

[46]. Rashid, Umer, and Farooq Anwar. "Production of biodiesel through optimized alkaline-catalyzed transesterification of rapeseed oil." *Fuel* 87.3 (2008): 265-273.

[52]. Smets, Koen, et al. "Flash pyrolysis of rapeseed cake: influence of temperature on the yield and the characteristics of the pyrolysis liquid." *Journal of Analytical and Applied Pyrolysis* 90.2 (2011): 118-125.

[53]. Ucar, Suat, and Ahmet R. Ozkan. "Characterization of products from the pyrolysis of rapeseed oil cake." *Bioresource technology* 99.18 (2008): 8771-8776.

[62]. Cornelissen, Tom, et al. "Flash co-pyrolysis of biomass: The influence of biopolymers." *Journal of Analytical and Applied Pyrolysis* 85.1 (2009): 87-97.,

[63]. Stolarski, Mariusz Jerzy, et al. "Willow biomass as a feedstock for gasification." *Journal of Research and Applications in Agricultural Engineering*58.1 (2013): 168-171,

[64]. Martin, J. R., et al. "Recent results of willow biomass gasification feasibility study." *First international energy conversion engineering conference, Providence, RI*. 2004

[66]. Crocker, Mark, ed. *Thermochemical conversion of biomass to liquid fuels and chemicals*. No. 1. Royal Society of Chemistry, 2010.

[67]. Stevens, Christian. *Thermochemical processing of biomass: conversion into fuels, chemicals and power*. Ed. Robert C. Brown. John Wiley & Sons, 2011.

[68]. Cheremisinoff, Nicholas P., and John Rezaiyan. *Gasification technologies: a primer for engineers and scientists*. CRC press, 2005.

[69]. Spliethoff, Hartmut, *Power generation from solid fuels*. Springer Science & Business Media, 2010

[70]. Koppejan, Jaap, and Sjaak Van Loo. *The handbook of biomass combustion and co-firing*. Routledge, 2012

[71]. Basu, Prabir. *Combustion and gasification in fluidized beds*. CRC press, 2006.

[82]. Branca, Carmen, et al. "Effects of the torrefaction conditions on the fixed-bed pyrolysis of Norway spruce." *Energy & Fuels* 28.9 (2014): 5882-5891.

[93]. De Wild, P. J., W. J. J. Huijgen, and H. J. Heeres. "Pyrolysis of wheat straw-derived organosolv lignin." *Journal of Analytical and Applied Pyrolysis* 93 (2012): 95-103.

[94]. DeGroot, William F., and Fred Shafizadeh. "Kinetics of gasification of Douglas Fir and Cottonwood chars by carbon dioxide." *Fuel* 63.2 (1984): 210-216.

[95]. Delgado, Raúl, et al. "Energy valorisation of crude glycerol and corn straw by means of slow co-pyrolysis: production and characterisation of gas, char and bio-oil." *Fuel* 112 (2013): 31-37.

[96]. Demirbas, Ayhan. "Combustion characteristics of different biomass fuels." *Progress in energy and combustion science* 30.2 (2004): 219-230.

[97]. Demirbas, Ayhan. "Pyrolysis of ground beech wood in irregular heating rate conditions." *Journal of Analytical and Applied Pyrolysis* 73.1 (2005): 39-43.

[98]. Demirbas, M. F. "Characterization of bio-oils from spruce wood (Picea orientalis L.) via pyrolysis." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 32.10 (2010): 909-916.

[99]. Desideri, U., Gh Lazaroiu, and C. Stroe. "Conventional pyrolysis of spruce wood and hazelnut shell delivering oily products." *Journal of sustainable energy*2.2 (2011): 55-58.

[100]. Ebeling, J. M., and B. M. Jenkins. "Physical and chemical properties of biomass fuels." *Transactions of the ASAE* 28.3 (1985): 898-0902.

[112]. Jablonski, Whitney, et al. "Pilot-scale gasification of corn stover, switchgrass, wheat straw, and wood: 2. Identification of global chemistry using multivariate curve resolution techniques." *Industrial & Engineering Chemistry Research*48.23 (2009): 10691-10701.

[114]. Karaosmanoğlu, F., E. Tetik, and E. Göllü. "Biofuel production using slow pyrolysis of the straw and stalk of the rapeseed plant." *Fuel processing technology* 59.1 (1999): 1-12.

[123]. Mani, Thilakavathi, et al. "Pyrolysis of wheat straw in a thermogravimetric analyzer: effect of particle size and heating rate on devolatilization and estimation of global kinetics." *Chemical Engineering Research and Design* 88.8 (2010): 952-958.

[124]. Moilanen, Antero, and Muhammad Nasrullah. *Gasification reactivity and ash sintering behaviour of biomass feedstocks*. Kopijyvä Oy, 2011.

[125]. Moralı, Uğur, and Sevgi Şensöz. "Pyrolysis of hornbeam shell (Carpinus betulus L.) in a fixed bed reactor: Characterization of bio-oil and bio-char." *Fuel*150 (2015): 672-678.

[129]. Nakanishi, Masakazu, Tomoko Ogi, and Yoshio Fukuda. "Thermogravimetric analysis with gas chromatograph mass spectrometry of Japanese fir wood (Abies sachalinensis) in helium with or without steam–oxygen." *Journal of thermal analysis and calorimetry* 111.1 (2013): 929-937.

[144]. Salik, Khwaja Muhammad. "Torrefaction and gasification of biomass Experimental and simulation studies." (2016).

[145]. Salimi, Mohammad, et al. "Hydrothermal gasification of different agricultural wastes in supercritical water media for hydrogen production: a comparative study." *International Journal of Industrial Chemistry* 7.3 (2016): 277-285.

[146]. Schröder, Elisabeth. "Experiments on the pyrolysis of large beechwood particles in fixed beds." *Journal of Analytical and Applied Pyrolysis* 71.2 (2004): 669-694.

[147]. Sevilla, Marta, Juan Antonio Macia-Agullo, and Antonio B. Fuertes. "Hydrothermal carbonization of biomass as a route for the sequestration of CO 2: chemical and structural properties of the carbonized products." *biomass and bioenergy* 35.7 (2011): 3152-3159.

[148]. Sharma, Tejasvi. "Gasification and combustion of corn kernels in a pilot scale system." (2015).

[149]. Sircar, Indraneel, Anup Sane, and Jay Gore. "A Study of High-Pressure CO2 Recycling Using Pinewood Char Gasification." *ASME 2013 International Mechanical Engineering Congress and Exposition*. American Society of Mechanical Engineers, 2013.

[150]. Sircar, Indraneel, et al. "A study of high pressure pinewood char gasification with CO 2." *Fuel* 134 (2014): 554-564.

[151]. Sonobe, Taro, Nakorn Worasuwannarak, and Suneerat Pipatmanomai. "Synergies in co-pyrolysis of Thai lignite and corncob." *Fuel Processing Technology* 89.12 (2008): 1371-1378.

[168]. Klašnja, Bojana, Saša Orlović, and Zoran Galić. "Comparison of different wood species as raw materials for bioenergy." *SEEFOR (South-east European forestry)* 4.2 (2013): 81-88.

[169]. Ozturk, H. Huseyin, and Ali Bascetincelik. "Energy exploitation of agricultural biomass potential in Turkey." *Energy exploration & exploitation* 24.4 (2006): 313-330.

[177]. Nussbaumer, Thomas. "Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction." *Energy & fuels* 17.6 (2003): 1510-1521.

[179]. Luque, Rafael, and J. Speight, eds. *Gasification for Synthetic Fuel Production: Fundamentals, Processes and Applications*. Elsevier, 2014.

[180]. Speight, James G. *Gasification of unconventional feedstocks*. Gulf Professional Publishing, 2014.

[187]. Baratieri, M., et al. "The use of biomass syngas in IC engines and CCGT plants: a comparative analysis." *Applied Thermal Engineering* 29.16 (2009): 3309-3318.

[188]. Proiect BIONov-PyroTECH – Producţia de BIOcombustibili prin metode iNOVatoare de PIROliză /gazeificare şi TEHnologii avansate - Un Program Dedicat Recrutării și Formării Tinerilor Cercetători Români în Domeniul Energiei şi Produselor din Biomasă

[189]. López-Linares, Juan Carlos, et al. "Bioethanol production from rapeseed straw at high solids loading with different process configurations." *Fuel* 122 (2014): 112-118.

[190]. Plis, P., and R. K. Wilk. "Theoretical and experimental investigation of biomass gasification process in a fixed bed gasifier." *Energy* 36.6 (2011): 3838-3845.

[191]. Deng, Jian, et al. "Pretreatment of agricultural residues for co-gasification via torrefaction." *Journal of Analytical and Applied Pyrolysis* 86.2 (2009): 331-337.

[215]. Johansson, Linda S. *Characterisation of particle emissions from small-scale biomass combustion*. Diss. Chalmers tekniska högsk., 2002.

[216]. Moroń, Wojciech, and Wiesław Rybak. "NOx and SO2 emissions of coals, biomass and their blends under different oxy-fuel atmospheres." *Atmospheric Environment* 116 (2015): 65-71.

[217]. Marculescu C., Procese antropice si impact generat asupra mediului,ISBN 978-606-8371-l l-5,Editura Academiei Oamenilor de Stiinta din Romania, Bucuresti, 201 1, 84 p.