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THERMODYNAMIC AND EXPERIMENTAL ANALYSIS OF A BIOMASS STEAM POWER PLANT: CRITICAL ISSUES AND THEIR POSSIBLE SOLUTIONS WITH CCGT SYSTEMS

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Abstract

This paper shows the experimental and numerical analysis of a biomass steam power plant from maximum power of 2.3 MW with a maximum pressure of 48 bar and a turbine inlet temperature of about 430°C at the design point. The analysis has been conducted using experimental data, collected directly on the power plant, at the design point, and they have been afterwards used to validate a thermodynamic model. The analysis of the biomass power plant pointed out some critical issues that can be summarized in three points: low plant efficiency due to the small size, biomass supply range and continuous variation of the operating point. In order to solve this problem, different plant configurations were numerically evaluated. The first solution to these problems consists of a 100 kWe micro gas turbine (MGT) fueled by natural gas, whose exhaust gas were sent to the steam generator of the biomass power plant in order to evaluate the benefits on the power fluctuations and on global electric efficiency. A thermodynamic model of the MGT has been developed and validated with experimental data from technical literature, creating a CCGT (Combined Cycle Gas Turbine) system. The analysis of the results of this system showed improvement in terms of efficiency and operational stability. The second option was to fuel the previously validated method of MGT with four different alternative fuels and to evaluate the integration with the biomass plant for all of them. Furthermore, to emphasize the benefits of this integration, the power of the micro turbine has been increased assuming the use of more MGT at the same time. These analyses show an increase of the system efficiency, it could been also used the biomass, not suitable for direct combustion (high humidity), to produce biogas that fuels the MGT, reducing the range of biomass supply.

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Keywords: Biomass; CCGT; biogas; syngas; micro gasturbine; steam power plant.

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1. Introduction

Biomass is a term for all organic material that has not undergone fossilization: plants, algae, trees and crops, but also the animal waste and organic waste civilians, are part of this collection. When the bonds between carbon, hydrogen and oxygen molecules are broken by digestion, combustion, or decomposition, these substances release their stored chemical energy. Biomass has always been a major source of energy for mankind and is presently estimated to contribute to the 10-14% of the world's energy supply [1].

The processes currently used are divided into two categories[2]: thermochemical processes and biochemical processes (Fig. 1).

The former include the direct combustion, gasification and pyrolysis, while the latter are the aerobic and anaerobic digestion proceedings [1].

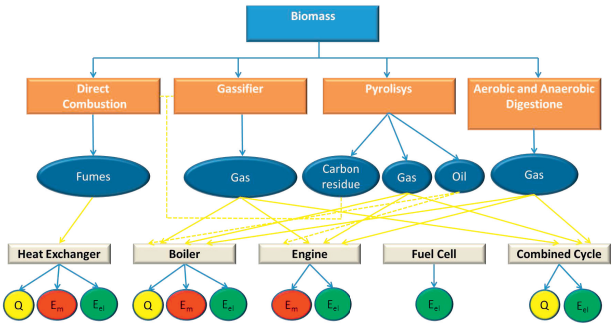

Fig. 1. Biomass Conversion Technologies Scheme

Although the direct combustion is the most common form of energy conversion, it creates insuperable problems when the biomass humidity is high as in these cases biomass cannot be directly burned. This factor penalizes the production of direct combustion biomass energy because low humidity biomass is not always available and the needed amount in a range of supply is not economically and energetically convenient. However, whenever the efficiency conversion of the thermal energy stored in the biomass increases with the size of the system [3] the range of supply of this resource does it as well and as a consequence the economic and energy costs for the transportation and related emissions, including also non-renewable CO_2 [4]-[6] .

In this contest, it would be important to consider low- powered Plants but the efficiency would be penalized.

The present system has relative low power (2.3 MW) but it does not penalize much the global electric efficiency (22,9% at design point) [7],[8] and it hence justifies the interest to perform an experimental and numerical analysis of this relative small Steam Power Plant.

The high variability of the lower heating value of the biomass involves a large fluctuation of the load and then of the operating parameters, creating difficulties in the management and maintenance of the system and decreasing the average efficiency of the biomass thermal energy conversion into mechanical energy and, consequently, of electric power.

In order to solve these problems, that is the increase efficiency, the reduction of the range of biomass supply and the power oscillations, different system configurations have been numerically analyzed.

Nomenclature

Latin:

LHV	Lower Heating Value;
BSPP	Biomass Steam Power Plant;
CCGT	Combine Cycle Gas Turbine;
MGT	Micro Gas Turbine;
NG	Natural Gas;
EGR	Exhaust Gas Recirculation;
$P_{t,f}$	Thermal Power of the exhaust gas,
P_r	Power of the Real Thermodynamic Cycle;
$P_{\lim}$	Power of the Ideal Thermodynamic Cycle;
$\dot{m}_b$	Biomass mass flow;
P_{ua}	Net Mechanical Power on the shaft;
$P_{e,net}$	Net Electric Power Generated;

Greek:

$\eta_{\lim}$	Efficiency of the Ideal Thermodynamic Cycle;
η_i	Internal Efficiency of all Plant Machines;
η_{ter}	Efficiency of the Real Thermodynamic Cycle;
η_m	Mechanical Plant Efficiency;
η_b	Combustion Efficiency;
η_g	Global Efficiency;
η_{gel}	Global Electric Efficiency

2. Biomass Steam Power Plant

As previously said, the steam power plant [10],[11] (Fig. 2a) at design point generates 2.3 MWe through direct combustion of woody biomass.

The plant consists of:

- Combustion chamber (CC Fig. 2a) physically separated from the steam generator;
- Steam generator (GV Fig. 2a), type vertical, natural circulation of water with vertical tubes, superheater and economizer;
- Steam turbine (T Fig. 2a) is a 10 stages unit: the first one is an action stage and the others are the reaction stages. There is a bleed steam between the fifth and sixth stage;
- Flue gas cleaning system (F Fig.2a) consists of a multi-cyclone and a bag filter;
- Condenser (C Fig. 2a) at ground water.

2.1. Experimental Analysis Of Biomass Steam Power Plant

The measurements of experimental data present some difficulties due to the continuous variation of the operating conditions. The biomass has a high humidity variability causing a change of LHV and, consequently, of operating conditions. The nominal point has been identified with numerous measurements and the relative operative conditions are reported in the Table 1 (more stable and repetitive values).

In the following chart (Fig. 2b), the continuous variation of the combustion chamber gas temperature generates bigger electric power variations. Combustion chamber temperature is, also, controlled by an EGR valve, but, as it can be seen from Fig. 2b, it’s not sufficient to control the Power Stability.

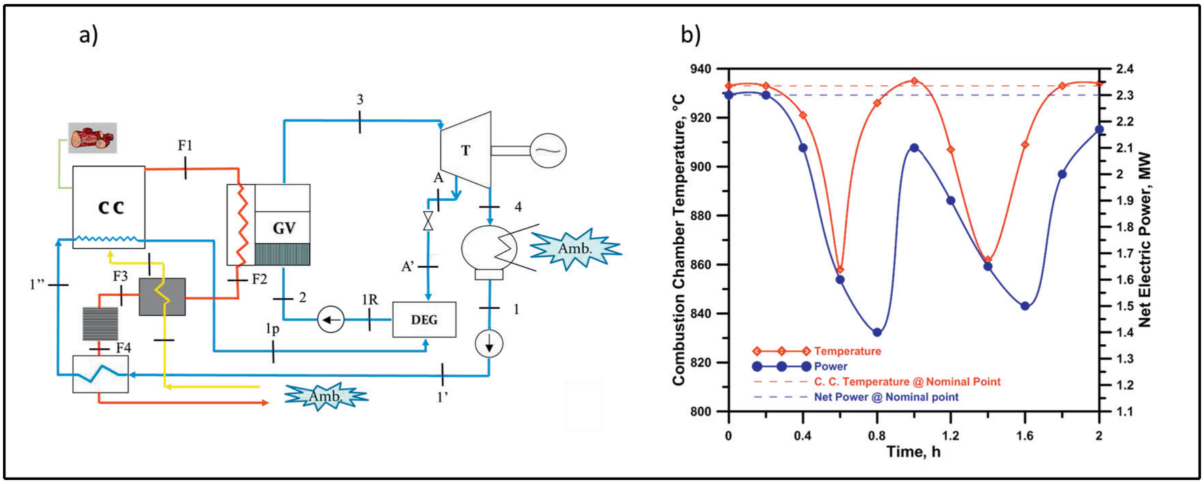

Fig. 2(a). Layout of Biomass Steam Power Plant - Fig. 2(b). C.C. temperature trends and Power Generated

The experimental data collected and used for energy analysis have been integrated with indirect data:

- Experimental data (Table 1):
- Ambient conditions: temperature, pressure;
- Steam Turbine: electric load, compression and expansion ratio, loss of load, temperature and pressure at various points of the thermodynamic cycle;
- Boiler: mass flow temperature and pressure of the exhaust gas at various points.

Table 1. Experimental Conditions at design point.

Points (Fig.2)		Temperature (°C)	Pressure (bar)
Burned Gas from the CC	Fumes 1	933.0	0.998
	Fumes 2	260.0	0.998
	Fumes 3	171.3	0.998
	Fumes 4	171.3	0.998
	Chimney	109,3	1.004
Water in the Thermodynamic Cycle	1	24.1	0.030
	1'	24.1	3.000
	1"	80.0	2.000
	1p	97.0	1.500
	1R	111.3	1.500
	2	111.8	55.000
	3	428.7	47.500
	A	296.7	11.000
	A'	284.7	1.500
	4	24.1	0.030
Air 1		21.7	1.004
Air 2		125.0	1.004

Indirect data (Table 2 and Table 3):

- Combustion efficiency: $\eta_b = P_{t,f} / \dot{m}_b \cdot LHV_b$;
- Efficiency of the Real Thermodynamic Cycle: $\eta_{ter} = \eta_{\lim} \cdot \eta_i = P_r / P_{t,f} = P_{\lim} / P_{t,f} \cdot P_r / P_{\lim}$;
- Mechanical efficiency: $\eta_m = P_{ua} / P_r$;

- Global Efficiency: $\eta_g = \eta_b \cdot \eta_{ter} \cdot \eta_m$;
- Global Electric Efficiency: $\eta_{gel} = P_{e,net} / \dot{m}_b \cdot LHV_b$

Table 2 show the comparison of experimental and modelling values of the indirect data.

Table 2. Efficiencies at design point.

	Experimental Data	Modeling Data
η_b	90.3%	90.5%
η_{ter}	34.1%	34.2%
η_m	80.6%	80.5%
η_g	24.8%	24.9%
η_{gel}	22.88%	22.9%

The evaluation of the biomass composition and its lower heating value was obtained iteratively with the help of a thermodynamic simulation software verifying that the composition assumed for the biomass and therefore the lower heating value, realized the same operating conditions of the experimental data [12],[13].

Table 3. Biomass composition and Lower Heating Value.

	Water	46.5%
Average Biomass Composition	Carbon	33%
	Oxygen	17%
	Hydrogen	2%
	Nitrogen	0.5%
	Ash	1%
	LHV [MJ/Kg]	14.6

2.2. Modeling Of Biomass Steam Power Plant

Using the experimental data and with the use of a thermodynamic simulator [14]-[16], it was possible to implement a model of the plant (Fig.2) through which has been verified the composition and lower heating value of the biomass.

Have been supplied the following inputs:

- ST and Pumps Efficiencies;
- Temperatures and pressures of the working fluid in all the thermodynamic cycle (Table 1);H
- Heat Exchangers Sizes;
- Fuel and Combustion Air Flow and Composition;

The outputs returned are the following:

- Flue Gas Temperature in the CC (Fig.2);
- Turbine Power Output;
- Thermal Power transferred from the flue gas to the motor fluid;
- Pumps Power;
- Efficiencies Values.

In particular, the flue gas temperature has been used as test. The Table 2 show the comparison of efficiencies. It is clear that the composition assumed for the biomass is very close to the real mean value.

3. CCGT(Combine Cycle Gas Turbine) System

Different system configurations were numerically evaluated , in order to solve problems pointed out previously, and then: increase the efficiency, reduce the use of biomass and therefore the range of supply and to mitigate the power fluctuations due to the variability of the biomass.

A MGT (Micro Gas Turbine) 100 kWe fueled by natural gas, it's been connected to the biomass power plant. The connection was realized sending the hot exhaust gases of the MGT, in the combustion chamber of the main system, realizing a CCGT (Combined Cycle Gas Turbine) system.

3.1. Modeling of MGT 100 kWe Fuelled by Natural Gas

To analyze different Plant configurations, a thermodynamic model of the MGT (Fig. 3) has been implemented. It has been validated with experimental data from literature [17]-[20].

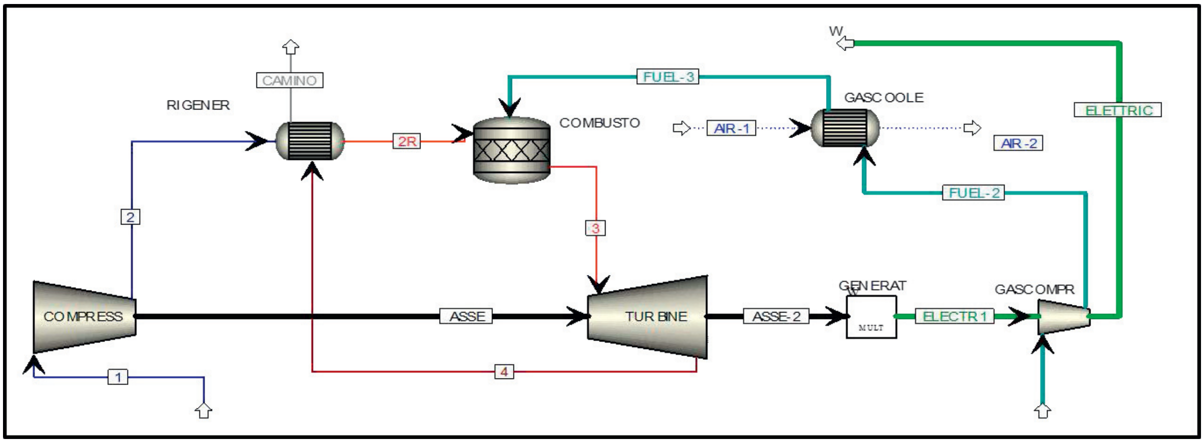

Fig. 3. Model of MGT 100 kWe

Validation is confirmed by the good approximation between experimental and numerical comparison. A natural gas supply compressor has been considered because is necessary a pressure of 6 - 8 bar to introduce the NG in the Combustion Chamber. This compressor is electrically powered and, therefore, it results a reduction of net electric power output. It has been, also, necessary to introduce an air exchanger to cool the exit gas from the compressor because a feed gas temperature between 0 °C and 60 °C is required. Under rated operating the simulation returns the performance values (Table 4).

Table 4. Characteristic values of MGT.

Mechanical power required by the compressor	147,97 kW
Mechanical power produced by the turbine	257,37 kW
Net mechanical power axis	109,5 kW
Electric power produced	100,1 kW
Net electric power	97,5 kW
η_{el} Electric efficiency	30,4%

3.2. Modeling of CCGT System

A numerical analysis of the CCGT system (Fig.4) has been realized sending the hot exhaust gases of the MGT, in the combustion chamber of the main system.

The verification of this connection has been made by varying the mass flow of biomass and air introduced into the cycle, leaving constant the temperature of the burned gas at the exit of the combustor and without changing the design point of the steam cycle.

The results show that the thermodynamic cycle design point is the same and a small variation is found in the exhaust gas temperature.

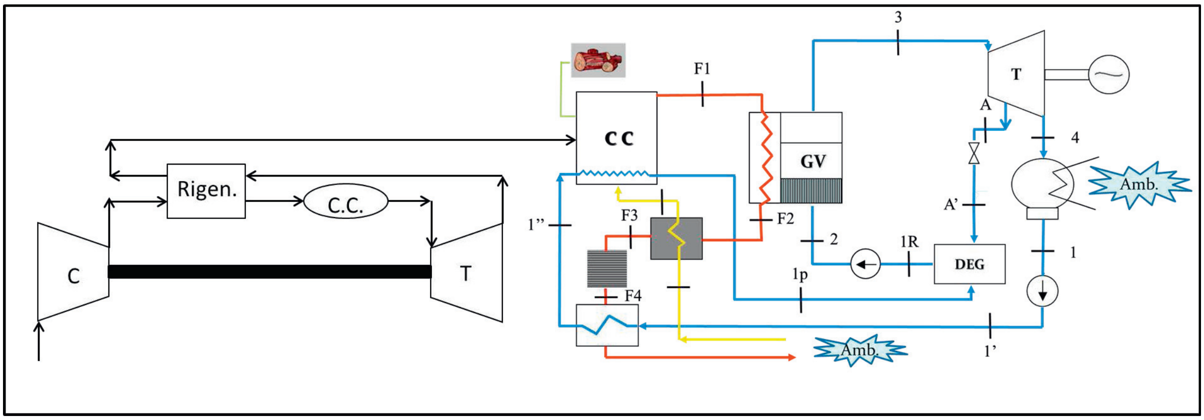

Fig. 4. Scheme of CCGT system.

The biomass mass flow was reduced of 1.54%, from 0,6944 kg /s to 0.679kg / s, and the ratio between the mass flow of natural gas and biomass of 1%. The CCGT global electric efficiency is about 1% higher than the BSPP.

The comparison between different configurations is synthesized in Table 5. From the results it is clear that it improves the three critical problems previously mentioned, in fact, with the reduction of the biomass it decreases the range of supply, making the system less sensitive to the humidity variation. In addition, is obtained a slight increase of the efficiency of the CCGT system. This connection could be realized by fueling the MGT with biogas thus obtaining a CCGT system powered completely from renewable sources and could use the biomass with high humidity for the production of biofuels, that fuel the micro turbine.

Table 5. Different configurations comparison.

	MTG	TV	CCGT
Biomass mass flow, kg/s	-	0.6944	0.679
NG mass flow, kg/s	0.0068	-	0.0068
Alpha	118.8	14	13.3
Net electric power, kW	97.5	2320.64	2418.14
Electric efficiency	31.1%	22.9%	23.9%

3.3. MGT Fuelled With Biogas And Syngas

Fueling the MGT with biogas it has been supposed a CCGT powered completely from renewable sources.
In the present paper the MGT is powered by 4 alternative fuels whose main characteristics are given in Table 6.
In particular, we have considered the following biofuels [17]:

- two syngas, one obtained from oxygen gasification [Biom (O)] and the other one by pyrolysis of Municipal solid waste [MSW];
- two biogas products from the anaerobic digestion of sewage sludge through a wastewater treatment [SW Dig.], and organic substances constituted by agricultural and animal waste [OW Dig.].

The lower heating value of the gaseous mixture, is from two to three times lower than that of natural gas. This factor will result effects in the operation of the micro turbine, analysis on the originally machine designed for the fossil fuel are required [18]. The MGT model should thus be perfected in case of supply from biofuels. However, it can assume that the biogas with a methane content higher than 50% should not require modifications to the micro turbine combustor [19].

Table 6. Biogas and syngas composition.

Composition (% molar)	Biom(O)	Syngas from MSW	SW Digestion	OW Digestion
CH_4	18%	7%	55%	63%
C_2H_6	2%	7%	---	---
C_3H_8	2%	7%	---	---
C_4H_{10}	2%	---	---	---
N_2	8%	---	2%	2%
H_2	25%	18%	---	---
CO	33%	61%	---	---
$C0_2$	10%	---	43%	35%
Molar mass, g/mol	21,92	23,76	28,31	26,07
LHV,kJ/kg	19170	21655	15558	19351

In these simulations it is assumed to keep constant the inlet temperature of the turbine to 950 °C. It has been noted that for biofuels characterized by a lower LHV will require a greater mass flow to reach the inlet temperature of the turbine, thus generating more power produced by the turbine. This difference in power does not increase much considering the net electrical power absorbed by the compressor fuel. In fact, a higher mass flow leads to a higher power generated by the turbine, however, it is also true that will be greater the work required by the compressor of natural gas, reducing the output of electric power.

Table 7. Characteristic data of MGT modeling for the different supply.

	NG	BIOM(O)	SYNGAS FROM MSW	SW DIG.	OW DIG.
$P_{EL,TOT}$	100.1 kW	102.03 kW	100.6 kW	103.3 kW	102.4 kW
$P_{EL,NET}$	97.5 W	96.8 kW	96.4 kW	98.4 kW	98.2 kW
$\dot{m}$	0.00680 kg/s	0.01705 kg/s	0.01490 kg/s	0.02132 kg/s	0.01697kg/s
$\dot{m}$	0.808 kg/s	0.808 kg/s	0.808 kg/s	0.808 kg/s	0.808 kg/s
Chimney	256.95°C	259.4°C	258.0°C	61.9°C	260.4°C
$_{ELECT}$	30.44%	29.60 %	29.87 %	29.19%	29.90%

After analyzing the MGT for different types of fuel, was carried out the same type of CCGT system shown previously in the case of natural gas supply.

Even for these connections has been employed the same method previously used, or rather was varied the biomass flow and the air flow in such a way that the exhaust gas temperature and the flow rate at the exit of the combustion chamber of the steam plant and the thermodynamic cycle, remain the same.

Has also been hypothesized to keep constant the heat exchangers surface (A) and has been calculated iteratively the value of the overall heat transfer coefficient (U) required so that the thermodynamic cycle remains constant, except for the air preheater because the temperature variation of the combustor inlet air, does not change the operating point of the thermodynamic cycle and therefore, in this case, it is left constant also the U value.

Table 8. CCGT Numerical output for different MGT fuels.

	CCGT NG	CCGT Biom(O)	CCGT MSW syngas	CCGT SW Dig	CCGT OW Dig.
$P_{el,tot}$	2418,14 kW	2417,44 kW	2417,04 kW	2419,04 kW	2418,14 kW
$\dot{m}$	0,679 kg/s	0,6791kg/s	0,67894kg/s	0,679194kg/s	0,67914kg/s
Biomass reduction	2,228%	2,212%	2,232%	2,196%	2,204%
$_{elett}$	23,62%	23,60%	23,61%	23,59%	23,61%
Increase η_{elect}	0,82%	0,8%	0,81%	0,79%	0,806%

Even for these alternative solutions there was a reduction of the biomass used which allows to reduce the range of biomass supply making the system less sensitive to the humidity variation.

Another advantage is the possibility to use the biomass does not suitable for direct combustion (high humidity) for the production of biogas and syngas that fuel the micro turbine. For each case, is obtained a small increase of the CCGT global efficiency which remains maximum in the case where the MGT is powered by natural gas.

3.4. Numerical Analysis Increasing MGT Size

To emphasize the benefits obtained with the CCGT system, we used a larger MGT size to evaluate the increase of the global efficiency. To calculate this solution, was supposed to be used some MGT 100kWe (previously validated) in parallel whose exhaust gases are sending to the combustion chamber of the biomass power plant.

This analysis was conducted only for two types of biogas: *Biom(O),* obtained from an oxygen gasification and *OW Dig*., obtained from anaerobic digestion of organic substances constituted by agricultural and animal waste. These two supplies were selected because realize a slightly higher efficiency among CCGT systems completely powered by renewable sources illustrated above.

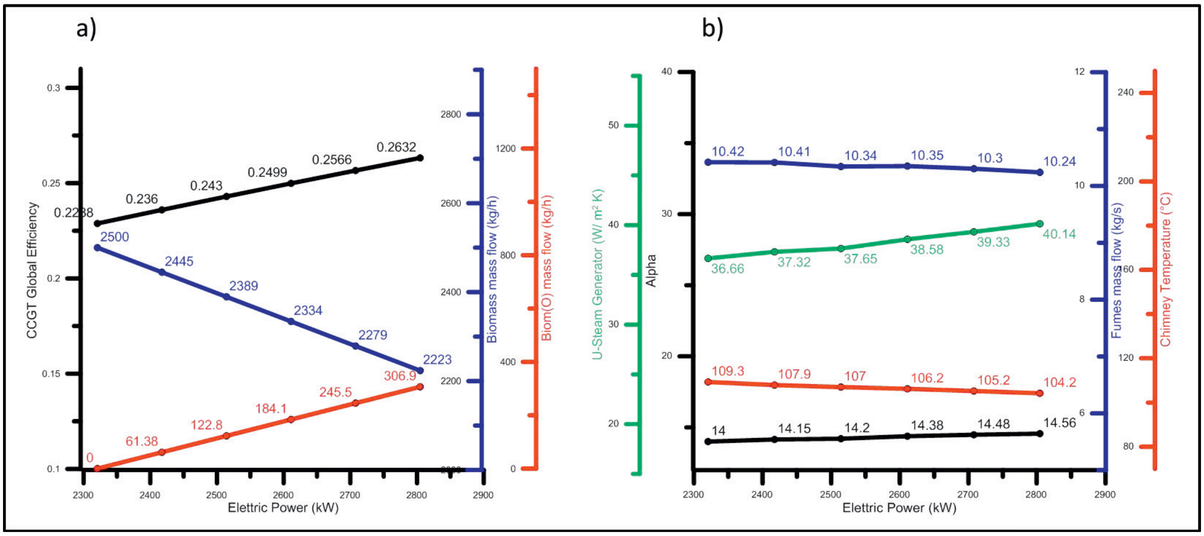

Fig. 5 CCGT characteristic data increasing size of MGT fuelled by Biom(O).

In the first chart Fig.5(a), relative to the case of MGT supply with Biom (O), it can be seen:

Black line - CCGT efficiency trend in black; blue line – biomass flow variation; red line - Biom (O) mass flow increase.

As is known, to an increase of MGT power and so of the CCGT system, there is clearly an increase of Biom (O) mass flow and a biomass reduction. Furthermore it has been noted an increase of efficiency from 22.8% (no MGT) up to 26.4% in case of 5 MGT in parallel.

In the second chart Fig.5 (b), always with a MGT powered by Biom(O), it can be seen, at varying of the power, the trend of: blue line - the overall exhaust gas mass flow; green line - the variation of the overall heat transfer coefficient of the steam generator; red line - the fumes temperature variation at the CCGT chimney; black line - the trend of alpha. To calculate alpha, it takes into consideration the air ratio in the MGT exhaust fumes. The alpha value increases slightly with the power, from 14 (no MGT) up to 14.56. The fumes overall mass flow decreases with increasing of electric power. In Addition, considering the same heat exchange area (A) and the thermal power exchanged ($P_{th} = U \cdot A \cdot \Delta T_{ml}$), it is necessary a higher overall heat transfer coefficient (U) value, as it can be noted from the diagram of the Fig. 6 b (green line).

Moreover, the chimney temperature (in red), decreases with increasing power, this trend is due that the thermodynamic cycle, as previously mentioned, is always the same, while the flue gas mass flow rate is decreasing with the power. Same evaluation was conducted for another CCGT system. However this time the MGT is fueled with biogas produced from the anaerobic digestion (OW.Dig) and the trends are the same of the previous case.

4. Conclusion

It is presented the experimental and numerical analysis of a biomass steam power plant. This plant has a relatively low power (2.3 MW) without penalizing a lot the global electric efficiency (22,9%). Experimental tests show the variability of the power delivered, which is due to oscillation high humidity of the biomass.

A thermodynamic model is implemented in order to propose solutions to these problems.

The use of a MGT, showed an improvement in terms of efficiency and stability, in fact there is an increase of the global efficiency and a reduction of the biomass used. Assuming the use of biogas for the MGT, the plant would be fully powered by renewable sources, but you must use biogas with a high lower heating value. Even with this power supply is unable to obtain an efficiency increase and a biomass reduction, also the biomass can't be used for direct combustion, can be used for the production of biogas that would fuel the micro turbine.

To emphasize the benefits obtained with the CCGT system, we used a larger MGT size, and as seen from the results, at the increasing of the MGT size, increases the efficiency and reduces the amount of biomass used. It should realize, however, a detailed analysis for the steam generator, to obtain the same thermodynamic cycle and having assumed constant the surface heat exchange, it is necessary to increase the overall heat transfer coefficient. The CCGT system realized both with biogas that with natural gas, intervenes to improve the three criticality of the biomass power plant object of study.

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