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Design Features and Performance Data of a New 400 kWel Biomass Gasification Power Plant of Downdraft Type

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Abstract

A new biomass-gasification power plant, of medium-size downdraft type, is presented and discussed in its design features and performance characteristics. Its configuration and overall dimensions, initially conceived for 800 kWel, were recently re-tuned, from a functional point of view and on the base of a parallel theoretical analysis, by decreasing to about 400 kWel the former design power level. This provision, jointly with the basic design choice of adopting a long and amply dimensioned inlet-biomass thermal pretreatment section, turned out quite effective in achieving high gasification temperatures and a low-tar content in the produced gas at fuel-to-air ratios well below the usually imposed, to the advantage of the heat value of the product-gas gas. The paper discusses the numerical analysis results which helped to properly adjust the operational parameters of the gasifier and then presents the experimental performance data of the overall power plant including biomass consumption, gasification temperatures, gas production, composition and pollutants content, cold-gas conversion efficiency and global electric efficiency. Special care is devoted to investigating the issue of a significant production of carbon-containing particulate matter in the product gas, which turns out made up of char and fixed carbon much more than of tar species.

Keywords

Biomass gasification, Downdraft gasifier, Product gas characterization, Tar species, Charcoal production.

1. Introduction

Historically, the coal gasification processes, by virtue of their continuous technical evolution during the 19th and the first half of the 20th century, had undoubtedly attained a remarkable level of 'mature' industrial technologies [1]. Unfortunately, even in most recent times, the widespread increasing interest in small to medium-size biomass gasification could not take full advantage of previous, coal-related, experiences and knowledge due to the inherent differences, both in energy value and physico-chemical characteristics, between the two feedstocks. Notice that the above is true from a strictly technological perspective, independently from the to-day more stringent environmental constraints.

In fixed-bed 'downdraft' gasification reactors, both the biomass and the air are fed at the top, and then 'flow' co-curently downward, at difference with 'updraft' reactors wherein the biomass is fed at the top and moves downward, whilst the air intake is located at the bottom. As a result of the different processes, the produced gas exits a downdraft reactor from near the bottom whilst it leaves from the top in an updraft configuration. In this latter case, a major drawback is represented by higher amounts of tar and pyrolysis products, because the pyrolysis gas is not combusted [2].

The basic entrepreneurial choice of selecting a downdraft technology for a medium-size (300 to 800 kWel) biomass gasifier, which has made it possible to pursue the overall endeavor including the achievement of the scientific-technological outcome here discussed, was dictated by several considerations: the expectedly cleaner product-gas exiting from a downdraft processor in comparison with an updraft solution [2,3], its lower costs due to a simpler power plant configuration with, correspondingly, a more manageable functional control, particularly in comparison to fluidised-bed solutions (e.g. in ref.[2] at pp.29-32), a previous, rather extended, experience of the present authors directly attained on small-size downdraft gasifiers [5,6,7,8,9].

A peculiar motivation of this study is also related to the extremely scarce available information on the impact on gasifier perfomance related to biomass thermal pre-treatment. In the present case, the feedstock undergoes, within a peculiar 'surface heat exchanger' an important thermal pre-processing, by exploiting, in regeneration modality, the thermal energy of the hot gasses. This point, which was already investigated by the authors within a laboratory-scale gasifier [7,8,9], is a non-secondary reason for the good performance recently shown by small-size gasifiers which implement this modality (e.g. [10]).

2. Overall power-plant characterization

The gasification power plant object of the study, formerly designed for an 800 kWel power level [4] and erected about 3 years ago, is based on a downdraft process reactor which very recently has undergone partial re-configuring and re-tuning onto a 400 kWel power size, thus positively attaining its final and operational setup, as attested by the several hundred hours of continuous and sufficiently reliable operation. It shows an efficient production of gas, with a significant dust content but low presence of tar species, so to become suitable for direct coupling to a power generating internal combustion gas-engine, after proper filtering, cooling and cleaning operations of the product gas. The site of the installation is located in Northern Italy, near Alessandria.

Fig. 1. Overall view of the pyro-gasification unit: main processor with the suction fans and, rearward, the dedusting cyclones.

The main processor is a pyrolytic biomass gasification unit, suited to be fed with woodchips and agriculture-residue feedstocks of 20% humidity max. The reactor, internally lined with refractory material, contains, in its upper part, the screw-type biomass stoker aimed, while feeding the feedstock, also at thermally pretreating it (in terms of desiccation and torrefaction processes) by means of ‘external’ heat transfer with the hot produced gas along its path toward the exit of the gasifier. This sort of internal heat regeneration turns out extremely important in helping achieve high temperatures in the gasification bed, without the need of introducing large amounts of air for driving the exothermal partial oxidation process. By this means, the tar production is efficiently contrasted and the introduction of air nitrogen is somewhat limited to the advantage of increasing the heat value of the produced gas. The ‘products’ of processes taking place in the long, screw-type, biomass stoker, externally heated by the hot gasses flowing all around it, are pyrolysis gasses, torrefied biomass and char-like solid materials, which then enter the gasification section proper. Here, a pseudo-toroidal duct feeds the gasification air by means of radially inward air injections, operated by two air fans in series. The column of gaseous and solid materials flow downward through the gasification section, undergoing the corresponding thermo-chemical conversions, until they reach, near the bottom, a periodically moving grid which, by action of the hot char material standing upon it, makes up the reduction bed. The grid, which induces the hashes to separate and fall further down (to be automatically discharged), extends sideways, so that the gasses are forced to pass twice across it, a first time descending downward, in line with the solid material column, then, ascending from the grid bottom in upward motion, through the side extension of the grid itself. This provision appears quite useful in inducing effective thermo-chemical reduction processes upon the product gas.

Therefrom, the hot gasses are allowed to flow through a sequence of a few chambers into which the overall internal volume of the gasifier is partitioned. The last chamber includes a metal-oxides filter suitable to help abate tar species as well as possible sulphur traces. Afterwards, the produced gas exits from the inside of the processor with a temperature of about 500 °C. Then, it needs to be cooled down, which is performed by means of two vertical-type tube-banks coolers arranged in parallel, followed by a scavenging line equipped with a double venturi-scrubber system and separation tower. Thanks to these after-treatments, the gas attains a temperature below 100 °C, but it still contains particulates and acidic micro-pollutants, which require a ‘basic’ cleaning process to be performed within a double quench tower provided with a proper inert bed. Finally, the product-gas encounters an activated charcoal filter for a last conditioning before injection into the internal combustion gas engine.

The gasifier is thoroughly instrumented, in particular it is equipped with 3 mass flowmeters, 12 thermocouples and 4 pressure sensors positioned in most appropriate locations in order to monitor, continuously and in real time, its inputs, outputs and performance parameters.

Fig. 2 shows a picture of one of the two gas engines.

Fig. 2. One of the two gas engines (405 kW each)

The gas engine main characteristics are shown in Table 1.

TABLE 1 – Gas Engine Technical Features	
Type	4 stroke – spark ignition
Power	405.5 kW
Cylinders	8
Bore-to-stroke	300 mm to 380 mm
RPM	500
Gas heat-values range allowed	4180-6480 kJ/Nm^3
Gas consumption (base load)	800-1200 Nm^3/h
Compression ratio	9:1
Discharge gas temperature	< 600 °C
Product-gas overpressure	2.5 kPa
Product-gas temperature	< 40 °C
Weight	16 ton

A twin set of gas engines of the type above shown were provided and installed, each engine driving a 562 kVA (400 V) electric generation set. The overall power plant operates under a plc Siemens S7 'supervisor' Control & Automation system.

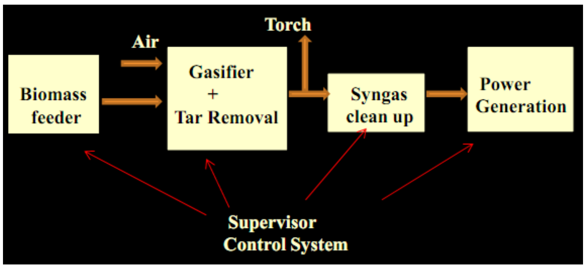

Fig. 3. Overall power plant control & automation system

3. Functional parameters re-assessment

The need of re-assessing the main operational parameters of the gasifier arose once it became clear that for power generation levels approaching the design value, which formerly was set at 800 kWel, the cold-gas energy conversion efficiencies turned out progressively lower, even below 60%, whilst the process stability was rapidly deteriorating and large amounts of carbonaceous dust were produced. In particular, the heat values of produced gas were decreasing down to about 4400 kJ/Nm^3, thus nearing the minimum level acceptable for the gas engines.

Taking advantage of the previous experience made by the authors during a 4-year long investigation addressed to improve performance of a 10 kWel downdraft gasifier (Ankur manufacturer, Fig. 4) operational at DIMSET/SCL laboratory [5-9], it was deemed useful to verify if, as it already happened in the laboratory gasifier, performance could be improved by way of increasing the heat value of the biomass by thermally torrefying it up to about 280 °C.

Fig. 4. The Ankur-Caema downdraft gasifier at DIMSET/SCL with gas cleaning equipment and a Fieldmarshal 10 kWel genset.

To this end, the on-line available EES numerical simulator [11] was applied, analyzing parametrically the impact on gasification performance obtained by feeding the gasifier with torrefied woodchips. In usual untreated conditions, standard wood molecule (normalized with respect to one C atom) can be represented with the chemical formula: $CH_{1.72}O_{0.79}$. After a torrefaction process performed, at atmospheric pressure, up to 230°C, it can be assumed that the wood molecule changes to $CH_{1.57}O_{0.60}$, whereas it becomes $CH_{1.16}O_{0.33}$ when torrefied to 280 °C [9]. This type of information is required by code EES in order to proceed with the prediction of the product-gas properties in function of wood characteristics as well as of gasification parameters' settings.

Prediction is of course simplified, chemical equilibrium is implied and no geometrical dimensions can be specified. Non the less, experimental/numerical comparisons, with un-treated and thermally pre-treated wood feedstocks, performed in the last years at DIMSET/SCL, have shown an adequate capacity of EES to capture the trends of a real gasification process [9].

In correspondence of the operational parameters of the gasifier object of this study, Figs. 5, 6 and 7 present the influence of the gasification temperature on, respectively, the LHV (lower heat value) of the product gas, its GEF (total gas-energy flow, given by the product of LHV with the gas mass flow-rate) and CGE, the cold-gas efficiency.

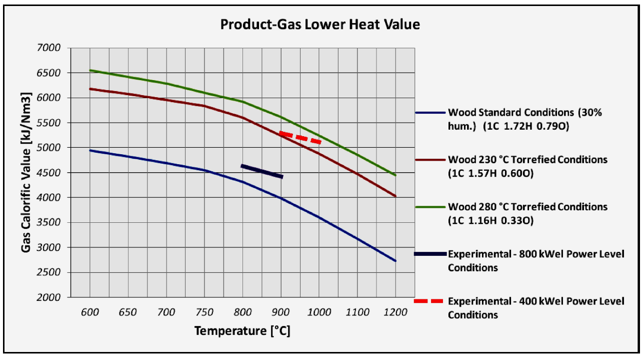

Fig. 5. Influence of wood thermal treatments on gas LHV

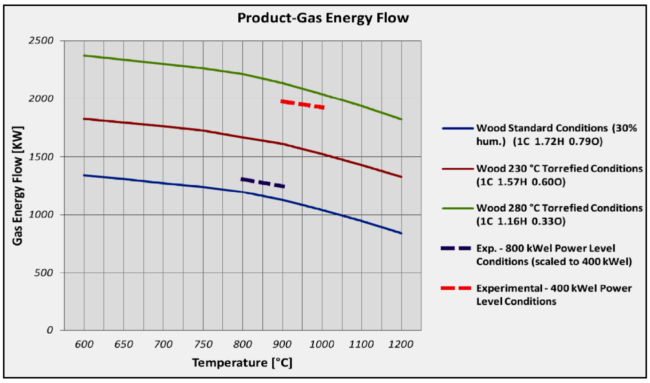

Fig. 6. Influence of wood thermal treatments on gas energy-flow. For purpose of comparisons, exp. values at 800 kWel are 'scaled' to 400 kWel conditions (notice the energy decrease).

To be noticed, the wood consumption is an input parameter and is thus held constant (a requirement of EES): here, its value has been specified equal to the real wood consumption (380 kg/h) as measured when a power of about 400 kWel is being generated by the power plant. This implies that, strictly speaking, performance trends shown in Figs. 5 to 7 are, to some extent, unreal, because the functional map of a gasifier does not follow a constant-wood-consumption line when the gasification temperatures are changing.

On the other hand, the trends shown, if correctly interpreted, do attain consistence in a 'normalized' way,

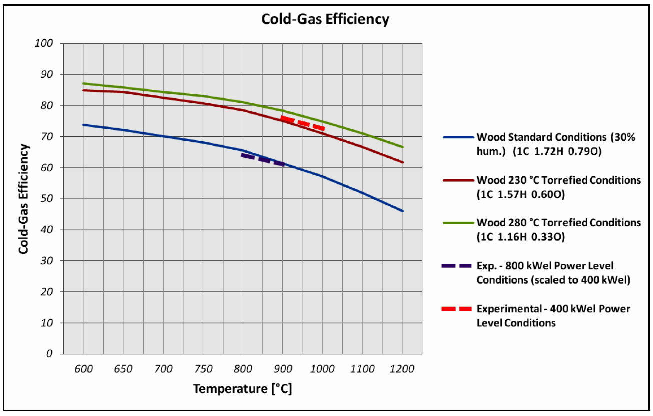

Fig. 7. Influence of wood thermal treatments on cold-gas efficiency.

because simulation gives 'intensive' results (at difference with the scale-dependent 'extensive' ones). Actually the EES outcome is sensitive, for example, to air-to-fuel ratios more than to scale-dependent parameters such as the wood consumption. On ground of above observations, we can expect that LHV and CGE trends are immediately consistent (being LHV and CGE already normalized, intensive parameter), whilst some care must be given in interpreting GEF trends (an extensive, mass flow dependent, parameter).
The first general consideration to be drawn from the numerical results is that the wood thermal pre-treatments appear as major beneficial provisions for improving a downdraft gasifier performance independently from its technology: by increasing the energy density of the feedstock also the conversion process is favored. More specifically, it must be realized that the thermal pre-processes, which the biomass undergoes in the present case, take place inside the long horizontal screw-type feeder 'externally' heated by the hot gasses along their path toward the exit of the gasifier. The power generation of the plant, as a function of wood mass flow, is controlled by the rotational speed of the screw: at max speed, ideally corresponding to an 800 kWel power level, the biomass would reside within the feeder for little more than 2 min, whilst at the lower feeder speed corresponding to about 400 kWel the residence time attains about 4.5 minutes. A rough prediction of the conditions achieved by the woodchips at the feeder exit in the first case (max power) would indicate a biomass temperature level of about 160 °C, whilst more than 270 °C would be achieved at mid power conditions (400 kWel).
If we now position, on above Figs. 5 to 7, the limited, but quite interesting, experimental evidence available, and compare it with the numerical trends reported in the same figures, we can relate the low conversion efficiencies and the operational difficulties, encountered while striving to reach a top power level of about 800 kWel, to incomplete thermal processes performed upon the inlet biomass. When the pre-treatments are allowed to induce almost complete torrefaction processes, thanks both to increased gas temperatures at exit (in consequence of higher gasification temperatures) and to adequate residence times (at mid power, say at 400 kWel power level), the gas LHV attains values compatible with cold-gas efficiencies around 75% and gasification temperatures approaching 1000 °C. On top of that, it is very important to remark that these conditions are achieved with an AF (air-to-fuel) ratio quite low (1.22:1), by virtue of the biomass energy densification and the internal heat regeneration. Indeed, whilst the stoichiometric AF ratio for complete biomass combustion is around 6.3:1 , in wood gasification the usual AF ratios range from 1.5:1 to 1.8:1. Although in an approximate way, Fig. 6 shows that, if the experimental performance data taken at max power level are scaled down to mid power (in practice, the energy flow is divided by two and the AF is adjusted to mid power conditions), the energy flow appears lower than required (to reach max power itself), symptom of an 'off-design' operative condition of the gasifier. Indeed, in order to strive to reach max power, experimental AF's had to be progressively increased, inducing lower conversion efficiencies, lower gas LHV's, system instabilities and higher through-flow velocities with strong entrainment of char-particulate within the gasses.
Taking into account the above considerations, it was decided to functionally re-tune the overall power plant (and its 'control & automation' system) onto a new power generation 'design point' positioned at about 400 kWel. To this end, one of the twin gas engines was disconnected from the product gas line and kept ready for resuming operation only during major overhauls of the companion engine. When all the re-adjustments were performed, the performance of the overall power plant remarkably improved, with a reliable operational stability, a high cold-gas efficiency (around 77%) and at all satisfactory lower heat-values of product gas, which turned out in accordance to theoretical values (Fig. 5). A general scenario of the re-tuned gasifier and overall power plant performance is shown in Table 2. Notice that the reference humidity content of biomass is here taken at 30%.

TABLE 2 – Power Plant Performance Parameters

Biomass consumption	380 kg/h
Inlet air flow-rate	390 Nm^3/h
Product-gas flow-rate	843 Nm^3/h
Product-gas average composition	51% N_2, 22% CO, 7% CO_2, 12% H_2, 4% O_2, 4% CH_4
Product-gas lower heat value	5300 kJ/kg
Product-gas density	1.24 kg/Nm^3
Cold gas efficiency	77%
Net electric power	384 kW
Global electric efficiency	29%

4. Product-gas characterization

In correspondence of the re-tuned operating conditions, at 400 kWel power level, typical gaseous components' average scenario, coming from several analytical assessments performed on off-line measured product gas samples, is presented in Fig. 8.
It appears that the concentration of CO is quite significant and also the H_2 presence is remarkable: undoubtedly, this result takes advantage of the action of the moving grid on the gasifier bottom which, thanks to its hot, 80 cm thick, char-material being traversed twice

by the gases, induces, on these latter, an efficient thermo-chemical reduction process.

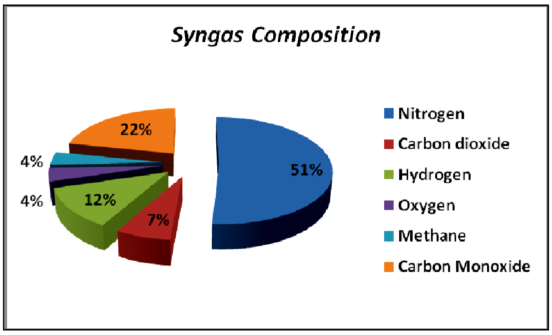

Fig. 8. Typical product-gas components (gaseous species)

To be noticed, the above values of CO and H_2 are in close agreement with EES numerical predictions for fully torrefied wood and 950 °C gasification conditions.
The overall particulate-matter presence in the product-gas, after the gas cleaning processes, i.e. at engine intake, is given in Table 3. Levels are at all acceptable for safe gas engines operation.

TABLE 3 – Product-gas Quality at Engine Intake		
Overall tar content	[mg/Nm^3]	≤ 15
Particulate granulometry	[μm]	≤ 5
Overall particulate matter	[mg/Nm^3]	≤ 40
Water content	[mg/Nm^3]	≤ 20

On the other hand, the particulate matter presence in the product-gas directly at gasifier exit can be roughly quantified in about 1 g/Nm^3 , of which about 800 mg/Nm^3 are separated by cyclones. Some samples have been taken, exactly from these latter solid residues, and their composition has been analytically measured in order to quantify the respective concentrations of tar species. The certified analyses, performed with advanced diagnostics instrumentation [12], are shown in Table 4. The units are milligrams (of condensed tar species) per kg (of solid residues).

TABLE 4

Tar Components (from a typical Sample of carbonaceous residues)	Units: mg/kg
Naphthalene	24,9
Acenaphthylene	3,27
Acenaphthene	1,14
Fluorene	0,05
Phenanthrene	4,21
Anthracene	0,54
Fluoranthene	4,08
Pyrene	6,21
Benzo ©phenanthrene	0,04
Benzo(a)anthracene	0,34
Chrysene	0,3
Benzo(j)fluoranthene	0,17
Benzo(b)fluoranthene	0,17
Benzo(k)fluoranthene	0,17
Benzo(a)pyrene	0,8
Benzo(e)pyrene	1,02
Perylene	0,66
Indeno(1,2,3,c-d)pyrene	0,39
Dibenzo(a,h)anthracene	0,04
Benzo(g,h,i)perylene	1,45
Dibenzo(a,l)pyrene	<0.01
Dibenzo(a,e)pyrene	<0.01
Dibenzo(a,i)pyrene	<0.01
Dibenzo(a,h)pyrene	<0.01

Notice the extremely low presence of poly-cyclic aromatic compounds (tar) within a particulate matter made up, to its greatest extent, by char-dust and ashes. This outcome is likely attributable to a gasification process that takes advantage of the torrefied feedstock's rich energy density for achieving higher temperatures, suitable to counteract formation, or anyhow to disaggregate, long-chain heavy tars of pyrolytic origin: their presence is hardly contrasted in standard wood gasification technologies.
Instead, significant amounts of char material are produced as a fine particulate matter, up to about 1 kg/h, as captured by the cyclones and filters. This problem is well known for fixed-bed gasification in mid to large scale processors, and is mostly due to entrainment of char-dust material by the gasses while traversing the reduction bed. The very low concentrations of tar species, however, keeps this particulate matter under form of an 'unsticking' dust, thus making conceivable its separation (and re-feeding into the processor) by available technologies. Provisions to this end are now under study.

5. Conclusion

The paper has presented an important on-going experience, of both technological and industrial interest, addressed at developing and testing a mid-size biomass gasifier, with annexed power plant, conceived to be suitable for penetrating the potential market of renewable decentralized energy generation of territorial interest.
Once erected, the gasifier configuration turned out mis-tuned in relation to an expected nominal power level of 800 kWel. A parallel numerical analysis has greatly helped in pointing out some functional parameters previously ill-settled, showing a strategy for their improved re-tuning. After implementation of this strategy, the overall power plant, functionally re-assessed on a lower nominal power level to the advantage of higher conversion efficiencies and lower emissions of dust-pollutants, has now totalled about 500 hours of near-continuous operation, including many hours in parallel with the mains, without showing any major technical hitches. Of course, further testing campaigns are required in order to better assess and to improve the single components' contributions to the overall performance. Among others, two main issues are still open and call for a deeper investigation: the product-gas shows, at the gasifier exit, an excessive amount of fine char-particulates hardly separable by the cyclones and, at internal combustion engine intake, too high temperatures, less compatible with a proper power generation by the engine itself.
The latest R&D efforts are exactly addressed toward these directions.

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References

[1] E. Stirling, “The History of the Gas Light and Coke Co. 1812-1949”, A&C Black, Publishers, London (Reprinted 1992), Limited for the London Gas Museum, ISBN 0-7136-3664-5

[2] H.A.M. Knoef, “Handbook Biomass Gasification”, Gasnet, BTG Publ., Enschede (2005), ISBN 90-810068-1-9, pp. 23-25

[3] T.B. Reed, A. Das, “Handbook of Biomass Downdraft Gasifier Engine Systems”, Solar Energy Research Institute, Golden (1988), SERI/SP-271-3022, DE88001135, pp. 43-45

[4] D. Accornero, M. Caruggi, A. Nilberto, F. Pittaluga, “Un nuovo impianto di produzione elettrica da 800 kW da gassificazione delle biomasse”, Proc. 66th Italian National ATI Congress, Rende (CZ), Sept. 2011

[5] M. Caruggi, A. Nilberto, F. Pittaluga, “Parametric experim. performance analysis of a downdraft gasifier for varying biomass mixtures”, Proc. First National SIBA Congress, Soc. Ital. per le Bioenergie e l'AgroIndustria, Salerno, Oct. 2007

[6] M. Caruggi, A. Nilberto, F. Pittaluga, “Exp. Characterisation of a Small Downdraft Gasifier Fed with Woodchar/Woodchips Mixtures", 15th European Biomass Conference, Poster Session, Berlin, 7-11 May 2007

[7] M. Caruggi, P. Formosa, A. Nilberto, F. Pittaluga, “Thermal Treatments for Improving Biomass Gasification”, Proc. IRPHE-ECM-CNIM Joint Research Workshop, Marseille, May 2008

[8] D. Accornero, A. Nilberto, F. Pittaluga, “Wood downdraft-gasification: integrated agronomic-technological provisions to increase bio-syngas quality and production efficiency”, Proc. Second National SIBA Congress, Soc. Ital. per le Bioenergie e l'AgroIndustria, Rome, May 2009.

[9] D. Accornero, E. Manzino, F. Pittaluga, “Rapid-Growth Forestation Techniques and Wood Thermal Pre-Treatments for Enhanced Energy Generation”, Central European Biomass Conference, Graz, Jan.26-29, 2011

[10] GEK ‘TOTTI’ Gasifier, “Catalog_092011.pdf”, All Power Labs, www.gekgasifier.com , 2011

[11] F.Fock, K.P.B.Thomsen, “Modelling a biomass gasification system by means of EES”, Proc. SIMS 2000 Conference, TUD, Lyngby, Sept. 18-20, 2000

[12] C.P.G. Analytical Laboratories, Cairo M., www.cpg.it