Fluidized Bed Gasification of a Natural Biomass: a Process Performance Comparison of Two Design Configurations

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1. ABSTRACT

A comparison between the most promising design configurations for the industrial application of gasification based, biomass-to-energy cogenerators in the 100-600kWe range is presented. Mass and energy balances and material and substance flow analyses drawn for each design solutions are based on the experimental data obtained from a pilot scale bubbling fluidized bed air gasifier. The technical performances of two energy generation devices, a gas engine and an externally-fired gas turbine, have been estimated.

2. INTRODUCTION AND FRAMEWORK

The possible utilization of the biomass energy content gained a great interest in the last decade, because of its potential to displace a large part of conventional fossil fuel for electricity production. A large amount of energy is potentially available from biomass, since sources that can be used for energy production cover a wide range of materials (wood and wood waste, agricultural crops and their waste by-products, organic fraction of municipal solid waste, etc.). Different gasification technologies are today available to convert biomass in a syngas able to provide a wide range of products, extending from clean fuel gas and electricity to bulk chemicals [1-3]. Fluidization is the most promising among all biomass gasification technologies, for a series of attracting reasons, such as the possibility to utilize different fluidizing agents, reactor temperatures and gas residence times, to inject reagents along the reactor height and to operate with or without a specific catalyst [4].

The aim of this study is to evaluate and compare the process performance of the most promising design configurations for the small scale industrial application of gasification-based biomass-to-energy cogenerators. To this end, a number of tests with a selected natural biomass was carried out in a pilot scale bubbling fluidized bed gasifier (BFBG). The collected experimental data were processed in order to obtain information useful to define design solutions and configurations suitable for different electricity generation devices. The energy conversion devices for the range of electric output of interest, among all those commercially available, are then analyzed and selected. The technical performances of the best two plant configurations are finally described in details and compared.

3. THE PILOT SCALE FLUIDIZED BED GASIFIER

The utilized pilot scale was a bubbling fluidized bed gasifier (BFBG) of about 500kWe nominal capacity. An olivine - a magnesium-iron silicate, $(Mg,Fe_2)SiO_4$ - was selected as material for the

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fluidized bed on the basis of results of previous investigations carried out on the same pilot-scale BFBG [5] and those reported on the scientific literature [6]. In the reported experiments, air was used as reducing agent and always injected at the bed bottom while the fuel was always fed by means of an over-bed feeding system. The fuel and blast flow rates were mutually adjusted so that, at the fixed fluidizing velocity, the desired equivalence ratio ER was obtained (where ER is defined as the ratio between the oxygen content of air supply and that required for the stoichiometric complete combustion of the fuel effectively fed to the reactor). The gas generated in the reactor was sent to the syngas cleaning section composed of a high efficiency cyclone and a wet scrubber (for the removal of tars, residual fly ashes and acid gases) and finally incinerated by a safety flare. An accurate description of the plant and of experimental procedures is provided elsewhere [7].

4. THE CONFIGURATIONS OF THE BIOMASS-TO-ENERGY SYSTEM

Table 1. Characteristics of the biomass fuel

Ultimate analysis, %	
C	45.3
H	5.6
N	0.5
S	0
Moisture	9.0
Ash	1.2
O (by difference)	38.4
LHV as received, kJ/kg	15700

The configurations of the gasification based, biomass-to-energy system investigated in this study were defined on the basis of the following design specifications. The plant is designed to be fed with a natural biomass: a commercially available beechwood for domestic heating, having the chemical characteristics reported in Table 1. The process is designed to produce electricity, even though additional thermal energy is available to use in case a demand is present at the installation site. The electrical size range of interest is that of small scale plants, between 100-600kWe. This leads to individuate the atmospheric bubbling fluidized bed air gasification as the conversion process to be adopted [4].

The design configurations for the industrial application of gasification plants in the range of interest can be sketched as a combination of three sections: syngas production, syngas cleaning and syngas utilization. The first defines the syngas that can be produced and then, for fixed biomass fuel and gasification technology, the quantity and quality of this syngas. The syngas utilization section indicates the syngas that can be utilized in a specific energy conversion device and then, for a given machinery (steam turbine, gas engine, internally or externally fired gas turbine), its temperature, heating value and cleaning level (i.e. tar and dust content but also that of alkaly and inorganic contaminants). The cleaning section must combine the characteristics of the produced syngas and those required by the specific generator set

The gasification section has been designed on the basis of an experimental activity carried out on the pilot scale BFBG operated under autothermal conditions, i.e. with the only external heat addition being provided for the pre-heating of the reducing and fluidizing air stream. The reactor was operated with the natural biomass, in a bed of olivine particles fluidized at a velocity of 0.6m/s, a bed temperature of about 850°C, an air preheating temperature of 545°C and with an equivalence ratio ER of 0.28. The performances of the BFBG were measured and recorded only when the chemical composition of the produced syngas and the temperature profile along the reactor reached stedy-state conditions (Table 2). The obtained results have been combined with a recently defined environmental assessment tool, the Material Flow Analysis, which is named Substance Flow Analysis when it is referred to a specific chemical species. MFA/SFA is a systematic assessment of the flows and stocks of materials and elements within a system defined in space and time. It connects the sources, the pathways, and the intermediate and final sinks of each species in a specific process [8]. The quantified flow diagrams reported in Figure 1 are the result of the MFA/SFA applied to the main process units (gasifier, cyclone, wet scrubber, water treatment system) of the pilot scale gasification system. Each flow in entrance to or in exit from a specific unit is identified by means of a black arrow if the specific data have been measured or fixed, or by a grey arrow if the data have been obtained by means of MFA/SFA. The layer of total mass flow rate is reported in Fig.1A. The input flows to the BFBG unit are the stream of biomass fuel, that of a small flow rate of nitrogen utilized to facilitate the fuel injection and that of air used as reducing agentand fluidizing gas. The output flow stream is the obtained syngas (14% CO_2, 17.9% CO, 12.3% H_2, 3.9% CH_4, 1.2% C_nH_m and the rest N_2) which still contains heavy hydrocarbons, inorganic pollutants and entrained fines. The dirty syngas is sent to the cyclone for dust abatement and then to the wet scrubber for removal of tars and inorganic compounds. The specific production of syngas is equal to 2.45kg_{syngas}/kg_{fuel} (i.e. 2.1$m^3_{N,syngas}/kg_{fuel}$) while that of elutriated fines is 20.9g_{fines}/kg_{fuel}. The stock of 145kg of bed particles is progressively incremented (0.30kg/h) as a result of opposite effects of elutriation losses and fuel ash accumulation.

Table 2. Operating Conditions and Output Process Data	
Operating Conditions	
ER (equivalence ratio), -	0.28
AF (air/fuel ratio), kg_{air}/kg_{fuel}	1.53
Temperature of fluidizing air at gasifier entrance, °C	545
Output Process Data	
Temperature of fluidized bed at thermal steady-state,°C	880
Temperature of syngas at gasifier exit,°C	740
Q_{syngas}, m^3_N/kg_{fuel}	2.1
LHV_{syngas}, kJ/m^3_N	5900
Specific energy, kWh/kg_{fuel}	3.4
CGE (cold gas efficiency), -	0.77
Entrained carbon fines, $g_C/kg_{C\text{-}fuel}$	31.2
PAH, mg/m^3_N	2300
HCl, mg/m^3_N	13
H_2S, mg/m^3_N	1
NH_3, mg/m^3_N	16

The experimental activity provides the complete chemical composition of streams leaving the cyclone and the water treatment system. These data have been used for the substance flow analysis of carbon [9] and for the feedstock energy flow analysis (Fig. 1B). Figure 1B reports the layer of feedstock energy, i.e. the heat of combustion of each input and output streams: the energy flow entering with the biomass fuel has been determined by means of a relationships recently proposed and validated specifically for biomass fuels [10], while the energy flows of exit streams have been evaluated on the basis of the heats of combustion of the specific substances. The resulting difference in feedstock energy, 151MJ/h, is that "invested" at the steady-state condition to convert the solid biomass in a gaseous fuel. Reported data allow to evaluate the cold gas efficiency CGE, defined as the ratio between the chemical energy of obtained syngas and that of injected fuel: the value of 0.765 is mainly determined by the chemical energy utilized inside the gasifier (19.5%) and, for a smaller fraction, by the fraction of feedstock energy lost with the entrained fines (3.2%) and with the heavy hydrocarbons of the purge stream from the water treatment system (0.8%). These results suggest two possible design solutions: the make-up of bed olivine particles and the recycle of entrained fines. These data were finally combined with relationships of fluidization engineering [11] in order to determine the main geometrical parameters of the gasification section.

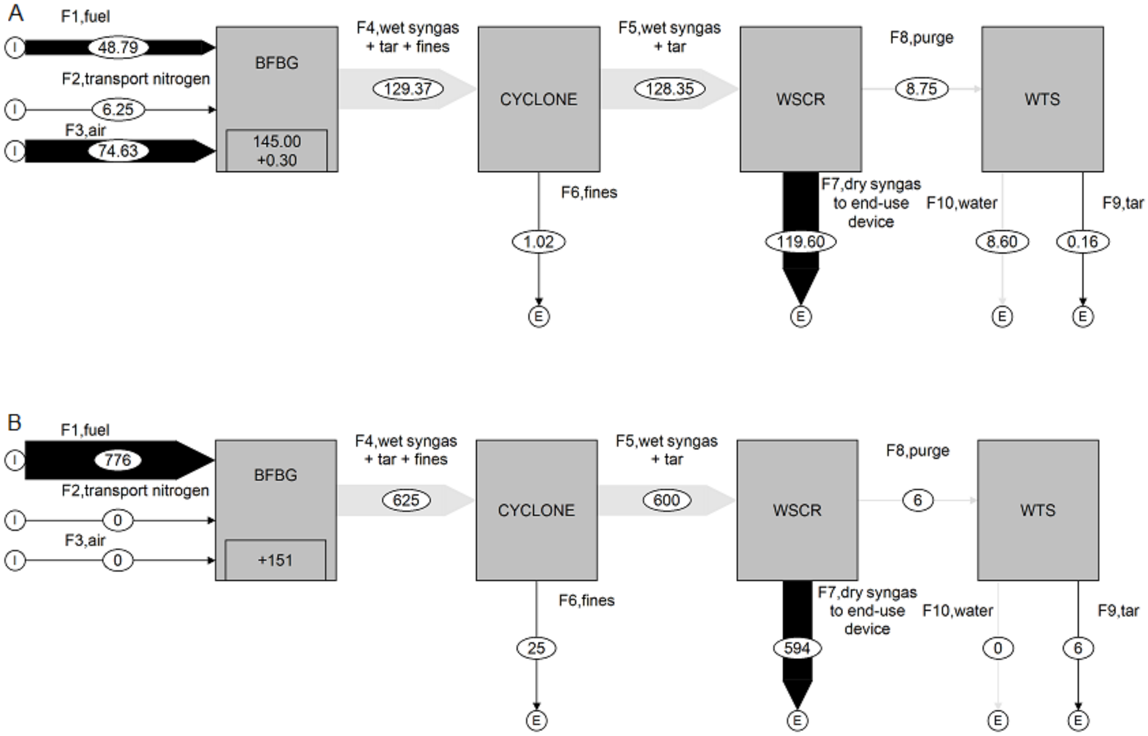

Figure 1. Layers of mass and energy balances throughout the pilot scale gasifier: A) total mass (kg/h); B) feedstock energy (MJ/h).

The possible devices that can be used in **the electricity generation section** have been compared and for each of them have been taken in account its advantages and disadvantages when coupled with a BFB gasifier. The steam turbine and boiler combination has its main positive feature in insuring that the expanding fluid is completely isolated from the syngas combustion fumes, therefore avoiding the corrosion, fouling and plugging of the rotating parts, but commercially available steam turbines in the size range considered for this study have an extremely low net electrical efficiency [10-20%] and additionally require a large condenser if the steam cycle is to be run in a closed loop configuration [12]. The intensive capital costs and the limited performance of the boiler and steam turbine configuration lead to the exclusion of this solution as a viable one. Another combination that was not further analyzed is that with an internal combustion gas turbine. Although internal combustion gas turbines offer very good net electric efficiency across small size ranges, the direct combustion and expansion of the syngas and its fumes into the turbomachinery poses technical difficulties. In fact, decontaminating the syngas of particulate, tar, alkali and acids to manufacturer's specification if often unfeasible due to incongruent costs of the equipment for the size range of the installation. Conversely, designing for costs can lead to residual contamination that fails to meet manufacturer's specifications which can cause unpredictable shortening of life or major failures of the machinery. Recently a customization of the basic gas turbine machine has been readied for commercialization that overcomes the main problems associated with internal combustion gas turbines. This configuration is named either externally-fired gas turbine or hot-air gas turbine, since the working fluid is ambient air and the heat addition happens in a gas-gas high temperature exchanger [13]. The separation of the working fluid from the combustion fumes assures that the rotating parts are not deteriorated, fouled or plugged, as for a steam turbine, while the use of the exhaust clean hot air from the turbine outlet as the oxidizing gas in the syngas combustion, assures that high thermodynamic efficiencies are achieved. The last solution that has been investigated is a syngas optimized high efficiency alternating engine. This type of engine is a proven technology that yields high electrical efficiency but has somewhat stringent requirements on both purity and technical conditions for the syngas supply [14]. In the case of the gas engine setup though, the decontamination of the syngas can be achieved with a sufficiently inexpensive equipment, an aspect that renders the solution viable and competitive. In fact, the engine based installation is usually regarded as the standard against which other alternatives have to be compared in terms of electrical and economical efficiency.

On the basis of the preliminary selection process illustrated above, **the cleaning section** has been designed for the two most promising plant configurations. The relative succession of the utilization and cleaning sections depends on the two possible types of biomass-to-energy gasification system that can be adopted: for the gas engine configuration is a tipical "power gasification" being the producer gas first cleaned then burned, while for that with the gas turbine it is a "heat gasification" where the syngas is first burned then cleaned [15]. In the first case the cleaning section (air preheating heat exchanger, dissipator, scrubber, chiller and demister) works as an interface between the characteristics of the producer gas and those required by the specific generator set. In the second case, downstream of the gasifier there is a combustion and heat recovery section that consists of a possible pre-treatment of the syngas to remove contaminants before it goes into the combustor, a high temperature heat exchanger, and, above all, an air-pollution control system for flue gas cleaning.

5. PROCESS PERFORMANCE COMPARISON

On the basis of considerations reported above, the process flow diagrams for the gas engine and for the externally fired gas turbine plant configurations have been defined (Figure 2). Both are composed by three sections: the gasification, cleaning and electricity generation. Although the two alternative configurations are based on the same gasification section, modelled on the basis of experimental data, they nonetheless differ in their energetic and environmental performance, as simulated on the basis of mass and energy balances and of the performance data claimed by manufacturers [16]. Comparing the two plants on the basis on one aspect of their performance alone, e.g. their overall energy conversion efficiency, might be reductive since this would overlook other equally important aspects of the operation of power generation systems, such as their environmental burden and ease of conduction. On one hand, the gas engine solution offers higher global efficiency (about 27%) due to the performance of the generator set and a lower capital cost, but has a generally lower availability and higher maintenance costs [12, 13]. Moreover, it requires a suitable treatment unit for the waste water from the scrubber purge that is contaminated by tars, particulate and inorganics. On the other hand, the externally-fired gas turbine solution has a less efficient process (about 23%) due to intrinsic thermodynamic limits and, for a less extent, to some losses inherent to the heat exchanger steps it embeds and a higher initial investment costs. The EFGT has a higher annual availability (about 3% more) and must dispose a solid waste stream (coming from APC unit) instead of a liquid one (coming from the wet scrubber unit), even though the advantage of the lack of an onerous water treatment system is balanced by the disadvantage of a very larger mass of flue gases to be treated at the stack. Moreover, the EFGT configuration has a lower specific biomass conversion rate, which results in a larger fuel feed rates, even though it can offer a more cogenerative capability, which is related to the higher temperature of the stack gas (313°C instead 145°C).

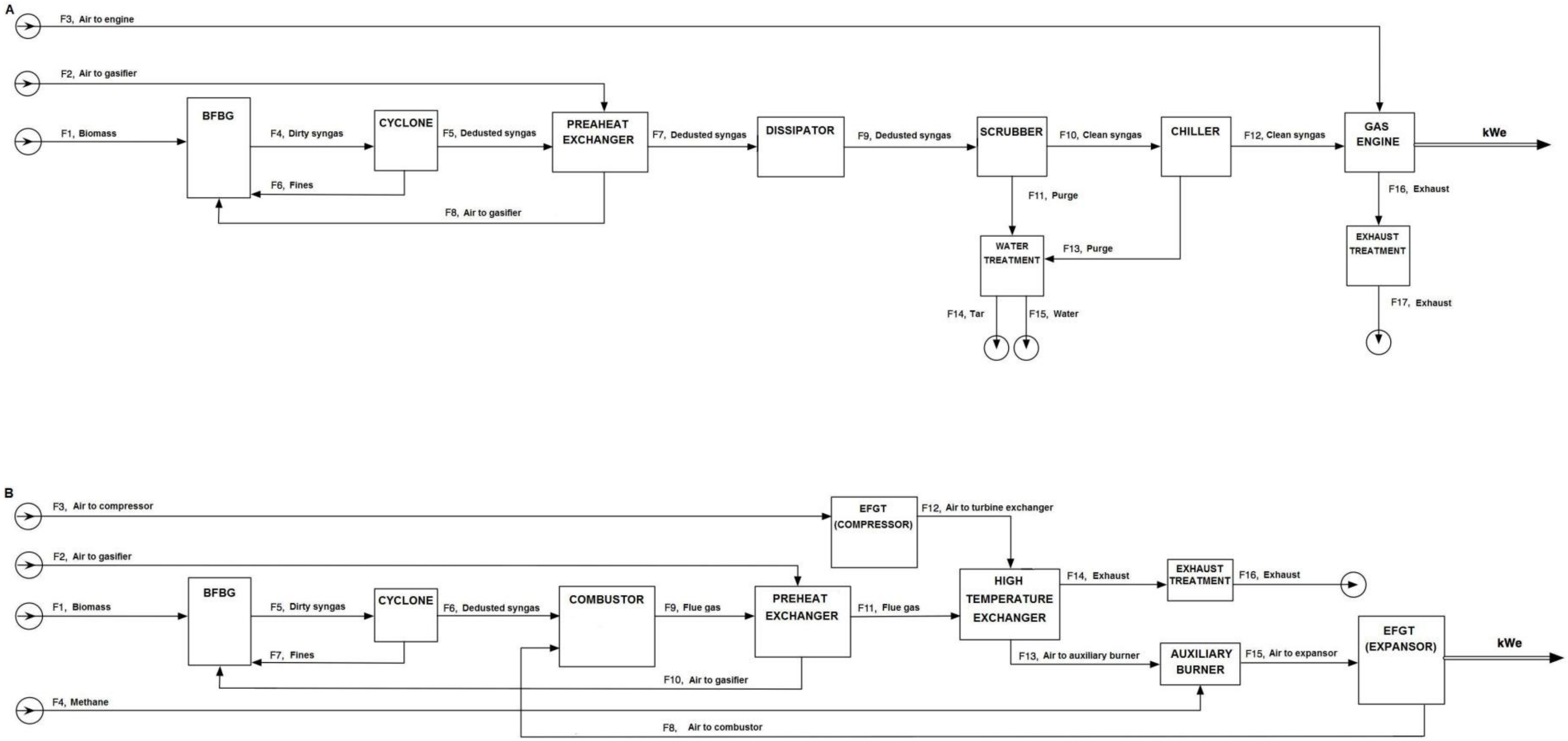

Figure 2. The process flow diagrams for the gas engine (A) and the externally fired gas turbine (B) configurations.

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