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Effects of upgrading systems on energy conversion efficiency of a gasifier - fuel cell - gas turbine power plant

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ABSTRACT

This work focuses on a DG-SOFC-MGT (downdraft gasifier - solid oxide fuel cell - micro gas turbine) power plant for electrical energy production and investigates two possible performance-upgrading systems: polyphenylene oxide (PPO) membrane and zeolite filters. The first is used to produce oxygen-enriched air used in the reactor, while the latter separates the CO_2 content from the syngas. In order to prevent power plant shutdowns during the gasifier reactor scheduled maintenance, the system is equipped with a gas storage tank. The generation unit consists of a SOFC-MGT system characterized by higher electrical efficiency when compared to conventional power production technology (IC engines, ORC and EFGT). Poplar wood chips with 10% of total moisture are used as feedstock. Four different combinations with and without PPO and zeolite filtrations are simulated and discussed. One-year energy and power simulation were used as basis for comparison between all the cases analyzed. The modeling of the gasification reactions gives results consistent with literature about oxygen-enriched processes. Results showed that the highest electrical efficiency obtained is 32.81%. This value is reached by the power plant equipped only with PPO membrane filtration. Contrary to the PPO filtering, zeolite filtration does not increase the SOFC-MGT unit performance while it affects the energy balance with high auxiliary electrical consumption. This solution can be considered valuable only for future work coupling a CO_2 sequestration system to the power plant.

1. Introduction

Due to the abundant availability and distribution, biomasses hold key-roles in plans for renewable energy production. This trend is becoming even more relevant thanks to the good degree of reliability and efficiency of the biomass-based technologies together with the high subsidies granted by several government for sustainable electrical energy production [1].

Depending on the feedstock quality and availability, biomasses are converted into energy through different technologies. In the case of ligno-cellulosic biomasses, a technolgy of great validity is gasification. This thermo-chemical process turns solid biomass into a gaseous fuel known as syngas, which can be converted into electrical energy through all those systems used for power production from gaseous fuels [2]. Gasification is today one of the most efficient technologies to convert wood into electricity and it is also sustainable in terms of the environmental balance of CO_2 [3,4].

Most of the gasification power plants use an IC engine-generator to convert the syngas chemical energy into electrical power. However, in some cases other conversion machines are used, i.e. Organic Rankine Cycles (ORC), External Firing Gas Turbines (EFGT) [5] and Stirling engines are used with the major advantage of having minor limitation about the syngas level of purification [2,6–9]. These systems are usually characterized by low conversion efficiencies of about 10–12%. Major conversion rates can be obtained only with electrochemical devices such as proton exchange membrane fuel cells [10], Molten Carbonate Fuel Cells (MCFC) [11,12], Solid Oxide Fuel Cells (SOFC) [13–15], systems composed of SOFC and Micro Gas Turbines (MGT) [16–26] and systems composed of SOFC-MGT-ORC [27]. Despite the high rate of energy conversion, these systems require perfectly clean syngas [28]. Downdraft gasifiers are the most suitable architecture due to the low tar and particulate content in their gas when compared to updraft, crossdraft or fluidized bed gasifiers [2,6,29]. However, downdraft gasifiers commonly use air as gasification agent. This solution generates a syngas with a low calorific value where the hydrogen, methane and carbon monoxide are diluted in non-burnable gases: N_2 (about 50%) and CO_2 (from 10% to 20%). Otherwise, it is possible to choose oxygen gasification that produces a syngas with negligible N_2 content. However, oxygen gasification is a complex and expensive technology due to the

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Nomenclature

$\dot{m}$	mass flow [kg/s]
$\dot{n}$	molar flow [mol/s]
τ	time [s]
ASH	ash content of the biomass [%]
B	Langmuir constant [1/kPa]
C	carbon
C_p	specific heat [J/(mol K)]
DG	downdraft gasifier
e	electron
EFGT	external firing gas turbine
ER	equivalence ratio [ad]
H	hydrogen
H_T	enthalpy [kJ/kmol]
HF^0	standard heat of formation [kJ/kmol]
HHV	higher heating value [MJ/Nm^3 or MJ/kg]
IC	internal combustion
K	equilibrium constant [ad]
L	work [kJ]
M	total moisture content of the biomass [%]
m	specific molar amount of oxygen [mol/mol$_{bio}$]
m_{tar,Nm^3}	volumetric tar amount [g/Nm^3]
MCFC	molten carbonate fuel cell
MGT	micro gas turbine
MW	molecular weight [g/mol]
N	nitrogen
n	specific molar amount of gases and tar [mol/mol$_{bio}$]
O	oxygen
ORC	organic rankine cycle
P	power [kW]
p	pressure [atm]
PDSM	polydimethylsiloxan
PPO	polyphenylene oxide
Q	molar flow [mol/s]
q	adsorbed amount [mmol/g]
R	universal gas constant [J/(mol K)]
SOFC	solide oxide fuel cell
T	temperature [K]
t	time [s]
V	volume [m^3]
w	specific molar amount of biomass moisture [mol/mol$_{bio}$]
x	molar fraction
y	molar fraction
z	polytrophic coefficient
ZEO	zeolite
α	selectivity
Δ	difference
γ	permeability [mol m^{-2} s^{-1} bar^{-1}]
ϕ	pressure ratio

Subscripts

ads	adsorption
ar	as received
bio	biomass
comp	compressor
daf	dry ash free
db	dry basis
g	gas
in	inlet
m	saturation
out	outlet
P	permeate
p	hydrogen coefficient of tar
prod	product
q	oxygen coefficient of tar
R	retentate
react	reactant
s	storage
x	hydrogen coefficient of the biomass
y	hydrogen coefficient of the biomass
z	nitrogen coefficient of the biomass

gasification agent supply sub-systems and reactor material choice. Indeed, temperatures inside the reactor can reach 1200–1300 K when oxygen is used instead of air [30].

The basic system discussed in this study is composed of an air blown-downdraft-fixed bed gasifier fed with poplar wood chips. This work is aimed at investigating the effects of different power plant designs on the overall energy conversion efficiency.

The first power plant upgrading sub-system consists of a polyphenylene oxide (PPO) membrane used to produce oxygen-enriched air. The gas separation characterization of this membrane is reported in literature [31,32]. In practice, membrane gas separation is applied to increase the oxygen content in the inlet air of biomass boilers [33]. Bisio et al. studied the thermodynamics of combustion with enriched air and reviewed several types of membranes [34]. Coombe and Nieh developed a membrane-based device for air enrichment in small scale burners [35]. Hao et al. applied an oxygen-permeable membrane to a reactor for the co-production of dimethyl ether (DME)/methanol and electricity [36]. This paper uses PPO membrane in order to obtain air with about 50% of oxygen then used as gasification agent. This solution is a hybrid between air and pure oxygen gasification. Enriched air reduces the reactor thermal stress compared to pure oxygen gasification, while the syngas has a lower N_2 content than the one obtained in pure air gasification. In addition, the syngas flow rate decreases because, for a fixed power output, the enriched air flow required for gasification is lower than air used in conventional gasification. This happens because the same amount of oxygen is used in both cases and its concentration in enriched air is higher than untreated air. Finally, the tar production is lower than air gasification as consequence of the higher temperature that cracks more efficiently the primary tars from pyrolysis [37].

A second solution discussed in this work consists of a porous media used to upgrade the syngas. In fact, syngas has a variable CO_2 content depending on gasification process as well as several boundary conditions. This value ranges from 10% to 30% and it reduces significantly the higher heating value of the syngas [37]. A solution to overcome this issue is to adopt a pressure-swing selective synthetic zeolite filter. This system is placed before the gas storage in order to separate carbon dioxide from syngas [38,39]. The filter can be constantly regenerated using a rotary valve packaged into modules as described by Tagliabue et al. [40]. Literature investigation about zeolite filtration outlines several works. Bacsik et al. studied the biogas CO_2-CH_4 separation through zeolites [41]. Kacem et al. investigated the pressure swing adsorption for CO_2/N_2 and CO_2/CH_4 separation using activated carbon and several types of zeolites [42]. Dirar et al. investigated intrinsic adsorption properties of CO2 on 5A and 13X zeolite [43].

The syngas obtained from gasification is stored and then used in a SOFC unit able to produce electrical and thermal energy. The number of stacks within the cell is optimized taking into account the optimal electrical current density. The chosen number guarantees a good efficiency, however the gas discharged from the cell