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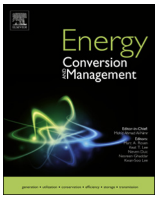

Performance analysis of a biomass powered micro-cogeneration system based on gasification and syngas conversion in a reciprocating engine

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ABSTRACT

The present paper describes an experimental characterisation of a biomass powered micro-cogeneration system based on the coupling between a gasifier and an internal combustion engine. The ECO 20 unit is sized to deliver a maximum electrical and thermal power of 20 kW_e and 40 kW_{th}, respectively. In order to highlight possible inefficiencies along the biomass-to-energy conversion chain, the global energy balance of the system under real working conditions is derived. Ultimate and proximate analyses of the processed biomass are performed, accompanied by temperature and mass flow rate measurements and gas chromatograph characterization of collected samples of the produced syngas. The greatest inefficiency is found in the gasification section with a value of the cold gas efficiency in the range of 57–60%. The low quality of the syngas (lower heating value equal to 3731 kJ/Nm^3) affects the engine combustion efficiency, hence its electrical efficiency that does not exceed 22.5%. The global electrical efficiency of the plant is equal to about 13.5%. As a further analysis, waste heat recovery is considered under different conditions by decreasing the temperature of the water flowing in the secondary circuit from 68.35 °C to 20.50 °C for the use of the provided thermal energy. This determines an increase of the thermal efficiency of the engine from 11.3% to 56.2%, while the global thermal efficiency increases from 6.46% to 33.72%. A feature of the ECO 20 system is the cooling of the syngas delivered to the engine by its same cooling water, for a considerable advantage on volumetric efficiency with respect to other analogous systems, also in the cases the thermal power is not utilised.

1. Introduction

The strict and unavoidable link between climate and energy has become a paradigm for development policies worldwide since it was recognised that a significant increase in energy demand due to the lifestyle of industrialized countries caused an extensive use of fossil fuels [1]. Their wide employment has determined uncertainty about continuous availability and supply, but also awareness that just the processes for their energy conversion are major causes of greenhouse gas (GHG) emissions and related global warming.

In this contest, European Union (EU) leaders have endorsed an energy policy aimed at mitigating climate change and assuring energy security. Recently, EU agreed on a new 2030 Framework for climate and energy, including EU-wide targets for the period between 2020 and 2030 [2]. The 2030 climate and energy framework sets three key targets for the year 2030, namely, at least 40% cuts in greenhouse gas emissions (from 1990 levels); at least 27% share for renewable energy; at least 27% improvement in energy efficiency.

Resorting to bioenergy systems is perfectly in line with the series of compulsory indications and regulations previously cited to counteract the extremely harmful effects of climate change on human living and wellness.

Cogeneration, or combined heat and power (CHP), is defined as the simultaneous generation of two different forms of useful energy by a single primary source [3]. CHP technologies based on the process of gasification of biomasses have been developed intensively over the past years [4] and their technical, economic and environmental performances have been so far analysed by many researchers. A common conclusion is that gasification is attractive as it provides more diverse forms of energy and less environmental pollution than conventional combustion. The scale of the plant, however, significantly affects the profitability of related investments and barriers must be faced by

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Nomenclature

Variables	SI (unit)
A/B_{stq}	Air/biomass stoichiometric ratio (–)
A/S_{stq}	Air/syngas stoichiometric ratio (–)
c_{pair}	Specific heat capacity at constant pressure of air (kJ/kg K)
c_{ash}	Specific heat of ash (kJ/kg K)
$c_{liquid\ \ H2O}$	Specific heat of the liquid water (kJ/kg K)
$c_{p\ \ vapour\ \ H2O}$	Specific heat at constant pressure of the vapour water (kJ/kg K)
$c_{p\ \ exh}$	Specific heat at constant pressure of the exhaust gas (kJ/kg K)
D_{IC}	Displacement (cm^3)
h_i	*i*-th species enthalpy of the syngas for $i = H_2$, N_2, CO, CH_4, CO_2, C_2H_6 (kJ/kmol)
$l_{vaporization}$	Latent heat of vaporization of pure water at 100 °C atmospheric pressure (kJ/kg)
LHV_{bio}	Lower heating value of biomass (kJ/kg)
LHV_{char}	Lower heating value of char (kJ/kg)
LHV_i	Lower heating value of *i*-th species of syngas for $i = H_2$, CO, CH_4, C_2H_6 (kJ/Nm^3)
LHV_{syn}	Lower heating values of the syngas (kJ/Nm^3)
$\dot{m}_{air}$	Air mass flow rate (kg/s)
$\dot{m}_{ash}$	Ash mass flow rate (kg/s)
$\dot{m}_{bio}$	Mass flow rate of the biomass entering into the gasifier (kg/s)
m_c	Biomass carbon content (kg_C/kg_{bio})
$\dot{m}_{char}$	Char mass flow rate (kg/s)
$\dot{m}_{exh}$	Mass flow rate of exhaust gases (kg/s)
$\dot{m}_{H2OI^{\circ}}$	Water jacket mass flow rate (kg/s)
$\dot{m}_{H2OII^{\circ}}$	User water mass flow rate (kg/s)
$\dot{m}_{moisture}$	Mass flow rate of biomass moisture (kg/s)
MW_{syn}	Molecular weight of the syngas (kg/kmol)
n	Revolutions per minute of ICE (rpm)
P_{air}	Biomass thermal power entering gasifier (kW_{th})
P_{ash}	Thermal power related to unconverted carbon losses (kW_{th})
P_{bio}	Biomass thermal power entering gasifier (kW_{th})
P_{char}	Thermal power related to unconverted carbon losses (kW_{th})
P_{cooler}	Thermal power transferred to the water in the cooler (kW_{th})
P_{drying}	Thermal power of exhaust gases used for drying the biomass in the reactor (kW_{th})
P_{el}	Electrical power engine (kW_{el})
P_{exh}	Thermal power available in the exhaust gases (kW_{th})
P_{Jacket}	Water in the jacket circuit engine thermal power (kW_{th})
$P_{loss\ \ engine}$	Thermal power losses through the engine (kW_{th})
$P_{loss\ \ heat}$	Thermal power losses through the reactor walls (kW_{th})
P_{PHE}	Thermal power of water sent to user into the plate heat exchanger (kW_{th})
P_{STHE}	Thermal power of water sent to user in the shell and tube heat exchanger (kW_{th})
P_{syn}	Total syngas thermal power (kW_{th})
$P_{syn\ \ sensible}$	Sensible syngas power (kW_{th})
$P_{syn\ \ useful}$	Useful syngas power (kW_{th})
P_{water}	Power related to the vaporization of moisture biomass (kW_{th})
P_{water1}	Power related to the vaporization of moisture biomass in the range $T_{ref} - 100\,°C$ (kW_{th})
P_{water2}	Power related to vaporization of pure water at 100 °C (kW_{th})
P_{water3}	Power related to the vaporization of moisture biomass in the range $100\,°C - T_{syn}$ (kW_{th})
T_{air}	Temperature of the air that enters the reactor (K)
$TK1$	Thermocouple upper part of the reactor (core) (K)
$TK2$	Thermocouple lower part of the reactor (K)
$T_{K\ \ A\ \ in}$	Temperature input secondary circuit water side for shell and tube heat exchanger water/exhaust gas (K)
$T_{K\ \ A\ \ out}$	Temperature output secondary circuit water side for shell and tube heat exchanger water/exhaust gas (K)
$T_{K\ \ F\ \ in}$	Temperature input exhaust gas side for shell and tube heat exchanger water/exhaust gas (K)
$T_{K\ \ F\ \ out}$	Temperature output exhaust gas side for shell and tube heat exchanger water/exhaust gas (K)
$T_{K\ \ F\ \ M}$	Temperature input reactor (K)
$T_{K\ \ ic\ \ in}$	Temperature input syngas into the cooler (K)
$T_{K\ \ ic\ \ out}$	Temperature output syngas into the cooler (K)
$T_{K\ \ MOT\ \ in}$	Temperature input primary circuit water side of the engine (K)
$T_{K\ \ MOT\ \ out}$	Temperature output primary circuit water side of the engine (K)
$T_{K\ \ P\ \ n}$	Temperature water inlet secondary circuit in the plate heat exchanger (K)
$T_{K\ \ RAD\ \ in}$	Temperature input primary circuit water side of the radiator (K)
$T_{K\ \ RAD\ \ out}$	Temperature output primary circuit water side of the radiator (K)
T_{ref}	Reference temperature (K)
T_{syn}	Temperature of the syngas leaving the reactor (K)
$\dot{V}_{syn}$	Volumetric flow rate (m^3/s)
y_i	Volume fraction of *i*-th species of syngas for $i = H_2$, CO, CH_4, C_2H_6 (v/v)

Acronyms/abbreviations

A	Ash content in the proximate analysis
BL1	Blower intake air flare
BL2	Blower inlet flare gas
CGE	Cold gas efficiency
CHP	Combined Heat and Power
CMD	Costruzioni Motori Diesel
CHP	Combined Heat and Power
CNR-IM	Consiglio Nazionale delle Ricerche - Istituto Motori
DD	Downdraft gasifier
EC	European Community
EGR	Exhaust Gas Recirculation
EN	Referred to European Committee for Standardization
EU	European Union
FBG	Fluidized bed gasifiers
FC	Fix Carbon in the proximate analysis
FICFB	Fast internal circulating fluidised bed
GHG	Greenhouse gas
GL1	Ignition electrode for triggering reactor
GL2	Ignition sparkplug flare
ICE	Internal Combustion Engine
IoT	Internet of Things
ISO	Referred to International Organization for Standardization
M1	Screw conveyor motor reactor
M2	Screw conveyor motor exhaust reactor ashes
M3	Biomass tank agitator motor
M4	Shaker motor
M5	Screw conveyor motor exhaust ash cyclone reactor
M6	Screw conveyor motor biomass tank
M7	Gate-valve engine
MC	Moisture content in the proximate analysis
mCHP	Micro-CHP
p1	Pressure sensor upper part of the reactor
p2	Pressure sensor lower part of the reactor
p3	Pressure sensor in the biological filter