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Thermodynamic analysis of small-scale externally fired gas turbines and combined cycles using turbo-compound components for energy generation from solid biomass

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ABSTRACT

This paper proposes the implementation of cost-effective commercially available automotive components in small-scale power plants for the energy generation from carbon-neutral biomass. Specifically, a turbocharger and a power turbine of turbo-compound systems are proposed to be coupled with an external combustor and a high temperature heat exchanger in order to obtain a cheap externally fired gas turbine capable of producing about 30 kW of electrical power from the combustion of pruning residues. The externally fired gas turbine cycle can be combined either with a final heat exchanger to generate useful thermal power or with a bottoming cycle to generate useful thermal power and an additional electrical power of about 15 kW. Two plant configurations are proposed for the bottoming cycle: the first is a water Rankine cycle employing the "green steam turbine" as the steam expander, whereas the second is an organic Rankine cycle using an axial turbine and toluene as the working fluid. The results of the simulations, obtained through a detailed thermodynamic model, show that the use of a combined cycle is fundamental to maximize the primary energy savings of the power plant. In the case of negligible pressure losses, the use of a bottoming water Rankine cycle leads to a maximum second law efficiency of about 0.25 and maximum primary energy savings of about 0.23. Instead, a bottoming organic Rankine cycle employing a single stage turbine can increase the second law efficiency and the primary energy savings up to about 0.27 and 0.26, respectively. It is also demonstrated that the use of a two-stage turbine for the organic Rankine cycle can further enhance the plant performance. The effects of the pressure drops in the system are investigated in detail to point out that the minimization of the pressure losses is fundamental to improve the performance parameters of all the proposed configurations.

1. Introduction

As a consequence of the current environmental policy aimed both at limiting the temperature increase to 2 °C compared to pre-industrial levels and at reducing pollutions in the atmosphere [1], a great effort has been put, on one hand, into the improvement of the efficiency of energy-production technologies employing fossil fuels, and, on the other hand, into the development of alternative renewable energy production technologies. Interesting research papers focused on the improvement of the combustion process in an attempt to control emissions (see, e.g., the double injection strategy applied to the gasoline partially premixed compression ignition spark assisted combustion concept [2]). Other research activities dealt with the development of new combustion technologies, also focused on micro power generation systems [3]. Other papers regarded the analysis and development of after-treatment technologies (see, e.g., the influence of structural and operating factors on performance degradation of the diesel particulate filter based on composite regeneration [4]).

However, in addition to improving energy systems fed with fossil fuels, it is crucial to investigate new energy systems representing a viable alternative to conventional ones (see, e.g., [5]). In this regard, the exploitation of wind and solar energy can be more effective if it is supported with more continuous energy sources, such as biomass [6]. Biomass feedstocks can be either converted into biofuels [7] or used directly as solid fuels. Although several advances have been recently achieved in systems for the gasification of biomass [8], the direct use of biomass needs further development in relation to the state of the art.

The energy exploitation of some forms of solid biomass can be considered carbon–neutral if they are properly used. The term carbon-neutral means that the transformation of biomass into useful energy does not alter the overall amount of carbon present in the environment [9]. For example, the combustion of some agricultural or forest residues

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Nomenclature

G	mass flow rate, [kg/s]
H_i	lower heating value, [J/kg]
h	enthalpy, [J/kg]
p	pressure, [N/m^2]
P	power, [W]
s	entropy, [J/kgK]
SP	size parameter, [m]
$\dot{Q}$	thermal power, [W]
T	temperature, [K]
Vr	volume ratio, –

Greek

β	compression/expansion ratio, –
Γ	corrected gas flow, [kg s^{-1} K$^{1/2}$ Mpa^{-1}]
Δ	difference
ρ	density, [kg/m^3]
η	Efficiency, –

Subscripts

a	air
abs	absorbed
b	fuel
cog	cogeneration
E	expander
el	electrical
in	input
is	isentropic
m	mechanical
pp	pinch point
PT	power turbine
ref	reference
T	turbocharger turbine
th	thermal
u	useful
v	vapour
y	hydraulic

Acronyms

BC	bottoming cycle
CHP	combined heat and power
EFGT	externally fired gas turbine
ESP	electro-static precipitator
FHE	final heat exchanger
HRSG	heat recovery steam generator
HTHE	high temperature heat exchanger
IPHE	immersed particle heat exchanger
ORC	Organic Rankine Cycle
RPM	revolutions per minute
TC	topping cycle
VGT	variable geometry turbine
WRC	water rankine cycle

in power plants does not affect the balance of CO_2 in the environment, provided that the biomass is burned on the site where it is produced, thus avoiding the production of additional CO_2 because of fuel transportation, which is commonly achieved by means of vehicles fuelled with fossil fuels [10]. In spite of this opportunity, in several regions the use of direct-combustion power plants fuelled with biomass is not encouraged and incentivized as it should be, mainly because in the past wrong-doing and speculations (e.g., too high temperatures of combustion, inefficient pollution abatement systems, misuse of every form of residuals, etc.) have caused a further increase in pollution (especially $N0_X$ and particulate matter) and concentration of CO_2 in the environment. However, a correct energetic use of carbon-neutral biomass must be regarded as one of the best ways of reducing the dependence on fossil fuels, by virtue of the fact that biomass is potentially the most continuous form among all the alternative sources of energy [6].

In this paper, a sustainable and economical way of generating electrical and thermal energy from carbon-neutral solid biomass, with no need to transform it into Syngas or other biofuels, is proposed. This would result in a significant reduction of capital costs, since the presence of a gasification system would be avoided; as an example, the cost (in Euros) of a small-scale gasification system analysed in [11] was estimated to be 1200 times the mass of fuel per hour. The solid biomass considered in this paper is in the form of pruning residues, whose large availability and potential, especially in the Mediterranean regions, were demonstrated in a previous paper [12]. At the state of the art, the best technology for the conversion of solid biomass into energy is the organic Rankine cycle (ORC) [13]. Interesting studies are available in the scientific literature that provide detailed analysis of ORC applications to high temperature heat recovery [14]. Other studies provide parametric analyses of ORCs to be used for low grade waste heat recovery, such as the parametric optimization and comparative study performed in [15]. The majority of manufacturers produces stand-alone ORC units generating electrical power greater than 100 kWe; however, only few manufacturers construct smaller stand-alone ORCs [16]. The electrical efficiency is usually well below 15% when the generated electrical power is smaller than 100 kWe, but it increases with the size of the plant. As an example, an ORC plant produced by an important manufacturer [17] is capable of generating 200 kWe with an electrical efficiency of about 16.5%.

This paper is focused on the development of an alternative technology to stand-alone ORC units, capable of generating up to about 50 kW of electrical power. Such a small size power plant has the potential to be implemented in proximity of the zone where the biomass is produced [18]; in contrast, higher size power plants (especially from 100 ~ 150 kWe upwards) would require more feedstock supplies in order to satisfy the needed input thermal power, thus making intensive fuel transportation necessary from different supplying zones. For example, a power plant capable of generating an electrical power of 200 kW would require an input thermal power of 1000 kW if the electrical efficiency was about 20%. If that plant was fed with wood biomass with a lower heating value of 19000 kJ/kg, then the mass flow rate of needed feedstock would be about 190 kg/h, which cannot be provided by a single supplying zone.

In order to burn solid biomass effectively in the proposed plant, either a fluidized bed combustor or alternative solutions, such as a moving grid burner, can be used to accomplish this task. Several models of combustors are available on the market that can be used to perform the combustion of solid biomass with excellent efficiencies, as high as 90% [19]. In order to perform an effective maintenance of the combustor for solid biomass, this could be assisted by a more traditional combustor. Concerning the high content of moisture usually present in pruning residues, it could be reduced by naturally drying the feedstock on the fields where the feedstock is produced and, additionally, by using a part of the produced thermal power to this purpose.

The novel idea proposed in this paper consists in using cheap components taken from the automotive industry, without the need for substantial modifications, to produce electrical and thermal energy from the combustion of solid biomass. In particular, commercially