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Novel, cost-effective configurations of combined power plants for small-scale cogeneration from biomass: Design of the immersed particle heat exchanger

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A R T I C L E I N F O

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This paper aims at proposing a general design procedure for the application of the Immersed Particle Heat Exchanger to a novel, small scale, externally fired combined cycle capable of generating electrical and thermal power from carbon-neutral biomass. The Immersed Particle Heat Exchanger serves as the high temperature heat exchanger needed to couple the Brayton cycle with an external combustor of biomass; it is composed of either one module or more modules, with each module being constituted by two heat exchange columns. The combustion gases and the working fluid (clean air) flow separately in the two columns, and ceramic particles are employed as solid intermediate medium to transfer heat between the two columns. Three particle-handling systems, mainly composed of rotary valves coupled with guillotine valves, are conceived in this paper to move the particles within the heat exchanger; analytical models are developed for the design of these systems and for the evaluation of the associated energy losses. A new architecture employing internal cooling channels is also proposed for the two heat exchange columns. In addition, an optimization design procedure, based on the coupling between a computational fluid dynamic model and a genetic algorithm, is developed to correctly select the number of heat exchanger modules as well as the main project parameters, with application to a combined cycle of 110 kW_e with an overall efficiency of about 70%. The numerical results show that the project is highly viable. Only a negligible part of the compressed air is lost because of the particle handling systems (about 0.2%); furthermore, the size of the heat exchanger results to be compact, as the selected optimum is characterized by two heat exchanger modules, with each having an overall height, necessary for the heat exchange, of about 4 m and a maximum diameter of 1.2 m.

1. Introduction

As established by the recent 2015 United Nations Climate Change Conference held in Paris, COP 21, all nations have to promote the employment of renewable technologies in order to reduce the quantity of CO_2 released into the environment. The declared target is to limit the temperature increase to 2 °C compared to pre-industrial levels [1]. To reach this goal, it is very important to develop novel and effective technologies capable of boosting the exploitation of renewable sources [2]. Among these, biomass is the most continuous source of energy [3]; biomass can be used either directly as solid fuel feeding power plants or indirectly after conversion into a secondary form of energy (e.g. syngas and biogas) by using air, oxygen and/or steam [4]. In spite of the several advances achieved in biomass gasification systems [5], the direct use of biomass needs further developments in relation to the stat of the art. Over the past years, the industrial and university research has been focused on the development and improvement in Organic Rankine Cycle (ORC) power plants [6]. These are, at the state of the art, the most widespread and profitable technology for small scale cogeneration (production of heat and power) from biomass [7]. Effective studies have been carried out to optimize the ORC parameters for a wide range of applications [8].

The main problem regarding ORC power plants is the need for organic fluids, which usually have a global warming potential greater than zero and are often toxic and inflammable. For these reasons, rather than focusing on the improvement in the ORC technology, the authors of this paper have been concentrating all their efforts on a different strategy, which aims at proposing a concrete alternative to stand alone ORC plants. The proposed alternative is a

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Nomenclature

c_p	specific heat at constant pressure, [J/(kg K)]
D_{top}	diameter of the top column, [m]
D_{bot}	diameter of the bottom column, [m]
D_r	rotor diameter, [m]
G_a	air mass flow rate, [kg/s]
$G_{a,lost}$	total loss of compressed air, [kg/s]
$G_{a,lost,1}$	loss of compressed air (first contribution), [kg/s]
$G_{a,lost,2}$	loss of compressed air (second contribution), [kg/s]
$G_{a,lost,3}$	loss of compressed air (third contribution), [kg/s]
G_b	fuel mass flow rate, [kg/s]
G_p	particle mass flow rate, [kg/s]
G_s	steam mass flow rate, [kg/s]
H_{top}	height of the top column, [m]
H_{bot}	height of the bottom column, [m]
i	enthalpy, [J/kg]
h	blade height, [m]
h_{int}	height of the internal inlet of the bottom column, [m]
n	rotational speed, [RPM]
n_{mod}	number of IPHE modules
p	static pressure, [Pa]
S_{tot}	overall heat exchange surface, [m^2]
T	temperature, [K]
t	width of the external channel in both columns, [m]
V	volume of the particles discharged per revolution, [m^3]
W	blade width, [m]

Greek

ε_{tol}	tolerance
ξ	coefficient accounting for blade thickness
λ	thermal conductivity, [W/(mK)]
λ_v	filling coefficient
η_{conv}	efficiency of the pneumatic conveyor
η_{IPHE}	efficiency of the IPHE

Subscripts

1	compressor inlet
2	compressor outlet
2′	inlet of the bottom column
3	turbine inlet
5	inlet of the top column
6	outlet of the top column
bot	bottom of the IPHE
top	top of the IPHE
p	particles
press	pressurization system
sim	simulation

Acronyms

CHP	combined heat and power
EFGT	externally fired gas turbines
HRSG	heat recovery steam generator
HTHE	high temperature heat exchanger
IPHE	immersed particle heat exchanger
ORC	Organic Rankine Cycle
PHS	particle handling systems
RPM	revolutions per minute

small-scale combined cycle employing a topping externally fired turbogas cycle followed by a bottoming steam cycle, which is capable of producing useful heat and power from solid biomass. This power plant, which was proposed in [9], has the advantage of using a natural fluid (water) instead of an organic molecule. Furthermore, the main idea is to feed this power plant with carbon neutral biomass and to position the plant on site (where the biomass is produced), thus avoiding the amount of CO_2 released into the environment because of feedstock transportation (an example of carbon neutral biomass is represented by pruning residues, which are usually unemployed in spite of their large availability, especially in the Mediterranean regions [10]). These characteristics make the proposed power plant fully sustainable; in addition, the feasibility in terms of efficiency was addressed in the previous paper [9], which demonstrated that the presented combined cycle has the potential to achieve a high level of electrical efficiency (up to 25%), in addition to being cost-effective. That analysis was performed for a very low size of the plant, namely for a produced electrical power of 100 kW_e. For such a level of electrical power produced from biomass, the electrical efficiency of stand-alone ORC cycles is usually well below 20% [9].

The realization of the proposed combined cycle is made possible by the external combustion configuration, in which the core is a gas to gas heat exchanger capable of coupling the turbogas with the external combustor (to be fed with carbon neutral biomass). With regard to externally fired and/or closed cycle gas turbine configurations, the studies present in the scientific literature mainly deal with the optimization of the thermodynamic parameters of the proposed solutions [11]. As an example, in [12] the optimal thermodynamic parameters were found for a plant with a power generation capacity of 1 MW and incorporating a biomass gasifier using paper as fuel. As a further example, in [13] the coupling between an externally fired gas turbine and a solar collector was investigated in detail.

However, the realization of an externally fired gas turbine (and therefore an externally fired combined cycle) is only allowed by the presence of a gas to gas heat exchanger, but to date the scientific literature has not highlighted effective gas to gas heat exchangers that are also capable of withstanding very high temperatures [14]. This is due to the fact that the design of the gas to gas heat exchanger is not a trivial task, since it must ensure low pressure drops while being capable of withstanding the high temperatures developed by a turbogas cycle. Furthermore, it must be compact and able to guarantee a continuous operation mode. Unfortunately, the realization of a gas to gas heat exchanger having all these characteristics has been proved to be very difficult. Technical solutions provided to date mainly refer to low temperature applications, namely to the design of recuperators for small- and micro-turbines, where the employed low pressure ratios make the heat recovery mandatory. A variety of gas-to-gas recuperators were discussed in [15], in which plate, plate fin, printed circuit, and spiral and tubular heat exchangers were compared, underlining that the only way to reach very high temperatures is to use an intermediate thermal medium, made of ceramic material, first to recover and then to release heat from a high temperature flow to another one. In another study, a wide range of heat exchanger concepts and demonstrators were compared [16], confirming the highest potential of ceramic recuperators compared to the other ones. The main problem is that currently available ceramic heat exchangers either have a non-continuous operation mode or produce too high pressure drops. Two innovative concepts for micro-turbine applications were proposed recently: a ceramic