Energy Conversion and Management 97 (2015) 111–120

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Novel, cost-effective configurations of combined power plants for small-scale cogeneration from biomass: Feasibility study and performance optimization

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ARTICLE INFO

Article history:
Received 8 November 2014
Accepted 12 March 2015
Available online 28 March 2015

Keywords:
Combined heat and power
Biomass
Combined cycle
Gas to gas heat exchanger
Cogeneration

ABSTRACT

The aim of this paper is to demonstrate that, thanks to recent advances in designing micro steam expanders and gas to gas heat exchangers, the use of small combined cycles for simultaneous generation of heat and power from the external combustion of solid biomass and low quality biofuels is feasible. In particular, a novel typology of combined cycle that has the potential both to be cost-effective and to achieve a high level of efficiency is presented. In the small combined cycle proposed, a commercially available micro-steam turbine is utilized as the steam expander of the bottoming cycle, while the conventional microturbine of the topping cycle is replaced by a cheaper automotive turbocharger. The feasibility, reliability and availability of the required mechanical and thermal components are thoroughly investigated. In order to explore the potential of such a novel typology of power plant, an optimization procedure, based on a genetic algorithm combined with a computing code, is utilized to analyze the trade-off between the maximization of the electrical efficiency and the maximization of the thermal efficiency. Two design optimizations are performed: the first one makes use of the innovative "Immersed Particle Heat Exchanger", whilst a nickel alloy heat exchanger is used in the other one. After selecting the optimum combination of the design parameters, the operation in load following mode is also assessed for both configurations.

1. Introduction

Among renewable energy resources, biomass is largely available worldwide and is considered the one with the highest potential impact on the energy development [1]. A wider exploitation of biomass along with ever-increasing improvements in the capture and storage of carbon emitted by fossil fuels combustion plants (see, e.g., the membrane reactor analysed in [2]) can play a key role in preventing global warming. 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 [3]. Because of its lower heating value and difficulties related to collection systems, packaging, transport and storage systems, biomass is best suited to small-scale power plants, where the electricity generation is coupled with the production of useful heat in order to compensate for the low electrical efficiency (typical of small power plants fed by biomass), thus increasing the total efficiency [4].

In addition to increasing eco-efficiency, such Combined Heat and Power (CHP) units for decentralized power generation eliminate the inefficiency of power transmission and distribution typical of centralized energy systems. Small-scale CHP systems with electrical power less than 100 kW_e are also particularly suitable for commercial buildings, hospitals, industrial premises, schools, office building, dwelling houses [5]. The demand for biomass in a small CHP plant can easily be satisfied by materials from surrounding areas, e.g. by exploiting agricultural and forestry residues, by-products of the food industry, residues from wood processing. Examples of how forest and agricultural biomass can be exploited profitably for small-scale energy production are provided in [6].

Despite all the potential benefits, the employment of CHP plants fed by biomass has not been so widespread as expected in those countries having large availability of biomass: apart from the above-mentioned difficulties in transport and storage systems along with uncertainties in feedstock availability and prices, this can be attributed to the high capital costs and long payback periods as well as the low ratio of electrical power to thermal power of typical CHP plants [7]. For instance, the maximum values of electrical efficiency attained by small-scale biomass-fired Organic

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http://dx.doi.org/10.1016/j.enconman.2015.03.047
0196-8904/

Nomenclature

c_p	Specific heat at constant pressure [J/(kg K)]
G_a	Air mass flow rate [kg/s]
G_s	Steam mass flow rate [kg/s]
G_b	Fuel mass flow rate [kg/s]
h	Specific enthalpy [J/kg]
h_b	Initial specific enthalpy of the fuel [J/kg]
p	Pressure [bar]
P_{el}	Total electrical power [kW]
P_{th}	Total useful thermal power [kW]
T	Temperature [K]
ΔT_{pp}	ΔT at pinch point [K]
β	Air compression ratio
ε	Heat exchanger efficiency
η_b	Combustor efficiency
η_{el}	Overall electrical efficiency
η_{is}	Isentropic efficiency
η_m	Mechanical efficiency
η_{th}	Thermal efficiency
η_{tot}	Total efficiency
x_s	Dryness fraction of steam

Acronyms

CHP	Combined Heat and Power
HRSG	Heat recovery steam generator
IPHE	Immersed Particle Heat Exchanger
LHV	Lower Heating Value
MOGAII	Multi objective genetic algorithm II
NAHE	Nickel alloy heat exchanger
ORC	Organic Rankine Cycle
PES	Primary Energy Saving
RPM	Revolutions per minute

Subscripts

1	Compressor inlet
2	Compressor outlet
3	Gas turbine inlet
4	Gas turbine outlet
5	Combustor exit
6	HRSG inlet (flue gas)
7	Exhaust
bot	Bottoming cycle
c	Compressor
E	Steam expander inlet
e	Expander
K	Water inlet in the HRSG
F	Steam expander outlet
pp	Pinch point in the HRSG
sw	Saturated water in the HRSG
t	Turbine
top	Topping cycle

Rankine Cycle (ORC) systems (the leader technology for CHP generation from biomass) are lower than 20%, as reported in [8]. In contrast, CHP plants should be capable of generating more electricity per unit of thermal energy produced, in order to increase the economic feasibility of small-scale plant investments [5]. To reach this target, current research works are primarily focused on both the optimization of ORC parameters (see, e.g., the optimization study proposed in [9]) and the best selection of the available organic fluids (see, e.g., the comparative analysis presented in [10]). Parametric investigations of ORC power plants have also been conducted using novel techno-economic approaches [11].

In this scenario, the aim of this paper is to demonstrate that, thanks to both novel cost-effective configurations proposed here and recent technological advances in designing gas to gas heat exchangers and micro steam expanders, the employment of small combined cycles as a valid alternative to ORC systems for CHP from biomass is feasible in the near future and can guarantee competitive thermodynamic performances. The direct use of solid biomass or low quality biofuels in gas turbines coupled with water steam cycles can be of great interest for a better exploitation of biomass, due to the simplicity, reliability and flexibility of this technical solution. Furthermore, the use of water steam is safe because it has no negative effects on the environment and is not toxic and explosive like some organic molecules; as a result, water steam can also be exhausted and used directly in technological processes or for district heating.

2. Methodology

2.1. Proposal of plant layouts for CHP from biomass

Fig. 1 shows the two power plant layouts proposed for CHP from biomass. Both layouts are based on an externally-fired combined cycle: the open Joule Brayton cycle is utilized as the topping, high-temperature plant, and the Rankine cycle as the bottoming, low-temperature plant. The working fluid of the topping cycle is clean air; after being compressed, the air flows through the high temperature heat exchanger, which is necessary to transfer heat from the flue gases exiting the external combustor to the compressed air. In the first plant layout (Fig. 1a), the clean hot air expands in the turbine (T) moving the compressor (C) and the electric generator simultaneously to produce the electrical power of the topping cycle. In the other layout (Fig. 1b), the air expansion is divided into two stages by using two turbines: the high-pressure turbine drives the compressor, while the low-pressure turbine (the power turbine) moves the electric generator.

In both layouts, the hot air discharged from the turbine is conveyed into the external combustor chamber to burn biomass.

The bottoming cycle allows the overall efficiency to be increased. As shown in Fig. 1a and b, the exhaust gases exiting the heat exchanger are delivered to a heat recovery steam generator (HRSG) to generate water steam, which can then expand through a steam expander moving the second electric generator. The steam is expanded to a certain level of back pressure depending on the needs of the thermal load, for instance the temperature of the hot water necessary for district heating. To allow the closed loop, the steam circuit also needs a condenser and a pumping system. Alternatively, the steam can be exhausted from the steam expander and directly used for technological purposes. In such a case, the bottoming plant does not need the condenser and can work in open cycle.

In order to greatly reduce the capital costs, a cheap turbocharger from the automotive industry is proposed to be used in place of the expensive microturbine, considering that automotive turbines are very suitable for this application because nowadays their blades are cast from nickel-alloys to allow high thermal resistance (900–950 °C). Apart from the coupling with the electric generator (which requires a re-design of the shaft and bearings), a turbocharger does not need other modifications to allow its implementation in the plant of Fig. 1a, so this cost-effective technology could successfully be used for serial production of turbocharger-like modules to be connected to electric generators.