Applied Thermal Engineering xxx (2013) 1–9

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Energetic analysis of biomass-fired ORC systems for micro-scale combined heat and power (CHP) generation. A possible application to the Italian residential sector

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HIGHLIGHTS

- The energetic performances of biomass-fired ORC systems are investigated.
- Combined heat and power (CHP) generation to meet household energy demand is studied.
- The influence of operating conditions, working fluid, and regeneration is evaluated.
- The economic feasibility of ORC systems for domestic applications is analysed.
- ORC is an attractive solution for micro-scale CHP applications in residential sector.

ARTICLE INFO

Article history:
Received 8 July 2013
Accepted 11 November 2013
Available online xxx

Keywords:
Organic Rankine Cycle
Combined heat and power
Biomass
Micro-scale
Energy demand
Residential sector

ABSTRACT

The work aims at investigating the energetic performances of biomass Organic Rankine Cycles (ORCs) for domestic micro-scale combined heat and power (CHP) generation. A parametric analysis has been carried out for different ORC configurations. Specifically, three organic fluids have been considered with both saturated and superheated conditions at the expander inlet and the possibility to adopt the internal regeneration has been evaluated.

The energetic analysis illustrates the significant influence of the maximum temperature and thermal regeneration on the main CHP performances. Furthermore, data reveal that the proper choice of the organic working fluid is essential to guarantee reliable operations and maximise the system performances.

Finally, an economic analysis has been performed considering the Italian tariff and incentives scenario, in order to evaluate the economic feasibility of Organic Rankine Cycles for domestic users in Southern Italy. The investigation demonstrates that biomass-fired ORC systems represent an attractive and efficient solution for sustainable micro-scale CHP applications in the residential sector.

1. Introduction

Nowadays, the combined heat and power production is considered an effective alternative to conventional systems with separate electric and thermal generation due to the higher energy efficiency and saving capability and to the lower pollutant emissions [1–3]. In this framework, biomass-fired Organic Rankine Cycles (ORCs) represent an attractive solution for sustainable and reliable energy supply in small and micro-scale CHP applications, where traditional plants are technologically and economically unfeasible [4–6].

Specifically, ORC systems present different advantages compared with conventional installations due to the lower costs and maintenance requirements, better partial load performances, faster start-up and stop procedures and higher flexibility and safety [7–10]. To this purpose, the definition of the most appropriate plant configurations and operating conditions is essential to optimise the efficiency of ORC systems [11–15].

In the last years, the attention of researchers community and manufacturers was mainly focused on saturated ORC cycles. Conversely, the adoption of internal regeneration and superheated conditions at the turbine inlet, mainly in biomass applications, appears of great interest, because these configurations may lead to higher efficiencies and lower costs [16,17].

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http://dx.doi.org/10.1016/j.applthermaleng.2013.11.024

The maximum operating temperature in biomass-fired ORCs reaches value up to 400 °C, provided that the fluid stability temperature is significantly higher [18]. A thermal oil circuit is required to avoid local overheating and to prevent organic fluids from becoming chemically unstable. In fact, during the combustion, the flame temperature is usually larger than 900 °C [7]. Furthermore, for combined heat and power production, it is noteworthy that the condensation temperature is relatively high (80–120 °C) [7,19,20]. As a consequence, most organic fluids for low temperature applications cannot be used due to the high vapour pressure at these temperatures [7], and more suitable working fluids should be adopted, taking into account the high temperature heat source availability. To this purpose, different organic fluids have been analysed in literature [21–25]. Specifically, Wiśniewski and Borsukiewicz-Gozdur [26], and Chacartegui et al. [27] demonstrated that toluene, cyclohexane, and decane are very suitable organic fluids in high-temperature ORC applications and guarantee interesting performances.

The aim of the present paper is the analysis of the energetic performances of biomass Organic Rankine Cycles for micro-scale combined heat and power generation.

In fact, ORC is a well-established industrial technology for cogeneration in the range of 200–1500 kW_{el} while few applications on micro-scale biomass ORCs are present both in industrial practice and in research activities, due to the high investment cost and the low electric efficiency if compared with traditional CHP system based on internal combustion engines [3,9]. Nevertheless, micro-scale ORC systems appear as a very interesting option to fulfil the household energy demands and to overcome the energy “trilemma” of affordability, supply security, and environmental protection [5,6].

To this aim, the investigation has been focused on domestic applications and the effect of both the operating conditions and working fluid on the ORC behaviour has been examined. Moreover, the influence of the internal regeneration on the plant performances has been evaluated and the economic viability of biomass-fired ORC systems for combined heat and power generation has been investigated. In particular, a possible application to the Italian residential sector has been considered and the national legislation and incentive schemes have been taken into account.

2. Methodology

The Organic Rankine Cycle (ORC) consists primarily of a pump system, an evaporator, an expander, and a condenser (Fig. 1a). The pump supplies the organic fluid to the evaporator (1–2 process), where the fluid is preheated (2–3) and vaporized (3–4). The vapour flows into the expander where it is expanded to the condensing pressure (5–6) and, finally, it is condensed to saturated liquid (6–1). Sometimes, an internal heat exchanger (IHE) can be used to recover the thermal energy at the expander outlet (6–7) and preheat the compressed liquid before the entrance in the evaporator (2–9) in order to improve the system efficiency. Fig. 1b shows the corresponding cycle in the T-s diagram for a typical dry organic fluid with saturated conditions at the expander inlet.

A thermodynamic model has been developed to characterise the performances of biomass Organic Rankine Cycles [28–30]. To this purpose, the REFPROP database [31] has been integrated with the energy model to define the thermodynamic properties of the organic fluids. For the analysis, a steady state condition has been assumed, while pressure drops and heat losses in the plant components have been neglected. The system performances have been expressed in terms of electric power and efficiency, energy utilisation factor, cogeneration efficiency, and primary energy saving index.

The ORC net electric power P_{el} is evaluated as follows:

$$P_{el} = \eta_{em} P_u \tag{1}$$

where

P_u is the net power output;
η_{em} takes into account the mechanical and electrical losses.

In particular, the net power output represents the difference between the expander power P_t and the power requested by the pump P_p:

$$P_u = P_t - P_p \tag{2}$$

The expander and pump power are calculated according to Equations (3) and (4) respectively:

$$P_t = \eta_{is,t}\dot{m}l_{is,t} = \dot{m}l_t = \dot{m}(h_5 - h_6) \tag{3}$$

$$P_p = \dot{m}\frac{l_{is,p}}{\eta_{is,p}} = \dot{m}l_p = \dot{m}(h_2 - h_1) \tag{4}$$

where

$\dot{m}$ is the organic fluid mass flow rate;
$\eta_{is,t}$ is the isentropic efficiency of the expander;
$\eta_{is,p}$ is the isentropic efficiency of the pump;
$l_{is,t}$ is the isentropic specific work of the expander;
$l_{is,p}$ is the isentropic specific work of the pump;
l_t is the specific work of the expander;
l_p is the specific work of the pump;
h_i is the specific enthalpy of the generic state point i.

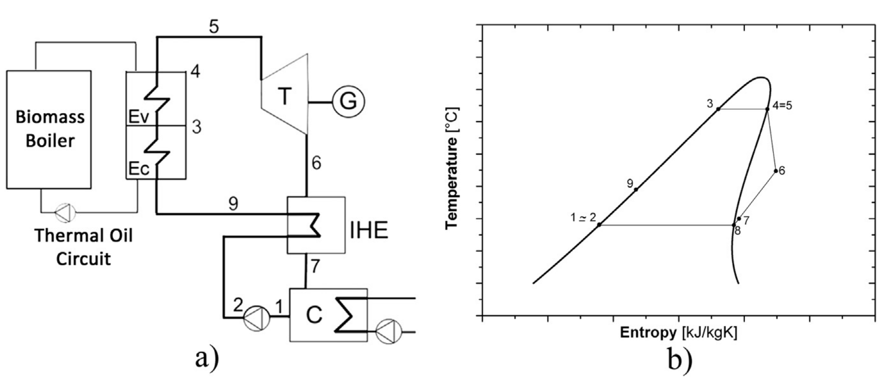

Fig. 1. Typical plant layout (a) and T-s diagram (b) for an Organic Rankine Cycle with internal heat exchange. Saturated cycle. C: Condenser, Ec: Economyser, Ev: Evaporator, T: Expander, G: Electrical generator, IHE: Internal heat exchanger.

Please cite this article in press as: A. Algieri, P. Morrone, Energetic analysis of biomass-fired ORC systems for micro-scale combined heat and power (CHP) generation. A possible application to the Italian residential sector, Applied Thermal Engineering (2013), http://dx.doi.org/10.1016/j.applthermaleng.2013.11.024