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Comparative energetic analysis of high-temperature subcritical and transcritical Organic Rankine Cycle (ORC). A biomass application in the Sibari district

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ABSTRACT

The present work aims to analyse the energetic performances of Organic Rankine Cycles (ORCs) for small-scale applications. To this purpose, a parametric energy analysis has been performed to define the proper system configurations for a biomass power plant. Saturated and superheated conditions at the turbine inlet have been imposed and subcritical and transcritical cycles have been investigated. Furthermore, the effect of operating conditions and the impact of internal regeneration on system performances have been analysed.

Finally, the possible exploitation of the biomass resulting from the pruning residues of peach trees in the Sibari district (Southern Italy) has been evaluated for the ORC configurations optimised during the energetic analysis.

The analysis shows that ORCs represent a very interesting solution for small-scale and decentralised power production. Moreover, the results highlight the large influence of the maximum temperature and the significant impact of the internal regeneration on the power plant performances.

1. Introduction

Nowadays, the Organic Rankine Cycle (ORC) represents a promising solution for power production. The ORC process guarantees high efficiencies for small-scale applications and/or low temperature heat sources, compared with other alternative technologies [1–5]. Furthermore, the system shows high flexibility and safety and low costs and maintenance requirements [6–10].

The use of an organic fluid represents the main difference between ORCs and conventional Rankine cycles and the choice of the working fluid is considered a fundamental key for the maximisation of the ORC global efficiency [11–17]. To this purpose, the heat source level and the application influence significantly the selection of the proper fluids and the definition of the suitable operating conditions. Particularly, ORC technology can be adopted to recover heat from different energy sources, both at low and at medium/high temperature.

Solar radiation, geothermal energy, and waste heat from industrial processes represent typical energy sources for ORC low temperature applications [18–21]. Hydrocarbons, fluorocarbons or hydrofluorocarbons are usually adopted as working fluids in these applications [4,21–24].

The Organic Rankine Cycles can be coupled also with internal combustion engines or gas turbines in order to recover their wasted heat at medium temperature [24–27]. As an example, Chacartegui et al. [28] demonstrated that combined cycles based on commercial gas turbines and ORCs represent an interesting and competitive solution for power production. Specifically, among the analysed working fluids for ORC bottoming cycle, toluene and cyclohexane guarantee the highest global performances in combined cycle power plants [28].

Furthermore, Organic Rankine Cycles can be used for the energy exploitation of agricultural residues and biomass (i.e., high temperature applications) [29–34]. In particular, power production and cogeneration from biomass are among the most effective solutions for reliable and sustainable energy supply in small-scale applications, where conventional power plants are technologically and economically unfeasible [21,29–34]. Biomass ORC plants guarantee several advantages compared with conventional installations in terms of costs, maintenance requirements, partial load performances and start-up procedures [31–33]. Furthermore, the use of an appropriate dry organic fluid eliminates the erosion problem of the turbine blades, improves turbine efficiency (up to 85–90%) and life, and lessens mechanical stress in comparison with water-steam turbine of the same size [32–34]. Following Schuster

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Nomenclature

Symbols

EUF	Energy utilization factor [%]
H_i	Biomass lower heating value [MJ/kg]
h_i	Specific enthalpy of the generic state point i [kJ/kg]
l	Specific work [kJ/kg]
$\dot{m}$	Organic fluid mass flow rate [kg/s]
η	Efficiency [%]
P	Power output [W]
$\dot{Q}_{th}$	Biomass thermal power [W]
$\dot{Q}_i$	Thermal power transferred to the working fluid [W]
φ	Biomass humidity [%]
Δt	Power plant working hours per year [h/year]

Subscripts

b	Biomass
bt	Boiler and thermal oil circuit
cog	Cogeneration
em	Electro-mechanical
g	Global
IHE	Internal heat exchanger
is	Isentropic
p	Pump
sb	Second boiler
t	Turbine
th	Thermal
u	Net output

et al. [21] and Rentizelas et al. [33] ORC plants represent the unique demonstrated technology for the exploitation of biomass in decentralised power production lower than 1 MW_{el}. Moreover, Turboden [29,30] with their installations in Northern, Central and Southern Europe, demonstrated that Organic Rankine Cycle is a well established industrial technology for application in small biomass plants (lower than 2.5 MW_{el}).

In ORC applications the proper choice of the organic working fluid is essential in order to guarantee reliable operations and maximise the system performances. Specifically, the maximum temperature in biomass-based power generation is high with respect to other ORC applications. The flame temperature of the combustion process is usually larger than 900 °C and a thermal oil circuit is necessary to avoid local overheating and to prevent organic fluids from becoming chemically unstable [31]. To this purpose, Angelino and Colonna Di Paliano showed that the maximum operating temperature for organic fluids to reach is 400 °C, provided that the fluid stability temperature is significantly higher [24]. Moreover, for combined heat and power (CHP) production, the condensation temperature is usually relatively high (80–120 °C) to permit cogeneration [21,24,30–33]. As a consequence, most fluids for low temperature source cannot be adopted, due to the high vapour pressure at these condensation temperatures [31–34]. Octamethyltrisiloxane (OMTS) has been adopted in most biomass applications [10,11,29,31]. However, Drescher and Brüggemann showed that the thermal and the global efficiency of the system is comparatively low when OMTS is used as organic fluid [31]. As a consequence, more suitable working fluids should be defined, taking into account the high temperature heat source availability.

Moreover, the definition of the most appropriate operating conditions is crucial to optimise the energy efficiency of ORC power plants. Nowadays, the attention of researchers is mainly focused on saturated ORC cycles. On the other hand, the adoption of both superheated and transcritical conditions with internal regeneration are of large interest, because these configurations may lead to higher system efficiencies and lower costs [11–14,35,36]. However, few studies are present in literature on this topic.

The present work aims to investigate the energetic performances of Organic Rankine Cycles (ORCs) for the exploitation of the biomass resulting from agricultural residues in a farmer cooperative area of about 3,000 ha. To this purpose a parametric energy analysis has been performed and the influence of the operating conditions on system performances has been evaluated. Cyclohexane, decane and toluene have been used as working fluids. Saturated and superheated conditions at the turbine inlet have been imposed and both subcritical and transcritical cycles have been investigated. Furthermore, the impact of the internal regeneration on the plant performances has been studied.

2. Methodology

2.1. Thermodynamic model

The Organic Rankine Cycle (ORC) consists primarily of a pump system, an evaporator, a turbine group, 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 turbine 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 turbine 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 turbine inlet. It is worthy to notice that the deaerator is unnecessary. In fact, air infiltrations are low (ORC plants are often sealed in industrial practise) and a small vacuum pump in the condenser can be used to remove the excess air [37,38].

Fig. 2a and b illustrates the ORC cycle with the adoption of superheated conditions at the entrance of the turbine and transcritical cycle respectively. In particular, the low critical pressure of organic fluids makes supercritical cycles feasible without running into extreme operating conditions [14,24,35,39–41].

A thermodynamic model has been developed to characterise the performances of Organic Rankine Cycles. To this purpose, the REFPROP database [42] 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 thermal and global efficiency, power output, and specific work.

The thermal efficiency η_{th} is defined as follows:

$$\eta_{th} = \frac{P_u}{\dot{Q}_i} \quad (1)$$

where, P_u-is the net power output; $\dot{Q}_i$-is the thermal power transferred to the working fluid.

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