Thermodynamic modelling of a Biomass Organic Rankine Cycle for sustainable heat and power cogeneration in greenhouses

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Abstract

Greenhouses play a key role in modern agricultural production and have been extensively investigated towards assuring the desirable indoor conditions with the minimum heating cost. Under the stressing fossil fuel prices and the uncertainty in supply, as well as the unquestionable need to comply with GHG emissions reduction, micro scale Combined Heat and Power (micro-CHP) fueled by residual biomass emerges as a promising sustainable solution for greenhouses heating. The heating needs of a greenhouse may reach up to 60% of its total operating cost, leading to increased product cost. In parallel, the residual biomass, constituting a renewable energy source that may be used as beneficial fuel for power generation cycles, remains unexploited in most Mediterranean case studies. An experimental facility has been developed at the Agricultural University of Athens (Greece), aiming to explore a micro-CHP system based on the technology of Organic Rankine Cycle (ORC), using as fuel the residual biomass for greenhouses. The main objectives of this experimental project are the design and selection of the individual components and their integration in a complete micro-CHP-ORC system for a capacity of 200 kW_{th} and power generation of 20 kW_e, covering the heating needs of a greenhouse area of 1,000 m^2. This paper describes the numerical assessment preceded the development of the system's experimental facility and signifies the lessons learnt from the components specification. The results of the project are going to enhance the use and efficient management of residual biomass as primary energy source.

Introduction

Nowadays, biomass is the most common renewable energy source in the European Union, since almost 70% of the final energy consists of solid, gaseous, or liquid biomass (Moradi et al., 2020). Greenhouses have a key role in the agricultural production and present significant scientific research and technological developments due to their high effectiveness compared to the field production, resulting in new growing techniques and higher water consumption efficiency. Nonetheless, the greenhouses' large heating needs still remain the main cost, reaching up to 60% of the total operating budget. The utilization of biomass in conventional boilers for greenhouse heating applications, leaves large amounts of energy unexploited (e.g., combustion fuels), constituting these heating systems inefficient. ORC is considered the most common and efficient technology for converting low-temperature waste heat into power. Furthermore, ORC units can be employed as bottoming cycles in direct-burning systems of biomass, exploiting the remaining thermal energy of the gases. In particular, micro-CHP(CHP) systems may be promising for the agricultural sector to cover the thermal and electricity needs of a greenhouse. A technoeconomic assessment of the small-scale biomass CHP units, was presented by Pantaleo et al. (2015), comparing steam and ORC cycle for varying energy demands. Moreover, ORC was examined as a bottoming cycle of a CHP system with an externally fired gas-turbine cycle of 1.3 MW by Camporeale et al. (2015), investigating how the ORC can compensate the lower efficiency of the topping cycle. Uris et al. (2017) presented a feasibility analysis of a cogeneration plant based on ORC technology and biomass combustion for the mainland of Spain. The selection of the working fluid is also a significant issue in the ORC design, since it depends on the temperature of the heat source, but also on the environmental regulations. Eyerer et al. (2019) investigated new generation refrigeration for an ORC cycle, presenting almost to 2% higher efficiency compared to conventional R245fa.

This study presents a thermodynamic modeling of a CHP system, designed to cover the thermal and electrical needs of a greenhouse. A quasi-state model is developed incorporating the energy requirements of a greenhouse in Greece, employing a biomass combustion boiler and an ORC system in a micro-CHP configuration. This numerical investigation aims to predict the system's performance under varying conditions, focusing on the ORC performance, before the experimental evaluation of the unit in a real environment takes place.

Modelling & Analysis

The proposed cogeneration system consists of a biomass combustor and an ORC unit for power generation, covering the energy needs of a small greenhouse. Firstly, a simulation model of the greenhouse is developed, considering various thermal exchanges between the internal and external of the greenhouse envelope, as presented in Figure 1. A biomass combustion boiler is used to heat a glycol-based working fluid, providing a thermal load up to 400 kW_{th} and heating it up to 130 °C. As the glycol flows to the hot side of the ORC evaporator and heat is transferred to the refrigerant, while the glycol is cooled down. An ORC engine is used to generate power and another cooling loop is used to cool the refrigerant in the condenser, while this rejected heat by the condenser is used to heat the air in the greenhouse (up to ~350 kW_{th}). The main components of the cycle, namely the condenser, the pump, the evaporator, and the expander, are designed for a power generation of 20 kW_e. An in-house model was developed, using the Engineering Equation Solver (EES), which contains built-in libraries with the refrigerants' properties, to model the ORC's components and their performance. The mass and energy balance equations are applied for each component (Cai et al., 2020). The net generated power and the thermal efficiency of the cycle are estimated using the following equations:

$$\dot{W}_{exp} = \dot{m}_{WF}\left(h_{exp,in} - h_{exp,out,is}\right)\eta_{exp} \quad (1)$$

$$\eta_{ORC} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{exp} - \dot{W}_p}{\dot{Q}_{in}} \quad (2)$$

where $\dot{m}_{WF}$ is the working fluid mass flow, $\mathrm{h}_{\mathrm{exp,in}}$ and $h_{exp,out,is}$ is the refrigerant's enthalpy at the inlet and outlet of the expander for isentropic expansion, respectively, η_{exp} is the expander's isentropic efficiency, $\dot{W}_{exp}$ and $\dot{W}_p$ is the power generated by the expander and consumed by the pump, respectively, while $\dot{Q}_{in}$ is the heat provided by the biomass boiler.

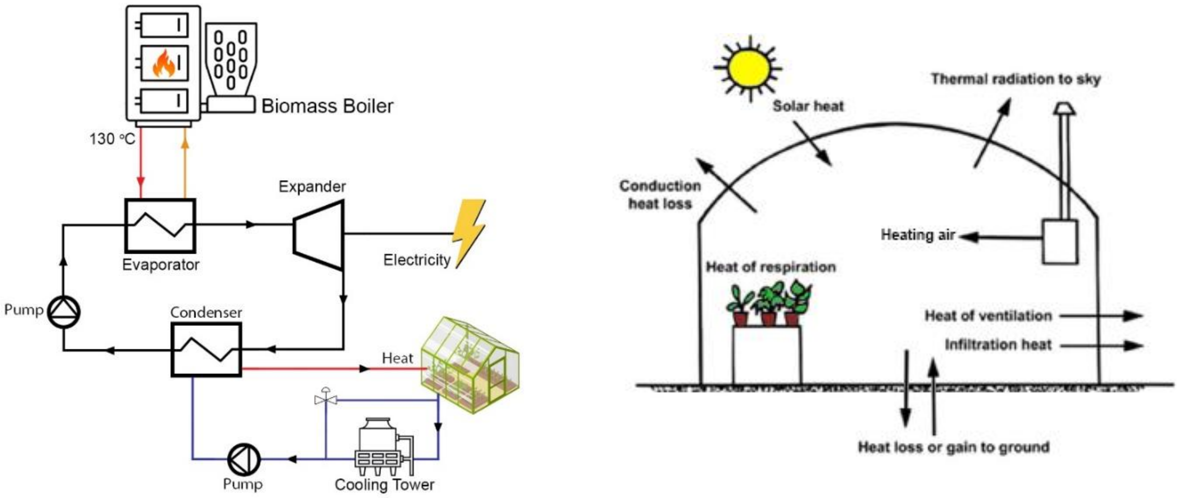

Figure 1: Schematic layout of the micro-CHP (left). Considered heat loads for greenhouse modeling (right).

The pinch-point between the hot and cold side of the heat exchangers was considered 5 °C, while the impact of subcooling and superheating on the cycle's efficiency was examined.

Finally, the refrigerant that was selected to be employed is the R1233zd(E) because of the eco-friendliness compared to R245fa and lower saturation pressure, which leads to lower power consumption presented, compared to R1224yd(Z), as presented in Figure 2.

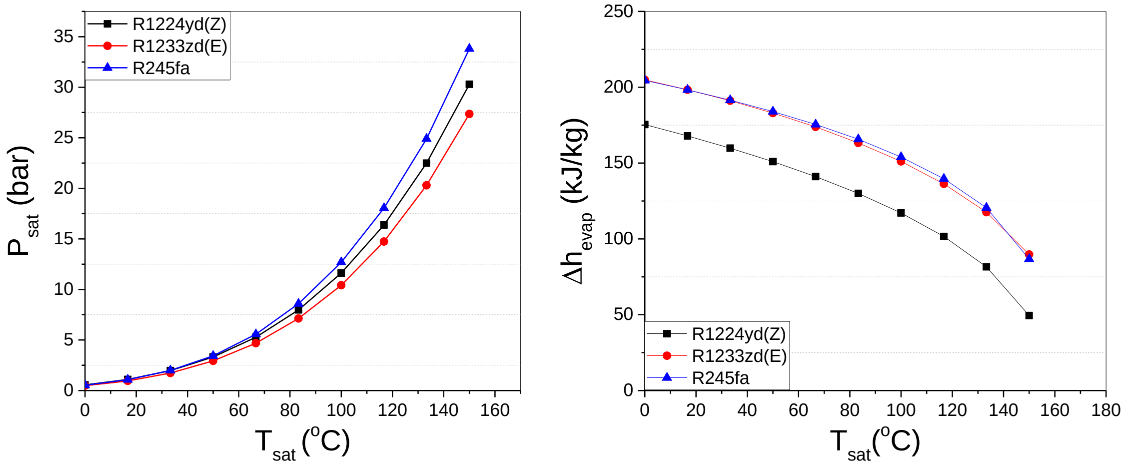

Figure 2: Saturation pressure (left) and evaporation latent enthalpy (right) as a function of saturation temperature.

Results & Discussion

The significant performance characteristics of the ORC engine are discussed in this section. First of all, the impact of the evaporation temperature of the refrigerant, corresponding to the cycle's high temperature, on the power generation and the cycle's thermal efficiency is investigated. Figure 3 presents the variation of the net generated electrical power as the evaporation temperature increases from 70 °C to 130 °C for three different scenarios of condensation temperature, in relation to the desired greenhouse indoor air temperature, which mainly depends on the selected cultivation.

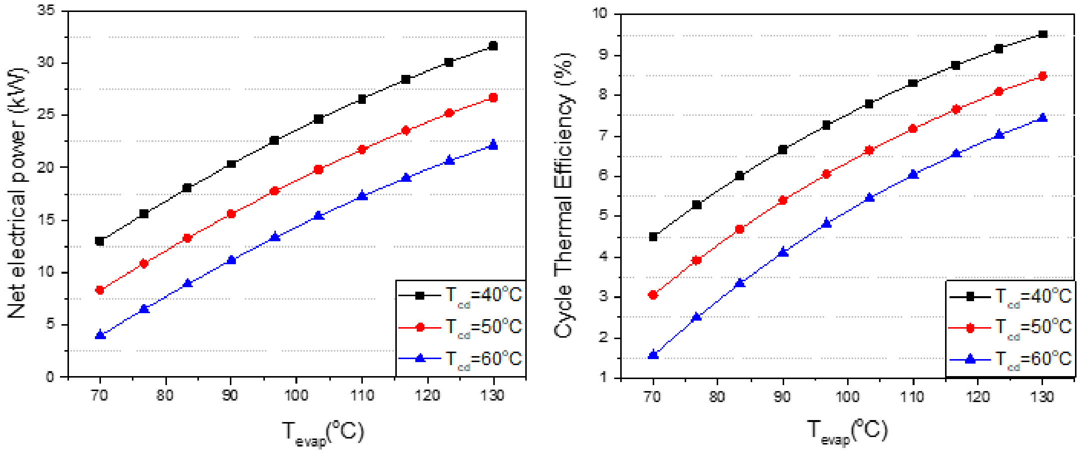

Figure 3: Net electrical power (left) and cycle's thermal efficiency (right) as the evaporation temperature increases for condensation temperature 40, 50 and 60 °C.

It is shown that the increase of the evaporation temperature and the lowest condensation temperature leads to increased power generation, while the thermal efficiency can reach up to 9.5% for evaporation temperature of 130 °C and condensation temperature 40 °C.

Furthermore, the impact of evaporation and condensation temperatures on the pressure ratio of the pump are investigated, which may lead to important results for the pump selection, and the impact of superheating on the power generation and the cycle's efficiency. Figure 4a illustrates the variation of the pressure ratio as the evaporation temperature increases in the range of 70 to 130 °C, while the condensation temperature varies from 40 °C to 60 °C. It is shown that the increase of the evaporation temperature in combination with lower condensation temperature leads to increased pressure ratio, which in turn leads to a larger pump selection. Figure 4b presents the net electrical power (left axis) and the cycle's thermal efficiency (right axis) as the superheating of the refrigerant at the evaporator increases. It can be observed that the increase of superheating at the evaporator may lead to increased power generation, while the cycle efficiency can be slightly improved.

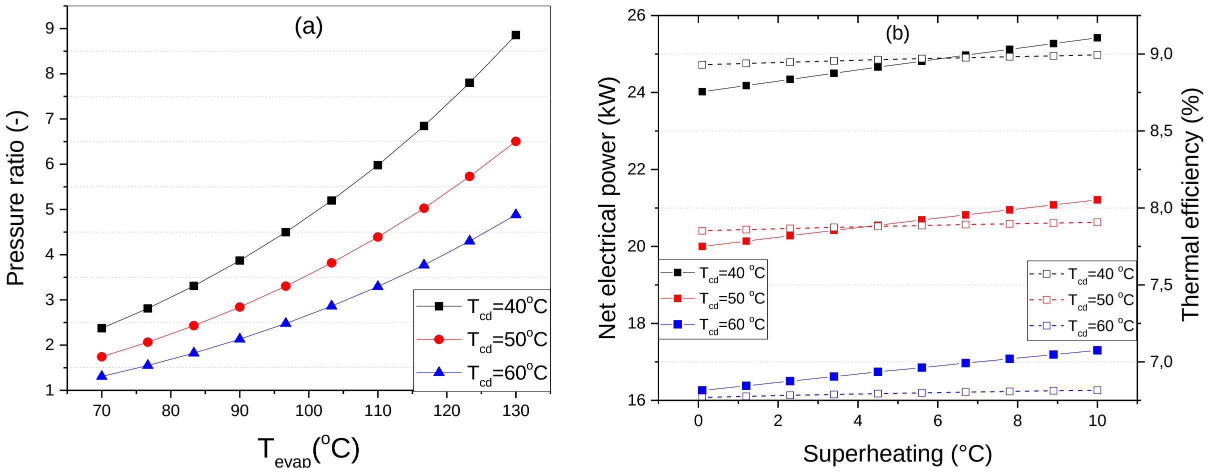

Figure 4: Pressure ratio of the pump as the evaporation temperature increases (a) and the variation of the power generation and thermal efficiency as the superheating increases (b), for condensation temperature 40, 50 and 60 °C.

Conclusions

This study presents an investigation on the performance of an ORC engine, which is used to cover the electrical needs of a greenhouse, as part of a raw biomass CHP unit. A numerical thermodynamic model was developed to simulate the performance of the engine, examining the impact of key parameters, such as the evaporation and condensation temperatures, on the sizing of main components such as the pump and the heat exchangers, the net power production and the cycle's thermal efficiency. It was shown that the required temperature of the ambient air in the greenhouse, which affects the condensation temperature, has a significant impact on the ORC efficiency, reaching up to 9.5%, while it may also significantly affect the pump sizing.

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