COMPARATIVE INVESTIGATION ON THE PERFORMANCES OF ORGANIC RANKINE CYCLES (ORCS) FOR THE EXPLOITATION OF LOW TEMPERATURE HEAT SOURCES

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ABSTRACT

The present work aims at investigating the energetic performances of Organic Rankine Cycles (ORCs) for the exploitation of low temperature heat sources in small-scale applications. Specifically, a thermodynamic model has been developed and a parametric energy analysis has been carried out considering several organic fluids.

Different system configurations have been investigated in order to define the proper ORC arrangements and the influence of the operating conditions on the system performances. Subcritical and transcritical cycles, with saturated and superheated conditions at the expander inlet, have been analysed and the impact of internal regeneration on ORC behaviour has been studied.

The analysis shows the large influence of the operating conditions and the significant effect of the internal regeneration on the system performances. Specifically, the comparison between the different ORCs highlights that the transcritical cycle with internal heat exchange offers the maximum electric efficiency. Furthermore, results reveal that the proper selection of the organic working fluid is fundamental to maximise the system performances.

INTRODUCTION

Nowadays, the Organic Rankine Cycle (ORC) appears as an attractive technology both for small-scale power production and for the exploitation of low temperature heat sources [1-4]. In fact, ORC system shows higher efficiency, flexibility, and safety, lower costs and maintenance requirements, faster start-up and stop procedures and better partial load operations when compared with tradition systems [5-8].

The main differences between ORCs and conventional Rankine cycles lie in the adoption of an organic fluid, and the selection of the working fluid is fundamental to optimise the performances of the system. To this purpose, the heat source level influences significantly the choice of the proper fluids and the definition of the suitable operating conditions [9-12].

In the last years, the attention of manufacturers and researchers has been mainly focused on saturated ORC cycles in simple configuration. On the other hand, transcritical cycles and the adoption of internal regeneration are of great relevance, owing to the possible raise in the system effectiveness [12-13].

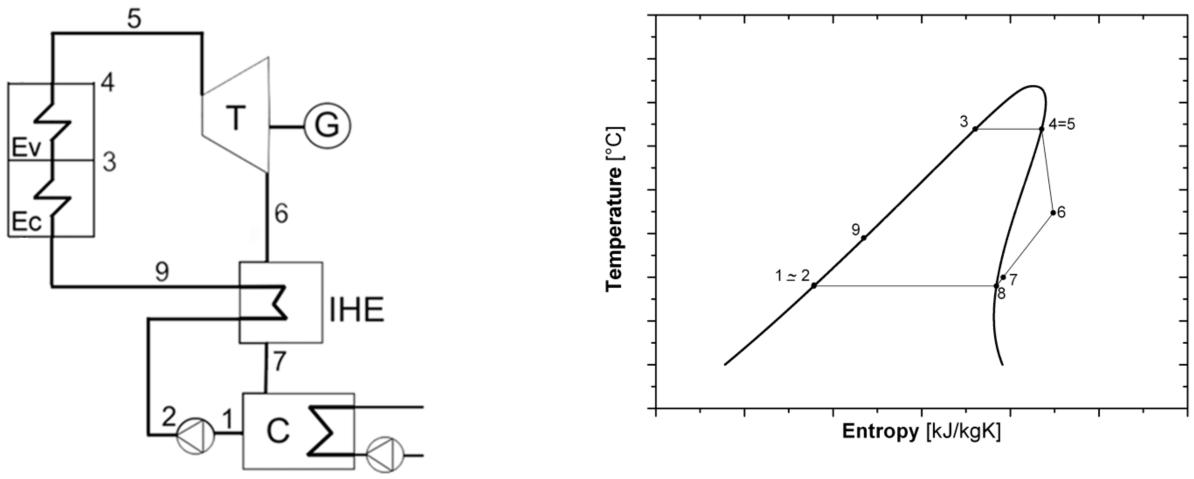
The paper aims to analyse the energetic performances of low-temperature Organic Rankine Cycles. A parametric analysis has been done and the influence of the operating conditions and ORC configuration on system behaviour has been estimated. To this purpose, five organic fluids have been adopted and both subcritical and transcritical cycles have been investigated. Furthermore, the impact of the internal regeneration has been investigated.

NOMENCLATURE

l	[J/kg]	Net specific work
$\dot{m}$	[kg/s]	Mass flow rate
p	[bar]	Pressure
P	[W]	Power
$\dot{Q}_{th}$	[W]	Thermal input
Special characters		
η	[%]	Efficiency
Subscripts		
crit		Critical
el		Electric
em		Electro-mechanic
s		Specific
Acronyms		
ORC		Organic Rankine Cycle
IHE		Internal heat exchange

METHODOLOGY

The main components of an Organic Rankine Cycle are a pump system, an evaporator, a turbine/expander, and a condenser (Figure 1a). The organic working fluid is fed by the pump system to the evaporator (1-2 process), where the fluid is preheated (2-3) and then vaporised (3-4). The fluid flows into the turbine where it is expanded to the condensing pressure (5-6) and, finally, it is condensed to saturated liquid (6-1). 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 evaporation process occurs (2-9) in order to improve the system efficiency. Figure 1b shows the cycle in the T-s diagram for a typical dry organic fluid with saturated conditions at the turbine inlet.



a) b)

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

		Butane	Isobutane	Isopentane	R236ea	R245ca
Critical conditions						
Critical temperature	[°C]	151.98	134.66	187.2	139.29	174.42
Critical pressure	[bar]	37.96	36.29	33.78	35.02	39.25
Saturated cycle						
Condensation temperature	[°C]	30	30	30	30	30
Condensation pressure	[bar]	2.83	4.05	1.09	2.44	1.22
Evaporation temperature	[°C]	100; 125	100; 107	100; 171	100; 122	100; 147
Evaporation pressure	[bar]	15.26; 24.16	19.86; 22.58	7.22; 26.29	15.72; 24.50	9.28; 24.43
Transcritical cycle						
Condensation temperature	[°C]	30	30	30	30	30
Condensation pressure	[bar]	2.83	4.05	1.09	2.44	1.22
Maximum temperature	[°C]	200	200	200	200	200
Maximum pressure*	[bar]	39.10	37.38	34.79	36.07	40.43

*Supercritical pressure

Table 1 ORC operating conditions and investigated configurations.

A thermodynamic model has been developed to evaluate the performances of low-temperature Organic Rankine Cycles [14-16]. The model is integrated with the REFPROP database [17] to define the thermodynamic properties of the organic fluid. A steady state condition has been assumed, while pressure drops and heat losses in the system components have been neglected.

The performance parameters used in the analysis are the electric efficiency and the net specific work.

The electric efficiency is defined as

$$\eta_{el} = \frac{P_{el}}{\dot{Q}_{th}} \tag{1}$$

where $\dot{Q}_{th}$ is the thermal input and P_{el} is the ORC electric power, defined as follows:

$$P_{el} = \eta_{em} P_u \tag{2}$$

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

The net specific work is defined as:

$$l_s = \frac{P_{el}}{\dot{m}} \tag{3}$$

where $\dot{m}$ is the mass flow rate of the organic fluid.

OPERATING CONDITIONS

For the energy investigation butane, isobutane, isopentane, R236ea, and R245ca have been chosen as organic working fluid, due to their properties, consistent with low temperature heat sources [18-20]. Both subcritical and transcritical cycles have been studied. Table 1 highlights the critical conditions of the five organic fluids and the operating conditions adopted during the energetic analysis. In particular, the condensation temperature has been always set to 30 °C.

For saturated cycles the minimum evaporation temperature has been imposed to 100 °C while the maximum value has been defined to avoid the presence of liquid during the expansion phase and it depends on the saturation curve of the selected fluid (Figure 1b).

Furthermore, ORC transcritical cycles have been analysed and the supercritical pressures have been set to 1.03 p_{crit} (the critical pressure), as suggested in literature [9]. In these conditions the maximum temperature is equal to 200 °C.

The adopted operating conditions are suitable for low temperature applications: geothermal sources, solar radiation, and waste heat from industrial processes.

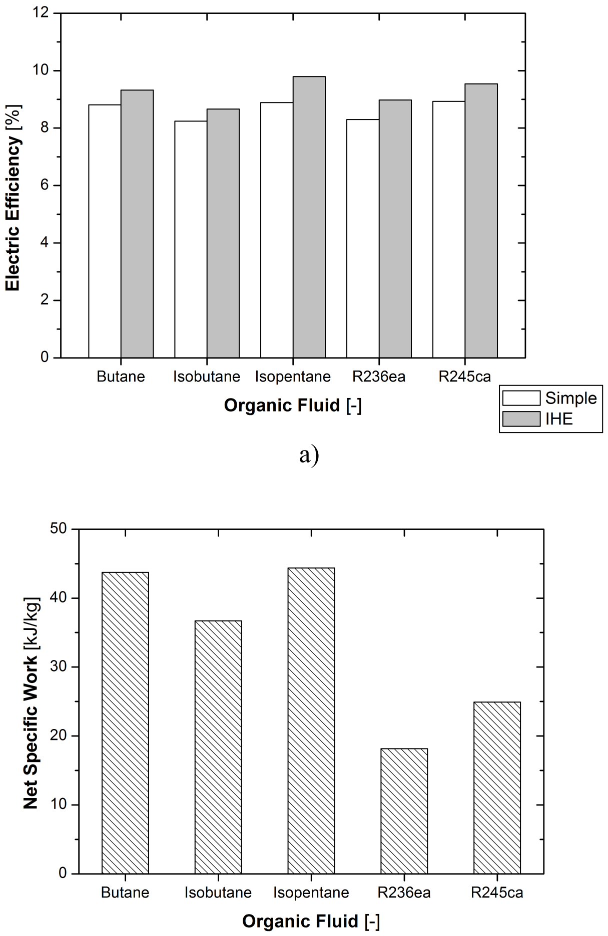
According to the literature, the ORC expander and pump efficiencies have been imposed equal to 0.70 and 0.60, respectively, the internal heat exchanger efficiency has been set to 0.95, the global efficiency of the heating process (from heat source to the organic fluid) is 0.90, the electro-mechanical efficiency is 0.95, whereas the temperature of the vapour at the exit of the internal heat exchanger (T_7) has been assumed to be 10 °C higher than the condensation temperature [7]. The temperature of the working fluid at point 9 (T_9) is calculated from the heat balance at the internal regenerator.

RESULTS

An energetic investigation on the performances of ORC systems for the exploitation of low temperature heat sources has been done. To this purpose, butane, isobutane, isopentane, R236ea, and R245ca have been chosen as working fluids. Particularly, the influence of the system configurations and operating conditions on the ORC behaviour has been analysed.

Figure 2 highlights the performances of saturated ORC apparatus in terms of electric efficiency (a) and net specific work (b). Results refer to a condensation temperature equal to 30 °C while the evaporation temperature is set to 100 °C. When the simple configuration is considered, similar electric efficiencies are found for the five organic fluids (Figure 2a). Specifically, the values range between 8.2% (isobutane) and 8.9% (isopentane and R245ca). The adoption of the internal heat exchanger guarantees an interesting increase in the ORC effectiveness. The higher electric performances are obtained with isopentane (η_{el} = 9.8%) and values larger than 9% are also found with R245ca and butane.

The effect of the organic fluid on the net specific work is shown in Figure 2b. It is interesting to notice that significant differences exist although similar electric efficiencies have been found for the different organic fluids.



a)

b)

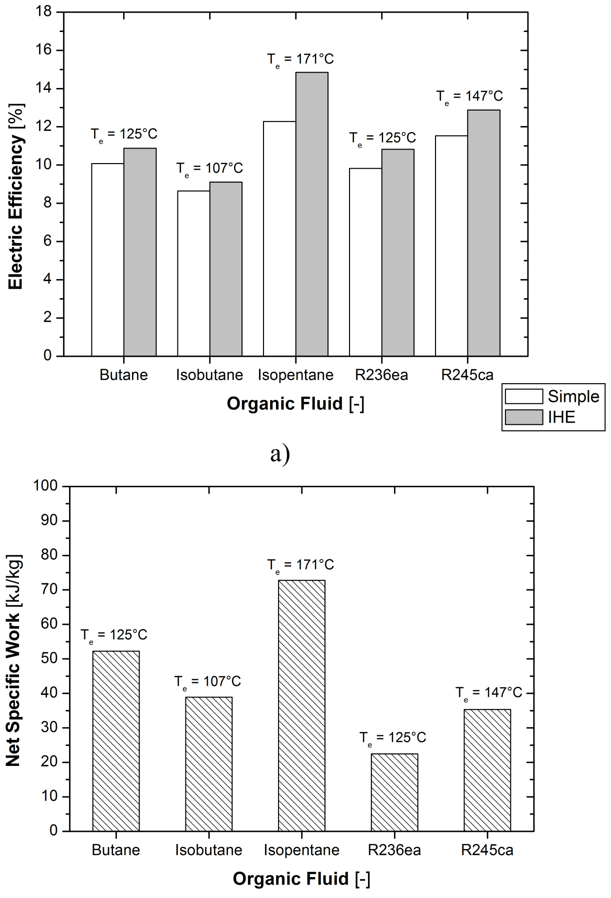
Figure 2 Influence of working fluid and ORC configuration on (a) electric efficiency and (b) net specific work. Saturated cycle – Evaporation temperature T_e = 100 °C.

Isopentane and butane guarantee values larger than 43.5 kJ/kg while the specific work reduces to 24.9 and 18.2 kJ/kg when R245ca and R236ea are selected as fluids, respectively.

The influence of the evaporation temperature on the performances of ORC systems with saturated condition at the entrance of the expander is presented in Figure 3.

The analysis has been carried out imposing the maximum evaporation temperature ($T_{e,max}$), that depends on the fluid (107 °C for isobutane, 122 °C for R236ea, 125 °C for butane, 147 for R245ca, and 171 °C for isopentane), according to Table 1. When the fluid is defined, results illustrate a progressive upsurge in the system performances with the evaporation temperature, owing to the larger energy content at the entrance of the turbine [21]. In the simple configuration, the electric efficiency moves from 8.6% (isobutane) to 12.3% (isopentane), whereas the dimensionless parameter reaches 14.8% if the internal regeneration and isopentane are adopted.

The positive effect of the evaporation temperature on the net specific work is illustrated in Figure 3b.



a)

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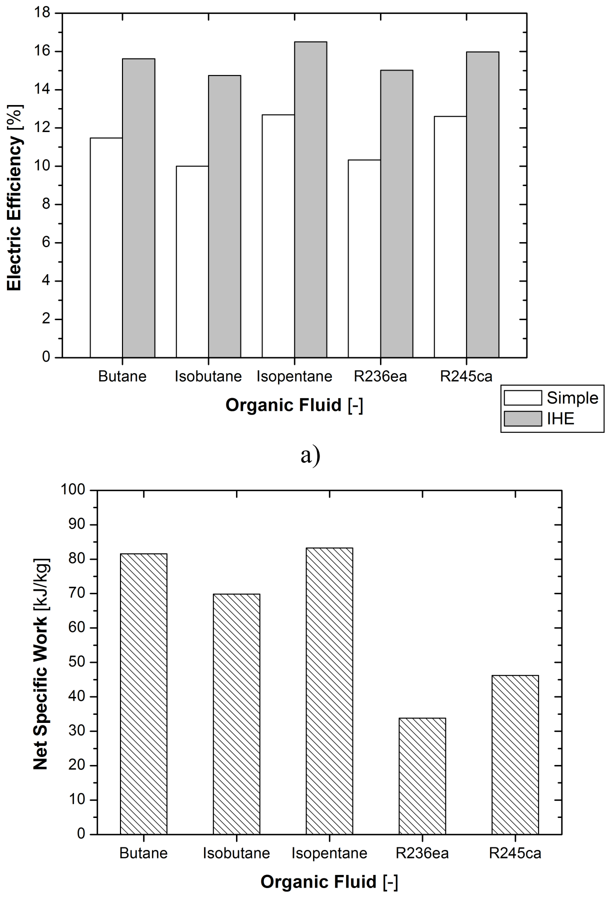
Figure 3 Influence of working fluid and ORC configuration on (a) electric efficiency and (b) net specific work. Saturated cycle – Maximum evaporation temperature.



a)

b)

Figure 4 Influence of working fluid and ORC configuration on (a) electric efficiency and (b) net specific work. Transcritical cycle – T_{max} = 200 °C.

The comparison with the corresponding values registered with the evaporation temperature equal to 100 °C put in evidence an increase always higher than 5.9%. As expected, the higher the evaporation temperature increase, the higher the raise in the specific work. In this case, isopentane guarantees the largest specific work (72.7 kJ/kg) and interesting values are found also for butane (52.2 kJ/kg) and isobutene (38.9 kJ/kg).

Furthermore, the energy investigation has been performed to evaluate the influence of the transcritical conditions on the ORC behaviour. To this purpose, the maximum pressures have been set equal to $p = 1.03\ p_{crit}$, as suggested in literature [9], whereas the maximum temperature has been fixed to 200 °C and the same condensation temperature adopted for saturated configurations (30 °C) has been used.

Figure 4a shows that the electric effectiveness in the simple configurations are always larger than 10% and become higher than 12% adopting isopentane (η_{el} = 12.7%) and R245ca (η_{el} = 12.6%). As already observed for the saturated configuration, the internal regeneration has a positive effect on the ORC efficiency, due to the possible exploitation of the fluid energy content at the end of the expansion phase. The larger percentage increases are registered for isobutene (+47%) and R236ea (+45%) but isopentane and R245ca maintain the higher electric efficiencies also when the regeneration is considered.

Specifically, the electric effectiveness is equal to 16.5% and 16.0%, respectively.

Transcritical ORCs show a higher net specific work if compared with the previous saturated configurations (Figure 4b). As an example, if the saturated ORCs with the evaporation temperature equal to 100 °C are assumed as a reference, the increase in the net specific work is larger than 46% for all the investigated fluids. In these conditions, isopentane provides the larger value (83.8 kJ/kg). High specific work is obtained also with butane (81.6 kJ/kg) but the larger critical pressure determines a larger operating pressure in comparison with isopentane, isobutane, and R236ea.

It is noteworthy that the triangular shape of the supercritical cycle generates also a more efficient heat exchange between the organic fluid and the heat source and a decrease in the irreversibility and energy destruction due to the heat transfer and losses, but more caution should be adopted due to the larger operating pressures. As an example, for isopentane the pressure increase is equal to 8.5 bar passing from the maximum evaporation pressure to supercritical conditions.

CONCLUSIONS

The work has analysed the energetic performances of Organic Rankine Cycles for the exploitation of low temperature heat sources. To this purpose, several organic fluids have been considered and the effect of the internal regeneration on the ORC behaviour has been evaluated. Moreover, subcritical and transcritical configurations have been investigated, with saturated and superheated conditions at the entrance of the expander.

The analysis highlighted that the system configuration and the working fluid significantly affects the system performances. For saturated configurations, similar electric efficiencies have been found when the evaporation temperature is fixed at 100 °C. The dimensionless parameter ranges from 8% to 10%, with the larger values obtained adopting the internal heat exchanger. On the other hand, large differences are found in the net specific work: about 44 kJ/kg for butane and isopentane, 37 kJ/kg for isobutane, less than 25 kJ/kg for R245ca, and slightly more than 18 kJ/kg for R236ea.

When the evaporation temperature increases, a progressive raise in the ORC performances is found owing to the larger energy content at the expander inlet. Specifically, isopentane exhibits the better characteristics both in terms of specific work (72.7 kJ/kg) and electric efficiency (14.8% with IHE and 12.3% for the simple configuration).

The comparison between the different ORC configurations reveals that the transcritical cycles with internal regeneration guarantees the highest electric effectiveness and specific work. Specifically, the investigation highlights that the electric efficiency is always higher than 14.7% when the maximum temperature is set to 200 °C. In this condition, the analysis suggests to adopt isopentane due to the better performances (η_{el} = 16.5%, l_s = 83.3 kJ/kg) and the lower supercritical pressure (p = 34.8 bar).

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