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A general framework to select working fluid and configuration of ORCs for low-to-medium temperature heat sources

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HIGHLIGHTS

- General guidelines are proposed to select ORC working fluid and cycle layout.
- Distance between critical and heat source temperature for optimal fluid selection.
- Separate contributions of cycle efficiency and heat recovery factor.

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ABSTRACT

The selection of the most suitable working fluid and cycle configuration for a given heat source is a fundamental step in the search for the optimum design of Organic Rankine Cycles. In this phase cycle efficiency and heat source recovery factor lead to opposite design choices in the achievement of maximum system efficiency and, in turn, maximum power output. In this work, both separate and combined effects of these two performance factors are considered to supply a thorough understanding of the compromise resulting in maximum performance. This goal is pursued by carrying out design optimizations of four different ORC configurations operating with twenty-seven working fluids and recovering heat from sensible heat sources in the temperature range 120–180 °C. Optimum working fluids and thermodynamic parameters are those which simultaneously allow high cycle efficiency and high heat recovery from the heat source to be obtained. General guidelines are suggested to reach this target for any system configuration. The distance between fluid critical temperature and inlet temperature of the heat source is found to play a key role in predicting the optimum performance of all system configurations regardless of the inlet temperature of the heat source.

1. Introduction

While power generation in the past mainly relied on fossil fuels, much of the recent efforts in the energy sector have been devoted to the conversion of low grade heat sources (geothermal heat, waste heat from engines or industrial processes, etc.). The *Organic Rankine Cycle* (ORC) systems are a promising option for the conversion of low-to-medium temperature heat into electricity. Differently from power plants based on the conventional Rankine cycle, ORC systems operate with organic fluids having a critical temperature (T_{crit}) much lower than water. The design challenge consists in the choice of the combination of organic working fluid and cycle parameters/configuration which maximize power output from the available heat source. Besides thermodynamic performance, the most suitable working fluids should fulfill technical and economic requirements, must be environmentally friendly and have a high level of safety.

Most of the recent literature on ORCs deals with optimization studies using thermodynamic or economic objectives. While the former are based on general thermo-physical properties and processes, the latter rely on the specific application and economic context. The selection of the optimum evaporation temperature maximizing the power output from a sensible heat source in subcritical ORCs is a recurrent topic in the literature and clearly shows the trade-off between cycle efficiency and capability to recover heat from the heat source (i.e., heat recovery effectiveness). Indeed, ideally the heat available from the heat source must be fully recovered and transferred to the ORC having the highest thermal efficiency. The early paper by Liu et al. [1] depicted the rising trend of thermal efficiency and the decreasing trend of heat recovery effectiveness with evaporation temperature, thus regarding

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Nomenclature

$T_{ev,C,opt}$	cycle optimal evaporation temperature
NBT	normal boiling temperature
GWP	global warming potential
ODP	ozone depleting potential
$T_{ev,S,opt}$	system optimal evaporation temperature
SV	saturated vapor
VER	vapor expansion ratio
VSL	vapor saturation line
h	enthalpy [kJ/kg]
m	mass flow rate [kg/s]
p	pressure [bar]
r	latent heat [kJ/kg]
R	general gas constant [kJ/kg °C]
Q	heat flow rate [kW]
s	entropy [kJ/kg °C]
T	temperature [°C]
UA	product overall heat transfer coefficient – heat transfer area [kW/°C]
w	specific work [kJ/kg]
W	power [kW]

Greek symbols

η	efficiency
ε	effectiveness
σ	molecular complexity

Subscripts

av	available
C	cycle
cond	condensation
crit	critical
ev	evaporation
hr	heat recovery
hs	heat source
id	ideal
lim	limit
max	maximum
opt	optimal
pp	pinch point
red	reduced
reg	regenerative
S	system
sub	subcritical
super	supercritical
sys	system
wf	working fluid

cycle efficiency alone as inappropriate for the selection of the most suitable working fluid. A similar approach was followed by Invernizzi et al. [2] in the search for the most suitable fluid exploiting the exhaust gases from a micro-gas turbine. The highest power output from the available exhaust gases (i.e., the highest system efficiency) was obtained using n-pentane due to its high thermal efficiency and better capacity of cooling the micro-turbine exhausts. Tchanche et al. [3] compared thermodynamic, environmental and safety performance of 20 working fluids for a low-temperature solar application of the ORC. Despite the high cycle efficiency of fluids with high latent heat of vaporization such as water and ammonia, the scarce heat recovery effectiveness and the presence of droplets at the end of the expansion excluded them from the selected fluids for the considered application. The analysis was extended to supercritical ORCs by Schuster et al. [4] who reported an 8% improvement in system efficiency compared to the subcritical cycle for a 210 °C heat source inlet temperature ($T_{hs,in}$). Similar findings were obtained for a lower $T_{hs,in}$ (90 °C) by Shengjun et al. [5] where supercritical ORCs outperformed subcritical ones due to their higher capability of recovering waste heat. The ineffectiveness of regeneration in the improvement of power output when exploiting a low temperature sensible heat source was demonstrated by Dai et al. [6]. He et al. [7] classified low-grade heat sources into sensible and latent heat sources. Theoretical formulas were derived to analytically correlate net power output and thermal efficiency with the Jakob number (*Ja*) for subcritical ORCs coupled with the two kinds of heat sources separately. For sensible heat sources, both the theoretical analysis and numerical simulations showed that the working fluids with high liquid specific heat and low latent heat of evaporation (high *Ja*) should be selected. In contrast, working fluids with low liquid specific heat and the high latent heat of evaporation (low *Ja*) are preferable for latent heat sources. A similar finding was obtained by Zhai et al. [8] who also showed the link between cycle efficiency and molecular structure: fluids with double bonds or cyclic structures provide higher cycle efficiencies.

Some attempts have been made in the recent literature to relate ORC performance with the fluid critical temperature, which is considered as the most significant among working fluid properties. Aljundi [9] analyzed the influence of T_{crit} on subcritical ORC cycle efficiency assuming a constant hot reservoir temperature of 96.9 °C. The working fluid showing the highest cycle efficiency (14.0%) was n-hexane having the highest T_{crit} (234.7 °C) among the selected fluids, while the fluid with the lowest efficiency (11.0%) was R-227ea, having the lowest T_{crit} (101.8 °C). Cycle efficiency correlated well with T_{crit} and increased from 11% to 14% as T_{crit} increased from R227ea to n-hexane. However, this study neglected the capability of the working fluid to recover sensible heat being the hot reservoir at constant temperature. Xu and Yu [10] developed a method based on T_{crit} to select the working fluids in subcritical ORCs. They considered a list of fifty-seven working fluids having T_{crit} ranging from 91.1 °C to 321.5 °C and calculated the area enclosed by the flue gases cooling profile and the working fluid heating profile in a *T–q* diagram, which is proportional to the exergy destruction in the evaporator. The best matching and, in turn, the maximum cycle and system efficiency (14.3%), is achieved by transbutene having T_{crit} slightly lower (≈20 °C) than $T_{hs,in}$ (=175 °C). Working fluids with $T_{crit} > T_{hs,in}$ showed a lower deviation from the optimum condition than those with $T_{crit} \ll T_{hs,in}$. So, a pretty wide range of $T_{crit}(T_{hs,in} - 20\text{–}30\,°C, T_{hs,in} + 100\,°C)$ was considered as suitable to obtain high power output. In this study cycle and system efficiency collapsed into one objective function only, being the heat input to the cycle fixed due to the fixed flue gases outlet temperature. Accordingly, the separate effects of thermal efficiency and heat recovery effectiveness on system optimum cannot be visible. Using the same assumption, in a previous work Xu and Liu [11] analyzed the performance of supercritical ORCs operating with R218, R134a and R236fa ($71.9\,°C < T_{crit} < 125.0\,°C$) for utilization of flue gases available at 150 °C. R236fa and R134a both achieve a maximum cycle efficiency (13%) significantly higher than that of R218, having the lowest T_{crit}. On the basis of the pinch point location in the supercritical evaporator the authors concluded that working fluids having $T_{hs,in} - T_{crit} > 78\,°C$ are not recommended in the search for the maximum power output. A higher number of working fluids in supercritical ORCs was considered in a subsequent work by Yu et al. [12], still assuming a