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Designed binary mixtures for subcritical organic Rankine cycles based on multiobjective optimization

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A R T I C L E I N F O

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A B S T R A C T

The use of binary zeotropic mixtures as working fluids applied to Organic Rankine Cycles (ORCs) is investigated in this paper. In total, six (6) hydrocarbons and (2) hydrofluorocarbons are considered, leading to twenty-eight (28) possible binary combinations. The mixtures were tested with a basic Rankine cycle while using the heat source temperature as independent variable, which assumed six different values, ranging from 80 °C to 180 °C, in steps of 20 °C. The simulations aimed to identify the ideal mixtures that maximized the net power and exergetic efficiency, and minimized the heat exchanger's global conductance for a given temperature of the heat source. The optimization process relied on a genetic algorithm and the selection of the best mixtures, on a non-dominated sorting method (NDS), which returned Pareto fronts gathering the best solutions. While no one specific ideal mixture was identified, the results showed that the range of the so-called ideal mixtures narrows as the heat source temperature increases, with mixtures including fluids like R245fa and pentane being good options, whereas at low temperature, a larger number of fluid mixtures perform well. Finally, a scale analysis is proposed and shows that the maximal net power varies linearly with a Number of Transfer Units (NTU) factor while its slope depends on the heat source temperature. The latter analysis is compared with the results obtained with the Pareto front and NDS, showing that both sets of results agree well while correlated by a single constant for the entire temperature range covered in the present study.

1. Introduction

Modulability, lower costs and higher efficiency are some of the advantages that Organic Rankine Cycles (ORC) offer while producing power from medium and low temperature heat sources [1]. Nevertheless, current heat-to-electricity conversion efficiency is still relatively low with such cycles, i.e. around 10% [2]. Recent research has focused on improving the performance of ORCs through the study and optimization of ORC configurations, expansion devices and suitable working fluids, among others [3].

For instance, the optimal working fluid highly depends not only on the conditions for which the cycle is designed (e.g., temperatures of heat source and of heat sink), but also on the criteria that are used to evaluate the cycle's performance (e.g., net power output, exergy efficiency, equipment size, overall cost, environmental footprint, etc.). In this regard, the working fluid choice is one of the most critical design parameters, and identifying the "best" fluid is far from trivial.

In the literature, several studies have aimed at identifying suitable working fluids for ORC applications. Recently, Habibzadeh and Rashidi investigated 13 different working fluids in ORCs, and found that R141b, R123 and R717 were the best isentropic, dry and wet working fluids, respectively [4]. Chagnon-Lessard et al. determined the best working fluid in ORCs among a list of 36 as a function of the heat source and condenser's temperatures while considering a single objective function, namely the specific power output, and only pure fluids were studied [5]. Optimal selection of working fluid from a list of 26 fluids was also proposed in Ref. [6]. It was found that the optimal working fluids (i.e. the ones leading to the maximal power output) typically had a critical temperature ~30–50 K above the heat source temperature.

Zeotropic mixtures have been receiving more and more attention over the last years as potential working fluids for ORC [7–12]. Indeed, in some applications, mixtures can be more suitable than pure working fluids because they allow a better temperature matching during the heat transfer processes, which decreases the irreversibilities and increases the system's efficiency and net power [13]. This is mainly due to the phase transition of mixtures, which is isobaric but not isothermal [7].

Chys et al. evaluated the heat recovery potential of 12 pure organic fluids as well as their binary and ternary mixtures considering heat source temperatures of 150 °C and 250 °C [9]. The authors determined

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Nomenclature

$\dot{I}$	flow rate of exergy destruction, kW
h	enthalpy, kJ/kg
h_{fg}	latent heat of evaporation, kJ/kg
$\dot{m}$	mass flow, kg/s
P	pressure, kPa
s	entropy, kJ/kg K
T	temperature, °C
(UA)	global conductance, kW/K
x	quality

Greek symbols

η	efficiency
Δ	difference
ϕ	mass fraction

Subscripts

0	dead state
C	cold
Co	condenser
Crit	critical
Eva	evaporator
Exe	exergy
G	generator
hs	heat source
H	hot
is	isentropic
L	low
mix	mixture
M	mechanic
P	pump
cs	cold source
T	turbine
wf	working fluid

Acronyms

GA	genetic algorithm
GWP	global warming potential
HFC	hydrofluorocarbon
HC	hydrocarbon
NDS	non-dominated-solutions
NTU	number of transfer units
ODP	ozone depletion potential

the optimal concentration in order to produce the maximum power output. The results showed that zeotropic mixtures had a positive effect on the system's performance and electric energy production, especially with the 150 °C heat source. However, the inclusion of a third component in the mix only had a marginal impact on the cycle performance. A comparison between a few mixtures and pure fluids was also performed in Ref. [14]. First law and second law efficiencies were studied. Better thermal performance was achieved when the temperature difference of the cooling water was near the temperature glide of the mixture in the condenser. Moreover, Braimakis et al. found that the substitution of pure fluids by hydrocarbons binary mixtures has the potential to increase the cycle exergy efficiency for both subcritical and transcritical conditions with heat source temperatures between 150 °C and 300 °C [15].

One of the advantages that fluid mixtures offer is the possibility to finely tune the fluid composition to the context for which the ORC is being designed. The idea of dynamic ORCs in which the fluid composition could change in time depending on the operating conditions was proposed in Ref. [16]. A systematic approach was also developed in Ref. [12] for a fast evaluation of large sets of fluids and mixtures. The authors found that for the temperature level considered in their study (138 °C), a mixture of R365mfc/R1234yf led to 10% more power and similar efficiency without wet expansion in the turbine when compared with the best pure fluid (R1234ze) with wet expansion.

The potential of zeotropic blends has also been addressed through multi-objective studies. In Ref. [17], ten defined zeotropic mixtures and R245fa as a pure working fluid were evaluated for three ORC configurations using geothermal water as the heat source. The net power output and TSP (turbine size parameter) were the two objective functions. The results showed that the use of zeotropic mixtures leads to more power generation in all configurations and lower values of TSP as well. The fluid composition was not optimized explicitly in that work. Feng et al. performed a multi-objective optimization of ORCs based on exergy efficiency and levelized energy cost [18]. Pure fluids and mixtures were compared as potential working fluids. Although only one type of mixtures was considered, it was found that mixtures typically had better exergy efficiency but worse levelized energy cost compared to pure fluids. Additionally, a multi-objective cost-power optimization for low temperature heat sources was done in Ref. [19]. The results indicated that working fluid mixtures show a thermodynamic improvement over the pure-fluids, but are also associated with higher costs.

Despite extensive research efforts over the last years to optimize ORC designs, and in particular to select optimal working fluids, there is still a lack of general design tools and guidelines for working fluid selection, in particular for fluid mixtures. Therefore, the objective of this article is to find suitable working fluid mixtures for typical heat source levels founded in ORC applications, considering three objective functions at the same time (multi-objective optimization). Two objectives are related to the system performance, i.e., net power output $\dot{W}_{Net}$ and exergy efficiency η_{Exe}, and the third objective function is the global conductance $(UA)_{Total}$ as an indication of the size of the system [20,21]. Different heat source temperature levels are investigated for a series of twenty-eight (28) working fluid binary mixtures, involving HCs and HFCs. The paper is divided as follows: Section 2 describes the thermodynamic model of the power cycle and the working fluids studied in this work. The multi-objective optimization problem and the approach used to solve it are presented in Section 3. The results and discussion follow in Section 4 while a scale analysis is proposed in Section 5.

2. Methodology

2.1. Heat source

Hot combustion gases are among the most common waste heat source in industrial installations. However, when these are used directly in heat recovery applications, potential corrosion problems can limit the minimum heat exchanger output temperature. Furthermore, recovering heat from gases requires large heat transfer areas because of the limited heat transfer coefficient of gases, which dominates the global heat transfer coefficient. In the present work, the heat source fluid was thus considered to be pressurized water. This choice eliminates the above-mentioned issues. Also, it applies to different power plants, such as those relying on geothermal heat. The inlet heat source pressure was assumed to be 1000 kPa in such a way that the heat source temperature could vary from 80 °C to 180 °C. In this work, considering increments of 20 °C, a total of six heat source temperatures were analyzed. The other characteristics of the heat source are presented in