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The ORC-PD: A versatile tool for fluid selection and Organic Rankine Cycle unit design

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ABSTRACT

The ORC (Organic Rankine Cycle) is an emerging and commonly accepted technology for converting medium and low temperature heat sources into electricity. Several ORC units are already in operation but there is a continuous need of new and more versatile computer tools able to perform fluid selection and plant layout optimization. For these reasons, the present work is devoted to present a computer tool able to perform the fluid selection and the plant design of ORC units maximizing, for example, the net electric power for different heat sources' type and temperature (low, medium and high temperature). The optimum fluid is selected among 81 possible candidates. The optimization is performed taking into account a wide range of operating conditions: subcritical and transcritical cycles, regenerative and non-regenerative units and heat transfer made from the hot side and the power cycle (with and without the oil loop). Being the expander a crucial component, the axial and radial efficiency prediction charts are employed to estimate the expander isentropic efficiency. An exergy and economic analysis is also performed. For the selected test case the maximum net electric power can be reached using Toluene with a recuperative subcritical cycle.

1. Introduction

In the last few decades, the world energy use has risen more than 40%. This results in a high growth of fossil fuel prices and a massive release of CO_2 and other emissions [1]; substances characterized by a great impact on global warming [2]. Moreover, an economic system based on oil and gas is energy dependent from Countries that have or control these reservoirs. Then, it becomes essential to promote energy saving, exploit new "indigenous" energy sources and modify the energy use.

In order to tackle these challenges, energy producers focused their attention on renewable energy sources (wind, solar, geothermal, biomass and so on), energy efficiency and waste heat recovery. On account of this, many researchers developed several methods for converting medium and low temperature heat into electricity, each one with its advantages and drawbacks. However, the main obstacle limiting the spread of medium and low temperature waste heat recovery units is the high initial investment cost which in turn results in high payback times and poor economic revenue [3–7].

An effective way to recover the heat rejected to the environment at medium and low temperature is to use the ORC (Organic Rankine Cycle) technology [1].

Although investigated since the 1880s, Organic Rankine Cycles have never been popular until today's growing interest on medium and low grade energy recovery systems where cycles using water as WF (working fluid) fail for technical and economic reasons [8,9].

The ORC operates in a similar way as the conventional steam Rankine cycle but it uses, as working fluid, an organic compound instead of water. Several types of HS (heat source), such as solar [10,11], geothermal [12,13], biomass [2,14,15] and ocean [16] energies, and industrial waste heat [8,17–20] have been investigated showing, in most cases, efficiency values less than 20%. Obviously, the efficiency is lower than that of conventional steam Rankine cycle due to the poor exergy input. To overcome this issue, several researchers have investigated more complex configurations (supercritical cycle [21–23], dual pressure cycle [24,25], Kalina cycle

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Nomenclature

A	heat transfer surface [m^2]
CF	cash flow
C_{BM}	bare module cost [$]
C_{GR}	cost of the site [$]
$C_{O\&M}$	operation and maintenance cost [$]
C_P^0	purchased equipment cost base conditions [$]
C_{TBM}	total direct and indirect costs [$]
C_{TM}	cost of evidence and taxes [$]
C_{el}	electricity sell price [$]
C_{fuel}	cost of the fuel [$]
E	recuperator efficiency [−]
E_{el}	annual electricity production [kWh]
F_{BM}	bare module factor [−]
H_{annual}	annual operating hour [hour]
I	exergy loss [W]
IP	profitability index
$LCOE$	levelized cost of energy
NPV	net present value
P	power [W]
RF	capital recovery factor [$]
SP	size parameter
SPB	simple payback
S_{annual}	annual incomes [$]
T	temperature [°C]
U	heat transfer coefficient [W m^{-2} K^{-1}]
VFR	volumetric flow rate
e	specific exergy [J kg^{-1}]
f	plant availability factor [−]
h	enthalpy [kJ kg^{-1} K^{-1}]
i	interest rate [%]
m	mass flow rate [kg s^{-1}]
p	pressure [bar]
s	entropy [J kg^{-1} K^{-1}]
t_{corp}	corporate tax rate [%]
x	steam quality [−]

Abbreviations

CFC	chlorofluorocarbons
CM	condensation medium
CO_2	carbon dioxide
COND	condenser
EM	electric motor
GA	genetic algorithm
GEN	electric generator
HC	hydrocarbons
HCFC	hydrochlorofluorocarbons
HFC	hydrofluorocarbons
HFO	hydrofluoroolefins
HS	heat source
HX	heat exchanger
LB	lower bound
MHE	main heat exchanger
ORC	Organic Rankine Cycle
P	pump
PFC	perfluorocarbons
REC	recuperator
TUR	expander
UB	upper bound
WF	working fluid

Greek letters

Δ	difference
η	efficiency [%]
ψ	loss factor [−]
ξ	specific dissipating factor [−]

Subscripts

0	ambient
cond	condensation
el	electrical
ev	evaporation
ex	exergetic
in	inlet
is	isentropic
mec	mechanical
oil	thermal oil
out	outlet
pp	pinch point
th	thermal

[26] and trilateral flash cycle [27,28]) with the aim of improving the performance and the profitability of the plant but, in practice, the subcritical unit is by far the most used for its simplicity [29].

As said, an ORC is similar to the conventional steam Rankine cycle: the working fluid at high pressure is firstly evaporated, then is expanded to a lower pressure thus supplying mechanical work. The cycle is closed by condensing the low pressure vapour (coming from the expander outlet) and pumping the liquid back to the high pressure. Hence, the ORC unit is fundamentally made up by the same devices as a conventional steam power module but for medium and low temperature heat sources it has several advantages [5,30]:

- Simple structure.
- High reliability.
- Easy maintenance.
- Being the most organic fluids isentropic (or dry), the slope of the saturated vapour curve is much closer to vertical (or positive) than water (the right curve of the dome has a negative slope). Therefore, the limitation of the vapour quality at the end of the expansion process disappears in an ORC cycle and there is no need to superheat the vapour before the turbine inlet section.
- Less latent heat is needed during the evaporation process being the entropy difference between saturated liquid and saturated vapour much smaller for organic fluids.
- Organic fluids have higher molecular weight than water. This will increase the fluid mass flow rate for the same sizes of turbine. More mass flow rates will give better turbine efficiencies and less turbine losses [31].
- Boiling point of ORC fluids are less than water; hence, they can be applied in various types of heat source, including the low temperature.
- The smaller temperature difference between evaporation and condensation means that the pressure ratio will be much smaller and thus simple single stage turbines can be adopted.

Notwithstanding the above mentioned advantages, the design of an ORC unit is a complicated task. The type and temperature of