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# Influence of axial turbine efficiency maps on the performance of subcritical and supercritical Organic Rankine Cycle systems

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ABSTRACT

The utilization of low-to-medium enthalpy geothermal resources for electricity generation is commonly done using the binary cycle power plant technology. The low temperature of the geothermal fluid necessarily results in low thermal efficiencies but it can be profitably used as a driver to reduce the equipment cost. In particular, single stage axial flow turbines, a cheaper option compared to multistage solutions, can be used due to the moderate enthalpy drop in the expansion process. In this work the design performance of ORCs (Organic Rankine Cycle systems) equipped with single stage axial flow turbines is optimized for utilization of a 150 °C geothermal fluid. Accurate predictions of turbine efficiency are included in the optimization procedure to take into account the influence of the thermodynamic cycle parameters, fluid properties and size on the maximum achievable efficiency. A set of six fluids is considered to examine a wide spectrum of design conditions. Results show that supercritical ORCs outperform subcritical ORCs even taking into account the detrimental effect of high expansion ratios on turbine efficiency. Hydrofluoroolefins are found to exhibit a net power output approximately equal or even higher than the best hydrofluorocarbons.



## 1. Introduction

Binary cycle power plants are recognized as the most efficient power cycles in the utilization of low-to-medium enthalpy geothermal resources. Besides the environmental benefits of a closed cycle on both the working fluid and geofluid sides, binary cycles offer several advantages related to the properties of the working fluids which behave in a much different way from water. Several investors complain about the low thermal efficiency attainable by such systems while disregarding the potential capital cost savings in the purchase of the equipment. Accordingly all the options to improve the thermodynamic performance while reducing plant costs are highly regarded. Furthermore, a low environmental impact is a key variable to speed up the acceptance of an energy project by the local community where the plant is installed and may be pursued even in the absence of binding laws on emission levels.

Knizley et al. [1] evaluated the operational cost savings derived from ORCs (Organic Rankine Cycle systems) installed in the U.S. for utilization of waste heat from power generation units. They found that ORCs enable cost savings both in the residential and commercial sectors in almost all States. The maximum cost reduction compared to a conventional system where electricity is purchased from the grid was obtained in Alaska and California. This study has demonstrated that ORCs are a cost-effective technology in the current energy market conditions. Walraven et al. [2] performed an economic optimization of an air-cooled ORC system for a geothermal project in Belgium having brine wellhead temperatures in the range 100–150 °C. The goal was the maximization of the NPV (net present value). They found a marked increase of NPV with rising brine inlet temperature, a negligible effect of the brine outlet temperature constraint for reinjection temperatures up to 50–60 °C and an improvement derived from the addition of a second pressure level. Ventura et al. [3] developed a simulation model for both subcritical and supercritical regenerative ORC configurations. They found that R125, R143a, RC318, R236ea and R152a yield the maximum power output for geothermal fluid temperatures at 100 °C, 120 °C, 150 °C, 180 °C and 210 °C, respectively. The authors highlighted that the main limitation of the model was the assumption of a constant efficiency for the turbine independently of the operating conditions. Liu et al. [4] analyzed the response of geothermal ORCs performance to the variation of

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**Nomenclature**

| | |
|---|---|
| $ex$ | specific exergy, kJ/kg |
| $h$ | specific enthalpy, kJ/kg |
| $m$ | mass flow rate, kg/s |
| $p$ | pressure, bar |
| $P$ | power, kW |
| $q$ | quality |
| $Q$ | heat load, kW |
| $s$ | specific entropy, kJ/(kg K) |
| $SP$ | size parameter, m |
| $T$ | temperature, °C |
| $\dot{V}$ | volumetric flow rate, $m^3/s$ |
| $VR$ | volumetric expansion ratio |

*Greek symbols*

| | |
|---|---|
| $\zeta$ | exergy recovery efficiency, % |
| $\eta_T$ | isentropic turbine efficiency, % |
| $\eta_{th}$ | thermal efficiency, % |

*Subscripts*

| | |
|---|---|
| $C$ | cold |
| $COND$ | condensation |
| $CR$ | critical |
| $GEO$ | geothermal fluid |
| $H$ | hot |
| $id$ | hydraulic |
| $in$ | inlet |
| $is$ | isentropic |
| $max$ | maximum |
| $out$ | outlet |
| $rec$ | recovery |
| $rec$ | recuperator |
| $surr$ | superheating |
| $T$ | turbine |
| $th$ | thermal |
| $TURB$ | turbine |

*Acronyms and abbreviations*

| | |
|---|---|
| ACC | air cooled condenser |
| GWP | global warming potential |
| HC | hydrocarbons |
| HFC | hydrofluorocarbons |
| HFO | hydrofluoroolefins |
| ORC | organic Rankine cycle |
| WF | working fluid |

many system parameters and considered R245fa, R134a and R600a as working fluids. Results showed that the pinch temperature differences in evaporator and condenser have the highest influence on the net power output when the geothermal fluid temperature is lower than 100 °C, whereas the evaporation temperature becomes the most important factor at temperatures higher than 100 °C. Wang et al. [5] used the minimization of the payback period as objective function to optimize the internal parameters (evaporation and condensation temperatures and the pinch point temperature differences) of ORCs using waste heat at temperatures between 150 °C and 250 °C. R236fa, R245fa and R113 yielded the lowest payback period at flue gas temperatures of 150 °C, 200 °C and 250 °C, respectively.

In the search for the optimum selection of the working fluids some criteria have been proposed in the literature which relate the ORC performance with the distance between the critical temperature of the working fluid and the inlet temperature of the heat source [6]. Following this approach Liu et al. [7] identified the OHSTs (optimal heat source temperatures) for thirteen working fluids. The OHST criterion can provide a direct indication on the best working fluids maximizing global system efficiency. For instance the OHST for R227ea is 140 °C. A similar analysis was carried out by Li et al. [8] who selected the working fluids from the critical temperature to ensure a good thermal match with the heat source. These criteria can be used for a first screening before cycle optimization.

The use of mixtures in place of pure fluids enables a better coupling with the heat source due to the glide in the evaporation process at subcritical pressures. Feng et al. [9] considered mixtures of R245fa and R227ea for utilization of a low grade heat source at 120 °C. Selected solutions were characterized by a low pinch point temperature difference (3–5 °C) and a small superheating (3 °C). Liu et al. [10] investigated the performance of isobutane/isopentane (R600a/R601a) mixtures in subcritical ORCs fed by geothermal heat sources in the range 110–150 °C. The maximum net power output was obtained with isobutane mole fractions in the range 0.7–0.9 and it was from 4% to 11% higher than that using pure isobutane. Mavrou et al. [11] investigated working fluid mixtures in solar ORCs employing flat plate collectors with heat storage. Habka et al. [12] investigated the potential of using mixtures to maximize power output from low enthalpy geothermal sources (<120 °C). They found that R438A, R422A and R22M yield the highest power output at geofluid temperatures of 80, 100 and 120 °C, respectively. The power output gain compared to the most efficient pure fluid (R227ea) varied between 15 and 21%. Mixtures were found to give significant advantages at supercritical pressures as well: Braimakis et al. [13] showed that supercritical mixtures of butane–propane, butane–hexane and butane–cyclopentane exhibit the highest exergetic efficiency in the range 150–300 °C.

A breakthrough in the achievement of high system efficiencies is a radical change of the cycle architecture. Lecompte et al. [14] compared the subcritical and supercritical ORCs against the partial evaporation ORC (i.e., a generalization of the trilateral cycle) for utilization of waste heat in the temperature range 100–350 °C. Optimization results showed that the partial evaporation ORC reaches a higher second law efficiency (and power output) than the other layouts especially at low to moderate heat source inlet temperatures. Li et al. [15] analyzed two-stage ORC configurations for utilization of geothermal heat sources in the range 90–120 °C. A parallel arrangement of evaporators was compared against a series one. The parallel arrangement provided an incremental power output of 3.3–4.5% compared to the single-pressure ORC. A higher improvement in the range 6.5–9.0% was achieved by the series arrangement due to the better match between heat source and working fluid. A new configuration has been recently proposed by Andreasen et al. [16] which is based on a simplification of the Kalina cycle using hydrocarbon mixtures in place of a mixture of water/ammonia. In the utilization of a 90 °C heat source this configuration using an isobutane/pentane mixture yields a 14.5% higher net power output than an optimized ORC.

A few studies have recently appeared about the evaluation of the performance of hydrofluoroolefins, pure or mixed with hydrofluocarbons or hydrocarbons. Petr et al. [17] evaluated the applicability of R-1234ze(Z) to replace the widely used R-245fa for