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ScienceDirect
Energy Procedia 61 (2014) 71 – 74
Energy Procedia

The 6th International Conference on Applied Energy – ICAE2014

# Thermo-economic comparison of advanced Organic Rankine Cycles

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## Abstract

*To improve the performances of the Organic Rankine cycle, several advanced cycle designs are proposed. Because different studies use varying boundary conditions, an assessment of the benefit of the cycle designs is complicated. Furthermore, the inclusion of economic parameters is valuable for a sound comparison. In this work, the subcritical cycle, the trilateral cycle and the transcritical cycle are compared on a thermodynamic and economic basis. The investigated cycles are optimized for three waste heat recovery cases within a temperature range of 100 °C to 300 °C. From a pure thermodynamic analysis only a marginal performance benefit is achieved for high temperature cases with the working fluids under consideration. Therefore, a thermo-economic analysis is provided for the low-temperature case. A multi-objective optimization is at the basis of the thermo-economic analysis and comparison. The thermodynamic performance of the cycles is compared with equal boundary conditions and actual cases are used. The results of such investigation are particularly interesting for manufacturers of ORCs.*

Peer-review under responsibility of the Organizing Committee of ICAE2014

*Keywords:*Organic Rankine Cycle, thermo-economic, multi-objective optimization, advanced ORC architectures

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Peer-review under responsibility of the Organizing Committee of ICAE2014
doi:10.1016/j.egypro.2014.11.909

## 1. Introduction

The subcritical Organic Rankine cycle (SCORC) is recognized as a viable technology for converting waste heat into electricity. The benefits of using an ORC are: low maintenance, autonomous operation, favorable operating pressures and the opportunity to recuperate low temperature waste heat. Still, there is potential for increased performance by considering advanced cycle designs. Especially at low temperatures, a relatively large exergy share is destroyed in the evaporator because of the subcritical heat exchange process [1, 2]. As such, numerous modifications to the basic ORC are proposed in the literature. Some of the most readily deployable are: the transcritical cycle (TC) [3] and the trilateral cycle (TLC) [4].

## 2. Description of the investigated cycles, cases and working fluid selection

In a transcritical power cycle (TC), heat addition occurs in a supercritical state, while condensation occurs in the usual two-phase region. The major difference with a subcritical ORC lies in the heating process of the working fluid. The working fluid is brought directly to supercritical pressure and heated to a supercritical state, effectively bypassing the two-phase region. In a trilateral cycle (TLC) the working fluid is not boiled but only brought to a saturated liquid state before entering the expander. Fischer et al. [5] claims that the pure TLC always has a better performance than the supercritical cycle. However, according to Schuster et al. [3] the supercritical cycle is most promising.

Three cases are defined. In a first case (Case I), water with a flow rate of 15 kg/s at 98 °C is available from a chemical process. In a second case (Case II), the heat source is flue gas from drying expanded clay. The flue gas has a flow rate of 100,000 $Nm^3/h$ at 240 °C. In the third case (Case III), flue gas at 350 °C with a flow rate of 800,000 $Nm^3/h$ is available from a furnace.

The selection of the working fluids is based on an extensive literature survey [6, 7, 2, 5]. Only working fluids which are used in contemporary ORC installations are retained. These fluids are not necessarily optimal for the discussed advanced cycles. However, they provide an excellent benchmark and lead to suggestions for a better fluid selection. Furthermore the stability of the working fluid in the operating regime is taken into account [8]. This leads to the selection of working fluids as given in Table 1.

Table 1. Final selection of working fluids.

| Cycle/Case | Case I | Case II | Case III |
|---|---|---|---|
| Subcritical | R245fa | n-pentane | toluene |
| Transcritical | R125 | n-pentane | toluene |
| Trilateral | R245fa | toluene | water |

## 3. Thermodynamic analysis and thermo-economic optimization

In a first step the SC, TLC and SCORC are modeled based on the first and second law of thermodynamics. The net power output ($\dot{W}_{net}$) is maximized by optimizing the evaporation pressure (and input temperature of the turbine for the transcritical case). The pinch point temperature differences in the evaporator and condenser are assumed 5 °C. The isentropic efficiency of the turbine and pump are respectively 60 % and 70 %. It is clear from Fig 1. that advanced cycle designs show a significant performance increase for the low temperature case. However, the needed overall heat transfer coefficient multiplied with the heat exchange area (U.A) suggests increased investment costs. Therefore a thermo-economic approach is essential for further analysis of Case 1.

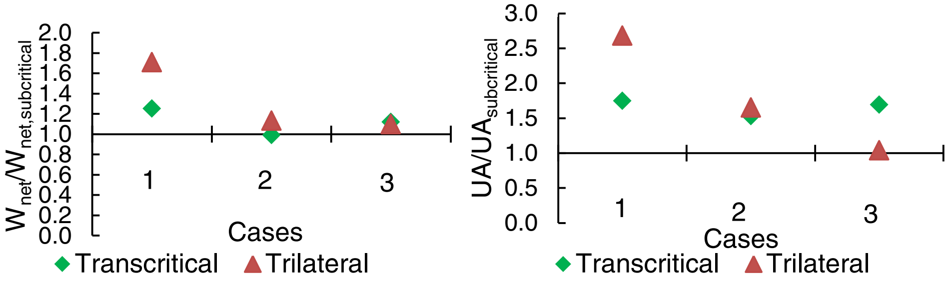

Fig. 1. (a) Maximized net power output; (b) UA value for maximal net power output (reference: SCORC)

Lecompte et al. [9, 10] provides details about the thermo-economic model. All heat exchangers are plate heat exchangers. For the single phase flows, the two phase flows in the evaporator, the two phase flows in the condenser and the supercritical flows, the correlations of respectively Martin et al. [11], Han et al. [12], Han et al. [13] and Petukhov-Kranoschekov [14] are used. The cost model is taken from Turton et al. [15]. A genetic algorithm locates the Pareto front of net power output versus investment cost by optimizing the pinch point temperature differences, the evaporation and condensation pressures, the number of passes and mass flux rates in the heat exchangers. The Pareto front for the investigated cycles is given in Fig. 2. Each Pareto front seems to converge to an asymptote, indicating that a further increase of investment cost has marginal effect on the net power output. The maximum power output of the SCORC, TC and TLC is respectively 116 kW, 159 kW and 195 kWe and the minimum specific investment cost ($Cost_{components}/\dot{W}_{net}$) is respectively 2275 €/kWe, 3189 €/kWe and 2709 €/kWe. Especially the TLC looks promising for low temperature heat conversion.

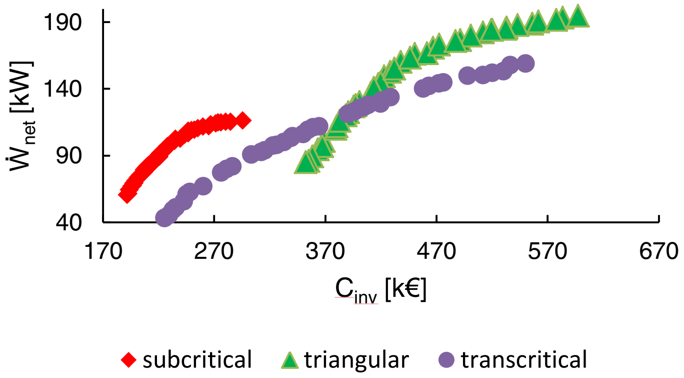

Fig. 2. Pareto front of investment cost versus net power output for the subcritical, transcritical and trilateral cycle.

## 4. Conclusions

A thermo-economic model is developed for the subcritical, the transcritical and the trilateral cycle, based on currently used fluids. Only at low temperatures the modified cycles show a performance improvement over the subcritical ORC. The thermo-economic analysis indicates that especially the TLC is promising. However, the initial investment costs of the investigated advanced architectures are always larger than for the subcritical ORC for comparable net power output.

## Acknowledgements

The results presented in this paper have been obtained within the frame of the IWT SBO-110006 project The Next Generation Organic Rankine Cycles (www.orcnext.be), funded by the Institute for the Promotion and Innovation by Science and Technology in Flanders. This financial support is gratefully acknowledged.

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