Thermodynamic analysis of the partially evaporating trilateral cycle

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EXTENDED ABSTRACT

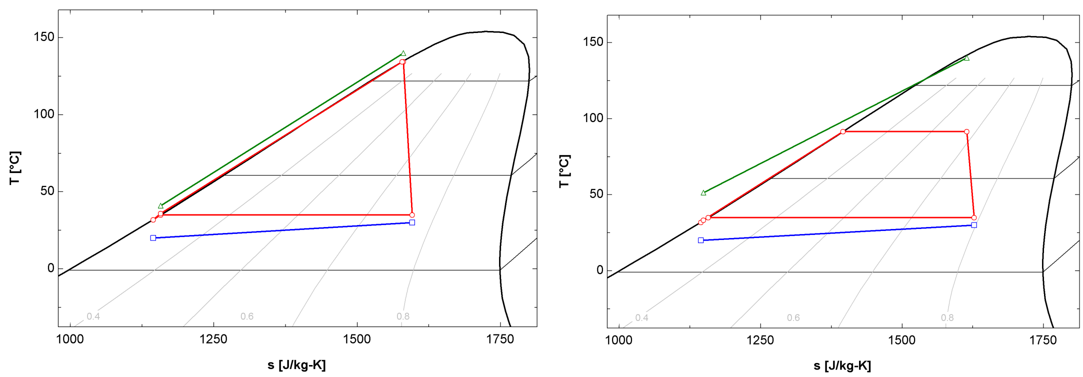
INTRODUCTION

The potential of Organic Rankine Cycles (ORC) to recover low grade waste heat is well known. The high heat recovery potential is partially attributed to a good match of the temperature profiles between working fluid and waste heat stream in the evaporator. This preferable characteristic is mainly induced by the selection of an appropriate working fluid. However, because of the constant temperature evaporation of the working fluid, the heat recovery potential is restricted. In order to overcome this limitation the trilateral cycle (TLC) has been investigated [1].

A Trilateral cycle (also called Triangular cycle) is a modified Rankine cycle. The main difference is that the working fluid is not evaporated but only heated to the saturation temperature. Compared to the ORC, the heat carrier stream can be cooled further and the thermal efficiency is lower [2]. In this study the effect of partial evaporation of the working fluid is investigated.

DESCRIPTION OF THE PARTIALLY EVAPORATING TLC

Thermodynamics of the partially evaporating TLC



(a) TLC **(b)** partially evaporating TLC

Figure 1: Cycle Ts diagrams for R245fa

In figure 1 the TLC (1a) and partially evaporating TLC (1b) is shown in a Ts diagram. A pinch point shift appears when evaporating past a certain vapour quality. For both cycle types the expansion process traverses into the two-phase region. This necessitates the use of a wet expander. Scroll [3] and screw expanders [1] are known to tolerate a small amount of liquid. Furthermore, Smith et al. [4] confirmed that for screw expanders isentropic efficiencies of more than 70 procent are attainable.

With the assumption that both cycles are irreversible, the ORC (carnot cycle) has inherently a higher thermal efficiency than the ideal TLC, when working between the same temperature levels [2]. Furthermore, because of the large enthalpy of vaporization, the required working fluid mass flow rate is lower in the ORC for an equal heat input. The required heat transfer area is expected to be larger for the TLC due to a decrease in overall heat transfer coefficient (omitting of boiling) and the increase in heat input.

Therefore the idea is conceived to optimize the TLC cycle by partial evaporation of the working fluid. A higher thermal efficiency and a reduction in heat transfer area can be achieved at the expense of a decreased heat input. In this work the thermodynamic implications are analysed.

Model and assumptions

A thermodynamic model of the partially evaporating TLC was developed based on the assumptions in table 1. The working fluid considered is R245fa. Three different heat sources (100 °C, 120 °C, 140 °C) are imposed.

Cycle	Isentropic pump efficiency	30%
	Isentropic turbine efficiency	70%
	Subcooling	3°C
	ΔT pinch evaporator	5°C
	ΔT pinch condenser	5°C
Heat source	Inlet temperature waste heat	100/120/140 °C
	Mass flow rate waste heat	1 kg/s
Heat sink	Inlet temperature cooling water	20 °C
	Outlet temperature cooling water	30 °C

Table 1: Model assumptions

RESULTS AND DISCUSSION

Sensitivity analysis

The result of the sensitivity analysis on the outlet vapour quality for a heat carrier stream of 140 °C is given in figure 2. The vapour quality at the outlet of the evaporator is set between 0 and 1, while optimizing the evaporating pressure for maximum net power output. The thermal efficiency is, as expected, highest for the pure ORC (x=1). Furthermore the pumping power is six times higher for a pure TLC cycle compared to the ORC. It can be noticed that there is an optimal vapour quality whereby the net power peaks (x=0.23), at this point the pumping power needed is reduced with 24 % compared to the pure TLC. Because of the pinch point shift at x=0.45 (see also figure 1) the heat input is gradually reduced and the thermal efficiency reaches a minimum at this value. After the pinch point shift the optimal evaporating pressure stabilizes around 10.5 bar. By solely looking at the thermodynamic performance, the partially evaporating TLC has some preferable characteristics. For heat streams with other temperatures the shape of the curve is similar but a shift is observed in the direction of lower vapour quality.

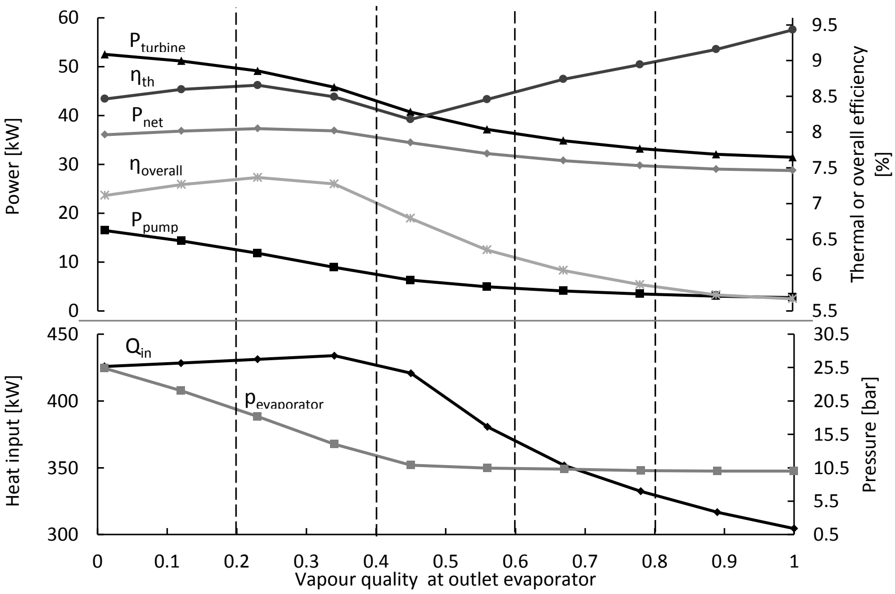


Figure 2: Sensitivity analysis on vapour quality, heat stream of 140 °C

Optimal working regime

Influence of heat stream temperature

For the three given heat streams (100°C, 120°C, 140°C) the net power output is maximised by optimizing the saturation temperature and vapour quality at the outlet of the evaporator. In order have a sound comparison, the overall efficiency is used. This is defined as the ratio of the net power output over the heat available if the waste heat stream is cooled to ambient temperature (20°C). For the waste heat stream of 100°C, 120°C, 140°C the overall efficiency is respectively 3.99 %, 5.69 %, 7.37 %. The results show a linear dependency of the overall efficiency in function of the waste heat temperature when optimizing both the saturation temperature and outlet vapour quality. This linear dependency is also observed for the pure TLC cycle [2].

Influence of pump efficiency

In figure 3 the effect of the pump isentropic efficiency on the optimization parameters is shown. In order to maximize the net power output, partially evaporating the working fluid is beneficial if the pump efficiency is low. When the isentropic pump efficiency reaches 60% or more the pure TLC cycle has the highest power output. However the size of the installation remains larger compared to a partially evaporating TLC due to a large mass flow rate.

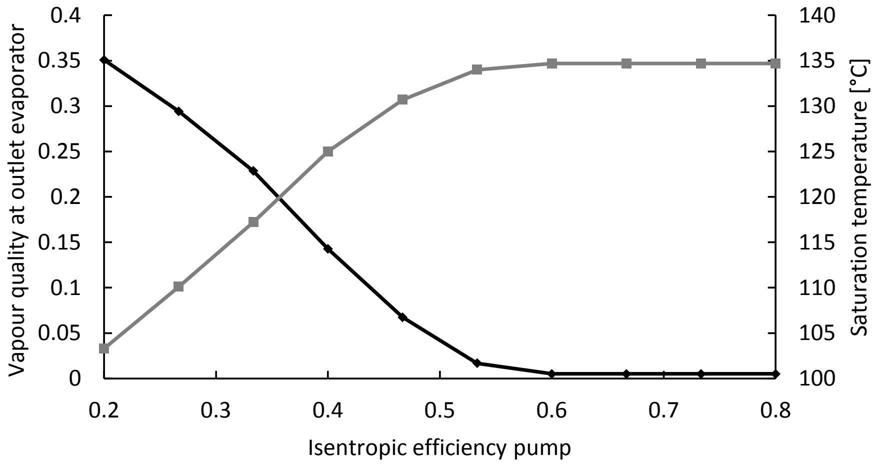


Figure 3: Influence of pump isentropic efficiency on optimization, heat stream of 140°C

CONCLUSIONS

In this work it is shown that the partially evaporating TLC can improve the net power output of the system. Partial evaporation is promoted when the pump isentropic efficiency is low. Furthermore, the pumping power is reduced by 24 % compared to the pure TLC. A linear relation exists between output power and heat stream temperature when optimizing both outlet vapour quality and pressure at the evaporator. Further research includes a comparison of the sizing and cost of the partial evaporating system.

ACKNOWLEDGEMENTS

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