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Design and optimization of a novel organic Rankine cycle with improved boiling process

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ABSTRACT

In this paper we present a novel organic Rankine cycle layout, named the organic split-cycle, designed for utilization of low grade heat. The cycle is developed by implementing a simplified version of the split evaporation concept from the Kalina split-cycle in the organic Rankine cycle in order to improve the boiling process. Optimizations are carried out for eight hydrocarbon mixtures for hot fluid inlet temperatures at 120 °C and 90 °C, using a genetic algorithm to determine the cycle conditions for which the net power output is maximized. The most promising mixture is an isobutane/pentane mixture which, for the 90 °C hot fluid inlet temperature case, achieves a 14.5% higher net power output than an optimized organic Rankine cycle using the same mixture. Two parameter studies suggest that optimum conditions for the organic split-cycle are when the temperature profile allows the minimum pinch point temperature difference to be reached at two locations in the boiler. Compared to the transcritical organic Rankine cycle, the organic split-cycle improves the boiling process without an entailing increase in the boiler pressure, thus enabling an efficient low grade heat to power conversion at low boiler pressures.

1. Introduction

Compared to the steam Rankine cycle, the ORC (organic Rankine cycle) is a more appropriate technology for conversion of low grade heat into electric power [1], but, due to thermodynamic limitations, it is challenging to achieve high heat to power conversion efficiencies when the heat source inlet temperature is low. A crucial aspect of maximizing system efficiency is to reduce heat transfer irreversibilities, which correlate with the temperature difference between the heat exchanging streams. The irreversibilities are minimized when the temperature profiles of the streams are optimally matched. Pure fluids are traditionally used as working fluids in ORCs; however, the isothermal evaporation and condensation at subcritical pressures do not enable an optimal temperature profile match in the condenser or the boiler, when the heat source and heat sink are non-isothermal. In the scientific literature different methods for reducing heat transfer irreversibilities of condensation and boiling have been suggested. In transcritical cycles the temperature profile is improved by adopting a supercritical boiler pressure, thereby eliminating the isothermal two-phase evaporation at the expense of relatively high cycle pressures [2,3]. By implementing a zeotropic mixture as the working fluid, it is possible to evaporate and condense the working fluid non-isothermally at subcritical pressures. This enables a reduction in the temperature difference between the heat exchanging streams both for the condenser and the boiler resulting in an increase in cycle performance [4]. Analyses of the irreversibilities in the cycle components have identified the condenser as achieving the largest benefits from the non-isothermal phase-change, and the mixture composition minimizing the condenser losses tends to coincide with the composition which maximizes cycle performance [5,6]. In a recent study, Weith et al. [7] investigated the potential of using a siloxane mixture (MM/MDM) as the working fluid for an ORC utilizing the 460 °C exhaust heat from a biogas engine. By using the mixture they obtained an increase in the second law efficiency of 3% for combined heat and power generation and 1.3% for electricity generation compared to pure MM. Chys et al. [8] showed that the relative increase in cycle efficiency for mixtures compared to pure fluids decreases when the heat source inlet temperature increases. For a 150 °C inlet temperature they reported a cycle efficiency increase of 15.7% when using binary mixtures instead of pure fluids.

Using a zeotropic mixture, it is possible to modify the properties of the working fluid by changing the composition of the mixture

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Nomenclature

Acronyms

ARC	auto-cascade Rankine cycle
Bp	bubble point
ORC	organic Rankine cycle
OSC	organic split-cycle

Symbols

A	area, [m^2]
h	mass specific enthalpy, [kJ/kg]
$\dot{m}$	mass flow rate, [kg/s]
n	Number of discretization points, [−]
P	pressure, [bar]
$\dot{Q}$	heat transfer rate, [kW]
T	temperature, [°C]
$\overline{U}$	average overall heat transfer coefficient, [kJ/kgK]
$\dot{W}$	power, [kW]
x	vapour quality, [−]
X	mole composition, [−]
Y	mass composition, [−]

Greek symbols

Δ	difference
η	efficiency

Subscripts

boil	boiler
cond	condenser
cool	cooling water
eff	effective
evap	evaporator
exp	expander
g	glide
hf	hot fluid
i	inlet
intm	intermediate
l	lean
min	minimum
NET	net
o	outlet
p	polytropic
pump	pump
r	rich
recu	recuperator
s	isentropic
tot	total
wf	working fluid

within the cycle. In the Kalina cycle a separator is implemented to separate the vapour and liquid phases of a two-phase ammonia/water stream, enabling the creation of two streams with different compositions. The review by Zhang et al. [9] provides an overview of the literature on Kalina cycle systems in which many different cycle layouts have been proposed and analysed. Hettiarachchi et al. [10] investigated a simple Kalina cycle with a separator placed between the evaporator and the expander for utilization of a low temperature heat source at 90 °C. Compared to two ORCs with ammonia and isobutane as the working fluids, the overall performance of the Kalina cycle was found to be higher. Bombarda et al. [11] compared the performance of a Kalina cycle, with the separator located at an intermediate pressure level, and an ORC for utilization of diesel engine waste heat at 346 °C. They found that the two cycles produced similar power outputs, while the pressure in the Kalina cycle was significantly higher than in the ORC. Modi and Haglind [12,13] optimized four Kalina cycles for utilization of concentrated solar energy (expander inlet temperature over 450 °C). They found that the cycle layout with the most recuperators obtained the highest cycle efficiency. Bao and Zhao [14] developed a novel cycle layout based on the Kalina cycle: the ARC (auto-cascade Rankine cycle). In this cycle a separator generates a vapour stream, which is superheated and expanded, and a liquid stream, which is evaporated in an internal heat exchanger and subsequently expanded in a second expander. For a geothermal heat source the ARC obtained an exergetic efficiency of 59.12%, while an ORC obtained 52% and a Kalina cycle 44%.

In addition to the Kalina cycle, Alexander Kalina developed the split-cycle concept [15] by also implementing a separator to generate a saturated vapour stream and a saturated liquid stream at different compositions. The vapour and liquid streams are split and mixed until two working fluid streams with desired compositions are created. The two working fluid streams are then evaporated simultaneously in a multi-stream evaporator, such that the pinch point (normally at the saturated liquid point) is smoothened. This makes it possible either to increase the boiler pressure or increase the working fluid mass flow and thereby increase the power output of the cycle. Larsen et al. [16] modelled the Kalina split-cycle and found that the Kalina split-cycle with reheat obtained an increase in power output of 11.4% compared to a reference Kalina cycle without reheat. Nguyen et al. [17] used an exergy analysis to compare the Kalina split-cycle and the Kalina cycle, and found that the irreversibilities in the Kalina split-cycle were 2.5–5% lower than the irreversibilities in the Kalina cycle, primarily due to an improvement of the boiling process.

In this paper we present a novel organic Rankine cycle layout, named the OSC (organic split-cycle), which is based on a simplification of the Kalina split-cycle. The OSC also includes the multi-stream evaporator, but implements a simplified method for the split stream generation. The paper encompasses an optimization study, two parameter studies, initial considerations on the design of the multi-stream evaporator and a comparison of the OSC process to the ORC and the Kalina split-cycle processes. In the optimization study, eight hydrocarbon mixtures are optimized to maximize the net power output from utilization of a 120 °C and a 90 °C water stream representing either waste heat or geothermal water streams. In the parameter studies, we investigate how selected design parameters affect the location of the pinch points in the boiler, and ultimately how these affect the performance of the cycle. The analysis of the multi-stream evaporator illustrates the necessary $\overline{U}A$ distribution in order to achieve the desired temperature profile, and provides the basis for a discussion on the design requirements for this heat exchanger.

The paper begins with a description of the OSC process in Section 2. The modelling methodology is outlined in Section 3, and in Section 4 the results from the analyses are presented and discussed. Conclusions are given in Section 5.

2. Organic split-cycle

The OSC process results from an implementation of the thermodynamically beneficial split-stream evaporation in an ORC