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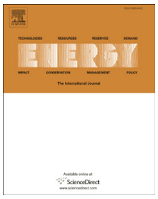

Thermodynamic evaluation of the Kalina split-cycle concepts for waste heat recovery applications

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A B S T R A C T

The Kalina split-cycle is a thermodynamic process for converting thermal energy into electrical power. It uses an ammonia–water mixture as a working fluid (like a conventional Kalina cycle) and has a varying ammonia concentration during the pre-heating and evaporation steps. This second feature results in an improved match between the heat source and working fluid temperature profiles, decreasing the entropy generation in the heat recovery system. The present work compares the thermodynamic performance of this power cycle with the conventional Kalina process, and investigates the impact of varying boundary conditions by conducting an exergy analysis. The design parameters of each configuration were determined by performing a multi-variable optimisation. The results indicate that the Kalina split-cycle with reheat presents an exergetic efficiency by 2.8% points higher than a reference Kalina cycle with reheat, and by 4.3% points without reheat. The cycle efficiency varies by 14% points for a variation of the exhaust gas temperature of 100 °C, and by 1% point for a cold water temperature variation of 30 °C. This analysis also pinpoints the large irreversibilities in the low-pressure turbine and condenser, and indicates a reduction of the exergy destruction by about 23% in the heat recovery system compared to the baseline cycle.

1. Introduction

The integration of WHR (waste heat recovery) systems in various processes presents thermodynamic and environmental benefits, as it results in a greater power generation for the same fuel input and smaller specific CO_2 emissions. Several power cycles have been suggested in the scientific literature: they differ by the selection of the working fluid, the size of application, the temperature and pressure levels, etc. The most well-known cycles are the steam Rankine cycle, the ORC (organic Rankine cycle) and the Kalina cycle, in which the working fluid is a mixture of ammonia and water. The two latter cycles are often suggested as alternatives to the steam Rankine cycle for waste heat recovery, as they may display a higher thermodynamic efficiency in low- and medium-temperature applications.

Both power cycles may be viable at the scale of application studied in the present work, i.e. for a net power output of 1–5 MW [1,2]. Victor et al. [3] compared the Kalina cycle and ORC in the temperature range 100–250 °C. It was suggested that, while the two cycles could produce similar power outputs, the ORC was preferable below 200 °C and the Kalina above 200 °C. Wang et al. [4] investigated WHR technologies for use in the cement industry with heat source temperatures of 340 °C. They compared the Kalina cycle and ORC with two steam cycle setups and found that the Kalina cycle had the highest efficiency, followed by the two steam cycles and the ORC. However, Bombarda et al. [5] also compared the Kalina cycle and ORC, for a heat source temperature of 346 °C, and showed that both cycles, when optimised, produced almost equal net power outputs. The present study does not directly compare the ORC with the Kalina cycle but is based on the boundary conditions used in the work of Bombarda et al. [5], to allow further evaluations of the power cycle performance.

Energy can neither be created nor destroyed, and an energy analysis illustrates the energy transformations and flows throughout the system under study. On the opposite, exergy is not conserved in any real process, illustrating therefore the locations, causes and magnitudes of the thermodynamic irreversibilities taking place. Exergy destruction also accounts for the additional exergetic fuel required because of the system imperfections. Several studies on the thermodynamic performance of the Kalina

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Nomenclature

T	temperature, K
$\bar{e}$	molar exergy, J/mol
$\dot{E}$	exergy rate, W
$\dot{Q}$	heat rate, W
$\dot{S}$	entropy rate, W/K
$\dot{W}$	power, W
$\dot{m}$	mass flow rate, kg/s
e	specific exergy, J/kg
h	specific total enthalpy, J/kg
p	pressure, Pa
s	specific entropy, J/(kg K)
y	component/sub-system exergy ratio

Abbreviations

EOS	equation of state
ORC	organic Rankine cycle
WHR	waste heat recovery

Greek letters

ε	exergy efficiency

Superscripts

*	relative
Q	heat
W	work
ch	chemical
ph	physical

Subscripts

d	destruction
f	fuel
j	stream
k	component
l	loss
p	product
0	dead state
bub	bubble point
cv	control volume
cw	cooling water
dew	dew point
gen	generation
in	inlet
out	outlet
r	rich ammonia concentration

cycle exist. Marston [6] carried out a parametric study of the Kalina cycle. The turbine inlet composition and separator temperature were identified as the key parameters to optimise. These findings were supported by Nag and Gupta [7], who performed an exergetic analysis of the Kalina cycle, and identified the turbine inlet temperature and composition, as well as the separator temperature, as having the largest influence on the thermodynamic performance of this cycle. Dejfors and Svedberg [8] conducted an exergy analysis to compare the Kalina cycle with a steam Rankine cycle for a direct fired biomass-fuelled cogeneration plant. They noted that the aspect of being direct fired lead to significantly higher exergy losses in the boiler for the Kalina cycle compared to the Rankine cycle. Jonsson [9] investigated the Kalina cycle as WHR system for gas engines and gas diesel engines. It was argued that the Kalina cycle presents the potential to generate more power than the steam Rankine cycle, and that the additional costs could be justified by the gains in efficiency. Singh and Kaushik [10] investigated a Kalina cycle coupled to a coal fired steam power plant. They identified the primary source of exergy destruction, and therefore the greatest potential for optimisation, as the boiler.

The present paper presents and evaluates a unique power generation cycle, called the Kalina split-cycle. This process is also based on the ammonia–water mixture as a working fluid, like the conventional Kalina cycle, but is characterised by a varying ammonia concentration in the heat recovery system. This can result in a smaller entropy generation in the heat transfer process, and potentially in a higher exergetic efficiency of the complete power cycle. This concept was briefly mentioned in the work of Kalina [11].

In the system analysis presented in Larsen et al. [12], it was suggested that the components that affect the process efficiency and optimisation the most are the separator, the recuperators, the boiler and the turbine. Moreover, it was indicated that the most important variables that impact the thermal efficiency are the ammonia concentration and the cooling water temperature. A simplified cost analysis of the Kalina split-cycle was also conducted, and the payback time of this particular process layout is sensibly similar to the payback time of a conventional Kalina cycle. The major costs were related to the boiler and turbines. The boiler costs are estimated to be about 40% higher if the Kalina split-cycle with reheat is compared to the conventional Kalina cycle, and about 45% if compared to the Kalina cycle with reheat. The turbine costs are estimated to be about 30% higher if the Kalina split-cycle with reheat is compared to the conventional Kalina cycle, and about 6% if compared to the Kalina cycle with reheat.

The literature appears to contain little on the thermodynamic performance of such cycles, and this study aims at closing this gap, following these three objectives:

- estimation of the cycle potential, in terms of exergy efficiencies, economic costs and environmental impacts, compared to a conventional Kalina cycle, with and without reheat;
- analysis of the plant inefficiencies and of the exergy destruction trends;
- evaluation of the effect of the boundary conditions (heat source and cold reservoir temperatures) on the system performance.

Section 2 presents the design of the Kalina split-cycle system and the methods used in this work are reported in Section 3. The results are presented in Section 4 and concluding remarks are outlined in Section 5.

2. System description

2.1. Reference Kalina cycle

The Kalina cycle is similar in principle to the Rankine cycle, in which heat is supplied to a closed process loop, and where thermal energy is converted into mechanical work. The main difference lies in the properties of the working fluid, which is an ammonia–water mixture in the Kalina cycle. This two-component mixture is zeotropic, which means that the vapour and liquid phases do not have the same composition when condensation and evaporation take place. At constant pressure, the evaporation temperature changes during the heat transfer process, unlike pure substances, which have a constant evaporation temperature. The temperature glide results in a better match between the temperature profiles of the heat source and receiver. The exergy destruction caused by the heat transfer process is therefore smaller, but the area requirements of