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Research paper

Thermodynamic optimisation and analysis of four Kalina cycle layouts for high temperature applications

Anish Modi*, Fredrik Haglind

Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé, Building 403, DK-2800 Kgs. Lyngby, Denmark

HIGHLIGHTS

- Detailed methodology for solving and optimising Kalina cycle for high temperature applications.
- A central receiver solar thermal power plant with direct steam generation considered as a case study.
- Four Kalina cycle layouts based on the placement of recuperators optimised and compared.

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ABSTRACT

The Kalina cycle has seen increased interest in the last few years as an efficient alternative to the conventional steam Rankine cycle. However, the available literature gives little information on the algorithms to solve or optimise this inherently complex cycle. This paper presents a detailed approach to solve and optimise a Kalina cycle for high temperature (a turbine inlet temperature of 500 °C) and high pressure (over 100 bar) applications using a computationally efficient solution algorithm. A central receiver solar thermal power plant with direct steam generation was considered as a case study. Four different layouts for the Kalina cycle based on the number and/or placement of the recuperators in the cycle were optimised and compared based on performance parameters such as the cycle efficiency and the cooling water requirement. The cycles were modelled in steady state and optimised with the maximisation of the cycle efficiency as the objective function. It is observed that the different cycle layouts result in different regions for the optimal value of the turbine inlet ammonia mass fraction. Out of the four compared layouts, the most complex layout KC1234 gives the highest efficiency. The cooling water requirement is closely related to the cycle efficiency, i.e., the better the efficiency, the lower is the cooling water requirement.

1. Introduction

The Kalina cycle was introduced in 1984 [1] as an alternative to the conventional Rankine cycle to be used as a bottoming cycle for combined cycle power plants. It uses a mixture of ammonia and water as its working fluid, instead of pure water as in the case of a steam Rankine cycle. The composition of the ammonia-water mixture could be varied by changing the ammonia mass fraction which is defined as the ratio of the mass of ammonia in the mixture to the total mass of the mixture. Since its introduction, several uses for the Kalina cycle have been proposed such as in a geothermal power plant, for waste heat recovery, in solar power plants, etc. Most of the documented studies however focus on low or moderate temperature heat to power conversion applications. Ogriseck [2] presented the possibility of integration of a Kalina cycle in a combined heat and power plant. The net efficiency of the plant was calculated for different cooling water temperatures and ammonia mass fractions for the basic solution. Bombarda et al. [3] presented a thermodynamic comparison between the Kalina cycle and an organic Rankine cycle for heat recovery from diesel engines. They concluded that although the obtained electrical power outputs are nearly equal, the Kalina cycle requires a much higher turbine inlet pressure to attain the similar output, thereby making it unjustified for such use. Singh and Kaushik [4] presented energy and exergy analyses and optimisation of a Kalina cycle coupled with a coal-fired steam power plant for exhaust heat recovery. They found out that at a turbine inlet pressure of 40 bar, an ammonia mass

* Corresponding author. Tel.: +45 45251910.
E-mail address: anmod@mek.dtu.dk (A. Modi).

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Nomenclature

Abbreviations

GA	genetic algorithm
LMTD	log mean temperature difference, °C
PPTD	pinch point temperature difference, °C

Symbols

ΔT	temperature difference, °C
$\dot{m}$	mass flow rate, kg/s
$\dot{Q}$	heat rate, MW
$\dot{W}$	work rate, MW
η	respective component efficiency
h	specific enthalpy, kJ/kg
p	pressure, bar
T	temperature, °C or K
X	vapour quality
x	ammonia mass fraction
y	objective function

Subscripts, including components

cd1	condenser-1
cd2	condenser-2
gen	generator
mx1	mixer-1
mx2	mixer-2
net	net electrical output from the power cycle
pp	pinch point temperature difference, °C
pp,cd	minimum pinch point temperature difference in the condensers, °C
pp,re	minimum pinch point temperature difference in the recuperators, °C
pu1	pump-1
pu2	pump-2
re1	recuperator-1
re2	recuperator-2
re3	recuperator-3
re4	recuperator-4
rec	receiver/boiler
sep	separator
spl	splitter
thv	throttle valve
tur	turbine

fraction of 0.8 gives the maximum cycle efficiency. Coskun et al. [5] presented a comparison between different power cycles for a medium temperature geothermal resource. They found that the Kalina cycle and the double flash cycle provided the least levelized cost of electricity and hence the shortest payback periods. Wang et al. [6] presented a parametric analysis and optimisation of a Kalina cycle driven by solar energy. They found that the net power output and the system efficiency are less sensitive to the turbine inlet temperature under given conditions and that there exists an optimal turbine inlet pressure which results in maximum net power output. Sun et al. [7] presented an energy-exergy analysis and parameter design optimisation for a Kalina cycle with an auxiliary superheater for a low grade thermal energy conversion system using solar energy as heat input. Larsen et al. [8] presented the optimisation and a simplified cost analysis of the Kalina split-cycle using genetic algorithm (GA) in MATLAB with primary focus on the boiler, the turbine and the mixing system subsections of the cycle. They also compared the performance of the Kalina split-cycle to that of a normal Kalina cycle. Nguyen et al. [9] conducted an exergy analysis of the Kalina split-cycle. The two studies [8,9] concluded that the Kalina split-cycle with reheat was thermodynamically better than the normal Kalina cycle but this improvement came at the price of increased initial cost and a more complex cycle design.

With regards to high temperature Kalina cycles, few studies have been made. All of these studies however suggest potential thermodynamic benefits of using the Kalina cycle, thus motivating further research in the high temperature Kalina cycle applications. The Kalina cycle layouts for high temperature applications are inherently more complex than the layouts typically used for the low temperature applications. Marston [10] presented the parametric analysis of a Kalina cycle to serve a bottoming cycle for a gas turbine power plant. Marston and Hyre [11] compared the performance of a triple-pressure steam cycle and a Kalina cycle as a gas turbine bottoming cycle. They concluded that the Kalina cycle was more efficient. Ibrahim and Kovach [12] studied the effect of varying the ammonia mass fraction and the separator temperature on the cycle efficiency for a Kalina bottoming cycle using gas turbine exhaust as the heat source. The authors found that the Kalina cycle is 10–20 % more efficient than the Rankine cycle with the same boundary conditions. Nag and Gupta [13] performed an exergy analysis of a Kalina cycle with gas turbine exhaust as the heat source. They concluded that the important parameters affecting the cycle efficiency are the turbine inlet temperature, composition and the separator temperature. Thorin [14] presented the analysis of a Kalina cycle to be used for industrial waste heat recovery, biomass based cogeneration and gas engine waste heat recovery. Various methods for calculating the thermophysical properties of the ammonia-water mixture were also presented. Modi and Haglind [15] presented the exergy analysis of a Kalina cycle for a central receiver solar thermal power plant with direct steam generation. Their results suggested the cycle layout and the number of recuperators might have an affect on the optimal conditions for the maximum cycle efficiency, and that the Kalina cycle might be beneficial if more storage based operation takes place.

None of the studies for high temperature Kalina cycles presented a detailed algorithm for solving or optimising the Kalina cycle. Marston [10] briefly presented a simplified topology of the cycle for the calculation of the mass flow rates in the cycle. For the low temperature applications, Singh and Kaushik [4] and Sun [7] presented algorithms to solve a Kalina cycle for use as a bottoming cycle and as a solar based power cycle respectively. Along with the presentation of little information on the cycle solution methodology, there were few inappropriate assumptions made in the above studies. For instance, Marston [10] assumed the pinch point in the condensers to always occur at the working fluid outlet and both Singh and Kaushik [4] and Sun [7] used an overall log mean temperature difference (LMTD) for various heat exchangers, including the evaporator and the condenser, as an input to the cycle calculation. These issues are further discussed in the Section 4 of this paper.

The primary objective of this paper is therefore to present the detailed methodology of solving and optimising a Kalina cycle for high temperature and pressure applications which serves well on both the accuracy and the computational efficiency fronts. The study also improves on the assumptions made in the previous publications such as the location and values of the pinch point temperature differences (PPTDs) while using an approach where fewer iterations were required, thus saving computational time. As