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Performance analysis of a Kalina cycle for a central receiver solar thermal power plant with direct steam generation

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HIGHLIGHTS

- Kalina cycle for a central receiver solar thermal power plant with direct steam generation.
- Rankine cycle shows better plant exergy efficiency when heat input is only from the solar receiver.
- Kalina cycle is advantageous when heat input is primarily from a two-tank molten-salt storage.

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ABSTRACT

Solar thermal power plants have attracted increasing interest in the past few years – with respect to both the design of the various plant components, and extending the operation hours by employing different types of storage systems. One approach to improve the overall plant efficiency is to use direct steam generation with water/steam as both the heat transfer fluid in the solar receivers and the cycle working fluid. This enables operating the plant with higher turbine inlet temperatures. Available literature suggests that it is feasible to use ammonia-water mixtures at high temperatures without corroding the equipment by using suitable additives with the mixture. The purpose of the study reported here was to investigate if there is any benefit of using a Kalina cycle for a direct steam generation, central receiver solar thermal power plant with high live steam temperature (450 °C) and pressure (over 100 bar). Thermodynamic performance of the Kalina cycle in terms of the plant exergy efficiency was evaluated and compared with a simple Rankine cycle. The rates of exergy destruction for the different components in the two cycles were also calculated and compared. The results suggest that the simple Rankine cycle exhibits better performance than the Kalina cycle when the heat input is only from the solar receiver. However, when using a two-tank molten-salt storage system as the primary source of heat input, the Kalina cycle showed an advantage over the simple Rankine cycle because of about 33 % reduction in the storage requirement. The solar receiver showed the highest rate of exergy destruction for both the cycles. The rates of exergy destruction in other components of the cycles were found to be highly dependent on the amount of recuperation, and the ammonia mass fraction and pressure at the turbine inlet.

1. Introduction

In recent times, solar thermal power plants (STPPs) have attracted interest as a large scale, commercially viable way to generate electricity [1]. In an STPP, the heat transfer fluid (HTF) and the working fluid play an important role as the carriers of energy from the collector/receiver to the turbine. This is commonly done in two stages for a plant operating with a Rankine cycle. The HTF (e.g. synthetic oil, molten salt, etc.) first collects the energy from the incident solar radiation. This energy is then passed on to the working fluid (water/steam) which carries it to the steam turbine. The main disadvantage of such two-fluid systems is that the maximum operating temperature of the HTF is limited by the fluid stability concerns (e.g. approximately 400 °C for the synthetic oil), thus resulting in a low turbine inlet temperature and consequently a low cycle efficiency.

Application of direct steam generation (DSG) in STPPs presents the prospect of improving the overall plant efficiency, while simultaneously decreasing the cost of electricity generation [2]. The pressurized steam is generated directly in the receiver and transported to the steam turbine. The advantages of DSG include a higher live steam temperature and the use of one fluid as both the HTF and the working fluid, possibly resulting in a simplified operation. The main disadvantage of using DSG for STPPs is that it

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requires a very complex storage system for uninterrupted plant operation [3]. The motivation behind the current study is that the exergy losses during a heat transfer process can be reduced by using a suitable multi-component working fluid which can evaporate or condense at a varying temperature, contrary to the constant evaporating or condensing temperature for a pure substance [4]. One such multi-component working fluid is the ammonia-water zeotropic mixture, as used in a Kalina cycle (KC). There have been discussions regarding the feasibility of using ammonia-water mixtures at high temperatures due to the nitridation effect resulting in corrosion of the equipment. However, the use of an ammonia-water mixture as the working fluid at high temperature has been successfully demonstrated in Canoga Park with turbine inlet conditions of 515 °C and 110 bar [5]. Moreover, a patent by Kalina [6] claims the stability of ammonia-water mixtures along with prevention of nitridation for plant operation preferably up to 2000 °F (1093 °C) for temperature and 10,000 psia (689.5 bar) for pressure using suitable additives. It should be noted that the term *direct steam generation* is used here for both water and ammonia-water mixtures.

There were proposals to incorporate the KC for waste heat recovery plants, geothermal power plants or solar energy driven power plants. Such plants operate with low or medium range temperatures at the turbine inlet. Bombarda et al. [7] presented a thermodynamic comparison between the KC and an organic Rankine cycle (ORC) for heat recovery from diesel engines. They concluded that although the obtained electrical power outputs are nearly equal, the KC requires a much higher turbine inlet pressure to attain the same, thereby making it unjustified for such use. Singh and Kaushik [8] presented energy and exergy analysis and optimisation of a KC 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 fraction of 0.8 gives the maximum cycle efficiency and that the highest exergy destruction occurs in the evaporator. Campos Rodríguez et al. [9] presented an exergetic and economic comparison between a KC and an ORC for a low temperature geothermal power plant. They found that the KC produces 18 % more power than the ORC with 37 % less mass flow rate. In addition, the KC had 17.8 % lower levelized electricity costs than the ORC. Wang et al. [10] presented a parametric analysis and optimisation of a KC 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. Coskun et al. [11] presented a comparison between different power cycles for a medium temperature geothermal resource. They found that the KC and the double flash cycle provided the least levelized cost of electricity and hence the lowest payback periods.

With regards to using the KC with high turbine inlet temperatures, 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 KC turbine inlet conditions were 482 °C and 59.6 bar. The authors found that the KC is 10–20 % more efficient than the Rankine cycle with the same boundary conditions. Nag and Gupta [13] performed an exergy analysis of a KC with gas turbine exhaust as the heat source with a turbine inlet temperature between 475 °C and 525 °C, and a turbine inlet pressure of 100 bar. They concluded that the important parameters affecting the cycle efficiency are the turbine inlet temperature, composition and the separator temperature. Dejfors et al. [14] presented an analysis of using ammonia-water power cycles for direct fired cogeneration plants with a maximum temperature of 540 °C. They concluded that for a cogeneration configuration, the Rankine cycle performs better than the KC whereas for the conventional condensing power application, the performance of the KC is better. Knudsen et al. [15] presented the results from the simulation and exergy analysis of a KC for an STPP having a turbine inlet temperature of 550 °C when the heat input is from a solar receiver, and 480 °C when the heat input is from a molten-salt storage system. The authors varied the heat input to the cycle so as to maintain the turbine inlet conditions while assuming the same mass flow rate for all the cases. Modi et al. [16] presented a comparison between a Rankine cycle and an ammonia-water cycle for STPPs with a turbine inlet temperature of 450 °C. The cycle energy efficiency and the storage size requirement were used as the comparison parameters. With regards to the analysis of central receiver STPPs, Xu et al. [17] presented the energy and exergy analysis of a central receiver STPP operating with a Rankine cycle. They concluded that the efficiency of the plant can be increased by focussing on reducing the losses in the receiver and by using advanced power cycles.

A recent review of research on the KC by Zhang et al. [18] highlights the use of KC for various applications like bottoming cycle, low temperature geothermal, industrial waste, etc. In the review [18], and to the authors' knowledge, there were no studies on using the KC for high temperature STPPs with DSG. The purposes of the current study are to assess the potential benefits of using a KC for a central receiver STPP with DSG using exergy analysis, analyse the trend of the rate of exergy destruction in different components of the plant with respect to the pressure and the ammonia mass fraction at the turbine inlet, and compare the performance with a simple Rankine cycle (SRC). To attain these objectives, the KC was modelled and optimised for maximum work output for the assumed boundary conditions and analysed for operation when the heat input was only from the solar receiver, or when the primary source of heat input was a two-tank molten-salt storage system. The *ammonia mass fraction* is defined here as the mass of ammonia in the ammonia-water mixture to the total mass of the mixture. The paper is structured as follows: Section 2 presents the assumptions and the modelling procedure, Section 3 presents the results from the exergy analysis and the operation from molten-salt storage system, Section 4 discusses the results and Section 5 concludes the paper.

2. Methodology

The layouts of the compared cycles while receiving heat input solely from solar radiation are presented in Fig. 1 (SRC) and Fig. 2 (KC). With reference to Fig. 1, the superheated steam obtained from the receiver (stream 1) is expanded in the turbine. The low temperature, low pressure steam (stream 2) is then condensed to

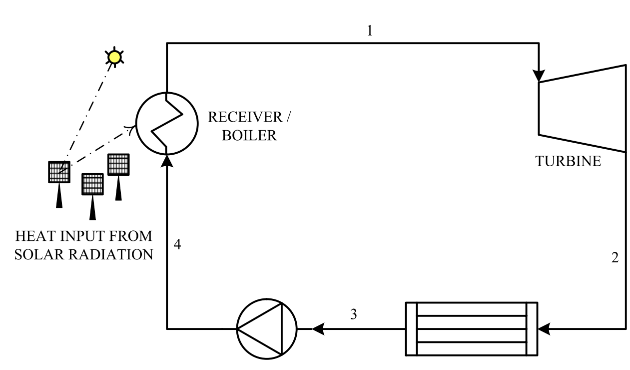

Fig. 1. Schematic for the simple Rankine cycle (SRC).