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Investigation on efficiency improvement of a Kalina cycle by sliding condensation pressure method

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ABSTRACT

Conventional Kalina cycle-based geothermal power plants are designed with a fixed working point determined by the local maximum ambient temperature during the year. A previous study indicated that the plant's annual average thermal efficiency would be improved if the ammonia mass fraction of the Kalina cycle could be tuned to adapt to the ambient conditions. In this paper, another sliding condensation pressure method is investigated. A theoretical model is set up and then a numerical program is developed to analyze the cycle performance. The condensation pressure adjustment in accordance to the changing ambient temperature has been numerically demonstrated under various ammonia-water mixture concentrations. The results indicate that the Kalina cycle using sliding condensation pressure method can achieve much better annual average thermal efficiency than a conventional Kalina cycle through matching the cycle with the changing ambient temperature via controlling condensation pressure. Furthermore, the sliding condensation pressure method is compared with the composition tuning method. The results show that the annual average efficiency improvement of the sliding condensation pressure method is higher than that of the composition tuning method.

1. Introduction

Geothermal energy has many advantages such as weatherproof, base-load power, high stability and reliability, less land usage, and less ecological effect [1]. With the progress of technology, power generation from low-temperature geothermal energy becomes economically attractive [2]. An annual average increment of 350 MW/year in the world has been achieved in the five-year term 2010–2015, mainly from the increase in medium-low temperature projects through binary plants [3].

The Kalina cycle uses a zeotropic mixture as the working fluid (normally ammonia-water) and can be applied for low-temperature geothermal power generation [4,5]. Hua et al. designed a triple-pressure ammonia-water power cycle and the results showed that the power recovery efficiency was about 16.6% higher than that of a steam Rankine cycle [6]. Pradeep Varma and Srinivas compared the thermodynamic performances of the Kalina cycle with organic Rankine cycle and organic flash cycle [7]. Fallah used an advanced exergy method to analyze a Kalina cycle system 11 (denoted as KCS-11 hereafter) [8]. Ma et al. compared three advanced absorption power cycles with KCS-11 system in terms of power output, energy and exergy efficiencies for low-temperature heat sources [9].

Among various Kalina cycle systems, KCS-34 is suitable for low-temperature heat sources [10]. A geothermal power plant was built in Husavik, Iceland in 2000 based on the KCS-34 Kalina cycle [11]. Saffari et al. carried out a thermodynamic analysis for the geothermal Kalina cycle employed in Husavik power plant using an artificial bee colony algorithm and the optimum thermal efficiency could achieve 20.36% [12]. Arslan investigated the performance of the KCS-34 cycle system using an artificial neural network and life cycle cost analysis and found that the most profitable ammonia mass fraction ranges from 80% to 90% [13].

In 2007, Lengert altered the position of the recuperator of the KCS-34 Kalina cycle and patented a new power cycle, i.e., the so-called KSG-1 Kalina cycle [14]. Mergner and Weimer compared the thermodynamic performances between the KSG-1 and KCS-34 Kalina cycles for geothermal power generation and the KSG-1 Kalina cycle achieved a slightly higher efficiency than the KCS-34 [15].

Various methods have been proposed to further improve the performance of Kalina cycle when the environmental conditions vary. Ibrahim and Kovach controlled the temperature of the ammonia-water mixture in the separator so that the ammonia mass fraction at the expander inlet could be adjusted [16]. Nguyen et al. studied a Kalina split-cycle concept that had a varying ammonia concentration during the

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Nomenclature

$\dot{E}$	exergy (kJ)
h	enthalpy (kJ/kg)
$\dot{I}$	exergy destruction rate (kW)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (MPa)
$\dot{Q}$	heat quantity (kW)
s	entropy (kJ/kg K)
T	temperature (K)
$\dot{W}$	power (kW)
x	ammonia mass fraction

Greek letters

α	improvement of net power output
β	improvement of heat transfer from the heat source
γ	improvement of thermal efficiency
η	efficiency

Subscript

0, *a*	ambient condition
b	basic solution
c	condenser
e	evaporator
ex	exergy efficiency
f	fan
m	mixer
n	net
p	pump
re	recuperator
s	separator
t	turbine
th	thermal efficiency
v	expansion valve

preheating and evaporation stages [17]. Recently, Mlcak and Mirolli invented a method to adjust the ammonia mass fraction according to the cooling source temperature to improve cycle efficiency [18]. Wang and Yu evaluated the efficiency improvement of this composition tuning method and found that the average thermal efficiency could be enhanced significantly [19].

The above investigations indicate that the performance of the Kalina cycle can be improved via adjusting the ammonia mass fraction. On the other hand, the sliding pressure control method is often used for steam Rankine cycles to improve the system efficiency [20–22]. In this method, when the Rankine cycle system operates on part-load conditions especially at low-load working points, the operation pressure at the inlet of the high-pressure turbine decreases as the load drops. To adapt to the variable geothermal fluid mass flow rate and temperature, Hu et al. performed an off-design performance analysis of an organic Rankine cycle system using three different control strategies including sliding pressure control [23]. Normally, sliding pressure control is used to fulfil the varying demand in load by changing evaporation pressure. Usman et al. experimentally investigated the performance of an organic Rankine cycle using sliding pressure control approach [24]. Compared with the organic Rankine cycle using a pure working fluid, the Kalina cycle uses a zeotropic working fluid such as an ammonia-water mixture and has an additional degree of freedom in terms of the ammonia mass fraction. Modi et al. [25] and Li et al. [26] investigated the off-design performances of the Kalina cycle using sliding pressure control. However, no investigation was reported to evaluate the efficiency improvement of the Kalina cycle using sliding condensation pressure method when the ambient temperature varies. Furthermore, it is meaningful to compare the efficiency improvement of the Kalina cycle between using sliding condensation pressure method and the composition tuning method.

The ambient temperature normally fluctuates with days and seasons. When the ambient temperature varies, the corresponding temperature at the outlet of the air-cooled condenser also changes if the pinch-point temperature difference inside the condenser is constant. Because the ammonia-water zeotropic mixture is in a saturated liquid

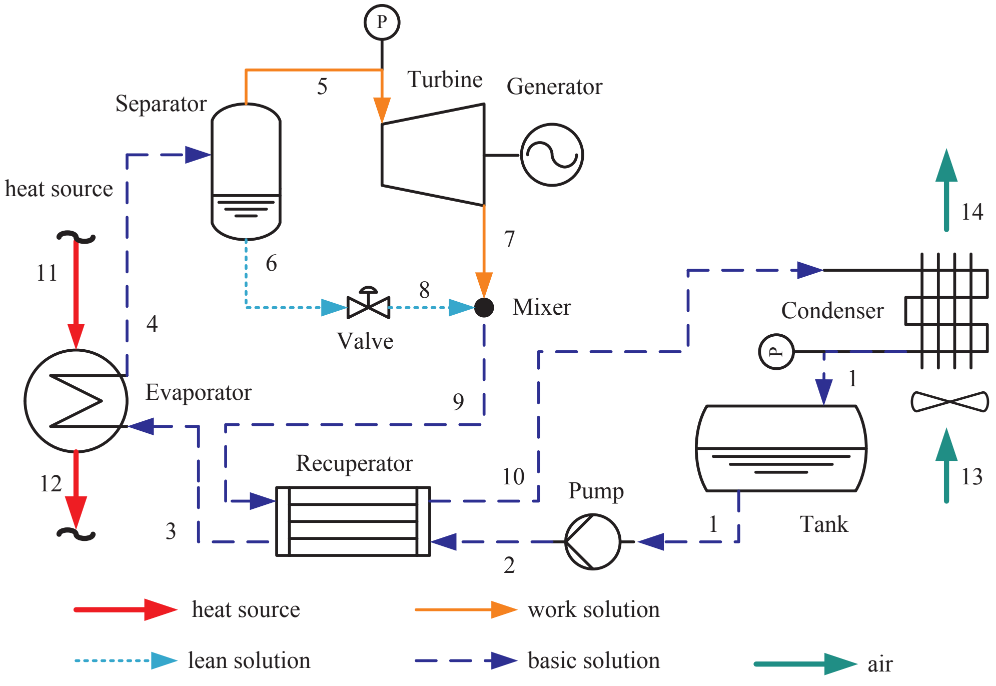

Fig. 1. Schematic of KSG-1 Kalina cycle for low-temperature geothermal power generation.