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A numerical analysis of a composition-adjustable Kalina cycle power plant for power generation from low-temperature geothermal sources

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HIGHLIGHTS

- A composition-adjustable Kalina cycle is analysed and presented.
- An air-cooled condenser is used and thermodynamic performance is analysed.
- Composition adjustment can improve system performance significantly.

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ABSTRACT

The Kalina cycle is believed to be one of the most promising technologies for power generation from low temperature heat sources such as geothermal energy. So far, most Kalina cycle power plants are designed with a working fluid mixture having a fixed composition, and thus normally operate at a fixed condensing temperature. However, the ambient temperature (i.e., heat sink) varies over a large range as the season changes over a year, particularly in continental climates. Recently, a new concept, i.e., composition-adjustable Kalina cycle, was proposed to develop power plants that can match their condensing temperature with the changing ambient conditions, aiming at improving the cycle's overall thermal efficiency. However, no detailed analysis of its implementation and the potential benefits under various climate conditions has been reported. For this reason, this paper carried out a comprehensive numerical research on its implementation and performance analysis under several different climate conditions. A mathematical model is firstly established to simulate the working principle of a composition-adjustable Kalina cycle, based on which a numerical program is then developed to analyse the cycle's performance under various climate conditions. The developed numerical model is verified with some published data. The dynamic composition adjustment in response to the changing ambient temperature is simulated to evaluate its effect on the plant's performance over a year. The results show that a composition-adjustable Kalina cycle could achieve higher annual-average thermal efficiency than a conventional one with a fixed mixture composition. However, such an improvement of thermal efficiency strongly depends on the heat source temperature, climate conditions, etc. The composition-adjusting system introduces extra capital and operation costs. The economic viability of a composition-adjustable Kalina cycle power plant depends on the balance between these extra costs and the increase of thermal efficiency.

1. Introduction

Reducing fossil fuel consumption and greenhouse gas emissions is particularly important for us to ensure a sustainable future. Power generation from a variety of renewable heat sources such as geothermal and solar thermal energy could make an important contribution to the decarbonisation of our economy [1,2]. In particular, low-temperature geothermal energy is being used increasingly for power and heat generation [3]. Power cycles utilising low temperature heat sources have been intensively studied and well documented in the past several decades [4–6], amongst which organic Rankine cycles and Kalina cycles are considered to be two most important technologies [7,8].

In 1984, Kalina proposed a power cycle using a binary mixture as working fluid to generate power from heat source with a relatively low temperature, denoted as Kalina cycle later on [9]. The Kalina cycle is essentially a further development of Rankine cycle. One key difference between them is that a Kalina cycle uses a mixture rather than a pure working fluid, so that isobaric

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Nomenclature

$\dot{E}$	exergy (kW)
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

η	efficiency
ψ	improvement of Cycle A relative to Cycle B

Subscripts

0	ambient condition
A, B	Cycles A, B
c	condenser
d	exergy destruction
e	evaporator
ex	exergy
f	fan
in	inlet
*m*1	Mixer 1
*m*2	Mixer 2
mix	mixture of the basic solution
n	net
out	outlet
*p*1	Pump 1
*p*2	Pump 2
re	recuperator
s	isentropic
*s*1	Separator 1
*s*2	Separator 2
t	turbine
th	thermal efficiency
tot	total
v	expansion valve

Acronyms

KCS	Kalina cycle system
KSG	Siemens' Kalina cycle system
OOL	optimal operation line
ORC	organic Rankine cycle
PPTD	pinch point temperature difference

evaporation and condensation processes occur under changing temperatures and the mixture composition varies throughout the cycle. Compared with a Rankine cycle, the efficiency of a Kalina cycle can be increased due to a close temperature match with heat transfer fluids in the evaporator and condenser. For instance, a Kalina cycle system using an ammonia-water mixture as the working fluid to generate power from the waste heat of a gas turbine achieved a thermal efficiency of 32.8% [10]. A Kalina power plant normally uses components (turbine, pumps, valves, etc.) similar to those for constructing a conventional steam power plant. Some investigations showed that a Kalina cycle can achieve a better thermal efficiency than ORC systems [11–14].

The Kalina cycle attracted considerable attention in the past decades. Fallah used an advanced exergy method to analyse a Kalina cycle (denoted as KCS-11 hereafter) for utilising a low-temperature geothermal source [15]. Cao et al. investigated a biomass-fuelled Kalina cycle system with a regenerative heat exchanger, and found the net power output and system efficiency increases as the temperature within the separator increases [16]. The performance of a KCS-11 system for solar energy application has also been studied. It was reported that the ammonia mass fraction was an important system operation parameter and should be optimised to reduce the system's irreversibility [17]. Recently, Yu et al. studied a combined system consisting of a Kalina power cycle and an ammonia absorption cooling cycle, of which the cooling to power ratio can be adjusted over a large range. Their theoretical results showed that the overall thermal efficiency could be increased by 6.6% by combining the two cycles in this way [18]. Wang et al. studied a flash-binary geothermal power generation system using a Kalina cycle to recover the heat rejection of a flash cycle [19]. The optimised results showed that the ammonia mass fraction, the pressure, and the temperature at the inlet of the turbine have significant effect on system's performance. Hettiarachchi et al. studied the performance of the KCS-11 Kalina cycle system for utilising low-temperature geothermal heat sources and found an optimum ammonia concentration exists for a given turbine inlet pressure [20].

Aiming at low-temperature heat sources, Kalina et al. proposed a power cycle which was later named KCS-34 [21], based on which a low-temperature geothermal power plant was built in Husavik, Iceland in 2000 [22]. Nasruddin et al. simulated a KCS-34 Kalina cycle using Cycle Tempo 5.0 software and compared it with the operation data of the Husavik power plant, showing a good agreement [23]. Later, Arslan studied the performance of a KCS-34 Kalina cycle system using an artificial neural network and life cycle cost analysis, and found that the most profitable condition was obtained when the ammonia mass fraction was in the range between 80% and 90% [24].

In practice, the expansion ratio of the turbine for KCS-34 cycle is relatively high and a multi-stage turbine is required. However, Lengert changed the location of the recuperator in a KCS-34 Kalina cycle and proposed a new power cycle, i.e., the so-called KSG-1 patented by Siemens. It can achieve high cycle efficiency and only requires a single-stage turbine [25]. Later on, Mergner and Weimer compared the thermodynamic performances between a KSG-1 and KCS-34 for geothermal power generation. The results showed that the KSG-1 achieved a slightly higher efficiency than the KCS-34 [26]. The architectures of KCS-11, KCS-34, and KSG-1 are compared and shown in Fig. 1.

In the past decade, different approaches have been proposed to further improve the efficiency of Kalina cycle power plants. Ibrahim and Kovach studied a method for controlling the temperature in the separator to adjust the ammonia mass fraction at the inlet of the turbine, and found that this method can improve the cycle's thermal efficiency [27]. Nguyen et al. developed a Kalina split-cycle that had a varying ammonia concentration during the pre-heating and evaporation processes [28]. He et al. studied two modified KCS-11 systems, which used a two-phase expander to replace a throttle valve [29]. Hua et al. investigated the transient performance of a Kalina cycle for high-temperature waste heat recovery, which can regulate the concentration of the working fluid mixture. This method controls the on/off state of two valves to maximise power generation when the temperature of the waste heat source fluctuates. Controlling the concentration of the working solution adjusts the turbine inlet pressure. It was reported that the cycle's