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Performance research on modified KCS (Kalina cycle system) 11 without throttle valve

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ABSTRACT

Two modified systems based on a KCS (Kalina cycle system) 11 with a two-phase expander to substitute a throttle valve are proposed. The two-phase expander is located between the regenerator and the absorber in the B-modified cycle and between the separator and the regenerator in the C-modified cycle. A thermodynamic performance analysis of both the original KCS 11 and the modified systems is carried out. The optimization of two key parameters (the concentration of working fluid and the temperature of cooling water) is also conducted. It is shown that the two modified cycles have different performance under the investigated conditions. Results also indicate that the C-modified cycle can obtain better thermodynamic effect than the B-modified cycle. The temperature of cooling water plays an important role in improving the system performance. When the cooling water temperature drops from 303 K to 278 K, the C-modified cycle thermal efficiency can be improved by 27%.

1. Introduction

With the rapid development of economy and society, the energy shortage becomes a worldwide critical issue. To meet the severe energy challenge, reclaiming the low-grade waste heat is important. However, the use of conventional steam power cycles to recover low-grade waste heat, such as exhaust gas from engines and waste heat from industrial process is economically infeasible [1]. The ORC (Organic Rankine Cycle) has the potential to use not only low-grade waste heat but also renewable energy sources, such as geothermal energy and solar energy [2–4].

Recently, more and more researches have been done on the choice of working fluids and the performance analysis of ORC. The influences of key system parameters such as the evaporation pressure, evaporation temperature and condensation temperature in ORC have been studied in detail [5,6]. However the constant evaporation temperature of pure working fluid leads to great irreversible loss of evaporation process in ORC.

Kalina cycle system, which was proposed by Kalina [7–9] in 1980s, is a series of power cycles using the ammonia-water mixtures as a working fluid for the low to medium temperature heat resource to generate electricity. According to the different temperature ranges of heat sources, Kalina cycle system can be divided into Kalina cycle system 5 (KCS (Kalina cycle system) 5) for direct-fired power plant, Kalina cycle system 6 (KCS 6) for a gas turbine based combined cycle, Kalina cycle system 11 (KCS 11) for geothermal temperatures from about 121to 204 °C and Kalina cycle system 34 (KCS 34) which is suitable for temperatures below 121 °C [10,11]. El-Sayed and Tribus [12] firstly analyzed the simplified Kalina cycle in detail and made a theoretical comparison of the Kalina cycle with the Rankine cycle. Comparing to ORC, the variable evaporation temperature of working fluid NH_3—H_2O in the evaporator matches well with the heat release process of the heat source and Kalina cycle can markedly reduce the irreversible losses in the evaporation process [13].

In order to meet the increasing demands for low temperature heat resources, KCS 11 and KCS 34 are being studied intensively. In 2002, a geothermal power plant based on KCS 34 was built to supply the electricity for a town in Iceland [14]. Nasruddin et al. [10] found that the maximum efficiency and power output of KCS 34 are achieved at 78% ammonia—water mixture in Indonesia environment conditions instead of 82% in Iceland. Hettiarachchi et al. [15] defined five parameters to study the performance of KCS 11, and concluded that KCS 11 has better performance than one of ORC at moderate pressures. Arslan [16] used an artificial neural network to make a decision for the optimum working

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Nomenclature

c	specific heat at constant pressure (kJ·(kg K)$^{-1}$)
E	exergy (kJ)
h	specific enthalpy (kJ kg^{-1})
I	thermodynamic irreversibility (kJ)
m	mass flow rate (kg s^{-1})
p	pressure (MPa)
Q	heat transfer rate (kW)
S	entropy (kJ K^{-1})
T	temperature (K)
W	power output (kW)
x	working fluid concentration

Greek letters

Δ	differential
η	efficiency (%)

Subscripts

0	state of the environment
1–14	states of the system
Abs	absorber
bio	boiler
c	cooling water
con	condensor
ex	exergy analysis
fir	first-law analysis
h	heat sources
in	heat input
me	mean temperature of heat source during the heat transfer
mccal	log mean temperature difference of condensor
mecal	log mean temperature difference of boiler
mrcal	log mean temperature difference of regenerator
out	heat output
pum	pump
reg	regenerator
sep	seperator
thr	throttle valve
Tur, A	A turbine
Tur, B	B turbine
wf	working fluid in the boiler

conditioned of a KCS 34, which generates electricity from the geothermal heat.

In recent years, the concept of combined power or power and cooling cycles based on Kalina cycles have gained much attention in order to achieve higher efficiency of cycle. Ikegami and Jia [17] studied a Kalina solar system with an auxiliary superheater and results showed that the Kalina solar cycle provides an effective and efficient way to improve feasibility of the solar energy system. Goswami and Xu [18,19] put forward a combined power and cooling cycle based on Kalina cycle. The effect of evaporation pressures, ammonia concentrations and isentropic turbine efficiencies on the performance of Kalina cycle were discussed in detailed. However, the cooling effect is much smaller than the power produced in this combined system [20].

Zheng et al. [21] proposed a new combined power and cooling cycle based on Kalina cycle. The overall thermal and exergy efficiency of this new cycle were 24.2% and 37.3% respectively. A novel ammonia–water cycle was proposed for combined power and cooling [22]. This system had a great reduction in energy consumption amount compared with the conventional system. Not all modified systems are desirable on thermodynamic effect. Boghossian [23] investigated a dual-temperature geothermal-solar Kalina hybrid cycle which displays no thermodynamic benefits. Specially, this hybrid plant produces 29% less net power than one of the combined single-energy mode plants.

The above mentioned researches focus either on the performance analysis of the Kalina-based cycles, or on the introduction of a novel system after modifying Kalina cycle. The poor-ammonia-mass-fraction loop of KCS 11 is scarcely considered even though it is significant for improving the cycle efficiency. The throttling process causes the loss of exergy in poor-ammonia-mass-fraction loop of KCS 11, which results in the efficiency of system decreased. Therefore, Li et al. [24] proposed a Kalina cycle (KCS 11) with ejector to recover this exergy from the throttling process.

Two-phase expander is one of various creative equipments to recover the expansion work during the throttling process. In recent years, Smith has engaged in developing high efficient two-phase expander to either recover the power from low temperature sensible heat sources or replace the throttle valve in a refrigeration system [25]. The efficiency of the two-phase expander using in a TFC (Trilateral Flash Cycle) exceeds 75% [26].

Because the technology of the two-phase expander is feasible [27], and the cost rates of the expander is not very high in the recover system of waste heat [28–30], two modified system with two-phase expander in the poor ammonia mass fraction loop based on KCS 11 to recover the expansion work are proposed in order to increase the power output and the efficiency of the KCS 11 cycle. The performance of proposed modified cycles is compared with that of KCS 11. Further, the optimization of cooling water temperature and ammonia fraction is also conducted.

2. System description, analysis and method

2.1. System description

In order to identify the most effective layout of the two-phase expander, two types of arrangements, namely the B-modified cycle and the C-modified cycle, are proposed. Combined with KCS 11, there are three cases studied in detail in this research. The three studied cases are illustrated as follows: KCS 11: The KCS 11 with a throttling valve.

B-modified cycle: The modified KCS 11 with a two-phase expander. The two-phase expander is located between the regenerator and the absorber.

C-modified cycle: The modified KCS 11 with a two-phase expander. The two-phase expander is located between the separator and the regenerator.

The schematic diagram of KCS 11 is shown in Fig. 1. The poor ammonia–water liquid (3) is throttled to the condensing pressure state (6) after being regenerated, and then absorbs the rich ammonia-water exhaust (4) in the absorber. The condensed mixture working fluid (8) is pumped to the evaporator, and then heated into wet vapor (1). Meanwhile, the wet vapor is separated into poor ammonia–water saturated liquid (3) and rich ammonia-water saturated vapor (2). This working process is also demonstrated on h-x diagram in Fig. 3.

The two proposed cycles are shown in Fig. 2. A throttle valve is replaced with a two-phase expander.