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Power generation and heating performances of integrated system of ammonia–water Kalina–Rankine cycle

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ABSTRACT

An integrated system of ammonia–water Kalina–Rankine cycle (AWKRC) for power generation and heating is introduced. The Kalina cycle has large temperature difference during evaporation and small one during condensation therefore with high thermal efficiency for power generation, while the ammonia–water Rankine cycle has large temperature difference during condensation as well as evaporation, thus it can be adopted to generate heating-water as a by-product in winter. The integrated system is based on the Kalina cycle and converted to the Rankine cycle with a set of valves. The performances of the AWKRC system in different seasons with corresponding cycle loops were studied and analyzed. When the temperatures of waste heat and cooling water are 300 °C and 25 °C respectively, the thermal efficiency and power recovery efficiency of Kalina cycle are 20.9% and 17.4% respectively in the non-heating seasons, while these efficiencies of the ammonia–water Rankine cycle are 17.1% and 13.1% respectively with additional 55.3% heating recovery ratio or with comprehensive efficiency 23.7% higher than that of the Kalina cycle in heating season.

1. Introduction

The industrial energy consumption accounts for about 70% of the total national energy consumption in China, thereby it produces large amount of industrial waste heat. The traditional steam Rankine cycle is not very suitable in the field of waste heat power recovery because of the low pressure and large specific volume of steam in low temperature region, which needs large turbine size, causing higher friction loss and cost [1]. The organic Rankine cycle [2–4] with the low boiling point feature and relatively small proportion of latent heat in evaporation process of organic medium effectively improves the drawbacks of pure water. However, due to the defects of ozone layer depletion effect and expensive of some organic substances, the ORC has not been a perfect cycle yet. Nevertheless, the attentions have also been attracted on ammonia–water power cycles of many experts and scholars. In addition to the low cost, the feature of variable temperature in the evaporation process with the non-azeotropic aqueous ammonia solution matching with the temperature of the heat source greatly reduces the irreversible loss of heat transfer process. In 1984, Kalina [5] proposed a novel bottoming cycle with aqueous ammonia solution as working medium for a combined cycle. Unlike the ammonia–water Rankine cycle, the Kalina cycle uses absorption condensers for heat discharge, thus makes great temperature difference of work solution in the endothermic process and small temperature difference of basic solution in the exothermic process at the same time. In this way the irreversibility is reduced in heat transfer processes with both heat resource and heat sink and the cycle thermal efficiency is increased. Maston [6], Mlcak [7] and Barhoumi and Snoussi [8] successively studied the Kalina cycle and the impacts of the cycle parameters to the performance. Zhang et al. [9] reviewed the relative research on the Kalina cycle. Zamfirescu et al. [10,11] proposed an ammonia–water trilateral Rankine cycle that absorbs heat only in liquid form and using displacement expander for saturated liquid to generate power. Coskun et al. [12] and Walraven et al. [13] respectively studied thermodynamic performance of the Kalina cycle driven by medium or low temperature geothermal resource. Chen tried to improve the Kalina cycle by adding a preheater before the evaporator [14] and simplified the Kalina cycle to a dual-pressure ammonia–water power cycle for lower than 120 °C temperature heat resource [15]. Hua et al. [16–18] made in-depth research on the Kalina cycle based dual-pressure or triple-pressure ammonia–water power cycles or power/cooling cogeneration cycles. The combined Kalina cycle with steam Rankine cycle or the

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Nomenclature

c_p	specific heat (J/kg K)
$(COP)_{hp}$	coefficient of performance of heat pump
f	circulation ratio
G	flow rate (kg/s)
h	enthalpy (kJ/kg)
p	pressure (kPa)
Q	heat transmitted (kW)
q	specific heat (kJ/kg)
t	temperature (°C or K)
W	work (kW)
w	specific work (kJ/kg)

Greek Symbols

Δt	temperature difference (°C)
η_0	power recovery efficiency
η_{ht}	heating recovery ratio
η_{th}	thermal efficiency
η_{wh}	waste heat absorbing ratio

Subscripts

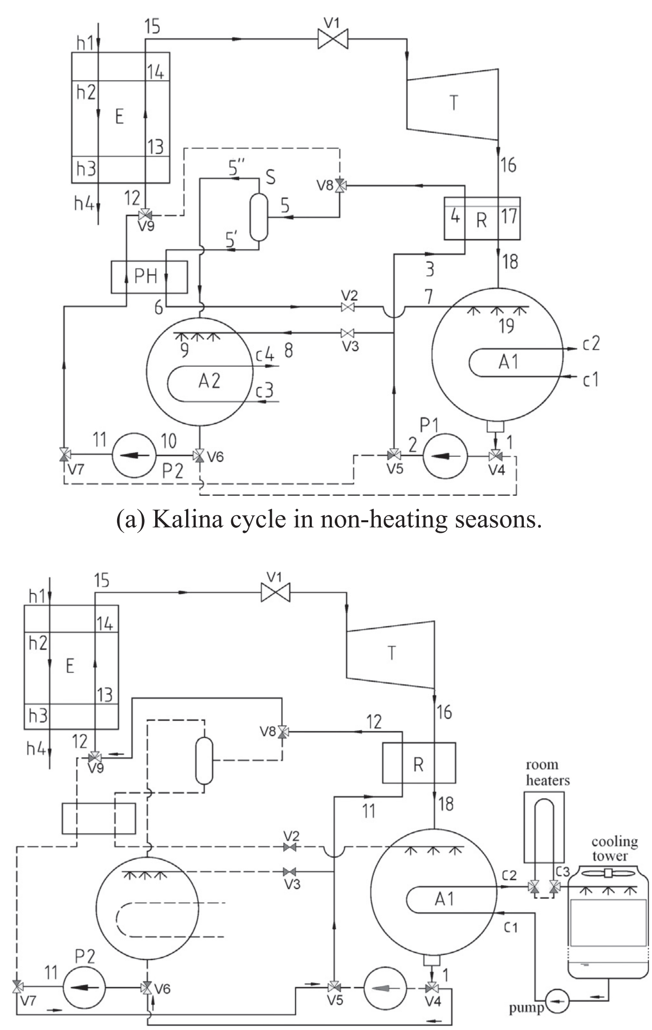
b	basic
c	cooling water
ct	cooling tower
d	dilute
h	heat resource, high
ht	heating
l	low
m	mid
p	pump
s	entropy
T	turbine
t	total
th	thermal
w	work, working
wh	waste heat
numbers	status points

cogeneration of power and heat or cooling have also been hot issues [19–21].

Room heating in winter is a dominant need especially for northern China area and the thermal and electricity load balance in both heating season and non-heating seasons is a key issue to thermal power plant operation. This paper introduces a waste heat driven integrated ammonia–water thermo-power cycle system operating on Kalina cycle or Rankine cycle in different seasons, hereinafter referred as AWKRC for short. It is proposed to meet the requirement of central heating in winter for thermal power plants. By taking advantage of large temperature difference of ammonia–water solution in condensation of the Rankine cycle, the turbine discharged heat could be used to produce heating-water in winter; while in the rest seasons the Kalina cycle is adopted for power generation with higher thermal efficiency. The AWKRC system is on the basis of the Kalina cycle and it is converted to Rankine cycle by switching a set of valves to make certain equipment out of the service. This paper analyzes the performance features of the AWKRC system operating on either the Rankine cycle or the Kalina cycle in corresponding seasons.

2. Integrated AWKRC system

The AWKRC system not only ensure the high waste heat power recovery efficiency in the non-heating seasons operating on the Kalina cycle, but also can realize the cogeneration of power and heating water in winter, thus to achieve two circulation loops with one set of installation. Fig. 1(a) shows the Kalina cycle operation loop in the non-heating seasons. The basic solution at the outlet of the low-p-absorber A1 (point 1, concentration of x_b) is boosted to medium pressure (point 2) by a low-p-pump P1, and then split into two streams, the split ratio is controlled by the valve V3, the majority (point 3) enters the regenerator R, by absorbing the turbine exhaust heat, the basic solution goes via bubble point (point 4) to the partially evaporated two-phase state (point 5), and then goes into the separator S. The dilute solution (point 5') sprays on the tube bundle in the low-p-absorber after cooling in the preheater PH (point 6) and throttling in the throttle valve V2 (point 7). The rich ammonia vapor (point 5'') goes into the mid-p-absorber A2, and is absorbed by the minority basic solution stream (point 8), forming work solution with concentration of x_w (point



(a) Kalina cycle in non-heating seasons.

(b) Rankine cycle in heating season.

Fig. 1. Circulation loops of the AWKRC in different seasons.