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Dual-pressure vaporization Kalina cycle for cascade reclaiming heat resource for power generation

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ABSTRACT

To further improve the cycle efficiency with the heat transfer curves between higher than 350 °C heat resource and the evaporating working medium of the Kalina cycle and to reduce the exhaust temperature of heat resource, the dual-pressure vaporization Kalina cycle for cascade utilization of high-to-mid grade heat resource is proposed. The optimization was conducted for parameters in this modified Kalina cycle such as concentrations of work solution and basic solution, evaporation dew point temperature. Under the conditions of inlet temperatures of heat resource and cooling water of respectively 400 °C and 25 °C and the constraints of proper heat transfer pinch point temperature differences, the maximum evaporation pressure not exceeds 20 MPa, the vapour quality at the turbine outlet is greater than 0.85 and the exhaust temperature of heat resource is not lower than 90 °C, the optimum parameters are obtained that the work and basic concentrations are 0.45 and 0.272 respectively, the dew point temperature of evaporation is 300 °C, and the corresponding power recovery efficiency of the dual-pressure vaporization Kalina cycle reaches 27%, which is 17% higher than that of the Kalina cycle with optimum parameters.

1. Introduction

The emission to atmosphere of industrial flue gas not only causes energy waste but also the haze on the environment, however, as to the power generation from waste heat resource, the traditional steam Rankine cycle is not well applicable, for the features of low vapour pressure and large specific volume of steam at room temperature. The alternative choices are the organic Rankine cycle (ORC) [1] and the Kalina cycle. The latter with inexpensive ammonia–water mixture as working fluid has been drawn the attentions of many scholars and experts. The Kalina cycle with its variable boiling temperature of non-azeotropic ammonia–water in evaporation process and unique absorption condensation process can match well simultaneously with the exothermic process of sensible heat resource and the endothermic process of cooling water, thus the heat transfer irreversible losses can be reduced.

Since Kalina [2] proposed the Kalina cycle in 1984, many scholars and experts have conducted investigation on this novel cycle and variety modifications have been proposed which enriched the Kalina cycle family [3]. The applications of Kalina cycle have been extended from bottoming cycle of combined power cycle [2,4,5] to variety areas. Bombarda et al. conducted thermodynamic comparison between Kalina cycle and ORC for heat recovery from diesel engines [6]. Jonnson and Yan [7] compared the performance of ammonia–water bottoming cycles for gas engines and gas diesel engines as prime movers. Nguyen et al. [8] studied power generation from residual industrial heat. Peng et al. [9] and Sun et al. [10] studied respectively different ways of implementing Kalina cycle for power generation from solar energy. Mlcak [11] and DiPippo [12] investigated respectively Kalina cycle concepts and second law assessment of binary plants for power generation from the geothermal energy. Guzovic et al. [13] presented a possibility study on electricity generation with Kalina cycle from geothermal energy in the republic of Croatia. Arslan [14] and Coskun et al. [15] performed respectively thermodynamic and economic analysis and optimization of the Kalina cycle for power generation from medium temperature geothermal resources. Singh and Kaushik [16] conducted energy and exergy analysis on Kalina cycle for a coal fired steam power plant and Sirko [17] performed a case study of integrate Kalina cycle in a combined heat and power plant. Zhang et al. [18] presented an integrated system of ammonia–water Kalina–Rankine cycle that using Kalina cycle with high thermal efficiency for power generation in non-heating seasons and the ammonia–water Rankine cycle with large temperature difference during condensation as well as evaporation for generating both

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Nomenclature

Latin letters

f	circulation multiple
G	mass flow, mass flow in turbine (kg s^{-1})
h	specific enthalpy (kJ kg^{-1})
p	pressure (MPa)
Q	heat (kJ kg^{-1})
R_1	relative transferring heat in evaporator E1
T, t	temperature (K, °C)
W	power output (kW)
x	ammonia concentration (kg kg^{-1})
Y	quality (dryness) of vapour

Greek letters

Δ	difference
η_0	power recovery efficiency
η_{th}	thermal efficiency
η_{wh}	waste heat recovery ratio

Subscripts

number	status point in Fig. 1
b	basic (concentration)
d	dilute (concentration)
h	heat resource
P	pump
T	turbine
w	work (concentration)

power and heating-water in winter. Padilla et al. [19] studied so called "Goswami cycle" for power and cooling cogeneration using ammonia–water mixture. Sadhukhan et al. [20] analyzed thermodynamic properties of ammonia–water mixture of power and refrigeration cycles. Hua et al. [21] presented a power and chilling cycle that generating chilling output with some work concentration solution from mid-p-absorber to partially evaporate at low pressure and the results showed that the total thermal efficiency of the proposed cogeneration cycle at chilling fraction 0.5 is 24.2% higher than that of the power cycle under the same condition. Jing and Zheng [22] proposed and investigated a new power and cooling cogeneration cycle with coupling-configuration on energy cascade utilization.

The Kalina cycle is quite complicated and the parameter optimization is always a hot issue. Energy and/or exergy analysis on the Kalina cycle were performed in many literatures. Ogriseck [23] conducted a case study to generate electricity with integration of the Kalina cycle in a combined heat and power plant for improvement of efficiency. Anish and Fredrik [24] analyzed four Kalina cycle layouts and obtained 30% thermal efficiency of the cycle with the turbine inlet temperature of 500 °C. Hettiarachchi et al. [25] investigated the performance of the Kalina cycle system with low temperature heat resources and found that the Kalina cycle has better overall performance at moderate pressures than that of the ORC. Nasruddin et al. [26] performed energy and exergy analysis on the Kalina cycles for utilization of geothermal brine water. Nag and Gupta [27] studied the effect of key parameters on the cycle performance and found that the mixture concentration at turbine inlet has an optimum value with respect to second law efficiency. Philippe et al. [28], Marston [29] and Wang et al. [30] performed respectively thermodynamic and parametric analysis of the Kalina cycle. Chen [31] and Hua et al. [32] conducted respectively thermodynamic analysis on a modified Kalina cycle for better cyclic performance. Zare et al. [33] applied exergoeconomic concept to compare the performance of the combined GT–MHR (Gas Turbine–Modular Helium Reactor)/Kalina cycle plant for power generation. The results indicate that the efficiency and total product unit cost of the combined cycle is 8.2% higher and 8.8% lower than the corresponding values for the GT–MHR. Walraven et al. [34] compared the performances of different types of organic Rankine cycles and the Kalina cycle for low-temperature geothermal heat sources and constructed a multi-pressure level evaporation ORC for higher plant efficiencies.

There are mainly two categories of Kalina cycle: triple-pressure [2,4] and dual-pressure [3,4]. The high and low pressures are separately for heat input from heat resource and discharge to cooling water and to ensure turbine enthalpy drop for producing power, while the mid pressure is for desorption process to reproduce work concentration solution. The triple-pressure Kalina cycle needs two working medium pumps while the dual-pressure Kalina cycle consolidates the high and mid pressures and needs only one working medium pump.

The most studied dual-pressure Kalina cycle is the one with separator after the evaporator [5,11–16], in which the enriched vapour from the separator goes to the turbine while the dilute liquid solution goes back the low-p-absorber after cooled in a recuperative heat exchanger and throttled with an expansion valve. However, as the heat acquisition of the work medium covers only minority of phase change section, the temperature increase of the work medium in evaporator of this cycle is not significant, thus it is mostly applied on geothermal heat resource or as the bottoming cycle of steam Rankine cycle [5,17]. The drawback of this cycle lies in that the heat recuperation of the high temperature dilute solution from the separator to the basic solution will squeeze heat release of both heat resource and turbine exhaust. The other dual-pressure Kalina cycle is the one with separator before the evaporator [35,36] in which the temperature of dilute solution is much lower with smaller heat loss. Since the high pressure of this cycle loop is restricted by the desorption process in recuperator, in which the basic solution should be heated to two-phase state by turbine exhaust, this cycle is suitable for even lower temperature heat resource (below 120 °C).

The heat absorbing process in the triple-pressure Kalina cycle usually comprises of three variable temperature sections of subcold liquid heating, evaporation and vapour super heating, which can match well with great temperature difference of sensible heat resource and acquire more heat from the heat resource. Also, its high pressure can be freely adjusted to fit the inlet temperature of the heat resource, thus it is the most recommended or applied form of the Kalina cycle.

From the knowledge of thermodynamics it is apparent that the efficiency of a power generating cycle depends mainly on the temperature of the heat resource and the higher temperature heat resource usually has higher thermal efficiency as well as economic benefit than that of the lower one. Thus the high/mid-grade heat resource should be placed in the priority position in utilization and exploration.

The Kalina cycle has high thermal efficiency mainly due to lower thermal irreversibility in the heat absorbing process, particularly between the heat resource and the evaporating working