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A novel ammonia-water combined power and refrigeration cycle with two different cooling temperature levels

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A new ammonia-water cogeneration system is proposed to produce power and refrigeration outputs simultaneously, which combines Kalina power cycle and ejector refrigeration cycle. This cycle has two evaporators that can produce refrigeration output in two different temperature levels and capacities, in which the first evaporator pressure may be selected independently. This capability of the proposed cycle increases the number of possible applications while the complexity of the system doesn't vary much. Adjustable power to cooling ratio is another feature of this novel cycle, by changing the reboiler reflux ratio different power to cooling ratios can be reached. The cycle performance was evaluated by exergy efficiency, net power and refrigeration outputs. The effect of key parameters such as turbine inlet pressure, heat source temperature, condenser temperature, evaporation temperature and basic working solution ammonia concentration on the cycle performance have been investigated. It is found that the cycle's thermal performance is acceptable with exergy efficiency of 38.97%, effective exergy efficiency of 42.75% and thermal efficiency of 19% for the base case study.

1. Introduction

Nowadays global warming and air pollution are among the most critical concerns of human life. Increasing consumption of fossil fuels is the major reason of this concern, therefore utilization of low temperature heat sources such as solar energy, geothermal energy and waste heat may be possible solution for these problems. Binary component mixtures exhibit variable boiling temperature during boiling process, which causes small temperature difference between variable temperature heat source and working fluid in heating process. In this way, irreversibility of the system is reduced, resulting in an increase in exergy efficiency of the system. Ammonia water mixture is one of the well-known mixtures which exhibits acceptable thermophysical properties and is also an environmentally-friendly material.

In 1950s Maloony and Robertson [1] proposed an absorption power cycle using ammonia-water mixture as the working fluid. Kalina [2] also proposed an absorption power cycle in which the same working fluid is employed. This cycle is designed to replace the currently used Rankine cycle as a bottoming cycle for a combined cycle systems and also for generating electricity using low temperature heat sources. Ammonia-water mixture evaporates at low temperature therefore low temperature heat sources can be used. Furthermore, variation of the evaporation temperature leads to a lower temperature difference between the heat source and the working fluid which decreases the irreversibility of the systems. Because of these reasons, Kalina cycle and also ammonia-water absorption cooling cycle have been used widely in recent years and are developed in various configurations for different applications and heat sources [3–7]. Goswami et al. [8] proposed a combined thermal cooling and power cycle with ammonia-water as working fluid. The proposed cycle combined a Rankine cycle and an absorption refrigeration cycle, in which the ammonia water mixture can be expanded to a very low temperature in the turbine without condensation, and it uses an absorption condensation process instead of the conventional condensation process. Some further developments and researches on the Goswami's cycle performance were carried out by him and other researchers [9–13]. Fontalvo A et al. [14] performed an exergy analysis and calculated the exergy destruction in each component of the Goswami's cycle and compared them for different absorber ammonia mass fraction, turbine efficiencies and pressure ratios. Zhang et al. [15,16] proposed a new ammonia-water system for the cogeneration of refrigeration and power. The plant operates in a parallel combined

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Nomenclature

$\dot{E}$	exergy, kW
h	specific enthalpy, kJ kg^{-1}
$\dot{I}$	exergy destruction
$\dot{m}$	mass flow rate, kg s^{-1}
$\dot{Q}$	heat transfer, kW
R	Power to cooling ratio
s	Specific entropy, kJ kg^{-1} K^{-1}
T	temperature, °K
$\dot{W}$	power output, kW
w	Combined cycle system ratio
x	ammonia mass fraction

Greek symbol

μ	ejector entrainment ratio
η	Efficiency

Subscripts

cond	condenser
d	diffuser
eff	effective
evap	evaporator
ex	exergy
hs	heat source
$H1, H2, H3, H4$	heat source states
i	state points
in	input
m	mixing
n	nozzle
ni	nozzle inlet
no	nozzle outlet
P	pump
p	primary flow
s	secondary flow, isentropic
T	turbine
th	thermal
0	environment state
$1-19$	state points
II	Second law

cycle mode with an ammonia-water Rankine cycle and an ammonia refrigeration cycle, interconnected by the absorption, separation and heat transfer processes. The performance is evaluated by determination of both energy and exergy efficiencies, and is compared with conventional separate cycles for generation of power and refrigeration. Zheng et al. [17] proposed a novel absorption power and cooling system based on Kalina cycle. The flash tank in the Kalina cycle was replaced by a rectifier, to enhance the separation process and to obtain a purer ammonia for refrigeration. A condenser and an evaporator were introduced between the rectifier and the second absorber. With these modifications, the cycle is able to provide refrigeration and power simultaneously. Liu and Zhang [18] also employed a splitting/absorption unit into their cycle to adjust some stream mass flow rates and thus maintain the desired ammonia concentrations in different processes. Wang et al. [19] proposed a combined power and refrigeration cycle with ammonia–water as working fluid and simplified the complication of cycle in Ref. [15], resulting in reduction of investment cost. The most significant difference between Wang's proposed cycle and the one introduced in Ref. [15] is that the pump and the condenser before and after the turbine are eliminated. In recent works, ejectors are used for two main purposes, improving the Kalina cycle performance or producing cooling in combined power and ejector refrigeration cycle. In the cycle proposed by Li et al. [4] the ejector is used to increase the power output and the thermal efficiency of the Kalina power cycle. In the refrigeration cycles ejectors are used to increase refrigerant pressure instead of the compressor. Implementation of ejectors in cooling cycles can increase the efficiency of the cycle which are investigated widely in recent years [20–24]. Wang et al. [25] also proposed a new combined power and ejector–absorption refrigeration using ammonia-water mixture as the working fluid. This combined cycle introduces an ejector between the rectifier and the condenser. Yu et al. [26] proposed and investigated a novel ammonia–water cogeneration system with adjustable cooling to power ratios. In the combined system, a modified Kalina subcycle proposed by Zheng et al. [17] and an ammonia absorption cooling subcycle are interconnected by mixers, splitters, absorbers and heat exchangers. The proposed system can adjust its cooling to power ratios from the separate mode, without splitting/mixing processes in the two subcycles, to the combined operation modes which can produce different ratios of cooling and power.

In the present study a novel ammonia-water power and ejector-absorption refrigeration cycle is proposed and investigated to produce power and refrigeration outputs simultaneously. This novel cycle is improved system of Wang's cycle (ref. [25]). The restriction of Wang's cycle and other previous combined cycles is about the evaporator pressure which is the same as the turbine outlet pressure, therefore at constant turbine outlet pressure, evaporator pressure and temperature cannot be changed. This cycle has two evaporators and can produce refrigeration output in two different temperature levels and capacities, which has not been carried out by previous authors. The first evaporator can operate at different pressures and temperatures while its pressure is independent to the second evaporator and turbine outlet pressure. Therefore refrigeration capacity can be produced in two different temperatures simultaneously, this feature is one of the major advantages of this novel cycle and according to that the cycle can be used in different applications such as food industries. Many industries need refrigerators with different temperature levels. In food production company raw materials and products should be kept at different temperatures, therefore this novel cycle can be used in these cases which have refrigerators at different temperature levels. Similar to other previous works, second evaporator pressure is the same as the turbine outlet, therefore its temperature cannot be changed. Using the rectifier instead of the flash tank, enhances the cycle to separate ammonia and water to a sufficient concentration, and also in this cycle ejector is introduced between rectifier and condenser to increase first evaporator outlet flow pressure. Adjustable power to cooling ratio is another feature of this novel cycle, by changing the reboiler reflux ratio different power to cooling ratios can be reached. Low grade heat sources such as flue gas from gas turbine, solar energy, geothermal energy or any other waste heats can be used to drive this combined cycle. The effect of key parameters such as turbine inlet pressure, heat source temperature, condenser temperature, cooling temperature and basic working solution ammonia concentration on the cycle performance have been investigated and it is shown that these parameters have a large effect on the cycle performance.