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Exergy analysis of a combined vapor power cycle and boiler flue gas driven double effect water–LiBr absorption refrigeration system

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ABSTRACT

A combined vapor power cycle (PC) and double effect water–LiBr absorption refrigeration system (ARS) is proposed in this study. The boiler leaving flue gas of the PC is the heat source for the high pressure generator (HPG) of the double effect ARS. Exergy analysis of the proposed system is performed to show the performance variation of both the topping PC and the bottoming ARS with changing HPG temperature from 120 °C to 150 °C. Further the performance of double effect ARS integrated combined power and cooling system is compared with a similar system integrated with a single effect ARS. HPG temperature of the double effect ARS and generator temperature of the single effect ARS are considered as 120 °C and 80 °C respectively. Results show that the power and efficiency of the topping PC decreases with HPG temperature due to reduction in steam generation rate in the boiler. COP and exergy efficiency of the double effect ARS also reduces with increasing HPG temperature. The irreversible losses in the PC components decrease while the total irreversibility of the combined power and cooling system increases with HPG temperature due to increase in exergy loss with the HPG leaving flue gas and irreversibility of the ARS components. PC performance does not vary much due to replacement of the double effect ARS with the single effect ARS, however higher COP and exergy efficiency of the double effect system are achieved with much lower irreversible losses in the HPG and ARS condenser of the double effect system.

1. Introduction

Water–LiBr absorption refrigeration cycles are available in various configurations ranging from half effect to triple effect [1]. The half effect cycle presents the lowest COP; COP increases with increase in number of stages and thus highest COP is obtained with the triple effect configuration [1]. In the double and triple effect (multi effect) cycles, generation of refrigerant vapor is distributed among two and three number of generators respectively. Multi effect absorption refrigeration cycles are also available in series, parallel and reverse parallel flow configurations. Details of all these configurations and their differences can be found in Refs. [1–4].

The double effect absorption refrigeration cycle was conceptualized during 1956–1958 [5] and has more commercial use in the refrigeration industry than the triple effect systems [2,3]. Over the years many studies have been performed on double effect water–LiBr refrigeration systems, while some of them deal with the energetic performance analysis [4,6–12] and some other articles [13–19] are specific to exergy analysis. In most of the energy analysis, mainly the COP of the water–LiBr ARS is evaluated and sometimes the effects of the component temperatures on COP are investigated through parametric study. However energy analysis alone is not sufficient for evaluating inefficiency of energy systems and often exergy is used as a tool as it provides the framework for evaluating irreversible losses occurring in various system components. Moreover for comparing the performance of a water–LiBr ARS with different generator heat input, exergy is the most appropriate method because depending upon the temperature of the heat source, the quality of energy input will be different and in this situation, the exergetic efficiency will give a better insight into the system operation rather than the COP.

Various analyses are performed on double effect water–LiBr absorption refrigeration. Manohar et al. [20] developed an artificial neural network (ANN) model to predict performance of a steam driven double effect series flow type water–LiBr absorption chiller. Farshi et al. [21] carried out an exergo-economic analysis to differentiate the three classes of water–LiBr double effect ARSs at a broad range of operating conditions. They concluded that the total cost of the system configurations and their selection depends mainly upon the operating conditions. Shin et al. [22] developed a model to simulate the dynamic performance of a double effect water–LiBr absorption chiller and validated the model results with the test data of a commercial medium chiller. Yin et al. [12]

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Nomenclature

C_p	specific heat (kJ/kmol K)
$\dot{E}_x$	exergy (kW)
ex	specific exergy (kJ/kg)
EUF	effective utilization factor
h	specific enthalpy (kJ/kg)
h^0	specific enthalpy at the reference state (kJ/kg)
$\dot{I}$	irreversibility rate (kW)
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
M	molecular weight
p	pressure (kPa)
$\dot{Q}$	heat load (kW)
R	universal gas constant
s	specific entropy (kJ/kg K)
s^0	specific entropy at the reference state (kJ/kg K)
T	temperature (K)
T_o	reference temperature (K)
t	temperature (°C)
$\dot{W}$	work (kW)
Y	mass fraction

Greek letters

η_I	energy efficiency (%)
η_{II}	exergy efficiency (%)
η_{SP}	solution pump efficiency (%)
η_{CS}	exergy efficiency of the combined system (%)

Subscripts

A	absorber
a	air
BFP	boiler feed pump
C	condenser
ch	chemical
COP	coefficient of performance
CT	cooling tower
CTP	cooling tower pump
CWH	closed water heater
E	evaporator
f	fuel
fg	flue gas
G	generator (single effect water–LiBr system)
HPG	high pressure generator
i	inlet/combustion gas species
LPG	low pressure generator
MC	mixing chamber
o	outlet
OWH	open water heater
PCC	power cycle condenser
s	steam
SHE	solution heat exchanger
SP	solution pump
tm	thermo-mechanical
v	water vapor
w	water

developed the design of a double effect steam driven water–LiBr chiller model to predict steady state performance of the chiller through refinement of model results using measured test data of a 16 kW water–LiBr double-effect absorption chiller under various conditions. Li and Liu [23] investigated the effect of generator heat load ratio (ratio of energy input between the high pressure and the low pressure generator) on COP and crystallization of series, pre-parallel, rear parallel and reverse parallel flow configuration of an air cooled water–LiBr double effect absorption chiller. They found that COP increases with decrease in heat load ratio while also the risk of crystallization increases. Jiang et al. [24] compared COP and the cyclic characteristics of a small double effect ARS with a three-pressure absorption–ejector hybrid refrigeration system through presentation of thermo-economic models of the two systems.

Often ARSs are coupled with other systems that provide the driving heat source, e.g. the articles [25–28] available in the literature deal with solar powered single effect water–LiBr ARS. Havelsky [29] and Manzela et al. [30] provided energetic performance analysis of single effect water–LiBr ARS driven by internal combustion engine (ICE) exhaust gas heat. Hwang [31] analyzed the energetic performance of a micro turbine system integrated with a single stage effect water–LiBr absorption chiller and vapor compression refrigeration system (VCRS). Khaliq [32] performed energy and exergy analysis of a trigeneration system combining a gas turbine with a heat recovery steam generator (HRSG) for process heat and a single effect water–LiBr ARS for cooling purpose. Gogoi and Talukdar [33,34] performed energy and exergy analysis of a combined reheat regenerative vapor power cycle and a single effect water–LiBr ARS. There are also articles that provide analysis of such combined systems (CSs) involving a double effect water–LiBr ARS. Some of them are discussed below.

Ameri and Hejazi [35] investigated the effect of inlet air cooling on power output of a gas turbine plant integrated with a HRSG and a steam driven double effect water–LiBr absorption chiller. Bruno et al. [36] analyzed several types of cogeneration systems involving biogas fueled micro gas turbine and commercially available single and double effect water–LiBr and ammonia–water absorption chillers. Bruno et al. [37] in another study made performance analysis of combined micro gas turbines and gas driven double effect water–LiBr absorption chillers with post-combustion to investigate the performance of the combined plant with and without addition of extra fresh air for post combustion. Huicochea et al. [38] acquired experimental exhaust heat data of a 28 kW micro turbine and analyzed theoretically the thermodynamic performance of a trigeneration system formed by the micro turbine and a double-effect water–LiBr absorption chiller. There are also published articles on solar energy driven air cooled double effect water–LiBr absorption cooling systems. Liu and Wang [10] proposed a novel solar/gas driven double effect water–LiBr absorption system where hot water produced from solar energy in the collector is first stored in a storage tank and later used as a source of heat for vapor generation in the low-pressure generator (LPG) together with water vapor leaving the high-pressure generator (HPG). Natural gas is burned to supply energy for vapor generation in the HPG. Li et al. [39] developed a parametric model to analyze the performance of a solar air cooled double effect water–LiBr absorption cooling system using monthly average meteorological data (hourly solar irradiance and ambient temperature) of subtropical Guangzhou at various collector temperatures. It was found that the suitable working range of inlet temperature of the solar collector is 110–130 °C for improved performance with lower crystallization risk. The possibility of crystallization is more in the air-cooled ARSs compared to water cooled systems, although they are attractive otherwise because of absence of the cooling tower (CT) and other associated installation. CT is an essential component of a steam turbine (ST) based thermal power plant. Hence it is possible to integrate a water cooled double effect water–LiBr ARS with a ST plant. The exhaust heat of boiler flue gas of a steam power plant can be used for driving a double effect ARS. In thermal power