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Techno-economic analysis of combined ammonia-water absorption refrigeration and desalination

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ABSTRACT

This paper investigates the opportunities for integrating single- and double-stage ammonia-water (NH_3–H_2O) absorption refrigeration systems with multi-effect distillation (MED) via cascade of rejected heat. Cooling capacity and hourly water production are calculated from thermodynamic properties of the working fluids at different operating conditions using simple models for each of the constituent systems. Additionally, the second law of thermodynamics is applied with the aim of examining the total exergy destruction of the entire stand-alone and combined systems. A cost model is developed as well in order to estimate the total annual cost of the system and the unit production cost (UPC) of both fresh water and cooling. The results indicate that the total exergy destruction of the combined systems, which consist of an MED unit driven by either a single- or double-stage NH_3–H_2O refrigeration system, decreases by an average of 55% compared to stand-alone NH_3–H_2O and MED systems. Relative to stand-alone systems, although water production decreases by 30% and 9% when an MED unit is integrated with single- and double-stage NH_3-H_2O absorption systems, respectively, cooling capacity remains unchanged for the double-stage NH_3-H_2O–MED system, and only decreases by 16% for the single-stage NH_3-H_2O–MED system. Moreover, the UPC of cooling decreases significantly by an average of 43% for both coupled systems, whereas the UPC of the produced water increases by only 19% and 3% for single- and double-stage NH_3H_2O–MED systems, respectively.

1. Introduction

Fresh water demand has gradually increased due to the rapid growth of population and domestic, industrial, and agricultural use. Seawater desalination has been the main, if not only, source of potable water in regions where physical water scarcity is the main challenge. Currently over 30% of the world's population lives in areas suffering from physical water scarcity, and this figure is estimated to surpass 50% by 2025 [1].

Furthermore, drought and desertification have been increasing remarkably in regions worldwide for the past few years, resulting from deficiencies in surface and ground water [2]. In addition, global warming will escalate the risk of drought thus placing more stress on water supplies, even in countries that may not face water shortages today [3]. Refrigeration and air-conditioning demands are also expected to increase from the rise of global temperatures. This makes the environmental impact worse since many common refrigerants in use today pose a threat to the environment because of their global warming potential (GWP) and ozone depletion potential (ODP) [4]. In hot and dry climates, such as the Middle East, desalination and refrigeration systems provide two essential products that can be generated in a combined system instead of by separate systems.

Absorption refrigeration systems (ARS) are becoming more attractive than before because they provide promising replacements for vapor compression refrigeration (VCR) systems by using working fluids with zero ODP, zero GWP, and can be thermally driven. Unlike water-lithium bromide (LiBr–H_2O) ARS, ammonia-water (NH_3–H_2O) ARS can provide very low refrigeration temperatures (down to −60 °C), compact unit size due to the low specific volume of NH_3 operating at high pressures, and trouble-free operation with no risk of crystallization [5]. Substantial amounts of heat must be rejected by the condenser, absorber, and rectifier of the NH_3–H_2O ARS into the environment in order to complete the refrigeration cycle. In fact, the heat rejection factor (ratio of heat

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Nomenclature

A	area (m^2)
COP	coefficient of performance
dx	mass concentration swing between strong-and-weak solution (%)
η	efficiency (%)
GOR	gained output ratio (kg_{water}/kg_{steam})
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat flow rate (kW)
ρ	density (kg/m^3)
T	absolute temperature (K)
TAC	total annual cost ($/yr)
UPC	unit product cost ($/$m^3$ or $/ton)
W	power (kW)
x	water salinity (ppm)

Abbreviations

ARS	absorption refrigeration system
LiBr-H_2O	water-lithium bromide
MED	multi effect distillation
TVC	thermal vapor compression
MSF	multi stage flash
NH_3-H_2O	ammonia-water
Nom	nominal
Opt	optimal
RO	reverse osmosis
SW	seawater feed
TBT	top brine temperature
mgd	million gallons per day
VCR	vapor compression refrigeration

rejection to the cooling capacity) is about 2.5 for ARS compared to 1.2 for VCR systems [6]. Consequently, the cooling tower and associated pumping system capacities of ARS are twice the size of those of VCR systems, which leads to higher initial and operating costs. This heat rejection is quite important to the system because the coefficient of performance (COP) decreases significantly as condenser and absorber temperatures increase. Thus, wet cooling is usually required in order to operate the system at higher COP [7].

Widely used desalination technologies can be categorized, based on the method of water-salt separation, into membrane and thermal desalination. The potential advantage of thermal desalination over membrane separation is the capability to utilize low-grade exhaust heat at a low top brine temperature (TBT): lower than 70 °C for Multi Effect Distillation (MED) and Multi Effect Distillation–Thermal Vapor Compression (MED–TVC), and 90–110 °C for Multi Stage Flash (MSF) [8]. Reverse osmosis (RO) is the most efficient existing desalination technology with an exergetic efficiency of about 32% [9]. Following RO in order are MED–TVC, MED, then MSF, with internal exergetic efficiencies of 9%, 6%, and 3%, respectively [9]. The exergetic efficiency of an RO system would be substantially lower if exergetic efficiencies are reported relative to fuel input exergy; note that the exergetic efficiency of a modern power plant is over 50% [10]. It is worth pointing out that the RO exergetic efficiency is only in the form of shaft work (electrical energy). Despite the low exergetic efficiencies of thermal desalination systems, these technologies are still widely used in many areas, like the Middle East, due mainly to the low cost of fossil fuel. Among all thermally driven desalination technologies, MED–TVC and MED have received more attention than other thermal desalination processes due to low TBT (<70 °C), low corrosion rate, high gained output ratio, and low specific energy consumption which ultimately leads to mitigating greenhouse gas emissions especially when exhaust heat is employed. Although MED–TVC is more efficient than MED as a result of reducing the required steam by recovering steam at the final effect through a steam jet ejector [11], MED can be operated below 60% capacity, which makes it suitable to be integrated with intermittent energy supplies such as exhaust heat and renewable energies [12].

In a recent report [13] prepared for Oak Ridge National Laboratory (ORNL), an assessment of the potential market for exhaust heat in the industrial sector in the United States was provided. A breakdown of the exhaust heat energy based on temperature has estimated that 12% is available below 150 °C, 25% from 150 to 235 °C, 53% from 235 to 650 °C, and 12% is above 650 °C. Apparently, exhaust heat with a temperature over 235 °C seems more appealing for power generation than any other applications. On the other hand, thermal energy with a temperature below 235 °C still has a broad spectrum of applications [14].

With the intention of minimizing the exergy destruction (irreversibility) associated with thermal desalination technologies, and improving the ARS' performance by operating at lower condenser and absorber temperatures, the possibility of integrating both systems has been previously investigated. Alarcón-Padilla and García-Rodríguez [15] showed that one of the best techniques for thermal desalination processes, to compete with RO, is by integrating an absorption heat pump with an MED system.

Li et al. [2] studied the feasibility of coupling an ammonia-water absorption heat pump with an MED system, where superheated ammonia vapor generated by low-grade heat gets compressed, releasing heat to the MED system as the ammonia vapor is absorbed into the ammonia-water weak solution. The results compared favorably to RO in terms of specific power consumption with a possible return of investment in three years. It is worth mentioning that their system provides only freshwater—no cooling.

Esfahani et al. [16] investigated, based on energy and cost measurements, a new system composed of a multi effect evaporation–absorption heat pump (MEE-ABHP) desalination system and a VCR system. The results show that the coupled system can save 57.1% in electrical energy, 5.6% in thermal energy, and 25.6% in total annual cost compared with individual MEE-ABHP and VCR systems.

Aly [17] proposed a system that combines LiBr-H_2O ARS with a multi-effect evaporation (MEE) desalination system. He suggested replacing the single-stage ARS condenser and evaporator with the MEE. The system was estimated to produce 1.53 mgd (5.8 ML/d) of fresh water at a performance ratio (PR) of 14.2, and a by-product cooling capacity equivalent to a 220-kW_{th} air conditioning unit at 6.5 °C.

Wang and Lior [18,19] considered replacing a single-effect LiBr–H_2O ARS condenser with a low-temperature MEE desalination system. The proposed system achieved an energy consumption reduction of 42%, compared to the stand-alone MEE and ARS systems, with a COP of 1.6 and an exergetic efficiency above 60%.

Gomri [20] proposed to utilize the heat rejection from the absorbers of single- and double-stage absorption heat transformer systems using a separation vessel for seawater desalination purposes. He studied the impact of absorber temperature on COP, second-law efficiency, and fresh water production, and found that fresh water production for the single-stage absorption heat transformer is slightly higher than that for the double stage combined with the desalination unit.

Gude and Nirmalakhandan [21] investigated the possibility of harnessing heat rejected by the condenser of a modified single stage LiBr–H_2O ARS to drive a desalination process. Their results