Applied Energy 104 (2013) 810–821

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A hybrid multi-effect distillation and adsorption cycle

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ARTICLE INFO

Article history:
Received 23 July 2012
Received in revised form 2 December 2012
Accepted 3 December 2012

Keywords:
Hybrid desalination
Adsorption
Multi-effect distillation
Low-temperature waste heat

ABSTRACT

This paper describes the development of a simple hybrid desalination system of a Multi-Effect Distillation (MED) and an adsorption (AD) cycle operating at sub-atmospheric pressures and temperatures. By hybridizing the conventional MED with an AD cycle, there is a symbiotic enhancement of performances of both cycles. The performance enhancement is attributed to (i) the cascade of adsorbent's regeneration temperature and this extended the usage of thermal energy emanating from the brine heater and (ii) the vapor extraction from the last MED stage by AD cycle which provides the effect of lowering saturation temperatures of all MED stages to the extent of 5 °C, resulting in scavenging of heat leaks into the MED stages from the ambient. The combined effects of the hybrid cycles increase the water production capacity of the desalination plant by nearly twofolds.

In this paper, we demonstrate a hybrid cycle by simulating an 8-stage MED cycle which is coupled to an adsorption cycle for direct vapor extraction from the last MED stage. The sorption properties of silica gel is utilized (acting as a mechanical vapor compressor) to reduce the saturation temperatures of MED stages. The modeling utilizes the adsorption isotherms and kinetics of the adsorbent + adsorbate (silica-gel + water) pair along with the governing equations of mass, energy and concentration. For a 8-stage MED and AD cycles operating at assorted temperatures of 65–90 °C, the results show that the water production rate increases from 60% to twofolds when compared to the MED alone. The performance ratio (*PR*) and gain output ratio (*GOR*) also improve significantly.

1. Introduction

Potable water is a necessity for life sustainability but such a resource, like all other natural resources on Earth, has finite availability. The accessibility or the balance of supply and demand for potable water is dependent on factors such as population growth, rapid urbanization, agriculture, climate uncertainties, and technological growth [1]. Furthermore, human's economic activities and urbanization contaminate the water sources and endangers the supply of potable or safe water. In many countries, the shortfall between natural water supply and demand can be mitigated by technology-driven desalination processes but such processes are usually energy intensive along with CO_2 gas emission and the discharge of chemical-laden brine solution. Although the thermodynamic limit for desalting of seawater (35 ppt) is about 0.7 kW h/m^3 [2,3], the actual desalting process, whether it is mechanically- or thermally-driven process, would consume two or more folds of this minimum specific energy consumption. A detailed analysis on the energy consumption for the cycle of water supply such as distribution, end-use, reclamation and disposal of wastewater has been reported by Plappally et al. [4].

Commercial desalination methods can be categorized into two main classes; (i) methods that involved a phase-change mechanism and (ii) those processes with liquid separation or simply without a phase-change mechanism. All the thermal desalination systems fall in the first group while the latter includes membrane-based processes such as reverse osmosis (RO). Liquid-salt molecules separation with membranes needs only to overcome its osmotic pressures and tend to be more energy efficient as compared with the former phase-change methods because it handles a fluid of higher density. Recent reports state that seawater reverse osmosis (SWRO) plants with capacities up to 1000 m^3/d have achieved energy consumption below 2.0 kW h/m^3 [5,6]. Thermal desalination systems such as Multi-Stage-Flashing (MSF) and Multi-Effect Distillation (MED) systems are predominant (up to 85% of total production capacities) in the Middle East and North Africa (MENA) regions for three reasons: (i) the higher salinity of seawater (up to 45 ppt) in the Gulf and Red Sea lowers the percentage of water recovery of membrane processes, (ii) the frequent occurrence of harmful algae blooms (HABs) have fouled many RO plants for weeks to months but has lesser effect to thermally-based MSF

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http://dx.doi.org/10.1016/j.apenergy.2012.12.007

Nomenclature

$\dot{m}$	mass flow rate
A	area
COP	the coefficient of performance
c_p	specific heat capacity
D_{s0}	a kinetic constant for the silica gel water system
E	activation energy of surface diffusion
h	enthalpy or heat transfer coefficient
h_{fg}	latent heat
m	mass
n	index of the Dubinin–Astakhov isotherm model
P	pressure
P_0	reference pressure
q	uptake by the adsorbent material
Q	the total heat or energy
q^*	the equilibrium uptake
q^0	the limiting uptake
Q_{st}	isosteric heat of adsorption
R	gas constant
R_p	average radius of silica gel
T	temperature
t	time
U	overall heat transfer coefficient or internal energy
v	specific volume
V	volume
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
X	concentration
q''	heat flux
ρ	density
D	diameter
μ	dynamic viscosity
r	radius
k	thermal conductivity
$LMTD$	log mean temperature difference
$c_{p,a}$	specific heat capacity of the adsorbed phase

Subscripts

ads	adsorption
des	desorption
f	liquid phase/feed
g	gaseous phase
hw	hot water
HX	heat exchanger
In	inlet
l	liquid
Out	outlet
sg	silica gel
v	vapor
hw	hot water
t	tube
o	outside
b	brine
e	evaporator side
i	inside
abe	adsorbed phase
s	saturation
cw	cooling water
bh	brine heater
bed	adsorber/desorber bed
cond	condenser

and MED plants and (iii) The synergy for co-locating power plants and desalination plants makes cost-effective designs when heavy oil-based fuels are burned.

Although basic thermal desalination systems tend to be energy intensive than RO systems, innovative designs with multiple re-use of latent/condensation heat and cascaded temperature-based cogeneration concept can be incorporated for efficiency improvement. Once the cogeneration concept is introduced, thermal desalination systems become more attractive and competitive [7]. Thermal desalination systems are coupled with power generation units where they complement each other since the power generation cycle requires heat sink at cooler temperature to be operational. Thermal desalination system absorbs the rejected heat from the upstream systems i.e., the power generating units and produces potable water. Thus, savings in primary energy consumption is realized contrary to RO systems that consumes high-grade energy source i.e., electricity which can be utilized for other activities.

Among thermal desalination systems, the Multi-Effect Distillation (MED) systems are thermodynamically the most efficient of all thermal distillation processes [8] but their wide spread usage may be hindered by corrosion and scaling problems when efforts to raise water production with higher top-brine temperatures (TBTs) [9]. The emergence of advanced tube materials, process technology (the implementation of falling film type evaporation devices) and the use of thermal-vapor compression (TVC) systems have permitted MED systems to regain considerable market shares [10–14]. The MED-TVC systems operate at sub-atmospheric pressures, lowering the fouling and scale problems as well as reducing the capital and operation costs [15,16].

In MED systems, the performance and cost parameters depend on the ability to design for the number of effects within a given temperature difference of the TBT to the ambient [17]. Thermoeconomic analyses of such systems have been conducted extensively using optimization methods and exergy analysis [18–20]. Some studies coupled the MED system with an absorption heat pump or refrigeration unit to boost performance of the overall cycle [21–26]. El Dessouky [27,28] proposed a MED system to integrate with an adsorption vapor compression (ADVC), utilizing the vapor from the last effect of MED for adsorption whilst the regenerated water vapor from desorption is sent to the first effect of the MED system. It eliminates the condenser of MED system and the performance ratio improvement is double in this combined cycle [27,28].

In this paper, we propose a simple hybrid desalination system that integrates a conventional MED system with an Adsorption (AD) cycle. The AD cycle maintains direct vapor communication with the last effect of MED system via the vapor uptake of adsorbent, establishing a low-pressure environment (hence low saturation temperatures) within the MED stages. This implies that the cooling effect from the vapor uptake by the adsorbent of AD cycle is now transferred to all MED stages, lowering their respective film-boiling temperatures of the solution or the feed seawater. At the cyclic steady conditions, the last MED stage may reach a temperature near to the freezing temperature of solution, rendering an energy scavenging by heat leaks phenomenon from ambient. Regeneration of the adsorbent, hydrophilic porous silica gel, occurs concomitantly using the hot water that leaves the TBT stage, typically between 55 and 85 °C [29–31], extending the energy extraction from the waste heat sources. The desorbed water vapor is sent