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Area optimization of solar collectors for adsorption desalination

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ABSTRACT

Adsorption desalination is an emerging method to address the shortage of fresh water. To achieve its energy-saving potentials, a renewable low-temperature heat source is the key. This paper focuses on the area optimization of solar collectors in combined solar heating systems that supply heat for adsorption desalination, aiming at achieving the maximum economic benefits during the lifespan of a project. The optimum tilt angle was discussed and the corresponding daily radiation data were calculated with HDKR (Hay, Davies, Klucher, Reindl) model. The area optimization function was proposed with the unit costs of fresh water as the optimization objective. A reference area calculated according to annual solar radiation was employed to describe the optimization results. Then the influences of the price of auxiliary energy sources, the performance ratio of adsorption desalination, and the heat loss of solar heating on the optimization results were studied with an actual adsorption desalination project in Tianjin. It has been found that the optimal area is positively associated with the auxiliary energy price, however approximately inversely proportional to the performance ratio of desalination and the energy efficiency of solar heating. The unit costs of producing fresh water can be reduced up to 20% after collector area optimization when the auxiliary energy is expensive. Besides, the overall costs of utilizing solar heating to supply heat for adsorption desalination is around 0.03–0.04 CNY/MJ which is lower than conventional energy sources. We also tested the optimization results with an altered precision of radiation data and different meteorological conditions. Findings in this paper proved the advantages of incorporating solar heating in adsorption desalination and provided instructions for designing solar adsorption desalination projects.

1. Introduction

The shortage of fresh water is now a challenge threatening a large amount of population in many regions of the world. To solve the problem, desalination has been proved to be a feasible and efficient method. Conventional seawater desalination methods comprise distillation, ion exchange process, dialytic process and reverse osmosis process and so on (Khawaji et al., 2008). Although these desalination processes provide adequate fresh water, a lot of fossil fuels or electricity are always required, resulting in severe global warming and other environmental problems (Garmana and Muntasserb, 2008).

Adsorption desalination (AD) is a new burgeoning desalination method utilizing low-temperature (55–120 °C) heat sources to drive an adsorption heat pump, which often incorporates a conventional single or multiple effect distillation process for generating vapor (Ng et al., 2013). Since AD mainly relies on low-temperature hot water, it co-operates excellently with renewable low-temperature energy sources and industrial waste heat (Kalogirou, 1997). A cooling cycle may also be incorporated in AD systems (Mitra et al., 2015). Therefore, it is often comparatively more energy-efficient and environment-friendly than conventional desalination methods (Ng et al., 2012).

Solar energy has been widely used for desalination (Garmana and Muntasserb, 2008; Goosen et al., 2000). However, there are still challenges such as the meteorological condition, solar technologies, the costs and the scale (Goosen et al., 2000). Although solar energy is often regarded as free when compared with other energy sources (Missimer et al., 2013; Thu et al., 2010), the initial costs of solar collectors are actually rather high and the profits may be influenced by many factors like the lifespan of the system, the richness of solar radiation and the price of competing energy sources (Landsberg, 1977). Therefore, a better understanding of the thermodynamic and the economic mechanisms behind solar heating supplying heat for desalination systems is in urgent need.

Plenty of research on the optimization of solar heating systems has been performed. The minimum unit energy price of solar water heating has been calculated through computer programming using the collector

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Nomenclature

b	bank rate, –
C	construction costs, CNY
C_p	specific heat capacity, kJ/kg
c_{unit}	unit costs of fresh water, CNY/kg
dc	rate of costs change, CNY/m^2
dp	rate of profit change, CNY/m^2
F_a	anisotropy factor, –
$G_{b,i}$	normal inner-atmospheric direct radiation, W/m^2
$G_{o,i}$	normal extra-atmospheric radiation, W/m^2
G_{sc}	solar constant, W/m^2
H	daily solar radiation, MJ/m^2
I	solar radiation, W/m^2
M	mass, kg
$\dot{m}$	mass flow rate, kg/s
n	lifespan of the project, y
P	price of energy consumed by desorption, CNY/MJ
Q_{des}	desorption heat consumption, kJ
Q_{epl}	latent heat of vapor regeneration, kJ
Q_{eps}	sensitive heat of vapor regeneration, kJ
Q_{sol}	heat output of solar heating, kJ
$Q_{l,h}$	heat loss of solar collectors, W
$Q_{l,o}$	optical loss of solar collectors, W
r	specific latent heat of vaporization of water, kJ/kg
R_b	direct radiation factor, –
t	duration of an adsorption cycle, s
U_c	overall heat loss factor of collectors, W/(m^2·K)
W	fresh water production, kg
w	specific adsorption capacity of the adsorbent, kg/kg
α	absorptance of the collector surface, –
β	tilt angle of solar collectors
γ	azimuth angle
δ	declination angle of the sun
η_c	diurnal efficiency of solar collectors, –
η_l	heat loss factor of tanks and pipelines, –
ρ	surface reflectivity, –
τ	transmittance of the collector surface, –
φ	solar hour angle

Subscripts

1	before desorption
2	after desorption
ab	absorbent
am	ambient air
aux	auxiliary energy sources
av	average
bed	adsorption/desorption bed
cyc	single adsorption cycle
des	desorption
dh	direct radiation on the horizontal plane
fresh	fresh water
h	total radiation on a horizontal plane
heat	combined heating system
hot	hot water for desorption
i	day i in a year
in	inlet
op	optimal
out	outlet
ref	reference
sh	scattered radiation on the horizontal plane
solar	solar heating system
t	total radiation on a tilted plane
w	adsorbed water

Abbreviations

AD	adsorption desalination
GSHP	ground source heat pump
OR	optimal ratio
PR	performance ratio of adsorption desalination
SE	sorption elements
SR	saving ratio
WSHP	water source heat pump

area and the storage tank volume as optimization parameters (Alemu, 1998). Besides, the optimal area of solar collectors has been studied with actual solar heating projects when natural gas serves as the auxiliary energy source (Qing, 2010; Zhi et al., 2009). The optimal design of solar heating combined with geothermal energy (Mehrpooya et al., 2015) and ground source heat pump (GSHP) (Wang and Yu, 2013) respectively has been discussed, either.

However, studies focusing on improving the overall economic efficiency of the combination of solar heating and desalination are scarce, especially for the novel desalination pattern as AD. The operation of AD mainly relies on low-temperature hot water at a relatively fixed amount despite diurnal variation of meteorology. Its unique heat consumption features may significantly influence the heat output of solar heating. Besides, most existing studies only discussed the system optimization under a certain condition. The variation of system patterns, system efficiency, competing energy prices and climate conditions has not been taken into comprehensive consideration. The lack of uniform expression also restricts the generalization of the optimization methods and results. Currently, the construction of many solar desalination systems still depends on former experience without diligent designing, which may result in poor thermal and economic efficiency.

Therefore, in this paper, we studied the optimization of the combined solar adsorption desalination system through searching the lowest unit costs of producing fresh water in a reasonable collector area range. The factors that may influence the optimization result were discussed with a case study, including the price of auxiliary energy sources, the performance ratio of AD, and the heat loss of solar heating. Moreover, the condition on which the optimal area can be obtained was explained in detail for better understanding of the optimization process. The universality of the method was also checked with an altered precision of radiation data and different meteorological conditions. This work aims to provide instructions for designing AD projects coupled with solar heating as well as to propose a universal economic optimization method for solar heating systems.

2. AD coupled with solar heating

2.1. Description of the AD system

Adsorption desalination basically utilizes an adsorption heat pump to produce fresh water by adsorbing and then regenerating vapor. Solid adsorbents such like silica gel and zeolite are efficient at adsorbing and storing vapor, maintaining a low partial pressure of vapor to accelerate its evaporating. Then the vapor is released again when the (SE) are heated and condensed finally into fresh water (Ng et al., 2013). This process consumes almost only hot water except for a small amount of electricity used by pumps. Furthermore, heat at a relatively low temperature of 55–85 °C is sufficient for the desorbing process, which is a big advantage for using heat from renewable energy sources or industrial exhaust.