

Solar assisted Dual-effect Adsorption cycle for the production of cooling effect and potable water

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ABSTRACT: This paper presents a solar assisted adsorption cycle that produces two useful effects simultaneously, namely, cooling and desalination. Low temperature hot water produced from solar collectors is stored in thermally-stratified tanks and is used to regenerate the Adsorption (AD) Cycle where the silica gel-water pair is used. In this paper, the modeling and experimental results are discussed in terms of key parameters such as the specific daily water production (SDWP), the specific cooling capacity (SCC) and the over conversion ratio (OCR). The experiments show that the system is producing both the chilled water (in evaporator) and potable water (at condenser). With two useful effects from only low temperature waste or renewable heat input, the AD plant is one the plant with the lowest electricity consumption per m³ high grade water in the world.

Keywords: Solar desalination, adsorption, cooling, silica gel

NOMENCLATURE

c_p	Specific heat capacity (J/kg K)
h_{fg}	Latent heat of vaporization (J/kg)
M_{sg}	Mass of adsorbent silica gel (kg)
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (Pa)
Q	Power (W)
T	Temperature (°C)
t	Time (s)
t_{cycle}	Cycle time (s)
τ	No of operating cycle/day (-)

Subscripts

ads	Adsorption
$cond$	Condenser
$cool$	Cooling water
des	Desorption
hot	Hot water
in	Inlet
$load$	Chilled water at the evaporator
out	Outlet

1. INTRODUCTION

Cooling and desalination are two processes that permeate our daily lives and they require substantial energy input to achieve useful effect; either from electricity or via thermal input. From the environmental perspective, is there such a cycle that can be driven by renewable/solar energy and yet producing the mentioned dual useful effects at a reasonably high efficiency? Judging from amount of publications found in the literature, the short answer is “yes” and it has been proven to be practical. Thus, the motivation of this presentation is to provide a review of the state-of-art of heat-activated adsorption (AD) cycle that produces both cooling and desalting effects. Recently, Ng et al. [9, 10, 11, 12] have pioneered an efficient adsorption cycles that are not only thermally-driven but with heat source temperatures as low as 65°C. It has been demonstrated that AD cycle with suitable absorbent-adsorbate pair can meet these objectives, namely, for cooling and desalination applications. The key advantages are (i) the utilization of waste or renewable heat at low temperatures, (ii) almost zero maintenance (as there is no major moving parts) and (iii) low fouling rates in the evaporator. Being low-temperature driven, thermal energy from solar collectors could also be utilized for driving the AD cycle [12].

Why Solar?

With greater awareness in environment friendly and climate change, utilization of thermal energy from the sun appears to be most logical and practical. The solar collectors available today, hitherto, are both cost effective (typically US\$300/m²) and efficient (in excess of 55 % at an application temperature up 85° C. Figure (1) shows the map of solar availability of the world with the desert regions having a solar incident radiation of 25 MJ/m².day and a place in Korea is of 13 MJ/m².day. However, the

solar energy availability is a function of many factors such as the latitude, orientation, tilt angle of collectors, class of collectors (with selective coating), storage capacity, thermal load demand distributions, etc.

The vapour uptake by an adsorbent provides a means of moving condensable refrigerant in the cycle that is akin to a vapour compression process [2]. As the sorption processes are primarily surface effects, i.e., van der Waals forces, between surface pores and the adsorbate rather than the conventional bulk processes, the adsorption plant can be scaled to the design capacity [3, 4]. The mass and heat transfer processes in the AD cycle are placated on the understanding of thermodynamic property fields of adsorbent-adsorbate systems at partial vacuum or pressurized conditions and theoretical approaches have been formulated for analysis.

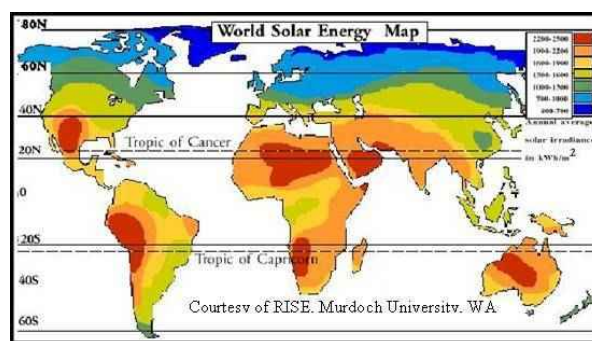


Figure-1 the map of the solar availability of the world

In 2006, Ng et al., patented the AD cycles for water desalination and a prototype plant has been demonstrated, producing high quality potable water a low specific energy input. The conversion of sea or brackish water to potable water is a priority research area as it concerns the economic interests of many regions of the world. It is noted that the dry weather conditions and highly populated cities are creating high demand of fresh water per capita. At least one billion people have no access to clean and fresh water. The WHO reported that about 41% of earth's population now live in water-stressed areas and these people in the water scarce regions may climb

to 3.5 billion by the year 2025. Therefore, innovative and cost-effective desalination technologies are needed to quench the global thirst for potable water.

Desalination is a process by which the salinity and unwanted chemicals in the sea or brackish water are removed. Hitherto, the desalination processes can be categorized into two major groups: The first category comprises the heat-driven processes such as multi-stage flashing (MSF) [5], multiple effect distillation (MED) [6, 7] and solar (stills) distillation and they have been widely used. The second category employs electrical power for the desalting processes which include processes such as freezing, mechanical vapor compression cycle, electro-dialysis, hybrid and reverse osmosis, etc. [8]. All desalination methods available, thus far, suffer from the major shortcomings; that is, either (i) the processes are highly energy intensive where with the specific energy consumptions are of the order of 3.5 to 8 kWh per cubic meter of water or (ii) the components interacting with saline solution at elevated working temperatures are susceptible to serious corrosion and fouling problems. One example is the evaporators or membrane in the desalting plant.

The AD cycle, on the other hand, mitigates the mentioned shortcomings [9] by being both energy efficient and lowers the fouling rates. As only low temperature waste heat (otherwise purged into ambient) is used, the desalting process in the evaporator reduces corrosion and fouling at the evaporators. At 85°C vapour off-take, all possible “bio-contamination” can be eliminated during the desorption processes [10, 11, 12].

In this paper, a simple AD cycle with elementary desorption and adsorption is discussed.

2. PERFORMANCE MODELING

The performance modeling of any adsorption system for cooling [27-29] and

desalination [10-12] is based on adsorption isotherms, kinetics and energy balances between the sorption elements, the evaporator and the condenser. The energy required (Q_{des}) to remove water vapors from silica gels can be calculated by using the inlet ($T_{hot,in}$) and outlet ($T_{hot,out}$) temperatures of the heat source, and this is given by

$$Q_{des} = \dot{m}_{hot} c_{p,hot} (T_{hot,in} - T_{hot,out}) \quad (1)$$

where $\dot{m}_{hot}$ indicates the mass flow rate and $c_{p,hot}$ defines the specific heat capacity of heating fluid. On the other hand, the energy rejected (Q_{ads}) to the cooling water during the adsorption process is estimated by measuring inlet ($T_{cool,in}$) and outlet ($T_{cool,out}$) temperatures of cooling fluid and this is written as

$$Q_{ads} = \dot{m}_{cool} c_{p,cool} (T_{cool,out} - T_{cool,in}) \quad (2)$$

where $\dot{m}_{cool}$ and $c_{p,cool}$ indicate the mass flow rate and the specific heat capacity of cooling fluid. The heat of evaporation (Q_{evap}), and the condensation energy (Q_{cond}) rejected at the condenser, are given by

$$Q_{evap} = \dot{m}_{load} c_{p,load} (T_{load,in} - T_{load,out}) \quad (3)$$

$$Q_{cond} = \dot{m}_{cond} c_{p,cool} (T_{cond,out} - T_{cond,in}) \quad (4)$$

The performance of the adsorption cycle is expressed in terms of specific daily water production (SDWP), specific cooling capacity, the performance ratio (PR), the COP and overall conversion ratio (OCR).

The SDWP and SCC of the adsorption cycle is defined as

$$SDWP = \int_0^{t_{cycle}} \frac{Q_{cond} \tau}{h_{fg}(T_{cond}) M_{sg}} dt \quad (5)$$

$$SCC = \int_0^{t_{cycle}} \frac{Q_{evap} \tau}{M_{sg}} dt \quad (6)$$

The performance ratio, the coefficient of performance and the overall conversion ratio of the adsorption cycle are given as

$$PR = \int_0^{t_{cycle}} \frac{\dot{m}_{water} h_{fg}(T_{cond}) \tau}{Q_{des}} dt \quad (7)$$

$$COP = \int_0^{t_{cycle}} \frac{Q_{evap} \tau}{Q_{des}} dt \quad (8)$$

$$OCR = \int_0^{t_{cycle}} \frac{(Q_{evap} + Q_{cond}) \tau}{Q_{des}} dt \quad (9)$$

3. RESULTS AND DISCUSSIONS

Figure (2) shows specific daily water production (SDWP) and the specific cooling capacity (SCC) of the adsorption cycle with the chilled water temperature ranges suitable for the air-conditioning and the machine cooling. The high grade water production or SDWP achieved at the same chilled water inlet temperature is 3 m³/tonne.day, and the corresponding specific cooling capacity or SCC is 25 Rtons/tonne.day obtained at a chilled water inlet of 12.5°C. However, at a 30°C “chilled water” inlet temperature, the values of SDWP and SCC are only 7.5 and 50, respectively. Such a high temperature coolant source may be used for the machine cooling.

The overall conversion ratio of the adsorption cycle (PR plus COP), defined here as the ratio of total useful effects to energy input, is shown in Figure (3). At a heat source of 85°C, the high overall conversion ratio achievable in the cycle is 1.2, and decreases to 0.9 if the cycle is operated at 12.5°C. The performance ratio (PR) for desalination is about 0.5 and the cooling COP is about 0.45.

For a solar-driven AD cycle, the hot water temperature fluctuates from 65°C to

85°C typically, depending on the design and regional climatic variations.

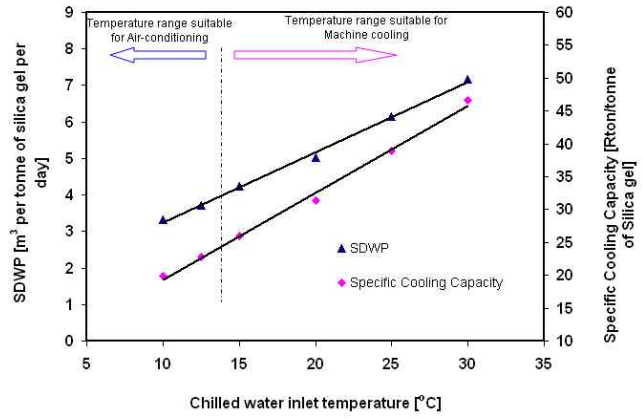


Figure-2 SDWP and SCC of a two-bed adsorption plant for the different chilled water temperatures at hot water 85°C

The SDWP and the specific cooling capacity of the adsorption cycle for the solar driven situations are given in Figure (4) and Figure (5). It can be seen that the SDWP and the SCC of the adsorption cycle linearly increased with higher heat source temperature for every set of chilled water inlet temperature. It is also observed that both the SDWP and SCC of the AD cycle improve at higher chilled water temperatures with higher heat source temperatures.

Figure (6) depicts the overall conversion ratio of the two-bed AD cycle for both Air-conditioning and desalting applications with assorted hot water inlet and chilled water inlet temperatures. The results show that overall conversion of the Adsorption cycle decreases with increasing hot water temperature. The overall conversion ratio of the Adsorption cycle can be as high as 1.5 for lower regeneration temperature 65°C. The results show that the adsorption cycles can operate with high efficiency using solar energy. The unique advantage of coupling the AD cycle to a solar hot water plant is that there is no risk of crystallization which is a major problem faced in most of the AB plants such as the Libr-water chillers.

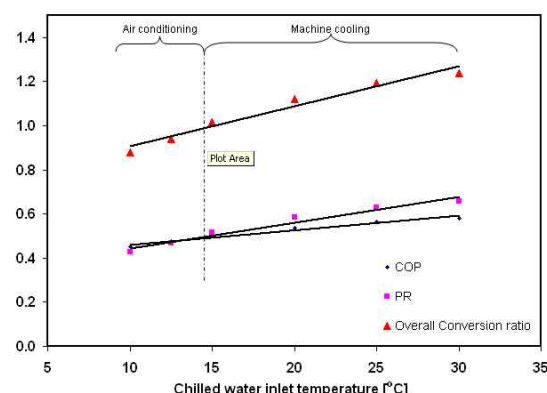


Figure-3 The performance of the two-bed adsorption cycle

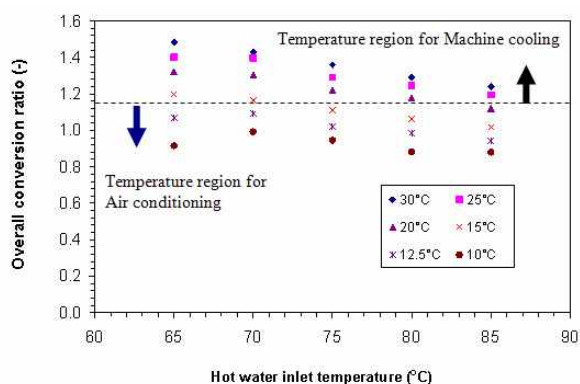


Figure-6 Overall conversion ratio for different heat sources

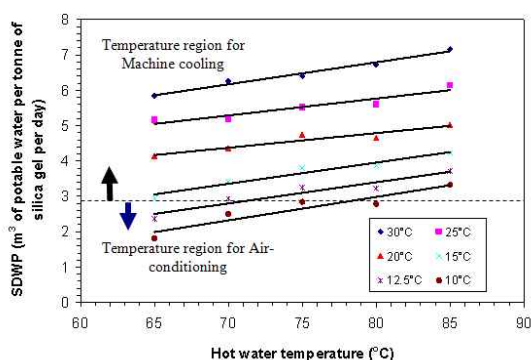


Figure-4 SDWP of the two-bed adsorption plant for different heat source temperatures

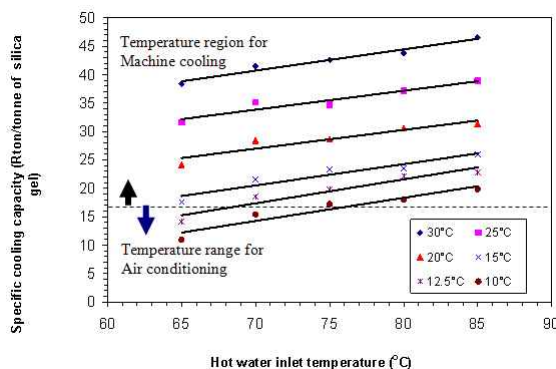


Figure-5 Specific cooling capacity of the two-bed adsorption plant for different heat source temperatures

4. CONCLUSIONS

The performance of the solar-powered, two-bed adsorption cycle, producing both the cooling and desalting effects, has been experimentally investigated. When operated by a 65°C heat source, the AD cycle is capable of producing the SDWP and SCC of 2.5 m³ of potable water and 16 Rton of cooling (at 9°C) per tonne of silica gel per day respectively. However, when operated as a desalination unit, the cycle is capable of producing up to 6 m³ of potable water and a high 38 Rton for cooling (at 23°C) per tonne of silica gel per day, and the overall conversion ratio of the plant is 1.5 (at maximum condition). It should be mentioned that the cycle, when configured as a desalination mode, is capable of producing high grade water at a specific energy consumption of only 1.5 kWh/m³, which is the parasitic electricity used to power the three pumps in the heat source, chilled water and cooling water circuits. This benchmark of 1.5 kWh/m³ is deemed to be the best ever recorded by an experimental desalination plant anywhere in the world.

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