Thermodynamic modelling of hybrid adsorption system

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Abstract. The ability of adsorption based desalination system to cogenerate distilled fresh water and cooling effect provides an increasing attention in the field of cooling and desalination technologies. Eco-friendly adsorption cycles are capable of producing the hybrid effects (desalination& cooling) with low temperature heat source having temperature range from 50°C to 90°C. Adsorption characteristics (isotherm) of silica gel-water and zeolite-water have been presented in this study. Dubinin-Astakov (D-A) and Dubinin-Radushkevich (D-R) adsorption equilibrium equations are used for comparing the performance of silica gel and zeolite. Results show that maximum water production rate in the case of silica gel adsorbent is stabilised at lower regeneration temperature, ranges from 80°C to 120°C, whereas in zeolite it is in the higher range from 150°C to 250°C. Maximum COP of the system obtained is 0.65 for silica gel-water at a regeneration temperature of 80°C whereas as 0.35 for zeolite–water at 110°C. Study concluded that the performance of the system using silica gel-water adsorbent is comparatively better than zeolite-water pair.

Keywords - Adsorption, desalination, cooling, silica gel, zeolite

1. Introduction

Today the water crisis affects billions around the world. Clean fresh water is an essential ingredient for a healthy human life. There is the same amount of fresh water on earth as there always has been, but the population has been exploded, leaving the world’s water resources in crisis. In this scenario the need to tap potable drinking water is a great challenge. One of the practical solutions to overcome this crisis is desalination which aims in separating dissolved salts and other minerals from brackish water. The process of desalination can be done in various ways, like thermally activated systems or pressure activated systems or chemically activated systems. Multi stage flash (MSF), multi effect desalination (MED), solar distillation, reverse osmosis and electro dialysis[1] are the major desalination methods. But difficulties of maintenance, relatively high energy consumption and high cost are became the major shortcoming of these technologies. Therefore there is a need for low energy consumption desalination with low running cost. One such method is adsorption desalination [2,3] process capable of producing potable water and cooling effect.

Adsorption desalination system is an emerging process of thermal desalination capable of utilizing low grade heat easily obtainable from solar collectors or waste heat or biomass energy. Moreover it has a range of advantages including; the use of low temperature heat (waste heat, biomass, solar), very few moving parts leading to reduced maintenance cost, fouling & corrosion is reduced due
to low operating temperatures, and confinement of brackish water to a fraction of the total system. Adsorption desalination is a thermodynamic cycle that consists of Evaporation/Adsorption and Desorption/Condensation processes where the adsorbent material adsorbs pure water from the boiling sea water in the evaporator. This evaporation process is maintained by the adsorbing action of the adsorbent. The desorbed water vapour is condensed in the condenser to produce potable water which is collected and pumped out of the condenser. Cooling effect is produced during the evaporation process which occurs at temperature ranging from 10°C to 30°C. As the adsorption desalination cycle utilizes only low temperature waste heat or solar energy [4-5], it has the potential to be the most efficient method of converting the sea or brackish water to potable water as the only parasitic electric power needed are those used for powering the valves and water pumps[6]. The paper first outlines about the working principle of single bed adsorption desalination system. The mathematical modelling of adsorbent is also presented in this study. The effect of regeneration temperature and cooling water temperature on water production, COP and energy requirement for water production is also investigated.

2. Single bed adsorption desalination cycle – Working principle

![Figure 1: Single bed adsorption cooling and desalination system](image)

Adsorption cycle utilizes adsorption assisted evaporation and desorption activated condensation processes to produce cooling in evaporator and fresh water at the condenser. These useful effects are achieved in an adsorption system with the help of low temperature heat source that can be extracted from industrial waste heat or solar energy [7-9]. Schematic diagram of single bed adsorption cooling and desalination system is shown in figure 1. Evaporator, adsorbent bed and condenser are the main parts of a single bed adsorption system. Firstly the saline or brackish water is charged into the evaporator. In the evaporator, the water is flash evaporated at the low pressure. Ambient water which
is circulated in the evaporator be used for cooling purposes. The concentrated brine is discharged periodically from the evaporator to regulate the sea water level and salt concentration. When the valve between the adsorbent bed and the evaporator is opened, water evaporates and travels from the evaporator into adsorbent bed where it is adsorbed by the silica gel. During adsorption process, the heat of adsorption is removed by the cooling water, circulating in adsorbent bed heat exchangers. The adsorption continues until the adsorbent saturated with water vapour and closing the valve between the adsorbent bed and evaporator. The saturated silica gel is regenerated using hot water coming from the solar collector and this process is known as desorption process. The valve between the adsorbent bed and condenser is in open position, the hot water drives off the regenerated water vapour to the condenser. In the condenser, the heat of condensation is rejected into cooling water circulating through the condenser and the condensate is collected as pure water. Then the desalinated water is collected in the collection tank. This thermodynamic cyclic process is represented in figure 2.

![Diagram of adsorption desalination cycle](image)

**Figure 2:** Adsorption desalination cycle

- Process 1→2 – Isosteric heating
- Process 2→3 – Desorption (Isobaric heating)
- Process 3→4 - Isosteric Cooling
- Process 4→1 – Adsorption (Isobaric cooling)

The P–T–X diagram on lnP vs. −1/T coordinates (where X is the amount of adsorbate adsorbed by the adsorbent at equilibrium conditions, kg of adsorbate/kg of adsorbent), is a convenient way to describe the thermodynamic cycle of an adsorption desalination system. Where X_{max} and X_{min} represent maximum and minimum amount of water adsorbed. T_{gen} and T_{ads} are the temperature at which desorption and adsorption process begins.

3. **Mathematical modelling of single bed adsorption desalination and cooling system**
Mathematical modelling is based on adsorption isotherm and energy balance of components of the system. To simplify the models, the following assumptions are made:

1. The temperature is uniform across the adsorbent (silica gel) layer.
2. Adsorption of the water vapour by the silica gel inside the adsorber bed is uniform.
3. The Adsorbent and the adsorbate gas phases are in equilibrium condition.
4. Heat loses from the adsorbent bed, evaporator, condenser are neglected.
5. The specific heat capacities of water, adsorbent, metallic wall are constant.

Adsorption isotherms represent the amount of adsorbate that can be adsorbed per unit mass of dry material at a specific vapor pressure. These are helpful to assess the maximum amount that can be adsorbed/desorbed under certain conditions. Different isotherm models [10] have been developed for predicting the adsorbent material performance. In this model two different adsorbent are used silica gel and zeolite. The uptake of water vapour by the silica gel at a temperature (T) and pressure (P) can be estimated using Dubinin–Astakhov (D-A) [11,12] equation as

\[ X = X_0 \exp\left(-\frac{RT}{E} \ln \left( \frac{p}{p_0} \right)^n \right) \]  

(1)

Where \( X_0 \) (kg/kg of adsorbent) is the maximum adsorbed amount, \( E \) (kJ/mole) is the characteristic energy and \( n \) is the D-A constant, \( R \) (J/mol.K) is gas constant, \( P \) (Pa) is the adsorption pressure and \( P_0 \) is the equilibrium pressure. The unknown values in Dubinin-Astakhov equation for type RD silica gel are available in literature[12-14]. The values of parameters used are given in Table 1. The mathematical modelling equations of the adsorption desalination cycle are solved using MATLAB 2015.

| Parameter | Value          |
|-----------|----------------|
| \( X_0 \) | 0.592 (kg/kg of silica gel) |
| \( E \)  | 3.105 (kJ/mole)    |
| \( n \)  | 1.1              |
| \( R \)  | 8.314 (J/mol. K)  |

Table 1. Properties of silica gel

The adsorption behaviour of the zeolite–water pair for adsorption and desorption processes is modelled by Dubinin-Radushkevich Isotherm [13].

\[ X = X_0 \exp \left[ -K \ln \left( \frac{T}{T_{sat}} \right)^n \left( \frac{T}{T_{sat}} - 1 \right) \right] \]

(2)
Table 2. Properties of zeolite

| Parameter | Value             |
|-----------|-------------------|
| $\bar{X}_0$ | 0.124 (kg/kg of zeolite) |
| $K$       | 5.012             |
| $n$       | 1.4               |

Energy balance is applied for all the processes of the adsorption desalination cycle for finding out COP and energy requirement.

$$Q_{heating} = Q_{1-2} + Q_{2-3}$$  \hspace{1cm} (3)

Where $Q_{1-2}$ is the total sensible heat input during this process 1-2 and $Q_{2-3}$ is the heat of desorption.

Energy required per kilogram of water produced is given by:

$$E = \frac{Q_{heating}}{n_{water}}$$  \hspace{1cm} (4)

The cold production takes place in the evaporator is given by:

$$Q_{ev} = n_{bed} (X_1 - X_4) h_{fg,cw}$$  \hspace{1cm} (5)

Where $h_{fg,cw}$ is the latent heat of vaporization of saline water at the evaporator temperature.

Coefficient of Performance,

$$COP = \frac{Q_{ev}}{Q_{1-2} + Q_{2-3}}$$  \hspace{1cm} (6)

4. Results and Discussion

Performance of single bed adsorption system has been compared for two different adsorbents namely silica gel-water and zeolite-water. Using adsorption equilibrium isotherms and energy balance equation the system has been thermodynamically modelled for two adsorbents. Amount of water produced, COP of the system and energy required for desorption and adsorption have been discussed and presented.

4.1. Effect of regeneration temperature on water production

Figure 3 represents the variation of amount of water production during the cycle with respect to the varying inlet hot water temperature (regeneration temperature) which is circulated through the bed. Amount of water produced using silica gel and zeolite as adsorbent are presented in figure 3.(a)&(b). In both cases the water production rate increases with increase in bed temperature and gradually flat out at higher temperatures. As hot water inlet temperature increases desorption also increases and hence the quantity of water desorbed is also increased and reaches a maximum value when adsorbed quantity completely removed from the adsorbent. It is clear from these comparison that the heat source for desorption process using zeolite as adsorbent must have comparatively higher temperature range.
Figure 3. Effect of regeneration temperature on water production for silica gel and zeolite

4.2 Effect of regeneration temperature on energy required per kg of water production

Variation of energy required per kg of water produced with hot water temperature is presented in figure 4. Energy required per kg of water produced is the ratio between the heating requirement of the system and the amount of water produced during a cycle. The energy consumption per kg of water production firstly decreases up to a minimum value and then increases. The decreasing tendency is due to the increased rate of water production. In the case of silica gel the energy consumption per kg of water production reduces to its minimum value at 80°C while in the case of zeolite is 150°C.
4.3 Effect of regeneration temperature on COP

Figure 5 represents the variation of COP based on regeneration temperature. There is a certain temperature at which there exists a maximum COP for a fixed cooling water and condenser temperature. COP increases rapidly with the bed temperature and attains a maximum value then decreases slowly. It is because initially, the increase of refrigeration effect is more than the increase of heat input. COP is maximum at 80°C and 150°C in the case of silica gel and zeolite respectively. After these temperatures the heat input is very high, therefore COP decreases.

4.4 Effect of varying cooling water temperature on water production, energy required and COP.

Figure 6. Effect of varying cooling water temperature on water production for silica gel and zeolite
The effect of cooling water temperature on water production is presented in figure 6. When cooling water temperature is low, the adsorbent bed temperature is also low and the adsorbent will adsorb more amount of water at low temperature. It will increase the amount of water production during the desorption stage. The increased adsorbed amount of water vapour at low adsorbent temperature increases the refrigeration effect. Due to decrease in cooling water temperature, more water production occurs and hence energy consumption per kg of water production decreases.

For validating the result, energy required for water production with hot water temperature is compared with result obtained by Wu et al. [14], who had conducted a thermodynamic analysis on two bed adsorption system using silica gel. As can be observed from figure 7, the simulated result of present study agree well with reported data. Both study indicates that the energy consumption per kg of water firstly decreases to a minimum value and then increases. The decreasing tendency is due to increased rate of water production.

5. Conclusion

In this study working principle of single bed adsorption desalination system is described and a mathematical model is developed using Dubinin-ashtakov isotherm. The performance characteristics of two working pair namely silica gel-water and zeolite-water are discussed. Results show silica gel-water pair have better adsorption characters and zeolite-water pair requires comparatively high temperature heat source for stable desorption process. The obtained simulation results show that the hot water inlet temperature of the adsorbent and cooling water temperature have an impact on the water production, energy consumption and COP of the system. The better performance of the system can be obtained for low cooling water temperature and high hot water inlet temperatures of the adsorbent bed. From the study it can be concluded that silica gel is a better performer than zeolite for this hybrid system.
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