Modeling and Performance Prediction of an Adsorption Cooling System with Single Bed

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Abstract- This article presents a mathematical model for simulating the thermal performance of a single bed zeolite-water adsorption cooling system. A set of energy balance equations for the system components have been solved using the Engineering Equation Solver (EES) program. An experimental test loop has been installed to prove the technical visibility of the system and validate the model. The variations in the temperature of the adsorption bed, condenser, and evaporator were investigated. The system coefficient of performance (COP) varied with the mass concentration ratio of the water vapor. The optimum COP reached a value of 0.39 at a minimum and maximum adsorbate concentration ratio of about 0.077 and 0.2, respectively. The maximum COP was achieved at a heating temperature of about 170 ºC. The results of the model proved an acceptable compatibility with the experimental results thus the model can be considered as a valuable tool for researchers and engineers to design and simulate the performance of the adsorption cooling system.

Keywords Cooling system; Modelling; Zeolite-water; Adsorption system; Validation.

Nomenclature			
A	surface area (m^2)	x	instantaneous concentration (kg_w/kg_{ad})
C_z	specific heat of zeolite (kJ/kg K)	**Subscript**	
C_{pw}	specific heat of water (kJ/kg K)	ad,m	adsorbent bed metal
ΔH_{ad}	adsorption heat (kJ/kg)	ad	Adsorbent
ΔH_v	latent heat of evaporation (kJ/kg)	b	Bed
m	mass of zeolite (kg)	e	evaporator
$\dot{m}$	Mass flow rate (kg/s)	w	Water
$\dot{Q}$	heat transfer rate (kW)	wv	water vapor
T	temperature (°C)	Z	Zeolite
U	overall heat transfer coefficient (W/m^2 K)	chw	chilled water

1. Introduction

Using vapor compression cycles for cooling may cause some harmful effects as it utilizes the non-natural working fluids. The absorption and adsorption cooling systems have received a lot of attention and developed amazingly in recent years [1, 2]. Several types of the adsorption systems have been constructed and investigated. The selection of the appropriate adsorbent and refrigerant pair is considered as an important step to design and manufacture the proper system that suits the application. Several pairs of the adsorbent and refrigerant are available and possess certain specifications that affect the performance. The best choice depends on the required specifications of the cooling system, the properties of the adsorbent and adsorbate materials, the heating fluid temperature, the costs, availability and its effect on the environment. The Zeolite-water solar refrigeration system is less expensive than other traditional methods and it is more suitable for remote and rural areas. This system is considered as one of the new technology for using solar energy in the refrigeration system that will be widely introduced to the industrial sector. The natural Zeolite adsorbs a large volume of water vapor at a low temperature and desorbs the same quantity of vapor through heating [3]. It can be considered as an excellent adsorbent material to be utilized in adsorption cooling systems. It was also observed by Exell et al. [4] that, the volume of adsorbed water by zeolite depends mainly on the temperature and less on pressure. A zeolite-water cooling system powered by solar energy was fabricated and tested by Tchernev [5]. The results exposed that with a solar irradiance of 6.0 kWh/m^2, the cooling produced was 900 Wh/m^2. Two different adsorption refrigeration systems with two concepts of cooling the condenser were tested with Zeolite-water couple [6]. The solar system that used the water-cooled condenser was the best where the COP varied over the range of 0.04 to 0.14. Grenier et al. [7] investigate a cold store where the solar energy used as a heating source for the adsorption cooling system with zeolite–water as a working pair. The temperature of the evaporator reached 2.5 ºC, at a COP of 0.086. An intermittent zeolite–water adsorption system powered by solar energy was investigated and tested by Phillip et al. [8]. They fabricated an adsorption system heated by a solar collector with a flat plate. The results indicated that, during the daytime, the maximum cycle temperature was 130 ºC and nearly 3% of desorption was achieved. While through the night, an evaporator temperature of about -8 ºC was achieved. The water can be considered as the best refrigerant due to its availability, its high latent heat of vaporization, and its safety. The water can't be used as a refrigerant in systems with temperature under zero due to its freezing point. A design for constructing and examined of a zeolite-water adsorption cooling system was provided by Amber Ityona [9]. The generator drives the refrigerant around the system through a condenser and an evaporator to complete the refrigeration system. Designing of the adsorbent bed is an important and difficult point in the adsorbent/adsorbate part of the cooling systems since it requires a special design for controlling mass and heat transfer between the refrigerant and the adsorbent pairs. Anyanwu [10] used a zeolite-water in a flat plate solar collector and it is found that the COP reached about 0.3. Based on the thermodynamic design and procedure, Saravanan and Rathnasamy [11] analyzed numerically the effects of operating conditions (mass concentration ratio, temperature, and refrigerating effects) on the COP of adsorption refrigeration cycle. The adsorption cycle can operate more efficiently at specified maximum and minimum concentration ratios. Anyanwu [12] reviewed the solar adsorption applications. He concluded that the Zeolite-water was the appropriate working couple for adsorption refrigeration where the maximum COP was 0.3. The cylindrical bed was proposed in many experimental and numerical studies [13, 19]. Other researchers are interested in improving the thermal performance of the bed by proposed a finned-bed in their studies [20, 23]. The cylindrical geometry divided into two categories according to the mechanism of heating, i.e. center-heated generator and external-heated generator. Tubreoumya et al. [24] developed a model to simulate the adsorption process and predict the adsorbate rate of the zeolite-water pair. The results provided encouraging indicators for the development and improvement of the solar adsorption cooling system. Suleiman et al. [25] applied a simulated model of flat plate solar collector using AC-methanol pair in air conditioning application, which produced refrigeration effect, COP, and heating efficiency of 4815 kJ, 0.24, 0.46, respectively and achieved a cold room temperature of about 1 ºC. The experimental determination of the adsorption capacity of synthetic Zeolite A water pair has been presented by Amber et al. [26]. The maximum adsorption capacity of water in the synthetic Zeolite A (X_{max}) was found to be nearly 26% and is dependent on the water vapor pressure at high Zeolite temperatures. The amount of water adsorbed however increased with increasing water vapor pressure and decreasing Zeolite temperature

In the present work, a synthetic zeolite that has been manufactured from commercial raw materials in Egypt was used due to their uniformly distributed Nano-pores with the same size at the molecular level. The implementations of single bed adsorption system depend on a zeolite-water couple still a major issue for developing the adsorption techniques in the solar cooling market of Egypt. A simulation program was developed to simulate the thermal performance of an adsorption cooling unit using Zeolite-water couple. Moreover, the transient simulation of adsorption and desorption processes was used to investigate the performance of a small-scale prototype of the single bed adsorption refrigeration system. It was used for a cold store located under environmental conditions of Egypt. The equations of the heat and mass transfer for the bed, condenser, and evaporator are solved simultaneously using the engineering equation solver (EES) to determine the temperature profiles and the mass concentration ratio of the water vapor inside the zeolite granular. The effect of the minimum and maximum adsorbent concentration ratio on the COP was investigated. Also, the effect of the operating parameters on the COP was investigated. An experimental test facility was installed to investigate the thermal performance of the small scale adsorption unit. The results of the numerical model were validated with experimental measurements. The results were used to provide information for designing and estimating the adsorption cooling system performance for the given period. The present simulation and experimental results can be considered and used to support the adsorption system designers with the optimum operating condition for more efficient adsorption refrigeration system.

2. Mathematical Model

The present study presents a transient simulation model of an indoor adsorptive refrigeration system with a single adsorption/desorption bed. The adsorption cooling apparatus contains three major elements: adsorber bed, evaporator, and condenser. The adsorber unit is supplied with heating and cooling oil circuits working alternatively during desorption and adsorption processes, respectively. A transient simulation of the single bed zeolite-water adsorption refrigerant system is investigated. The adsorber bed is fabricated as a shell tube. The shell tube contains five circular tubes where the zeolite granules were placed on the external surface of each tube, a metallic net was placed around the zeolite from the outside as shown in Fig. 1. The bed is heated by a hot oil flow inside the five tubes. The temperature gradients in axial and radial directions through the bed are generally small and are neglected in this analysis. Analysis of the simulation results was performed to study the temperature profile and the mass concentration ratio of the water vapor in the adsorbent material with the progress of time for the three main elements forming the adsorption apparatus.

The governing equations are developed for the adsorbent bed, condenser, and evaporator. The mathematical modeling of the adsorbent bed includes the heat energy balance for the heating and cooling fluids, the metal tubes and the adsorbent bed. The heat of the adsorption (ΔH_{ad}) through the bed is taken into consideration. The developed model assumed that the adsorbent bed contains particles of Zeolite with a small size, and the bed porosity is nearly uniform. In addition, the local equilibrium for both heat and mass transfer is maintained between the solid, liquid and gas phases. The pressure inside the bed is assumed to be uniform, and the gas behavior is an ideal. The heat losses of the tube are negligible.

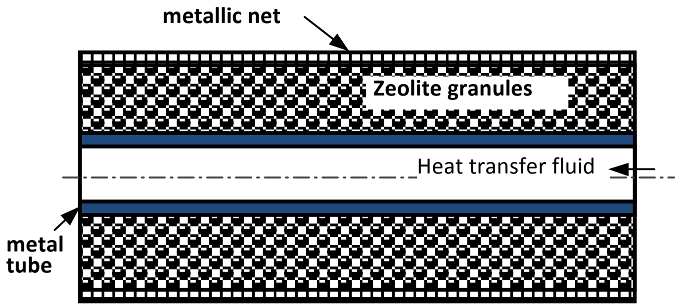


Fig. 1. The new design of the adsorber tube with the surrounding zeolite.

The non-equilibrium adsorption equation that used in the simulation is expressed as:

$$\frac{dx}{dt} = k_1 \exp\left(-k_2/T_z\right).\left(x^* - x\right) \tag{1}$$

The coefficients for zeolite-water k_1 and k_2 are given values of 0.019 and 906, respectively [27]. T_z is the zeolite temperature. The equilibrium uptake x^* of the zeolite-water pair is estimated using the equation developed by Sakada [28] which is expressed as follows:

$$x^* = 0.331 \exp\left[-2.99\left(\frac{T_z}{T_s} - 1\right)^2\right] \tag{2}$$

Where x and x* are instantaneous mass fraction uptake and the equilibrium uptake, respectively. T_s is the vapor adsorbent saturation temperature. Through the first period of the process, the temperatures of the bed, tubes, and fluid were assumed to be equal.

2.1. Governing Equation

In the desorption process, the heated fluid heats the adsorption bed to start the water vapor desorption from the Zeolite pores flowing into the condenser through connecting tube. The exit water vapor is condensed in the condenser and flow as a liquid to the evaporator by gravity. The equations of the energy balance for the adsorber bed, condenser, and the evaporator can be expressed as follows:

2.1.1. Bed energy balance

During the adsorption and desorption process, the equation of the energy balance for the bed is expressed as:

$$\begin{aligned} & m_z\left(C_z + xCp_w\right)\frac{dT_z}{dt} + m_{ad,m}C_{ad,m}\frac{dT_{ad,m}}{dt} = \\ & \delta\, m_z \Delta H_{ad}\frac{dx}{dt} + \delta\, m_z\left(1-\varphi\right)Cp_{wv}\left(T_e - T_z\right)\frac{dx}{dt} \\ & + \dot{m}_j Cp_j\left(T_{J,in} - T_{J,out}\right) \end{aligned} \tag{3}$$

Where δ =1 through adsorption and process operation and δ =0 through the change of the adsorption to desorption process and vice versa. The symbol ϕ equal 0 for adsorption and 1 for desorption. The symbol j defines the cooling and heating fluid. The outlet temperature of the heating source is modeled by the following equation:

$$\frac{T_{J,out} - T_z}{T_{J,in} - T_z} = \exp\left(-\frac{UA_b}{\dot{m}_w Cp_w}\right) \tag{4}$$

2.1.2. Condenser Energy Balance

The refrigerant vapor flowing from the adsorber bed during the desorption process is condensed in a water-cooled condenser, supplying the condensed liquid to the evaporator. The equation of the energy balance for the condenser is expressed as:

$$\begin{aligned} m_c C_{cu}\frac{dT_c}{dt} = {} & m_{wv}Cp_{wv}\frac{dx_{de}}{dt}\left(T_c - T_z\right) - \\ & m_z\frac{dx_{de}}{dt}\Delta H_v + \dot{m}_{cw}Cp_w\left(T_{cw,in} - T_{cw,out}\right) \end{aligned} \tag{5}$$

2.1.3. Evaporator Energy Balance

The equation of the energy balance for the evaporator is expressed as:

$$\begin{aligned} & \left(m_e c_{cu} + M_w(t)Cp_w\right)\frac{dT_e}{dt} = -m_z\frac{dx_{ad}}{dt}\Delta H_v \\ & -m_z\frac{dx_{de}}{dt}Cp_w\left(T_c - T_e\right) + \dot{m}_{chw}Cp_w\left(T_{chw,in} - T_{chw,out}\right) \end{aligned} \tag{6}$$

Where m_w is the amount of liquid water inside the evaporator at time t and is expressed as follows:

$$m_w(t) = m_w - m_z x_{ad} - m_z dx_{des} \tag{7}$$

The values of input parameters that used in the simulation program are tabulated in Table 1. The latent heat and the thermo-physical properties of adsorbate were calculated by the database of the Engineering Equation Solver (EES) program.

2.2. Basic Thermodynamic Cycle

The basic adsorption cooling cycle contains three main components: an adsorber, containing the adsorbent material (such as zeolite), a condenser for condensing the vapor of the refrigerant (such as water) and an evaporator containing the refrigerant fluid. The adsorption cycle works by moving the adsorbate between the adsorber, the condenser, and the evaporator due to the pressure difference. The simple adsorption cycle contains four processes which are isosteric heating process indicated by (A-B), isobaric desorption process indicated by (B-C), isosteric cooling process indicated by (C-D) and isobaric adsorption process indicated by (D-A) as shown in Fig. 2.

The adsorption unit is heated through the steps A-B and B-C while the cooling effect comes only in step D-A. Consequently, the basic cycle runs intermittently. In case of using the direct solar-irradiance as a heating source, the one cycle runs for a one complete day. Consequently, the COP of the adsorption cycle can be determined as:

$$COP = \frac{Q_{D-A}}{Q_{A-B} + Q_{B-C}} \tag{8}$$

Table 1. Samples of the input parameters for the simulation program

Input parameter	Value	Unit
Mass of the adsorbent bed, m_{ad}	4.23	kg
Mass of the condenser, m_c	1.9	kg
Mass of the evaporator, m_e	2.0	kg
Mass of zeolite, m_z	1.25	kg
Mass of water, M_w	0.3125	kg
Latent heat of evaporation, ΔH_v	2500	kJ/kg
Desorption heat, ΔH_{ad}	2800	kJ/kg
Flow rate of the heating oil, $\dot{m}_j$	0.09	kg/s
Flow rate of the cooling water, $\dot{m}_{cw}$	0.1	kg/s
Flow rate of the chilled water, $\dot{m}_{chw}$	0.01	kg/s
The hot oil inlet temperature	180	^oC
The chilled water inlet temperature	25	^oC
The cooling water inlet temperature	33	^oC

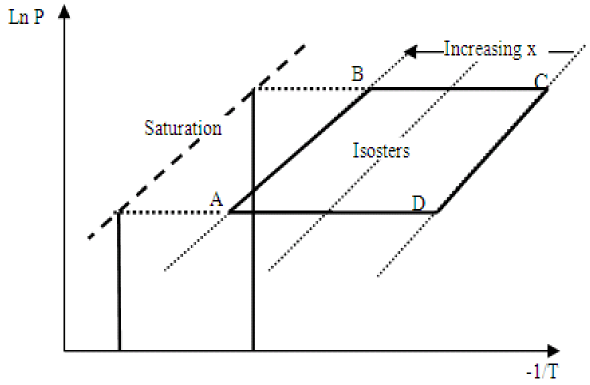


Fig. 2. The P_T_X of the adsorption cycle in a Clapeyron diagram.

3. Simulation Results and Discussion

The heat balance equations of the bed, evaporator, and the condenser are solved using the EES program. The mathematical model presents the dynamic development of temperature and mass concentration ratio during the adsorption and desorption processes. The maximum inlet temperatures of the heating and cooling fluids are 180 ºC and 32 ºC, respectively. The numerical results of the simulation were presented versus time for the adsorption and desorption cycle. The output results of the simulation program were validated with the present experimental results.

The variations of the adsorbent concentration ratio during desorption and adsorption processes were presented versus time as shown in Fig. 3. It is found that the quantity of adsorbed water into the zeolite is desorbed through the desorption process where the water concentration ratio decreased from 0.30 to 0.094 through 1277 seconds. The hot inlet temperature of HTF is maintained at 170 ºC which is the appropriate temperature for Zeolite activation. The sharp change in the equilibrium uptake occurs at the end of the desorption process where the adsorption process starts. The desorption and adsorption processes time are adjusted to be 2693 s (1277 s for heating and 1416 s for cooling) and the switching period is adjusted to be 30 seconds.

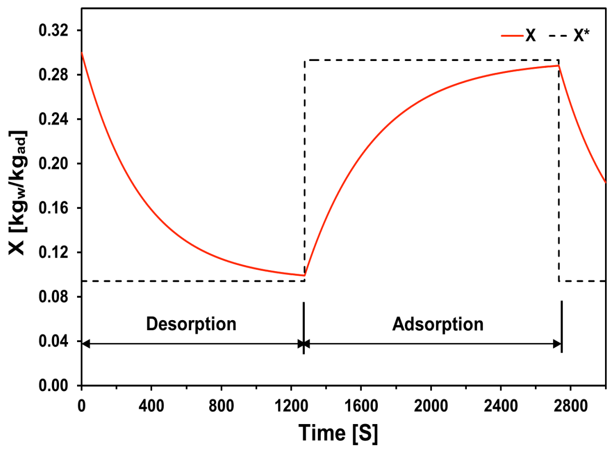


Fig. 3. The instantaneous and equilibrium water uptake during the adsorption and desorption processes.

The variations of the bed, condenser, and evaporator temperature during the adsorption and desorption processes for the cooling system is shown in Fig. 4. Through the desorption process, the temperature of the bed reaches its maximum value at 164 ºC after 1277 second, and the evaporator temperature remains constant at a value of 25 ºC where the adsorption process has not yet started. While in the adsorption process, the bed temperature begins to decrease to reach a minimum value of about 49.7 ºC. Through the first period of the adsorption process, a sharp decreasing in the evaporator temperature was observed where the temperature reaches its minimum value at 14.9 ºC, then the evaporator temperature increases gradually to reach a constant value and remain at this value through the desorption process. Also, the condenser temperature increases with a relatively small value at the first period of the desorption process and followed by a decrease until approaching the inlet cooling water temperature, then the temperature remains constant through the adsorption process.

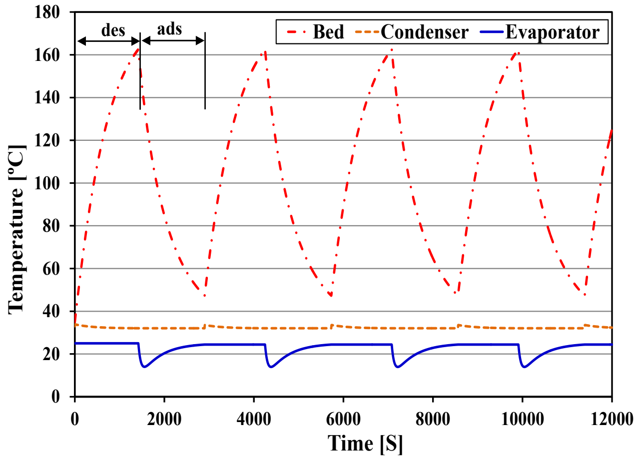


Fig. 4. The bed, condenser, and evaporator temperature during the adsorption and desorption processes.

The temperature profiles of the cooling and chilled water are presented in Figs. 5 (a) and (b) during the adsorption and desorption processes. Figure 5 (a) shows the cooling water temperature profile for condenser the through the desorption process. During the first period of the desorption process, it is observed that the cooling water temperature difference between the inlet and the outlet of the condenser is about 2.0 ºC. This temperature difference reaches a value of about 0.1 ºC after 1280 s where no more heat can be removed by the condenser at this point. Figure 5 (b) shows the chilled water temperatures profile at the inlet and outlet of the evaporator versus time. From the figure, it can be observed that the temperature of the water coming out of the evaporator decreases very sharply and reaches a minimum value of 14.2 ºC at a duration time of 280 s during adsorption process then the adsorption rate decrease due to the approaching to the saturation state.

The evaporator temperature profile with time is shown in Fig. 6 for different values of adsorbent mass (0.5, 0.75, 1.0, and 1.25 kg). A strong adsorption rate was observed for a large amount of adsorbent then a sudden decrease in the evaporator temperature was observed. The lowest evaporator temperature was reached 6.0 ºC for 1.25 kg of adsorbent in

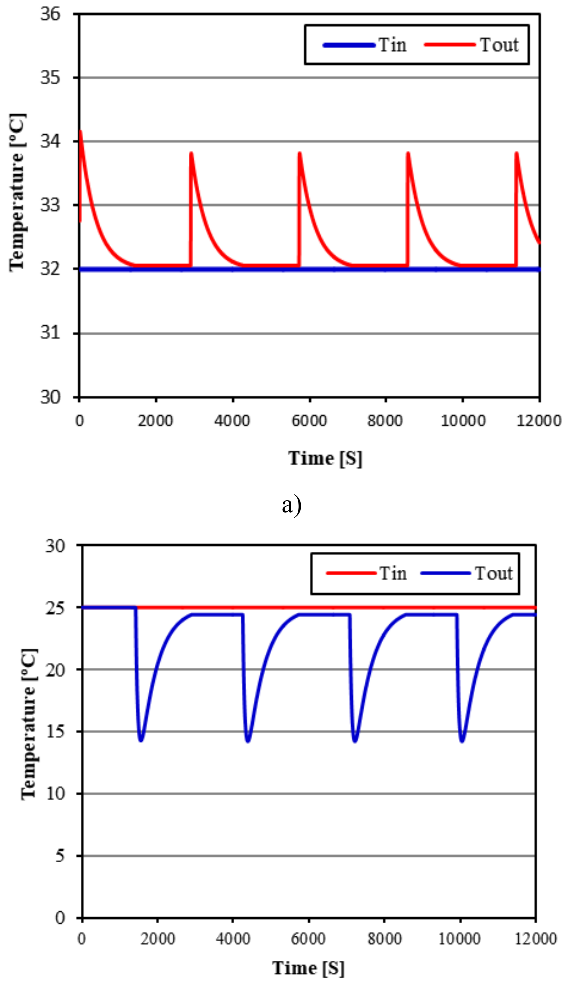


Fig. 5. The inlet and outlet temperatures versus time for (a) the condenser cooling water (b) the evaporator chilled water.

bed. The evaporator temperature decreases to the lowest values in 23.6 minutes then raises up to approach the inlet chilled water temperature.

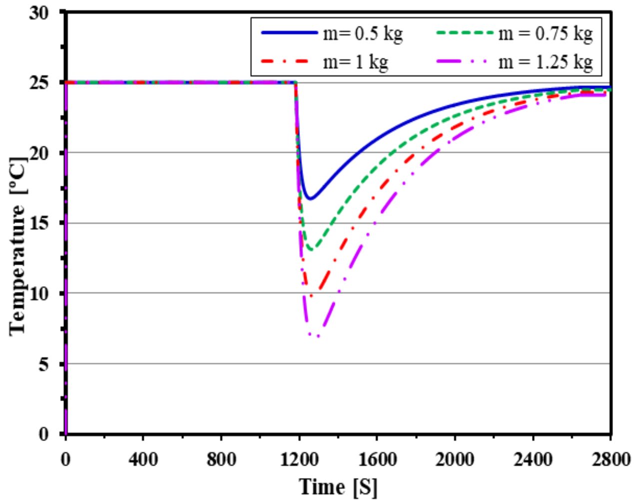
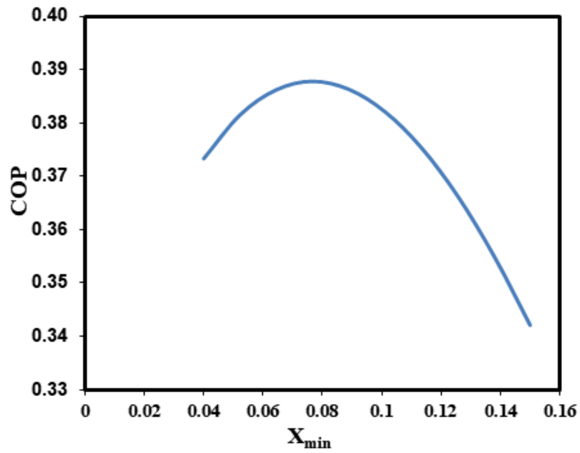
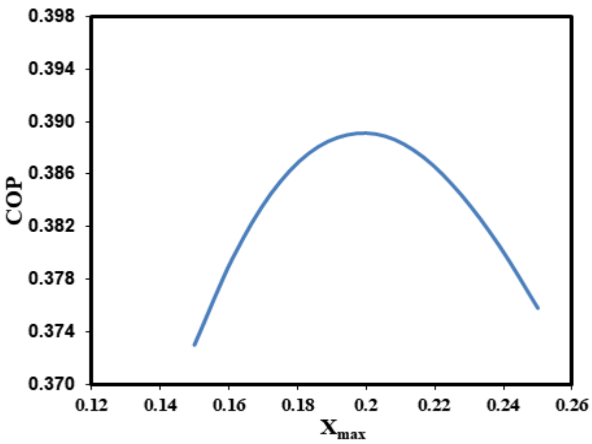


Fig. 6. Effect of the adsorbent mass on the evaporator temperature profile.

Figure 7 (a) illustrates the effect of minimum adsorbate concentration ratio (x_{min}) on the COP of the adsorption refrigeration system. A control valve was located between the adsorbent bed and the condenser to adjust the minimum values of the adsorbate concentration ratio (x_{min}). For decreasing the value of x_{min}, the control valve is opened for long interval time where the isosteric curve in Fig. 2 is moved to the right consequently the period length of the isobaric desorption process increases. Vice versa for increasing the value of x_{min}, the control valve is opened for a short time interval. Hence the isosteric curve in Fig. 2 is moved to the left consequently the period length of the isobaric desorption process decreases. The maximum COP of 0.388 is achieved at a minimum adsorbate concentration ratio of 0.076. Figure 7 (b) presents the effect of maximum adsorbate concentration ratio (x_{max}) on the COP of the adsorption refrigeration system. A control valve was located in the tube connecting the evaporator and the adsorbent bed is used to adjust the maximum values of x_{max} that ranged from 0.15 to 0.25. The maximum value of the COP was of 0.39 at a maximum adsorbate concentration ratio of about 0.2. The results showed that the adsorbate concentration ratio is one of the main factors that affect the thermal performance of the adsorption cooling system.



a)



b)

Fig. 7. Effect of (a) minimum and (b) maximum adsorbate concentration ratio on the COP.

The effect of the generation temperature on the COP of the adsorption system at different evaporator temperatures is presented in Fig. 8. From the figure, it was observed that at T_{evp} of 12 ºC, the COP has an optimum value of 0.4 ºC. Decreeing the evaporator temperature to 8 and 5 ºC leads to decrease of the optimum value of the COP to 0.39 and 0.38, respectively. These results have a significant and important impact in designing and sizing of the adsorbent bed. The maximum COP is always achieved at T_G of about 174 ºC.

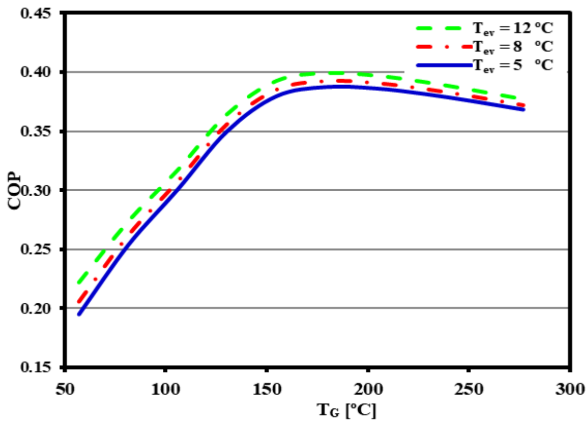


Fig. 8. The COP versus the regeneration temperature at different evaporator temperatures.

4. Experimental Works

A prototype of a single bed adsorption system has been designed and constructed to carry out several experimental tests on this prototype. The adsorption cooling system prototype uses the zeolite–water as a working pair. The prototype was built and tested under different conditions. Figure 9 presents a photograph of the prototype unit with its wooden cold store at the bottom of the picture. A schematic diagram of the single bed adsorption cooling system and its components are illustrated in Fig. 10.

Fig. 9. A Photograph of main components of the adsorption system with the cold store.

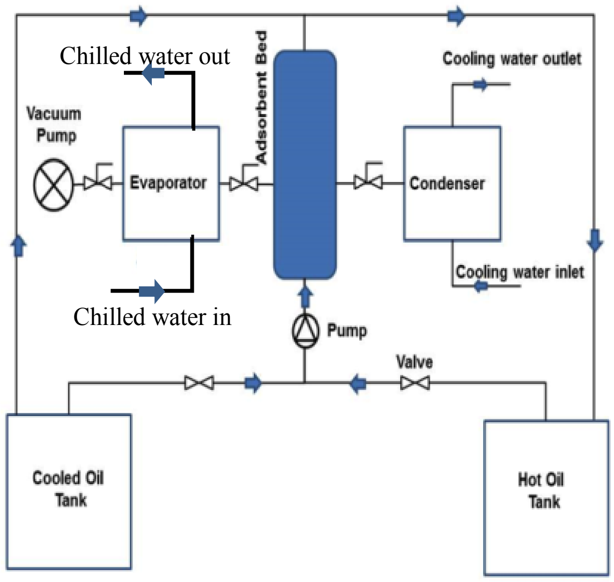


Fig. 10. A Schematic diagram of the single bed zeolite-water adsorption cooling system.

Five compact fin-tubes are used to improve the adsorption/desorption performance. These compact fin-tubes were placed inside a vacuum tight shell tube fabricated from stainless steel. The shell tube is 250 mm in diameter. It is connected to an oil circulator through a manifold to distribute the oil uniformly into each fin-tube as shown in Fig. 11. The adsorbent bed has two manifolds of 200 mm in diameter and five stainless steel tubes of 12.5 mm outside diameter. The tubes have 2 mm in thickness and 0.5 m in length with closely spaced 85 circular-fins of thickness 1.0 mm, 40 mm in outer diameter, and 16 mm in inner diameter. The spaces between the fins of the tubes were filled with about 1.1 kg of spherical zeolite granular (2-3 mm diameter) as shown in Fig. 12. The inlet heat source temperature was set to be 184 ºC and the inlet cooling source temperature was set to be 32 ºC and the designed cooling load effect was 250 W.

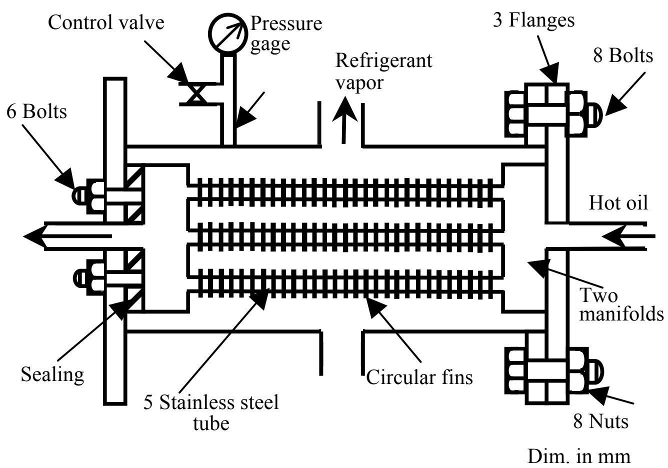


Fig. 11. A Schematic diagram of the new design of the adsorbent bed.

Fig. 12. Finned tubes surrounded by zeolite granules.

4.1. Uncertainty

Several Researcher [29, 30] estimated the uncertainties in the experimental measurements and calculated COP of the adsorption system based on the equation (9) for different individual inputs.

$$U_{COP} = \pm\sqrt{\left[\frac{\partial COP}{\partial Q_{DA}}U_{Q_{DA}}\right]^2 + \left[\frac{\partial COP}{\partial Q_{AB}}U_{Q_{AB}}\right]^2 + \left[\frac{\partial COP}{\partial Q_{BC}}U_{Q_{BC}}\right]^2} \quad (9)$$
$$= \pm 4.5\%$$

The pressure and temperature measurement accuracy is ± 0.4 kPa and ± 0.1 ºC, respectively. The maximum uncertainties for the evaporator capacity (Qr), heat supplied (Q_{BC}&Q_{AB}), and coefficient of performance (COP) are ± 1.4, ± 1.7, and ± 4.5 %, respectively.

5. Experimental Results

The experimental results were used to investigate the temperature of the bed, condenser, and evaporator through the desorption and adsorption process and used also to validate the simulation program results. Figures 13 and 14 illustrate the variation of the inlet and outlet temperature of the adsorber bed and condenser during the desorption process, while Fig. 15 presents the evaporator temperature through the adsorption process. From Fig. 13, it can be seen that the inlet hot oil temperature was kept at 184 ºC and the outlet temperature decreased to 91 ºC at the first seconds of the desorption process and reached nearly the steady state at.

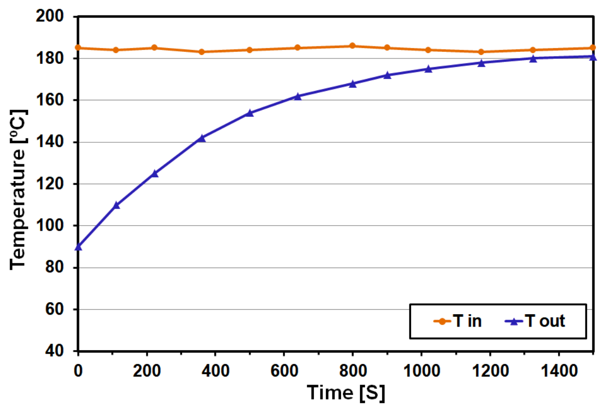


Fig. 13. The inlet and outlet hot oil temperature versus time for the adsorber bed during the desorption process.

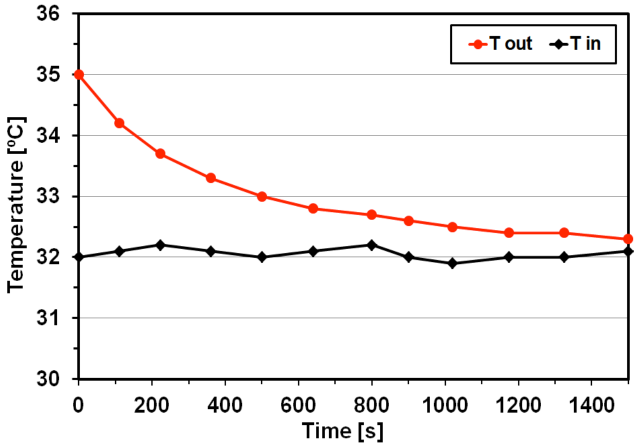


Fig. 14. The variation of the inlet and outlet cooling water temperature for the condenser during the desorption process.

179 ºC after 1495 seconds. While the inlet cooling water temperature for the condenser was kept nearly at 32 ºC, the outlet temperature increased to 35.1 ºC in the first period as shown in Fig. 14, then decreased to reach its steady state at 32.8 ºC after 1315 seconds. Figure 15 presents the inlet and outlet chilled water temperature of the evaporator during the adsorption process. From the figure, it can be observed that the chilled water temperature decreased gradually to reach its minimum value of 8.8 ºC after 1315 seconds.

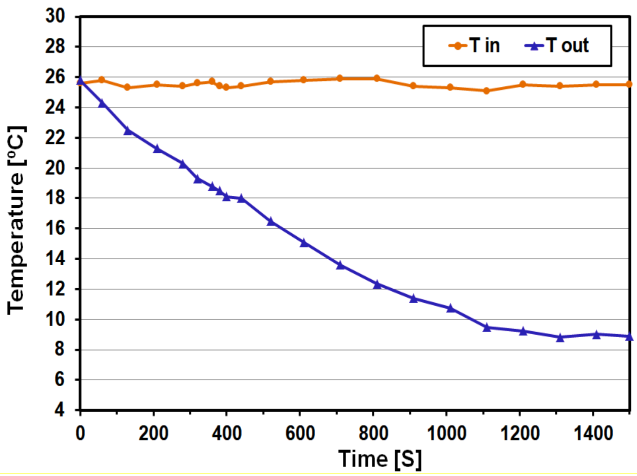


Fig. 15. The variation of the inlet and outlet chilled water temperature for the evaporator during the adsorption process.

The experimental results were used also to validate the simulation results in this section, therefore, the experimental measurements were compared with the theoretical results for validation purpose.

The experimental results for the desorber bed, condenser and the evaporator temperatures development versus time were compared with the simulation results as shown in Figs. 16, 17 and 18, respectively. The experimental measurements of the adsorber bed compared with the theoretical results as shown in Fig. 16. From the Figure, It can be clearly observed that there is a good agreement between the measured and the calculated values. The minimum and the maximum difference between the measured and calculated results are 2.1 to 9.4 ºC (1.3 to 12 %), respectively. The comparison between the measured and the calculated temperature of the

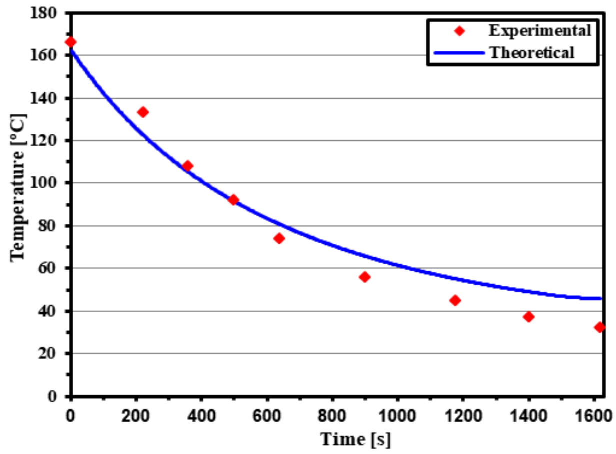


Fig. 16. The temperature of the adsorbent bed versus time through the adsorption process.

condenser was presented in Fig. 17. It can be observed that there is a significant difference between the measured and calculated values of the condenser temperature in the first period, this difference decreases gradually from 0.5 to 0.2 ºC (1.2 to 0.6 %) with the progress of the time. The condenser temperature becomes constant at a value of 32.1 ºC after 1150 seconds. The observed significant difference can be attributed to the small range of the working temperature.

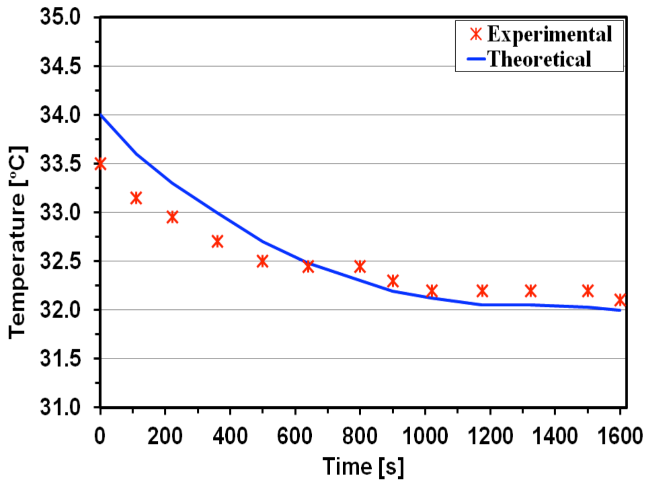


Fig. 17. Experimental and theoretical values of the condenser temperature versus time through the adsorption process.

Figure 18 presents the measured and the calculated values of the evaporator temperature. It can be seen that there is a good agreement between the predicted and measured results through the first 100 s of the adsorption process where the difference ranged from 0.4 to 2 ºC (1.6 to 8.3 %). This deviation can be attributed to the model assumptions of pressure and temperature uniformity. Also, there was a heat loss by conduction from the adsorption bed to the evaporator and condenser through the connecting tubes that was not taken into consideration through the simulation work. Finally, there was a pressure difference between the evaporator and each of the adsorption bed and the condenser that couldn't be neglected in the experimental work. After 100 seconds, the deviation in evaporator temperature ranges from 1 to 3 ºC (6.5 to 13 %).

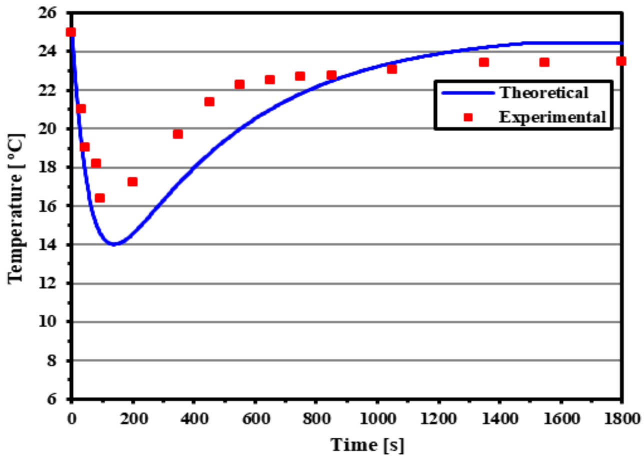


Fig. 18. The evaporator temperature versus time through the adsorption process.

The experimental measurements of the adsorbate concentration X during the adsorption process were compared with the theoretical values of this work and the work of Peng [31] as shown in Fig. 19. From the figure, it can be observed that there is an acceptable consistency between the experimental and the simulation values. The minimum and maximum differences between the measured and calculated values are 3 and 16 %, respectively. The mass concentration of the water vapor in the zeolite granules

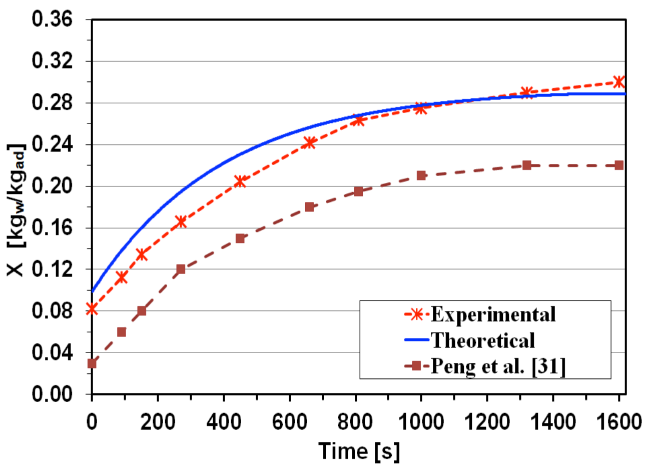


Fig. 19. Variation of the adsorbate concentration versus the time during the adsorption process.

increases gradually with a high rate where the value of X increases from 0.09 to 0.28 kg_w/kg_{ad} through 1025 seconds. Then the rate became slow where the value of X increased to 0.29 kg_w/kg_{ad} through 600 seconds. Although the comparison was carried out in the same working conditions (inlet temperature and mass flow rate), some deviations were found due to some assumptions in the simulation model. It was observed also that the mass concentration values calculated by Peng are less than the values calculated in this work by about 0.05 to 0.06 kg_w/kg_{ad}.

The agreement of the experimental results with the predicted simulation results reveals trust in the simulation results and reveals confidence in the experimental setup and the used measurement techniques.

6. Conclusion

In this work, a novel design of an adsorption cooling system with a single adsorption bed was fabricated and tested using Zeolite-water as a working pair to work as a refrigerator for food preservation in farms and rural areas. The theoretical and experimental results of the novel design of the single bed adsorption cooling system have been presented. The energy balancing equations of the adsorption system have been solved by the EES program. A prototype has been built and tested under different conditions. The experimental results were used to validate the theoretical results. According to the previous results, the conclusions can be summarized as follow:

- The adsorption system performance of the adsorption unit is affected by the concentration ratio of the water vapor in the adsorbent material where the maximum COP of 0.38 and 0.39 have been obtained at X_{min} of 0.077 and at X_{max} of 0.2.
- The maximum COP of 0.4 has been recorded at a heating fluid temperature of 174 ºC and an evaporator temperature of 12 ºC. The regeneration temperature has a significant impact on the design and sizing of the adsorbent bed and the heating source.
- For 1.25 kg of adsorbent material, it was observed that the lowest recorded temperature for the evaporator was 6.0 ºC. While reducing the mass of the adsorbent material to 0.5 kg leads to increase the minimum value of the evaporator temperature to be 13.5 ºC.
- There is a good compatibility between the experimental and theoretical results predicted by the simulation program. Where the percentage difference for the adsorber bed temperature ranged from 1.2 to 13 % and for the condenser temperature ranged from 0.6 to 1.2 %. Therefore, the agreement between the experimental and predicted simulation results reveals confidence in the simulation model, the experimental setup, and the used measurement techniques.

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