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Experimental investigation on adsorption and regeneration behavior of silica gel powder by using solar powered desiccant coated heat exchanger

Abstract

This paper presents the adsorption and regeneration behavior of silica gel powder. For this, an experimental set-up has been purposed. The experimental set-up consists of silica gel coated heat exchanger, evacuated tube solar water heater and cooling tower. The evacuated tube solar water heater is used to generate hot water by using solar energy. This hot water is used to regenerate silica gel. The cooling tower is used to generate cooling water. This cooling water is used during adsorption process. Experimental results demonstrated that silica gel has a good adsorption capacity under northern Indian climatic condition and it can be easily regenerated by the help of solar energy. The adsorption capacity of the silica gel is significantly enhanced by using circulating water.

Keywords: evacuated tube solar water heater, silica gel coated heat exchanger, cooling tower

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Introduction

The desiccant material is a material which has ability to remove moisture from air. According to the physical and chemical properties, there are two types of desiccant material namely solid desiccant material and liquid desiccant material. In this experimental study, solid desiccant material is used. Solid desiccant material adsorbs moisture from air due to water vapour pressure difference. Some common examples of solid desiccant material are silica gel, activated charcoal, molecular sieve and activated alumina. In recent years, numerous researchers have experimentally and theoretically investigated the adsorption and regeneration behavior various solar desiccant materials. Singh et al.1 experimentally investigated the regeneration behavior of silica gel by using multi self regenerator. The required regeneration temperature varied between 42°C to 72°C with a variation in velocity of 0.175 m/s to 0.55 m/s. Techajunta et al.² experimentally and theoretically investigated adsorption and regeneration behavior of solid desiccant material for the application of air conditioning. Ge et al.³ experimentally compared silica gel and polymer coated fin-tube heat exchangers. It was found that the DCHE overcome the adsorption heat during desiccant dehumidification process and achieve good dehumidification performance under given conditions. The SCHE performed better as compared to the polymer coated heat exchanger. Ge et al.4 developed a mathematical model to predict the performance of SCHE cooling system under ARI summer condition and optimized the copper tube external diameter and distance between the fins. Ge et al.⁵ developed a mathematical model of a self-cooled solid desiccant cooling system by the combination of DCHE and regenerative evaporative cooler. The performance of the system was investigated under ARI summer condition and effect of outdoor air condition was analyzed. It was found that cooling power of the system increased by 30% as compared to DCHE cooling system. Yadav et al.⁶ experimentally investigated adsorption and regeneration behavior of different solid desiccant and found that silica gel was the best solid desiccant material among all solid desiccant material. Kumar et al.7 regenerated the silica gel by using parabolic dish and found that silica gel can be easily regenerated by using solar energy. Kumar et al.8 experimentally investigated an air conditioning

system with various solid and composite desiccant material for the application of heating and humidification. It was found that silica gel is the most suitable desiccant material for particular application.

The main objectives of this experimental work are to investigate the regeneration and adsorption behavior of silica gel powder. The experimental setup has been fabricated and installed at NIT Kurukshetra, India [29° 58′ (latitude) North and 76°53′ (longitude) East].

Experimental setup

Figure 1 shows the schematic diagram and photograph of the experimental setup. The main components of the experimental setup are:

- a. Evacuated tube solar water heater
- b. Silica gel coated heat exchanger (SCHE)
- c. Cooling tower

Evacuated tube solar water heater

It has 15 evacuated tubes and a header which is at an angle of 30° relative to horizontal surface with south facing. The evacuated tube has 2 coaxial tubes, namely glass and absorber tube. The length, outer diameters of the glass and absorber tube is 1500 mm, 47mm and 37 mm respectively. The header has a cross section of $100 \times 140 \text{ mm}^2$ with a length of 1160 mm respectively.

Silica gel coated heat exchanger

SCHE is constructed on the basic structure of shell and tube type heat exchanger with water capacity of 17.3 litres as shown in Figure 2. It has 64 aluminium tubes having a diameter of 25.4mm. The column chromatography silica gel is used as the coating desiccant material in this heat exchanger. Firstly, the silica gel particles are coated on the aluminium tubes of heat exchanger and then the aluminium tubes are dried and soaked in the silica gel solution repeatedly. The weight of silica gel coated on aluminium tubes is 1.7 kg.

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(a)



(b)

Figure I (a) Schematic diagram and (b) photograph of the experimental setup.





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Cooling tower

The cooling tower is used to produce cooling water for SCHE during the dehumidification process and also for heat exchanger in pre-cooling dehumidification. It has a cylindrical drum with a water capacity of 50 litres and a cellulose pad having a rectangular cross sectional area of 610×305 mm² with a width of 51 mm. A water pump is used to circulate cooling water in SCHE and heat exchanger. The outlet water of the SCHE and heat exchanger is sprayed on the cellulose pad to regenerate the cooling water.

Working principle of experimental setup

The system has been operated for, firstly regeneration process, then rest time and finally for adsorption process. During the regeneration process, the experimental setup was exposed to the Sun at 09:00 hr and reading was recorded from 10:00 hr to 15:00 hr. With the help of valves path-I was in working. The evacuated tube solar water heater produced the hot water and this hot water was transferred to the SCHE through connecting pipes due to thermosyphon phenomenon.

Then the regeneration air (ambient air) was pumped in the SCHE with the help of axial fan. The water vapours were transferred from the desiccant material to the regeneration air due to water vapour pressure difference. The desiccant material was completely regenerated at 15:00 hr then the hot water was drained out from the SCHE. A rest time period of half hour was maintained between the regeneration and adsorption process, so that the desiccant material could transfer its regeneration heat to the atmosphere. Now, the adsorption process

was started at 15:30 hr. With the help of valves, the path-II was in working and the cooling water was circulated in the SCHE, which was generated by cooling tower. The adsorption heat produced by the desiccant material was taken by the cooling water. Then the process air (ambient air) was pumped in the SCHE with the help of axial fan. The water vapours were transferred from the process air to the desiccant material due to water vapour pressure difference. The dehumidification process was completed at 18:30 hr as the desiccant material was completely saturated.

Measuring instruments and uncertainty analysis

Different parameters measured in these experiments are:

- i. Water temperature
- ii. Air temperature and relative humidity
- iii. Solar intensity
- iv. Air flow rate

These parameters are measured by the following devices as given in Table 1. The uncertainty analysis used in this paper is based on the root mean square method as per Kline et al.⁹ The relationship for error analysis is given as

Table I measuring devices specifications

Sr. no.	Measurement	Sensors	Operational range	Accuracy
I	Water temperature	PT100 RTD	0°C to 200°C	± 0.3°C
2	Air Relative Humidity(RH) and temperature	Hygrometer	0 to 100 -10°C to 60°C	± 2% ± 0.3°C
3	Air flow rate	Anemometer	0 to 45 m/s	± 2%
4	Solar intensity	Pyranometer	0 to 2000 W/m^2	$\pm 2 W/m^2$

1

$$\frac{\Delta z}{z} = \left[\left(\frac{\partial f}{\partial y_1} \right)^2 \left(\frac{\Delta y_1}{z} \right)^2 + \left(\frac{\partial f}{\partial y_2} \right)^2 \left(\frac{\Delta y_2}{z} \right) + \dots + \left(\frac{\partial f}{\partial y_n} \right)^2 \left(\frac{\Delta y_n}{z} \right)^2 \right]^2$$
(2)

(2) Where f is a function of independent variable y_1 , y_2 , etc. stand for the variables of the function Δy_1 , Δy_2 etc. are the absolute error associated with the variables and $\frac{\Delta z}{z}$ means the relative error. Based

on these relationships, the test relative uncertainties for regeneration rate and adsorption rate are $\pm 5.3\%$ and $\pm 16.5\%$ respectively.

Performance indices

Performances of the system are evaluated in terms of regeneration rate and adsorption rate.

Regeneration rate (R_c) can be given as

Regeneration rate (R_{a}) can be given as [2]

$$R_{c} = m_{a} (Y_{out} - Y_{in})....(3)$$

Adsorption rate (A_d) can be given as [2]

$$A_{d} = m_{a}(Y_{in} - Y_{out})....(4)$$

Where Y_{out} and Y_{in} is humidity ratio of process air at outlet and inlet condition of SCHE and is the mass flow rate of the process air.

Results and discussion

For the system, the mass flow rate of process air and regeneration air are 0.046 kg/s. The hot water is naturally circulated in SCHE during the regeneration process. In adsorption process, the cooling water is circulated in the SCHE at the flow rate of 0.286 kg/s.

Regeneration process

The performance of desiccant material in regeneration process is greatly affected by circulated hot water temperature and the temperature of the hot water is affected by available solar intensity. So solar energy directly affects the regeneration rate of desiccant material.

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Figure 3 represents the variations in water temperature of SCHE and solar intensity with time. It is observed from the graph that the water temperature of SCHE increases with solar intensity and attains its maximum value of 67.6°C and decreases slightly in last. After 13:00 hr the solar intensity decreases sharply and the water temperature of SCHE still increases, this is because of the sensible heat storage capacity of water.

rate increases with increase in water temperature of SCHE, this is because, with an increase in surface temperature of desiccant material, the water vapour pressure difference between the desiccant material and the regeneration air increases. Hence the water vapour moves from desiccant material (high vapour pressure) to regeneration air (low vapour pressure). Then decrement in regeneration rate can be observed irrespective of increase in the water temperature. This shows that, the desiccant material is about to complete regeneration.

Figure 4 shows the variation in water temperature of SCHE and the regeneration rate of desiccant material with time. Initially, regeneration



Figure 3 Variation in water temperature of SCHE and solar intensity with time.



Figure 4 Variation in regeneration rate of the desiccant material and water temperature of SCHE with time.

Adsorption process

After complete regeneration of desiccant material, the dehumidification process has been started followed by a time gap. Figure 5 represents the variation in dehumidification rate and inlet air humidity ratio with time. In this case cooling water in not circulated in the SCHE. It is observed that the adsorption rate the desiccant material decreases continuously, which is the fundamental behavior of desiccant material. The average dehumidification rate of process air is 0.25 kg/h. The inlet air humidity ratio varies from 0.0205 kg water vapour/ kg dry air to 0.0218 kg water vapour/ kg dry air.

Figure 6 shows the variation in adsorption rate of the desiccant material with time. In this case, cooling water is circulated in the

SCHE and desiccant material is regenerated at nearly similar condition as in last case. The adsorption rate of the desiccant material decreases continuously. This is because adsorption capacity of a desiccant bed decreases with time during the process. The average value of dehumidification rate is 0.49 kg/hr, which is higher than the last case. This is because of circulating cooling water. The cooling water removes adsorption heat from the desiccant material continuously. At lower surface temperature, the adsorption capacity of desiccant material significantly enhanced. The inlet air humidity ratio varies from 0.0207 kg water vapour/ kg dry air to 0.0218 kg water vapour/ kg dry air which is nearly similar to last case.



Figure 5 Variation in adsorption rate of desiccant material and inlet air humidity ratio with time in case of without circulating cooling water.



Figure 6 Variation in adsorption rate of desiccant material and inlet air humidity ratio with time in case of with circulating cooling water.

Conclusion

In this work, the regeneration and adsorption behavior of the silica gel powder is experimentally investigated. The following conclusions have been extracted from this experimental investigation (Table 2).

Table 2 Appendix

A _d	Adsorption rate (kg/hr)	
R _c	regeneration rate (kg/hr)	
SCHE	silica gel coated heat exchanger	
Υ _{in}	humidity ratio of process air at inlet of SCHE (kg/kg)	
Y _{out}	humidity ratio of process air at outlet of SCHE (kg/kg)	

- I. The hot water temperature of the SCHE depends on the available solar intensity, whereas the regeneration rate of the desiccant material depends on the hot water temperature of the SCHE.
- II. The evacuated tube solar water heater produces hot water with an average temperature of 61.6°C, which is sufficient to regenerate the desiccant material of the system. So quite low regeneration temperature is required for the SCHE.
- III. The regeneration and adsorption rate of the desiccant material also depends upon the inlet air moisture content.
- IV. The circulating cooling water is significantly enhanced the adsorption capacity of desiccant material.

V. The amount of dry air produced by the SCHE is satisfactory, which can be used in air conditioning application.

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None.

Conflicts of interest

There is no conflict of interest.

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