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Analysis Of Adsorption Cooling System

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In this work experiments are carried out on single bed intermittent type of Adsorption Cooling System (ACS) comprising of silica gel-water as adsorbate-adsorbent pair. Regular Density (RD) type of silica gel with mesh size of 80-120 is used for performance analysis of ACS. Taguchi's design of experiments is conducted to build the array of experiments. Multiple linear regression equations are developed to build performance prediction model for response variable for all three control variables. Finally confirmation test are carried out to validate the performance prediction model. A detailed analysis report and output file is built using MINITAB-17. It is concluded that the most significant effects are inlet temperature of hot water, flow rate and adsorption cycle respectively.

Keywords: Adsorption cooling, Silica-gel, Linear regression models

Nomenclature

COP	Coefficient of performance,
M_{des}	Desorbed mass of refrigerant, ml
M_{ads}	Adsorbed mass of refrigerant, ml
X*	Equilibrium uptake, kg.kg-1
q_{sh}	Isosteric heat of adsorption, kJ.kg-1
Q_c	Cooling capacity, W

Introduction:

Cooling systems are required for food and beverages preservation for both domestic and commercial cooling needs. The global demand for cooling need is increasing and the commonly used vapour compression refrigeration (VCR) systems consume high electrical energy. Most of this electrical energy is either by using oil, coal, and natural gas originating from fossil fuels and their combustion is harmful to the environment. The refrigeration and air conditioning systems are consuming around 30% of energy from total energy consumption [1]. Thus, it is required get the solution for minimizing the energy consumption by using innovative cooling system with less utilization of energy and more durability as compared to the conventional cooling system. One such alternative solution is adsorption cooling system in which compressor is replaced by adsorption bed [2].

This work reports the design of adsorption cooling system using first principle utilizing the fundamental knowledge of heat transfer. The system is fabricated and installed. It uses silica gel and water as adsorption working pair. Silica gel has high affinity for capturing of water vapor. Silica gel can be regenerate with relatively low temperature below 100ºC. [3]. Thus silica gel-water is selected to be as an adsorbate-adsorbent working pair for this experiment. Water is used as a refrigerant as it has the high latent heat of vaporization. Beside this water is environment-friendly and easily available.

Most of the researchers modelled the adsorption cooling system using various modeling approaches such as thermodynamic model, lumped parameter model, heat and mass transfer model [4]. While other researchers have modelled adsorption cooling system using different dynamic simulation tools and programs like SIMULINK [5-9], Trnsys [10-14], MATLAB [15-16], Modelica [17,18], Fortran [19,20], Insel [21], Cosmol [22-24]. Yet there is no work reported on optimization of performance parameters using Design of Experiment (DOE). DOE helps to understanding the behavior of the mechanical system at component level. The data collection is done by systematic variation of influencing factors helps to describe underlying phenomena. An experimental program recognizes the key “Factors” that affect the outcome of the research. These factors are acknowledged looking at the parameters that may affect the product of the experiment. The levels for each factor are chosen and the data is gathered for this value of factors by performing the experiments at selected values. The DOE is controlling approach to minimize the number of experiments yet pull out all the knowledge about the dependence of outcome on the process parameters. This work uses Taguchi experimental design and ANOVA analysis has to find Adsorption cooling capacity.

Design and development of adsorption cooling system

Adsorption cooling system (ACS) was designed using fundamental equations of heat and mass transfer, thermodynamics and principles of adsorption. The ACS was fabricated and installed in the laboratory. It uses silica gel- water as working pair for adsorption/desorption process. For data collection of temperature at various points, flow rates of water and pressure during the adsorption/desorption process. A calibrated temperature sensor (±0.3°C), flow meter (±3%) and pressure gauge (±0.15%) is used respectively. Honeywell Data logger is used to log the required data. The experiments are carried out with predesigned experimental process.

The planning of experimentation is done using DOE as per Taguchi's experimental methodology while ANOVA was used for the analysis. Three factors identified are flow rate of water, inlet temperature of hot water, adsorption cycle time and six responses were Coefficient of Performance COP, desorbed mass of refrigerant M_{des}, adsorbed mass of refrigerant M_{ads}, equilibrium uptake X*, Isosteric heat of adsorption q_{sh}, and Cooling capacity Q_c are selected for the performance analysis of the cooling system. The results are plotted as main effect plots, normal probability plots and interaction plots.

Terminology

COP for the system is defined as how the efficiently transforms input energy into a useful output. It is the ratio of evaporative cooling effect to the heat input. The cold production takes place by evaporation of saturated liquid refrigerant in the evaporator. The differential cooling effect is the multiplication of mass of refrigerant vapor which is coming from the evaporator and being absorbed in the adsorption bed heat exchanger to the latent heat of evaporation of refrigerant at evaporator temperature and wetness fraction. The Isosteric heating is described as the amount of heat required to adsorb or desorbs a unit mass of the adsorbate.

Design of Experiment using Taguchi Methodology

Taguchi is powerful technique for designing the experiment for collecting the data in a control way and to analyze the influence of process variables over some specific variables. This is an unknown function of process variables for the design of high quality system [25]. Taguchi method of DOE is used to generate orthogonal ray for conducting limited experiments at set points. Factor information for the DOE is as given in Table 1.

Table 1. Factor information with levels of controllable values

Factor	Type	Levels	Values
Flow Rate, lpm	Fixed	4	10, 15, 20, 25
Inlet Temperature of Water, ^{o}C	Fixed	4	55, 60, 65, 70
Ads Cycle Time, min	Fixed	4	15, 20, 25, 30

Table 1 shows the fixed value of three factors at four regular intervals. The input factors are selected for observing the significance effect of it on the performance of ACS. The selected factors are flow rate of hot water, inlet temperature of hot water, and adsorption cycle time. These factors are kept as input parameters in the Taguchi design and the effect on responses is generated. The levels indicate the controlled variable changing value for each factor. The selection of controlled parameters is based on the previous case studies on which researchers performed the experiment [26]. For the experimentation the three controllable significant parameters were selected from the research study. The values of range for each controllable parameter have been decided from the Taguchi method. Taguchi method of design is used to set predefined control factors affecting the performance of the adsorption cooling systems. The uncontrollable parameters of the adsorption cooling system are taken as responses in design.

Schematic diagram of experimental setup

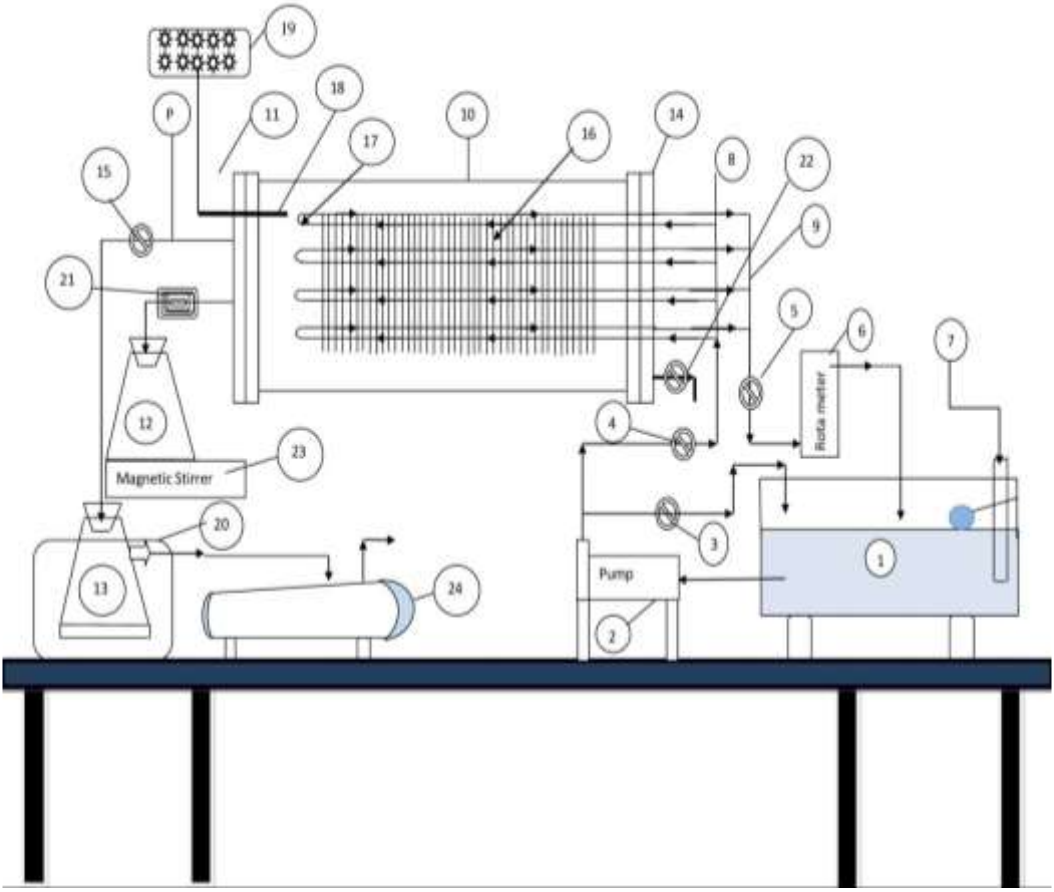

Figure 1. Schematic of actual experimental setup of adsorption cooling system at PDPU campus

1. Source water Tank
2. Water Pump
3. Bypass Control valve
4. Inlet Control Valve
5. control Valve
6. Rota-meter
7. Immersion Heater
8. Inlet Header
9. Outlet Header
10. Bed shell
11. Back Flange
12. Refrigerant Flask
13. Condenser Flask
14. Front Flange
15. Condenser Isolate Valve
16. Fins of Heat exchanger
17. Copper Tubes of Heat exchanger
18. Bed Shell Temperature
19. Data Logger
20. Ice Box
21. Air Heater
22. Drainage Valve
23. Hot Plate
24. Vacuum Pump

Table 2 shows the L16-Orthogonal array of Taguchi Design of Experiment for the controllable parameters such as flow rate, inlet temperature of hot water, and adsorption cycle time in which the controlled parameters are changing in four regular intervals. It also shows the predesigned test run for optimizing the performance parameters. The Level 1 start with the Minor, Level 2, Level 3 and Level 4 ends with the regular increment in value. Taguchi Orthogonal Array Design with L16 (4^3) in which Factors: 3; Runs: 16; Columns of L16 (4^5) Array.

Table 2. Orthogonal Array of Taguchi Experimental Design: L16 (4^3) Array

Run	FR(lpm)	Tin (ºC)	ACT (min)	FR (lpm)	Tin (ºC)	ACT (min)
1	1	1	1	10	55	15
2	1	2	2	10	60	20
3	1	3	3	10	65	25
4	1	4	4	10	70	30
5	2	1	2	15	55	20
6	2	2	1	15	60	15
7	2	3	4	15	65	30
8	2	4	3	15	70	25
9	3	1	3	20	55	25
10	3	2	4	20	60	30
11	3	3	1	20	65	15
12	3	4	2	20	70	20
13	4	1	4	25	55	30
14	4	2	3	25	60	25
15	4	3	2	25	65	20
16	4	4	1	25	70	15

Taguchi design method is divided in three basic stages such as pre-planning stage, execution stage, and analyzing stage. In planning stage the experiment was planned with orthogonal array to observe the effect of several factors on the output parameters and defining the plan of the experiment. The experimental results are analyzed using the Analysis of means and variance to examine the influence of factors. The design of experiments using the orthogonal array is, in most cases, efficient when compared to many other statistical designs [25]. The minimum number of experiments that are required to conduct the Taguchi method are calculated based on the degrees of freedom approach. The orthogonal array should be greater than or equal to the sum of the variables. Each variable and corresponding interaction was assigned to a column defined by Taguchi method [26]. In the experiment three controlled parameters and six uncontrolled parameters for that the sum of variables was 9 which is the acceptable orthogonal array. Experiments were carried out as pre defined array of the Taguchi design.

Experimental Setup

Experimental setup as in Figure 1 consists of 4 main components namely bed shell, adsorber bed Heat exchanger (comprising of copper tubes and aluminum fins), condenser flask and refrigerant flask. Bed shell has inside diameter of 200 mm, 15mm wall thickness, 500 mm long and made of mild steel. Adsorber bed is a fin tube type heat exchanger with copper tubes and aluminum fins. Thickness of fin is 3 mm and surface area is 0.98m^2. Tubes have inside diameter of 16mm and are connected to front flange with 12 mm brass fasteners and fins are tightly attached to copper tubes with regular intervals.

The inlet and outlet header is fitted with the male-female fasteners and single inlet/outlet has been provided. The Rota-meter is used to measure the flow rate of water coming out from adsorber bed heat exchanger. Flow of water is regulated by control valve which is provided between the outlet header and Rota-meter. Crompton CG centrifugal pump is used to circulate water. The bypass line and valve are provided between the pump and inlet header of the bed shell to reduce the back pressure generation which is driving the excess water towards the Source tank. The excess moisture from the bed shell is removed using the drainage valve. Six different PT-100 temperature sensors are provided to measure silica gel temperature, fins surface temperature in upper and lower side of the Adsorber bed heat exchanger. The four tubes surface temperature has been measured with the bulb type PT-100 sensors which are inserted from the rear flange. Also, the rear flange is having one bulb type PT-100 sensor to measure the bed shell temperature. The refrigerant flask has been connected with the flexible pipe at rear flange for allowing the water vapor to flow inside the Adsorber bed heat exchanger. The refrigerant flask is kept on to the hot plate and the air heater blows the hot air on to the flexible refrigerant pipe to reduce the condensation of water vapor inside the pipe. The swage lock pipe and fittings have been provided to ensure there is no leakage from the vacuum line to the rear flange and passing through the vacuum gauge then connected to the condensing flask which is inside the icebox further connected to the vacuum pump through vacuum line. Vacuum pump is of parag engineering make which is capable of achieving full vacuum condition (-14.35 PSI). Two 1500W heaters have been used to maintain the temperature of water inside the source water tank.

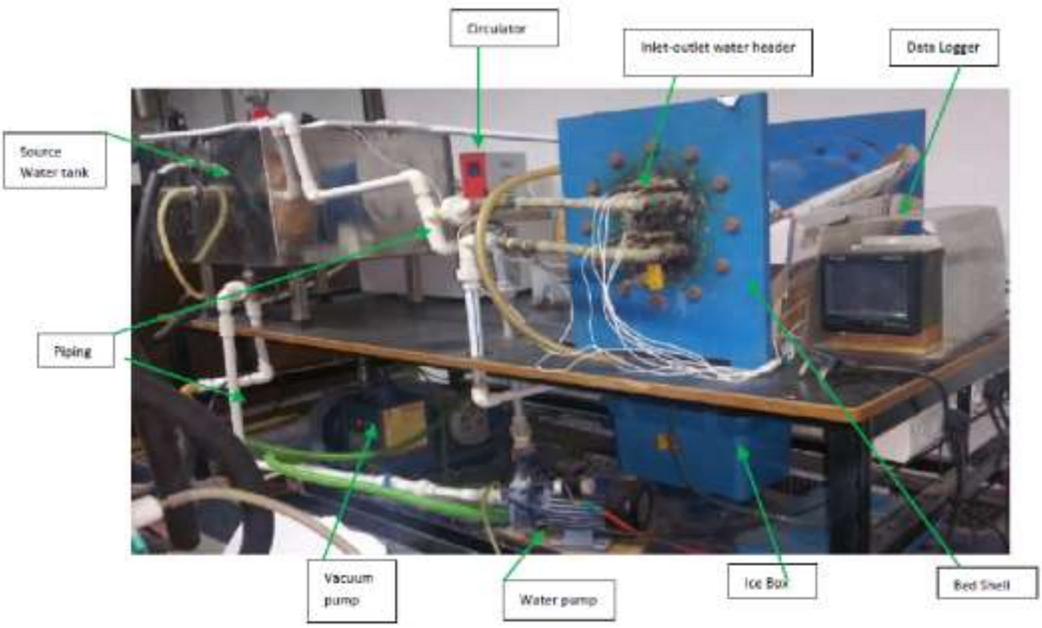

Figure 2. Actual experimental setup of adsorption cooling system at PDPU campus

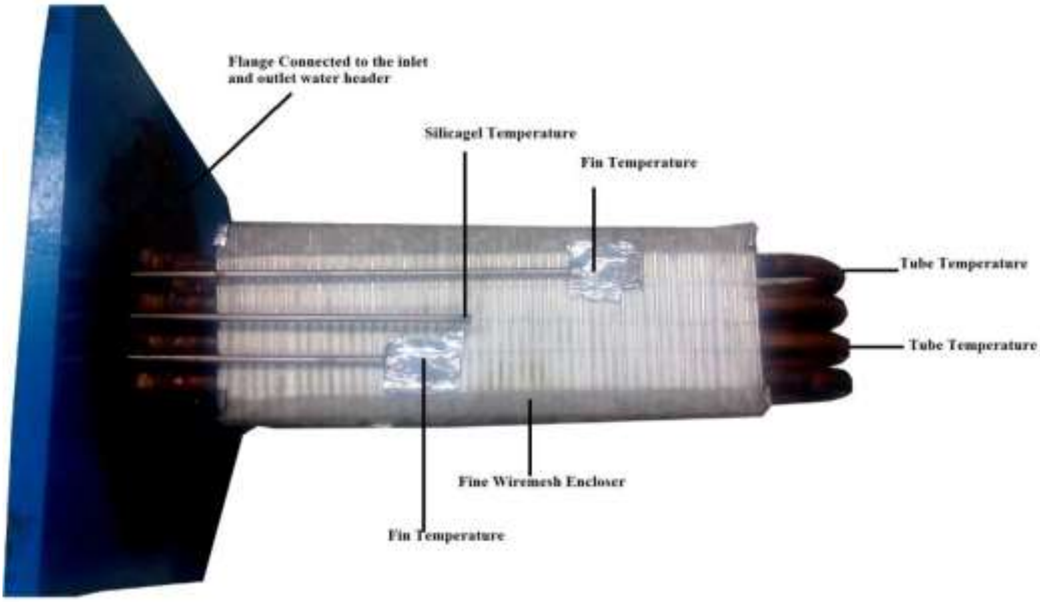

Figure 3. Thermocouple location in the experimental setup

The circulator is connected directly to the source water tank for even distribution of temperature and maintaining the temperature constant. All the PT-100 temperature sensors are connected directly to the data logger which is made by Honeywell. One PT-100 temperature sensor is fixed at the inlet of the header, outlet of the header, and immersed into the source water tank respectively. Figure 3 shows the location of temperature sensors inside adsorber bed heat exchanger.

Experimental Process

The experimental procedure conducted is described as follows:

The bed shell is fully vacuumed (-14.35 PSI) disconnecting the refrigerant flask. After obtaining full vacuum, the vacuum pump was switched off and disconnected. The water in the source tank is gradually heated there after control valve is closed. When the water temperature reaches over about 70°C, the water pump is turned on and the control valve is closed while the bypass valve is open. The water temperature is decreased due to heat losses to atmosphere and system parts. Thus water is again heated to about 70°C; the control valve is opened to start adsorbent bed regeneration. The water flow rate is regulated using the control valve and the bypass valve simultaneously. The adsorber bed heat exchanger is kept heated for one hour, and then the bed shell pressure is increased gradually by opening the drain line to facilitate condensation of the refrigerant vapor to be collected via the drainage line. The previous step is repeated to ensure the dryness of the adsorbent bed heat exchanger. The control valve is closed and the pump is turned off and subsequently, the source water tank is drained and then filled with cold water from the mains. The water pump is turned on, while the bypass valve is fully open. During the very short time, the flow is stabilized and the control valve is opened gradually to allow the water flow through the adsorbent bed heat exchanger. The required flow rate is controlled by the regulating control valve and bypass valve. The adsorbent bed heat exchanger is pre-cooled for five minutes and subsequently, the refrigerant flask is connected to the adsorbent bed to start the adsorption process. During this process, the connection line including the connection valve temperature is maintained at about 12 degrees above the refrigerant temperature by Air Heater to avoid water vapor condensation. During the pre-cooling and adsorption process, the vacuum pump is turned on. After the adsorption period for the predefined sorption time is completed, the refrigerant flask is disconnected, flow control valve is fully closed, the vacuum pump is stopped and secondary flow pump is turned off. The refrigerant level in the refrigerant flask is recorded and the condensed water vapor in the condenser flask is measured for analysis.

Result and discussion

A linear regression analysis attempts to model the relationship between two or more predictor variables and response variables by fitting a linear equation to the observed data. Based on the experimental results, multiple linear regression models were developed using MINITAB-17. Regression equations thus generated establish correlation between the significant terms obtained from ANOVA, namely, COP, M_{des}, M_{ads}, X*, q_{sh} and Q_c content and their interactions. The regression equations developed for performance are:

COP = 0.31 - 0.03*FR(lpm)_10 - 0.04*FR(lpm) _15+ 0.02* FR(lpm)_20
+ 0.05*FR(lpm)_25 - 0.18*Tin (ºC)_55 - 0.07*Tin (ºC)_60 + 0.07*Tin (ºC)_65
+ 0.18*Tin (ºC)_70 + 0.0042*ACT (min)_15+ 0.0095*ACT (min)_20-
0.02*ACT (min)_25 + 0.01*ACT (min)_30

M_{des} = 251.61 + 3.93*FR (lpm)_10 - 6.11*FR(lpm)_15 + 2.92*FR(lpm)_20 - 0.74*FR
(lpm)_25 - 38.03*Tin (ºC)_55 - 0.72*Tin (ºC)_60 + 15.90*Tin (ºC)_65
+ 22.85*Tin (ºC)_70 - 13.29*ACT (min)_15 - 0.68*ACT (min)_20
+ 4.27*ACT (min)_25 + 9.70*ACT (min)_30

M_{ads} =281.75 + 15.72* FR (lpm)_10 + 6.98* FR (lpm)_15 - 6.74* FR (lpm)_20 - 15.96* FR
(lpm)_25 - 53.51*Tin (ºC)_55 - 8.78*Tin (ºC)_60 + 20.91*Tin (ºC)_65
+ 41.38 Tin (ºC)_70 + 1.37*ACT (min)_15 + 3.11*ACT (min)_20
- 0.55*ACT (min)_25 - 3.93*ACT (min)_30

X^* = 0.25 + 0.01* FR (lpm)_10 + 0.00073* FR (lpm)_15 - 0.0055*FR (lpm)_20 - 0.0077* FR
(lpm)_25+ 0.04*Tin (ºC)_55+ 0.01*Tin (ºC)_60- 0.01*Tin (ºC)_65- 0.04*Tin (C)_7
0+ 0.001*ACT (min)_15- 0.002*ACT (min)_20- 0.001*ACT (min)_25+ 0.001*ACT
(min)_30

q_{sh} = 3300.85 + 83.7* FR (lpm)_10 - 4.5* FR (lpm)_15- 32.6* FR (lpm)_20 - 46.5* FR (lpm)_25 + 162.5*Tin (ºC)_55+ 65.2*Tin (ºC)_60 - 64.5*Tin (ºC)_65 - 163.1*Tin (ºC)_70 - 8.2*ACT (min)_15- 0.7*ACT (min)_20 + 19.3*ACT (min)_25 - 10.4*ACT (min)_30

Q_c = 646.88 + 35.3* FR (lpm)_10 + 15.0* FR (lpm)_15 - 15.5* FR (lpm)_20- 34.8* FR (lpm)_25 - 127.2* Tin (ºC)_55 - 20.7* Tin (ºC)_60 + 48.7* Tin (ºC)_65+ 99.1* Tin (ºC)_70 + 3.2* ACT (min)_15 + 7.8* ACT (min)_20 - 1.7* ACT (min)_25- 9.4* ACT (min)_30

The above equations can be used to predict the response. The constant in the equation is the residue. The regression coefficient (R2) obtained for the model was 96.70% for COP, 93.09% for M_{des}, 96.00% for M_{ads}, 99.11%for X^*, 98.30% for q_{sh}, 96.10% for Q_c. And this indicates the performance not scattered.

Example to verifying the data with regression equation for FR=12, Tin=57ºC, ACT=17 min

COP = 0.31 - 0.03*12- 0.04*12+ 0.02* 12 + 0.05*12 - 0.18*57 -0.07*57 + 0.07*57 + 0.18*57 + 0.004*17 + 0.009*17 -0.02*17 + 0.01*17

= 0.3114

M_{des} = 251.61 + 3.93*12- 6.11*12 + 2.92*12 - 0.74*12 - 38.03*57 - 0.72*57 + 15.90*57 + 22.85*57 - 13.29*17 - 0.68*17 + 4.27*17 + 9.70*17

= 251.61 ml.

M_{ads} = 281.75 + 15.72*12 + 6.98*12 - 6.74*12 - 15.96*12- 53.51*57 - 8.78*57+ 20.91*57 + 41.38*57 + 1.37*17 + 3.11*17 - 0.55*17 - 3.93*17

= 281.75 ml.

X^* = 0.25+ 0.012*12 + 0.0007* 12 - 0.005*12 - 0.007* 12 + 0.04*57+ 0.01*57 - 0.01*57 - 0.04*57+ 0.001*17 - 0.002*17 - 0.001*17+ 0.001*17.

= 0.25 $kg.kg^{-1}$.

q_{sh} = 3300.85 + 83.7* 12 - 4.5* 12- 32.6* 12 - 46.5* 12 + 162.5*57+ 65.2*57 - 64.5*57 - 163.1*57 - 8.2*17- 0.7*17 + 19.3*17 - 10.4*17.

=3307.75 $kJ.\ kg^{-1}$.

Q_c = 646.88 + 35.3* 12 + 15.0* 12 - 15.5* 12- 34.8* 12 - 127.2* 57 - 20.7* 57 + 48.7* 57+ 99.1* 57 + 3.2* 17 + 7.8* 17 - 1.7* 17- 9.4* 17.

= 639.48 W.

Conclusion

The experiment has been carried out on adsorption cooling system with the silica gel-water adsorbent pair. From the results, it has been concluded that the significant effect of the inlet temperature of hot water on all responses and followed by flow rate then adsorption cycle time effect is observed the negligible effect. It has been observed that the effect of flow rate and adsorption cycle time on all the responses are significant and the inlet temperature of hot water interaction is observed on q_{sh}, and Qc.

Further the performance prediction of adsorption cooling system was carried out to analyze the effect of flow rate, inlet temperature of hot water, adsorption cycle time on output parameter namely COP, M_{des}, M_{ads}, X*, q_{sh} and Q_c. The following conclusion are derived:

- Results indicates that the R-sq value is significantly influence (at 95% confidence level) by COP followed by M_{des}, M_{ads}, X*, q_{sh} and Q_c. Based on the analysis of the S/N ratio optimum for combination of Flow rate = 25lpm, Temp of hot water Inlet = 65º, Adsorption Cycle time = 30min gave the optimum range of parameters tested.
- The significant parameter affecting on the COP, M_{des}, M_{ads}, X*, q_{sh} and Q_c is inlet temperature of hot water.

- The constant in the regression equation is the residue. The regression coefficient (R2) obtained for the model was 96.70% for COP, 93.09% for M_{des}, 96.00% for M_{ads}, 99.11%for X^*, 98.30% for q_{sh}, 96.10% for Q_c. And this indicates the performance not scattered.

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