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Study the Performance of a Novel Desiccant Heat Exchanger

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HIGHLIGHTS

- A silica gel-coated heat exchanger was used for air drying purposes.
- The most important effects studied are the air flow rate in the process of dehumidifying and regeneration of silica gel, water flow, and the regeneration temperature.
- The heat exchanger could remove moisture from the air and work efficiently in hot and humid areas.

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ABSTRACT

Conserving energy and reducing emissions has become a global consensus. However, most air conditioning systems are highly energy-consuming, affecting global warming and the ozone layer because they use chlorine and fluorine refrigerating fluids. Evaporative cooling systems are one of the most important environmentally friendly air conditioning systems with low energy consumption. However, their performance is negatively affected by the high humidity of the inlet air. One of the solutions to control the relative humidity of the inlet air is using desiccant material. In this paper, a silica gel-coated heat exchanger was designed and constructed as a dehumidifying unit. The effect of airflow rate, hot water flow rate, cold water flow rate, and regeneration temperature on the system's performance has been studied. It was found that increasing the hot water flow rate improves the removing moisture from the desiccant. However, increasing the hot water flow rate has a negative effect on the thermal performance of the heat exchanger. The effectiveness of the heat exchanger was 53% in the regeneration phase and 52% in the cooling phase for the outside air temperature of 40ºC, W=20 g/kg, and an airflow rate of 0.48 m³/s. From the results shown above, it was noticed that the system could work efficiently in hot and high humidity climates and be used in Iraqi weather.

1. Introduction

One of the essential parameters that affect thermal comfort is the humidity ratio. This ratio must be within the parameters of the environment to meet the requirements of indoor thermal comfort (i.e., 24 ºC and relative humidity of 50% in summer conditions) [1]. High humidity in the ambient air has a negative effect on the thermal performance of air conditioning systems, the most important of which is evaporative cooling. Adding desiccant material to these systems is one of the most crucial ways to dry the system's inlet air. Humidity is reduced from the air by adding desiccant materials. These materials are highly porous that can absorb water in moist air, and they are several types, including solid, liquid, and composite, an example of silica gel desiccant materials. They are also installed in several ways as moisture removal units, such as fixed plates, desiccant wheels, and desiccant-coated heat. Fixed bed and desiccant wheel dehumidifiers have low efficiency in terms of adsorption and energy transfer capacity [2]. On the other hand, coated heat exchangers are a promising technology that can improve energy efficiency when combined with air conditioners [3]. Recently, this type of dehumidifying unit has received a lot of attention. It is a multi-objective and effective way to achieve performance improvement due to the treatment of sensible and latent heat for air loads by drying the air moisture and overcoming the heat associated with adsorption.

Many researchers have studied the factors affecting the coated heat exchangers' performance and effectiveness. Also, types of desiccant materials wrapped on the exchanger have been investigated. Ge et al. [4] experimentally verified two types of heat exchangers coated with desiccant, one with silica gel and the other with polymer. The effects of regeneration temperature (the temperature responsible for the desiccant regeneration is the hot air temperature in the desiccant fixed bed and desiccant wheel, and the hot water temperature in the desiccant coated heat exchangers), inlet air temperature, and humidity on the system performance were analyzed. It was found that the coated heat exchangers can effectively reduce the heat associated with the adsorption during the dehumidification process. Moreover, the silica-coated heat exchangers are better than polymer-

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coated ones (i.e., higher moisture removal and longer moisture removal time). In addition, the high regeneration temperature positively affects the dehumidification of both heat exchangers. The highest COP_{th} for the polymer-coated exchanger was recorded at a regeneration temperature of 70°C. Inlet air temperature slightly affects the system performance, but the high humidity of ambient air leads to the increased dehumidification rate and COP_{th}. The best airflow rates for obtaining the highest COP_{th} exchange rate were 1.3 m^3/s and 1.5 m^3/s for the polymer-coated and silica-coated heat exchangers. Zheng et al. [5] used a silica-gel-impregnated heat exchanger impregnated with LiCI (lithium chloride) as a composite desiccant. The results were compared with only a silica-coated heat exchanger. This study noticed that the sheets coated with the new compound have a thermal conductivity twice higher than those coated with silica. Furthermore, the heat exchanger coated with the compound has higher absorption and moisture removal rates. The study showed that the plates coated with silica gel with LiCL have better performance transferring heat and mass than plates coated with silica only. Zheng et al. [6] manufactured two powders similar to zeolite (sapo-34) and (fapo-34), which were coated on the heat exchanger plates. The performance of the materials was tested and analyzed to ensure the feasibility of the heat exchanger. Simulations were conducted to evaluate the dehumidification system performance of two exchangers coated with the new materials. It was found that the aluminum sheets coated with sapo-34 and fapo-34 have a higher absorption capacity than that of silica gel. The exchanger prepared from fapo-34 has a drying capacity of 2-3 times greater than sapo-34 and silica gel at low regeneration temperatures. Ge et al. [7] Utilized silica compound with potassium format as an organic acid salt in the desiccant coated heat exchanger. The results were compared with that of a silica-coated heat exchanger only. It was shown that the use of potassium format and its impregnation in silica gel positively improved the adsorption capacity, and the saturated potassium content was 75% to form the composite desiccant. It is possible to obtain a 20% moisture removal capacity and a 20% higher cooling capacity compared to only silica exchangers data. It was also found that decreasing the cooling water temperature improves the total load removal efficiency, and increasing the hot water temperature improves the ability to remove the latent heat load. Jagirdar and Lee [8] found experimentally that the smaller fin layer could achieve better moisture removal. However, a very small fin layer would increase energy consumption. Moreover, increasing the desiccant layer thickness increases energy consumption under the moisture adsorption process. In addition, increasing the water flow increases the performance of dehumidification and COP_{th}. Finally, Reducing the air velocity decreases moisture adsorption, $COP_{th,}$ and energy saving. Valarezo et al. [9] used an encapsulated heat exchanger for air dehumidification and humidification in summer and winter, respectively. An experimental investigation was carried out for a silica-coated and sodium-acetate-coated heat exchanger in Shanghai, China. Several factors were studied, such as hot and cold water temperature, inlet air flow, COPth of the system, and energy efficiency. The results were compared between the three heat exchangers. The new exchanger had an average hydration capacity twice higher than the silica heat exchanger and the sodium-acetate heat exchanger. To provide ideal operating conditions in the summer season, it is recommended that the hot water temperature be high and the air speed is low. However, Low hot water temperature, high inlet air speed, and low cold water temperature are preferable in winter. The dehumidification capacity of the new exchanger is 10% and 30% higher than those of the sodium format and silica exchangers, respectively. The wetting capacity of the new exchanger is two times higher than these of the other exchangers. To study the effect of coating on the performance of the adsorption system, several researchers studied this effect. Duong et al. [10] Conducted a numerical analysis to study the effect of the coating compared to the filled desiccant system. The effect of cycle time for adsorption applications was also studied. It was found that the thickness of the coating of 0.2-0.5 mm is optimal for the best adsorption. There were no other ways than a coating to bind the dried materials together, so it is recommended that the binders be as small content as possible. The COP_{th} of the system was improved by 22.01% when the thickness of the coating increased from 0.2 mm to 0.5 mm.

Some researchers have divided the dried materials between the exchangers according to their use in different environments. Zheng et al. [11] conducted a review study about the desiccant materials on a heat exchanger coated with thin materials. They investigated the suitability of these materials for different buildings and ambient air conditions. After the review, the researchers found that the porous salt-supported composite desiccant is utilized in most buildings and climates because of its flexible performance for removing moisture, except for indoor environments with high humidity. As for zeolite, it is suitable for climates with moderate indoor humidity, such as offices and residential buildings. On the other hand, polyelectrolytes are suitable for humid climates like restaurants with high humidity. Vivekh et al. [12] Utilized a heat exchanger coated with a new superabsorbent polymer desiccant and potassium formate salt. The results were compared with the heat exchangers coated with pure and compound silica gel. It was shown that the new exchanger could absorb 4-8 times more moisture than silica gel with a longer cycle time (15 minutes) and a regeneration temperature within (40-50)ºC.

The new exchanger can remove cooling load three times higher, two times higher thermal efficiency than the silica gel exchanger, and saves energy by 50% when combined with conventional air conditioners. Some researchers used a heat recovery exchanger to utilize the cold air returning from space to cool the incoming air as an initial stage. Then it is treated by the exchanger coated with a desiccant. Sun et al. [13] used a heat exchanger coated with a desiccant material, and the waste heat was employed to obtain hot water. A heat exchanger was also used to recover the waste heat from the exhausted recovery air to improve energy efficiency. The time needed to complete the renewal cycle was 3 minutes. This system can regenerate the desiccant material at a temperature of 50-70ºC to use waste heat. This system can save electricity through waste heating and cooling, bypassing the cold water through the exchanger tubes. The system can be employed in tropical and humid areas in summer, and because this type of heat exchanger is enclosed in a desiccant that can treat the air, it can be used in dry areas to humidify the air in the winter. Zhao et al. [2] presented a comprehensive review of the main components of the desiccant envelope exchanger in terms of manufacturing materials, cooling water source, desiccant drying water source, and desiccant materials, and each component affects the system performance. They indicated that the development of exchangers of this type and the expansion of the scope of research could lead to good results in the development of the areas of exchangers use, as well as the use of paint desiccant in cooling electric cars, painting walls, and drying the air of electronic circuit boards. Many other researchers shed light on this type of dehumidifier [14 -18]. A heat exchanger covered with silica gel was designed and manufactured as a dehumidification unit. A practical study was conducted for some factors affecting the dehumidification of the air and the thermal cop of the system.

2. Heat Exchanger Covered With Silica Gel

Finned tube H.E was covered by silica gel as a desiccant material with a diameter of 3 mm and was designed as a dehumidifying unit. The exchanger dimensions were calculated using the Energy Equation Solver (EES) software, as mentioned in Table 1, and Figure 1 depicts its design. A humidification system and heat sources were used at the device entrance to simulate the conditions in hot and humid climates. The air duct with a bounder of H.E and all the water pipes were insulated by a heat insulator

Table 1: Dimension list for Heat Exchanger Covered with Silica Gel

Dimension	Value	Description
D_{out}	1.6 cm	The outer diameter of the tube
th_{pipe}	0.102 cm	Tube thickness
$No._{row}$	15	Number of tube rows
$No._{t\ col}$	6	Number of tube columns
H	50 cm	Height of heat exchanger
W	55 cm	Width of heat exchanger face
L	30 cm	Length of heat exchanger in the air flow direction
$\dot{V}_{air}$	0.48 m^3/s	Volumetric flow rate of air
$\dot{m}_w$	0.05 l/s	Water flow rate
S_v	3.8 cm	The vertical separation distance between tubes
S_h	5 cm	The horizontal separation distance between tubes
th_{fin}	0.1 cm	Fin thickness
P_{fin}	1.2 cm	Fin pitch
ϵ	1.0 [micron]	The roughness of the internal tube surface
$\dot{m}_w$	0.05 [l/s]	The mass flow rate of water
$M_{des.}$	22 [kg]	Amount of silica gel
Q	4915 [W]	The capacity of the heat exchanger

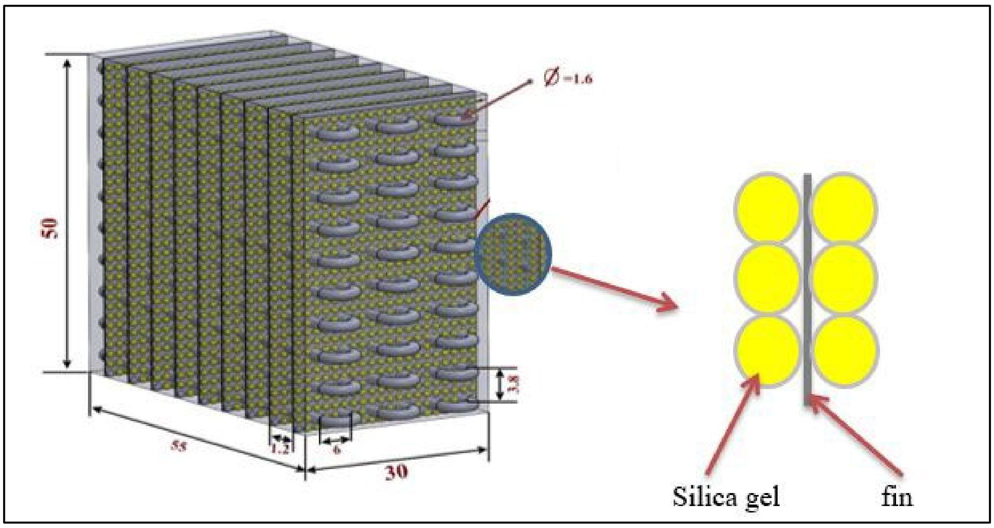


Figure 1: Section of Heat Exchanger Covered With Silica Gel

2.1 Heat Exchanger Manufacturing Steps

Aluminum sheets were cut with a thickness of (0.1 cm) and dimensions (55×30× 50 cm) with several 42 pieces, and then silica gel was glued to them on both sides using liquid glue. Ninety (90) tubes were used according to the design and were assembled with the plates to form the heat exchanger. Figures 2 (a, b, c, and d) demonstrate the heat exchanger manufacturing steps.

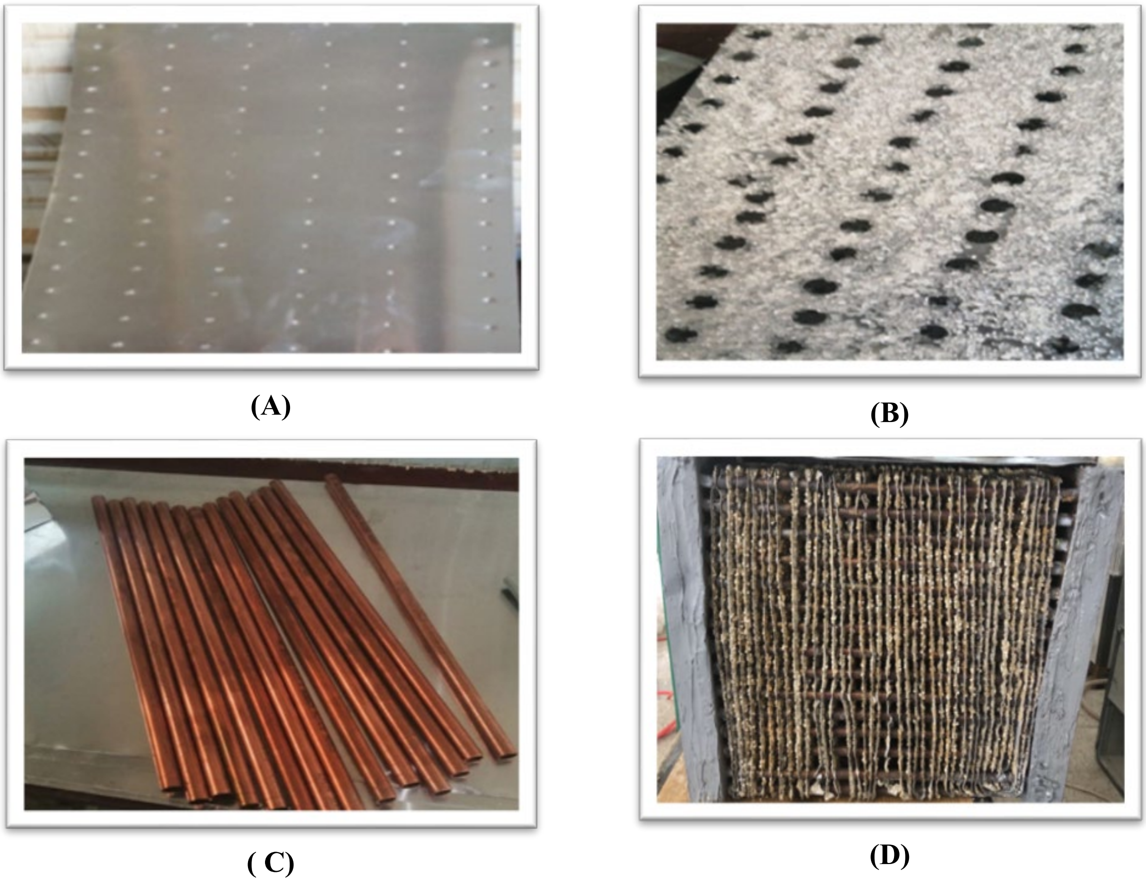


Figure 2: Heat Exchanger Manufacturing Steps(a) Aluminum sheets (b) Sheet perforation and covered silica gel (c) Tubes cutting(d) Heat exchanger covered with silica gel

2.2 Water System

In two water cycles, one cold water was used to overcome the heat of adsorption, and water at a temperature of 25-27ºC from a constant temperature water tank was used as cooling water during the process of dehumidifying. A Water tank, a pump, pipes, and valves were used to circulate the cold water. An electric heater was used with a storage tank to produce hot water, which is used to regenerate the desiccant material, and temperatures were within 45-65ºC. Figure 3 illustrates the water system. The desiccant is regenerated after it is saturated with moisture from the moist air entering the system. The regeneration is done by circulating hot water inside the heat exchanger tubes. Because of the high temperature of the silica gel beads, the vapor pressure inside them rises, and the water is disposed of and becomes dry and ready to work again.

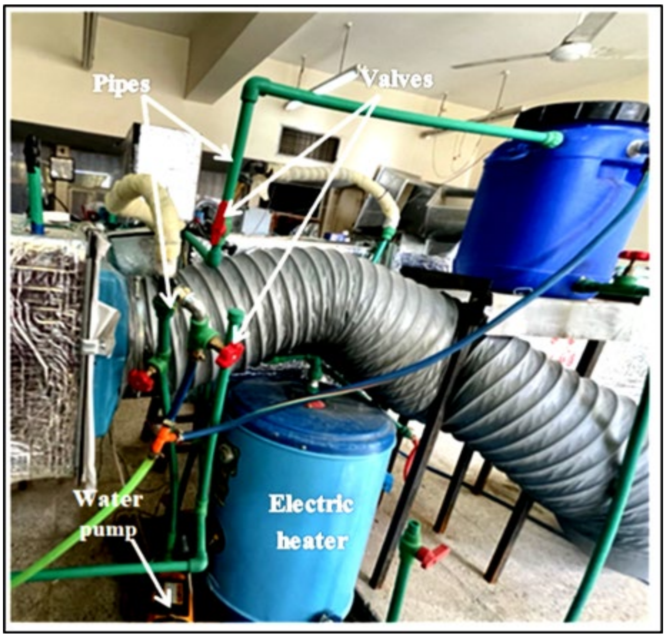


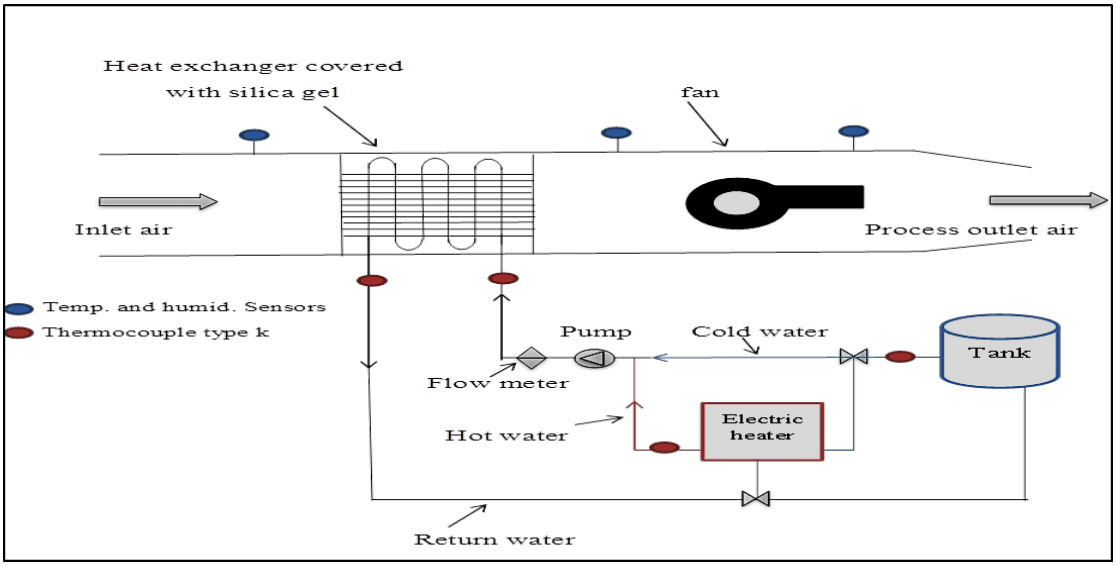
Figure 3: Water system

A water circulation pump with a power of (0.37 kW) and a centrifugal fan to pump or (blow) air with 566 rpm rotation speed and fan power is 100W. The air speed was controlled by changing the fan voltage using a voltage regulator device, and because the air duct cross-section is fixed, we get a variable airflow. A humidification system and heat sources were used at the device entrance to simulate the conditions in hot and humid climates. The duct and tubes are isolated by a heat insulator.

2.3 Measurements and Uncertainty Analysis

A sensor was used to measure the temperature and humidity before and after the heat exchanger installation. The thermocouple probe that was fixed over was thermally insulated. A flow meter was employed to measure the flow rate of water entering the exchanger and adjusts it according to the design. Integrated monitoring systems have been prepared to measure the air temperature and humidity in the system, as well as the water temperature and air velocity recorded by the ARDUINO – MEGA 2560 controller. The data to be recorded and analyzed is transferred to the computer. Sensors were used to measure the air temperature, and a humidity sensor; DHT22) was placed in the main duct before and after each process section. Four thermocouples (model type (k)) were used to measure the water inlet and outlet temperatures of the electric heater stage and cold water. Errors in measurements were estimated by uncertainty analysis. Experimental errors can generally result from instrument selection, instrument condition, environment, etc. Therefore, uncertainty analysis is required to prove the accuracy of the experiment data. The total uncertainties of the measurements are to be ±0.5%ºC for air temperatures, ±2%RH for humidity, 0.25%ºC for water temperatures, and ±0.025 m/s for air flow rate.

Figures 4 (a and b) manifest the schematic diagrams and final form of the system, respectively, after placing the heat exchanger in the duct and setting up the other parts.



(A)

(B)

Figure 4: System layout (a) Schematic diagrams (b) final form of the system

The electric heater was turned on to heat the water in the hot water storage, then the water pump was turned on to circulate the hot water inside the heat exchanger tubes, and the fan was turned on to start the regeneration process. After drying the desiccant material, the water system is controlled by valves to change from the hot storage to the cold storage to start removing the moisture from the air by the silica gel. Several experiments were conducted under different conditions.

3. Calculation

The total cooling capacity, the thermal performance coefficient of the system, the effectiveness of the silica-coated heat exchanger, and the difference in moisture removal were calculated from the following equations:

3.1 Cop Thermal

In this type of system, the system's efficiency is measured by the amount of moisture removed from the air and the value of thermal cop, as mentioned in most of the sources that have been viewed and mentioned in this research. The thermal performance coefficient is calculated through Equation no 1. It can be defined as the ratio between the total cooling capacity in the dehumidification process to the energy needed to regenerate the desiccant material in the regeneration process.

$$\text{COP th} = \frac{Q_{total}}{Q_{regeneration}} \quad (1)$$

where:
Q_{total}: Total cooling capacity

$$Q_{total} = \dot{m}_{air} \times (h_{in} - h_{out}) \quad (2)$$

h_{in}: Enthalpy air inlet to the heat exchanger.
h_{out}: Enthalpy air outlet to heat exchanger.
$(h_{in} - h_{out})$ is in(kJ/kg).
$Q_{regeneration}$: Regeneration heat consumption

$$Q_{regeneration} = \dot{m}_{w\ regeneration} \times CP_w \times (T_{w\ reg.inlet} - T_{w\ reg.out\ let}) \quad (3)$$

$T_{w\ reg.inlet}$: Inlet water temperature heat exchanger covered with silica gel
$T_{w\ reg.out\ let}$: Outlet water temperature heat exchanger covered with silica gel
Q is in (kW).

3.2 Heat Exchanger Covered With Silica Gel Effectiveness

The efficiency of the heat exchanger is defined as the ratio between the actual heat transferred through the heat exchanger to the maximum possible heat transfer, calculated through Equation 4.

$$\epsilon = \frac{Q_{act}}{Q_{max}} \quad (4)$$

Where:
Q_{act} : Actual heat transfer
Q_{max}**:** Maximum possible heat transfer
Maximum possible heat transfer rate:

$$Q_{max} = C_{min} \times (T_{c\ in} - T_{h\ in}) \quad (5)$$

Actual heat transfer rate:

$$Q_{act} = Q_{max} \times \epsilon \quad (6)$$

$$\epsilon = 1 - \exp\left[\frac{NTU^{0.22}}{C_R}\{\exp(-C_R NTU^{0.78}) - 1\}\right] \quad (7)$$

where:
$C_R = \frac{C_{min}}{C_{max}}$
Minimum C
$C_c = CP_c \times \dot{m}_c$
$C_h = CP_h \times \dot{m}_h$
$C_{min} = MIN\ (C_h, C_c)$
$\dot{m}_c = \rho_{air} \times \dot{V}_{air}$
NTU=UA/C_{min}

$R_{tot} = R_{in} + R_{f\,in} + R_{cond.} + R_{out}$

$UA = \frac{1}{R\ tot}$

3.3 Difference Moisture Removal

The moisture removal during the regeneration and dehumidification processes is defined by the moisture content difference between inlet air and outlet air (g/kg).

$$\Delta w = w_{air\ in} - w_{air\ out} \quad (8)$$

where:

$w_{air\ in}$: Moisture content of inlet air

$w_{air\ out}$: Moisture content of outlet air

4. Results and Discussion

4.1 Regeneration The Desiccant Material (Silica Gel)

The desiccant material needs to be regenerated after the process of dehumidifying. Several experiments were conducted during the regeneration process, as shown below:

4.1.1 The effect of regeneration air flow rate on the moisture removal from the desiccant material

Airflow rates with different testing values (0.165, 0.33, and 0.48 m³/s), as shown in Figure 5, depict the effect of regeneration air flow rate on the moisture removal from the desiccant material. Increasing the airflow reduces the silica gel's ability to remove moisture due to the low temperature of the water inside the pipe. The increase in the amount of air for the same amount of water leads to an increase in the heat exchange between them and a decrease in the hot water temperature, making it difficult to expel moisture from the silica gel granules. Through experiments, the amount of moisture released decreased by 60%. In addition, it was found that the flow of (0.165 m³/s) represents the best flow to regenerate the desiccant material. The least flow rate in the study was removed (8 g/kg) for the same period and regeneration temperature [19-21].

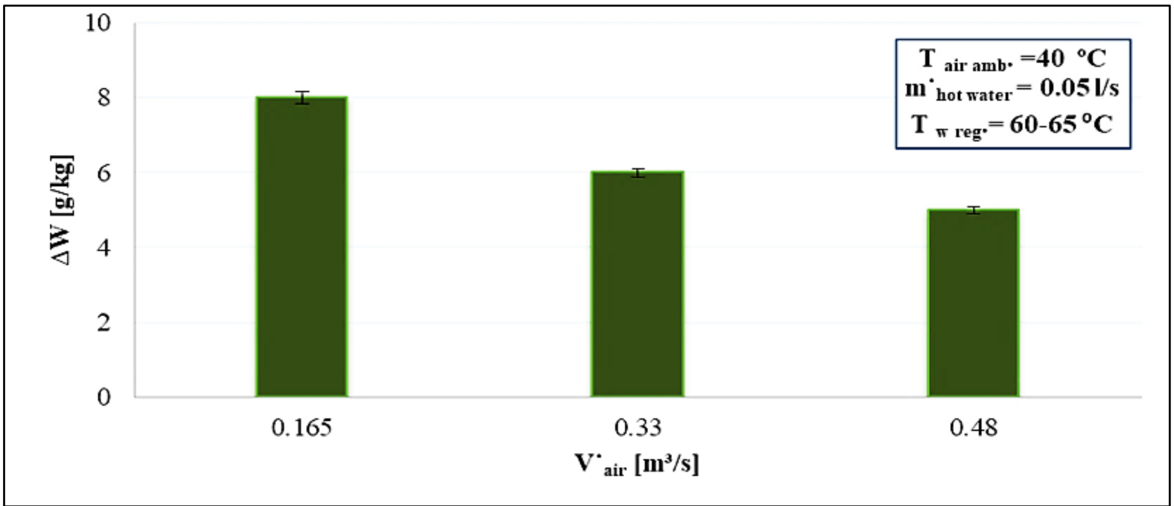


Figure 5: Amount of moisture removed from desiccant material for different air flows

4.1.2 The effect of inlet hot water flow rate on the moisture removal from the desiccant material

The effect of the hot water flow rate entering the exchanger on the desiccant dehumidification process is shown in Figure 6. Three hot water flow rates (0.05, 0.083, and 0.12 l/s) were tested. Increasing the inlet water flow rate increases the temperature of the tubes and fins and the air temperature surrounding the desiccant. Thus, Increasing the air temperature improves the desiccant material's ability to release moisture inside it by increasing the evaporation process. The moisture released increased by 34% with an increasing hot water flow rate from (0.05 to 0.12 l/s). The highest moisture removal rate from the silica gel was (ΔW = 4.5 g/kg) at the highest water flow during 10 minutes in this study [13].

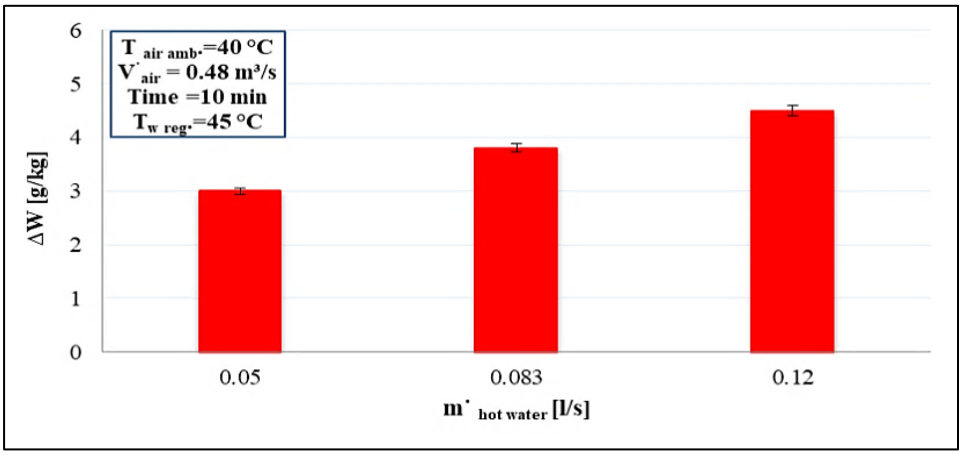


Figure 6: Amount of moisture removed from desiccant material for different hot water flows

4.1.3 Effect of inlet air flow rate on the time of regeneration

The effect of inlet air flow rate on the time of regeneration is shown in Figure 7. Three air flow rates are tested (0.165, 0.33, and 0.48 m^3/s). By increasing the inlet air flow rate with the same moisture content, regeneration temperature, and hot water flow rate, the time required to regenerate the desiccant silica gel increases because the increased air flow rate reduces the overall temperature of the heat exchanger covered with silica gel (fins, tubes, silica gel), so the ability of the desiccant to release moisture decrease. Therefore, the minimum time required to regenerate the desiccant is (7 minutes) at a flow of (0.165 m^3/s).

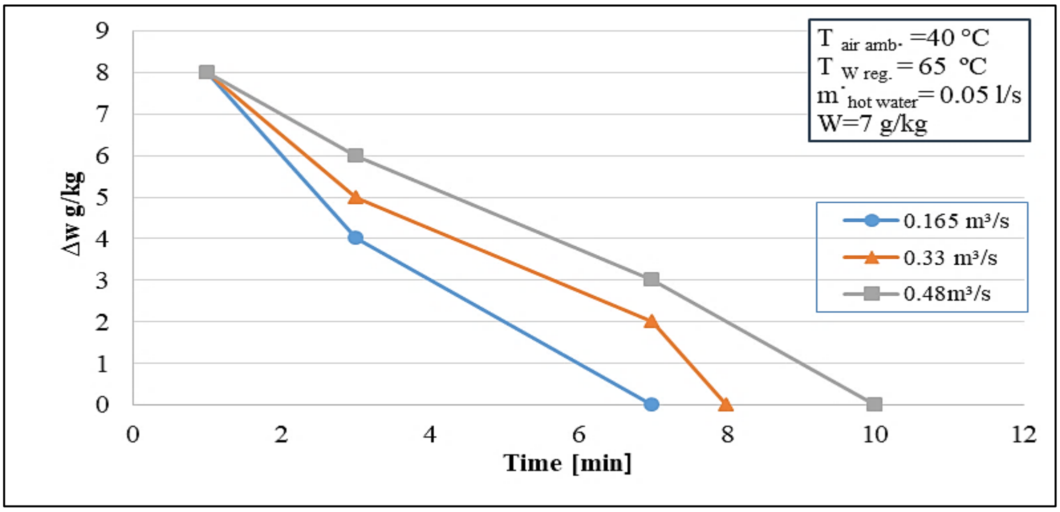


Figure 7: The minimum time required to regenerate the silica gel at the highest temperature for regeneration with different air flows

4.2 Dehumidification

The air entering the system is first treated by removing the moisture from the heat exchanger covered with silica gel. Some effects of this process have been studied, as mentioned below.

4.2.1 Effected of inlet air flow rates on moisture removal

Three air flow rates were tested (0.165, 0.33, and 0.48 m^3/s). Figure 8 elucidates the effect of airflow rates on the moisture removal from the cooling system inlet air. Increasing the airflow rate increases the air velocity in the heat exchanger. Thus it decreases the moist air contact with the desiccant material. That reduces the amount of moisture released from wet air, as the percentage of moisture removed from the air decreased to 19% by increasing the air flow rate. The figure also shows that by increasing entering air moisture content, the ability of the dryer to dry the air increases due to the increase in the moisture content difference between the dried substance and the air [22,23].

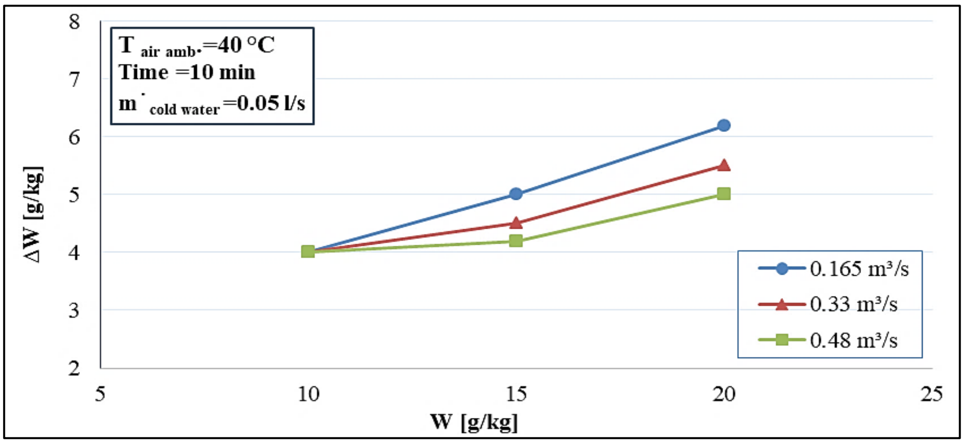


Figure 8: The ability of the desiccant to remove moisture from the air for different air flows and moisture contents

4.2.2 Effect of cold water flow on the moisture removal

Figure 9 shows the effect of cold water flow on the dehumidification process. Three cold water flows were studied (0.05, 0.083, and 0.12 l/s), and the water temperature was (27ºC). Experiments showed that by increasing the flow of cold water to the heat exchanger, the ability of the desiccant to draw more moisture from the air was increased. That is because of the decrease in the desiccant material temperature. The role of cold water is to remove the residual heat from the regeneration process and the heat associated with the adsorption process, which improves desiccant moisture removal [13].

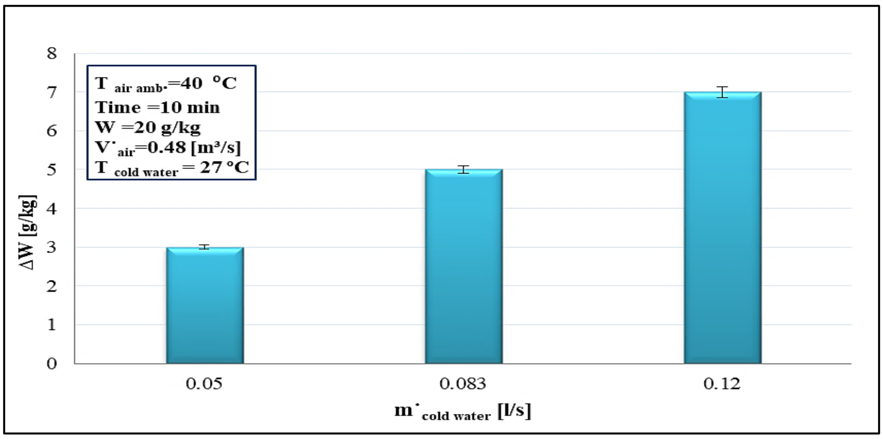


Figure 9: Amount of moisture removed from the air for different cold water flows air

4.2.3 Effect of inlet air flow rate on the time of dehumidification

Figure 10 shows the effect of the inlet air flow rate on the time of dehumidification is studied. Three air flow rates were tested (0.165, 0.33, and 0.48 m³/s). Through experiments, when the airflow rates of the incoming air were high (0.48 m³/s), the effectiveness of the desiccant was high in removing moisture from the air. In this case, the desiccant material (silica gel) can work for a longer period before being saturated.

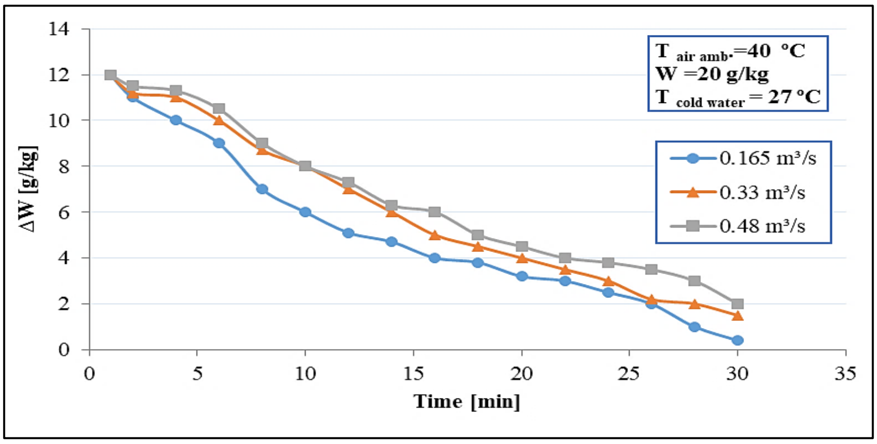


Figure 10: Effect of time on dehumidification of air with different air flows

4.3 Reducing the Adsorption Heat in the Desiccant Coated Heat Exchanger

In addition to the function of the heat exchanger covered by the desiccant in removing moisture, it also works in removing the heat associated with adsorption through the use of cold water in the pipes. The effect of using water is shown below.

4.3.1 Results of the system with cold water

The process accompanying the adsorption process is the release of heat into the air, which raises its temperature. This effect represents one of the most crucial issues facing dehumidification and air drying units. In the case of the heat exchanger covered by the desiccant, due to the use of cold water in the tubes, the process associated with adsorption decreases the air temperature, as a result of heat transfer between water and air, as shown in the psychometric chart in Figure 11. The result of using constant inlet water temperature (25°C), air flow rate (0.48 m^3/s), water flow rate (0.05 l /s), and moisture content (15 g/kg) have been observed. As a result, the exchanger reduced the air temperature by (5-6°C).

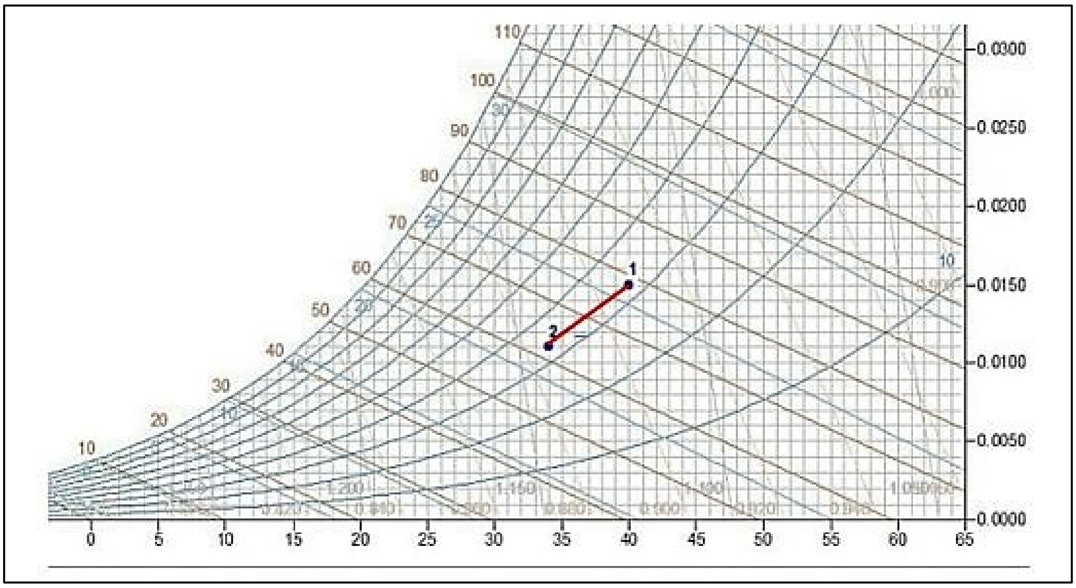


Figure 11: Clarification of the use of cold water on the psychometric chart

4.3.2 Results of the system without cold water

Experiment work was conducted without water passing through the exchanger during the air drying process. The same boundary conditions in section 6.3.1 were tested. It was found that the air temperature increased by (3°C) because the moisture extraction process releases heat, as shown in the psychometric chart in Figure 12.

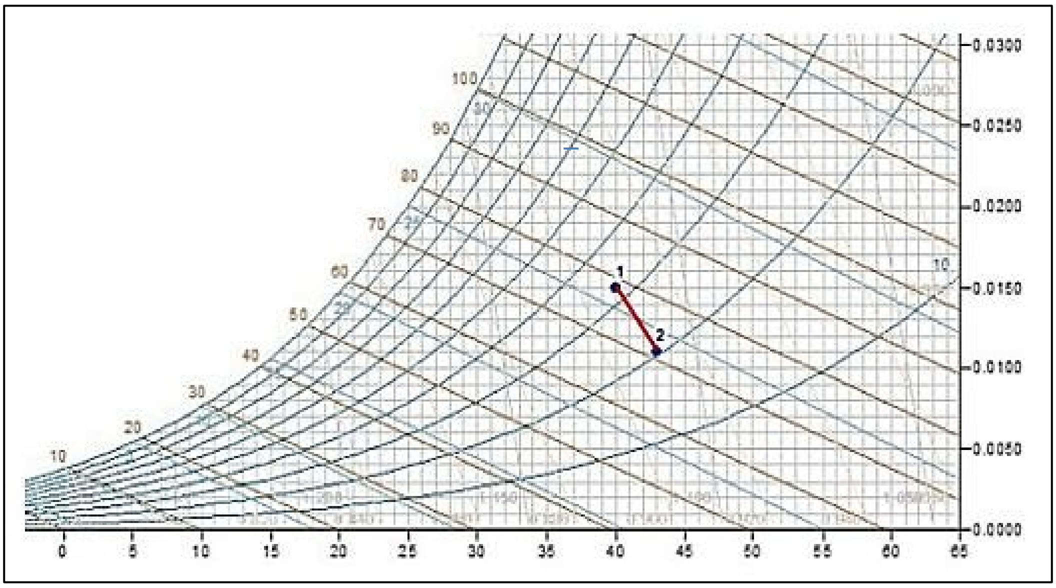


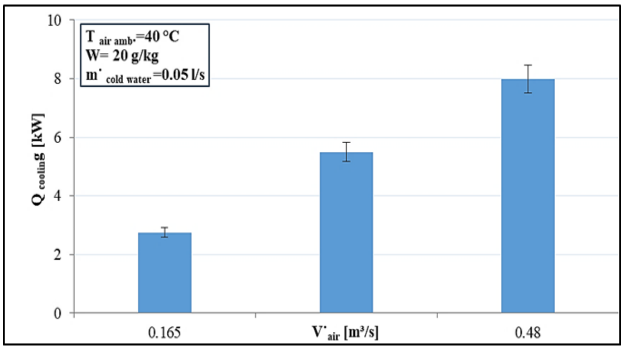
Figure 12: Clarification of not using cold water on the psychometric chart

4.4 Cooling Capacity and COP Thermal

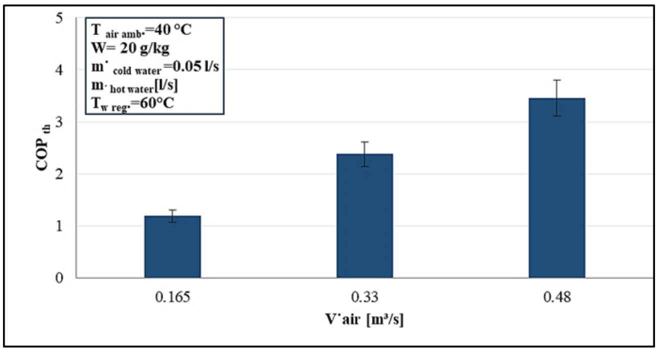
Several factors that affect the value of the cooling capacity and thermal performance coefficient of the system have been studied, and the following are some of those influences:

4.4.1 Effect of the inlet air flow rate on the cooling capacity and the cop thermal value

The effect of the inlet air flow rate on the cooling capacity and the value of the COP_{th} is shown in this section. Three air flow rates were tested (0.165, 0.33, and 0.48 m³/s). Constant inlet air temperature and humidity (40°C, 20 g/kg) were used, and the water flow rate was (0.05 l/s). When the airflow increases, the latent load increases significantly, and the sensible load also increases, and thus the cooling capacity increases where the increase was 65%, see Figure (13 a). Because the amount of air to be cooled increases with the same amount of water in the exchanger, the rate of heat transfer between air and water increases, and thus the (COP_{th}) increases, see Figure (13 b), until it reaches the highest value (3.5) at the flow of (0.48 m³/s) [24].



(A)



(B)

Figure 13: (A) Cooling capacity value at different air flows (B) COP_{th} value at different air flows

4.4.2 Effect of hot water flow on the cop thermal

Figure 14 shows the effect of hot water flow rates inside the heat exchanger on the coefficient of thermal performance. Three regeneration hot water flows were tested (0.05, 0.083, and 0.12 l/s). The test was carried out under the following conditions: ($T_{air\ ambient}$ = 40°C, $W_{air\ ambient}$ = 20 g/kg and $\dot{V}_{air}$ =0.48 m³/s). The regeneration hot water temperature (60°C) has been used. Through experimental work, it was found that increasing the flow rate of hot water increases energy consumption at higher flows. And the thermal energy required to regenerate the desiccant material increases because the energy required for regeneration depends on the amount of hot water flowing inside the pipes and increases with its increase. As for the COP_{th}, it is inversely proportional to the regeneration energy, according to Equation 1. It decreases when the water flow increases, which leads to a decrease in the value of COP_{th}, where its highest value was (3.5) at the flow of (0.05 l/s).

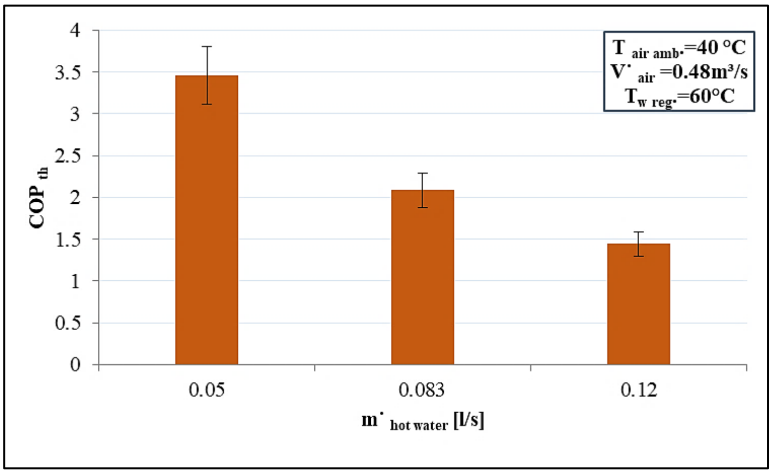


Figure 14: COP_{th} value at different hot water flows

4.4.3 Effect of regeneration temperature on the COP thermal

Figure 15 portrays the effect of regeneration temperature on the thermal COP. Five hot water temperatures were tested (45, 50, 55, 60, and 65°C), with constant water flow (0.05 l/s) and airflow (0.48 m³/s). Increasing the water temperature requires more energy consumption due to the increase in the temperature difference between the water entering and leaving the heat exchanger, which leads to an increase in the regeneration energy and a decrease in the COP_{th} because the relationship between them is inverse [24-26].

4.5 Heat Exchanger Covered With Silica Gel Effectiveness

The effectiveness was calculated for the silica gel-coated heat exchanger in a case of moisture removal from inlet air to the space and the desiccant regeneration phase.

In the dehumidification stage, the effectiveness was calculated for three outdoor air temperatures (35, 38, and 40ºC), constant temperature of the inlet water to the exchanger, air moisture content, airflow, and cold water flow with the values mentioned in Table 2. It was found that with the increase in the outside air temperature, the value of the maximum amount of heat (Q max) increases, and thus decreases the effectiveness of the exchanger, as shown in Figure 16.

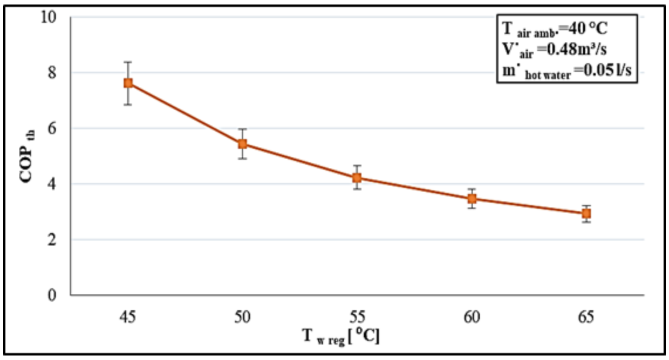


Figure 15: COPth value at different regenerationtemperature6

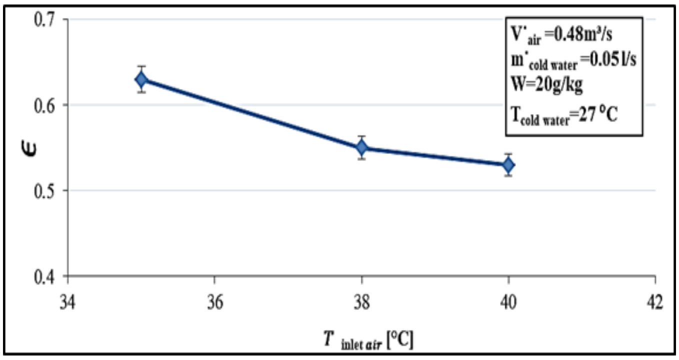


Figure 16: The effect of inlet air temperature on the values of effectiveness in dehumidification

Table 2: Factors affecting the effectiveness of dehumidification

T_{air} °C	$T_{w\,cold}$ °C	W g/kg	$\dot{V}_{air}$ m³/s	$\dot{m}_{cold\,water}$ l/s	ϵ
35	27	20	0.48	0.05	0.63
38	27	20	0.48	0.05	0.55
40	27	20	0.48	0.05	0.53

In the regeneration stage, the effectiveness was calculated for three external air temperatures (35, 38, and 40°C), and the temperature of the hot water inlet to the heat exchange, airflow, and hot water flow stabilized at the values mentioned in Table 3. It was found that increasing the temperature of the inlet air to the heat exchanger leads to increased heat exchanger effectiveness due to the reduction in the maximum heat (Q_{max}). Figure 17 exhibits the effectiveness of the heat exchanger in the regeneration process.

Table 3: Factors affecting the effectiveness of regeneration

T_{air} °C	$T_{w\,reg.}$ °C	$\dot{V}_{air}$ m³/s	$\dot{m}_{hot\,water}$ l/s	ϵ
35	65	0.48	0.05	0.44
38	65	0.48	0.05	0.49
40	65	0.48	0.05	0.52

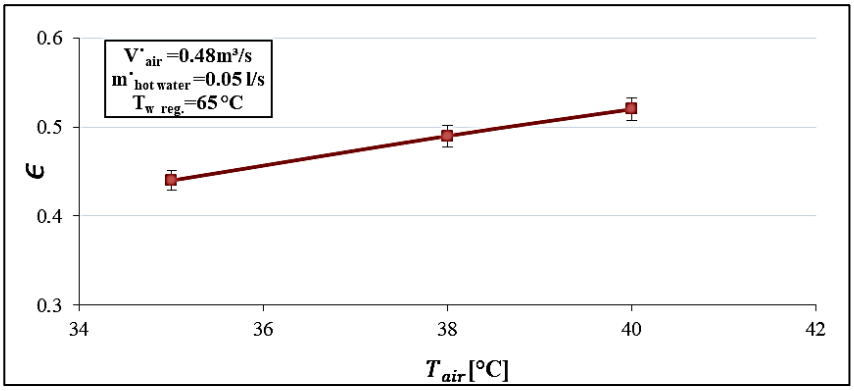


Figure 17: The effect of inlet air temperature on the values of effectiveness in regeneration

5. Conclusion

The Design and manufacture of a heat exchanger covered with silica gel have been accomplished in this study. In addition, a practical study was conducted to evaluate the performance of dehumidification in the heat exchanger in hot and humid areas. Several factors (airflow, hot and cold water, and their effect on the dehumidification and COP_{th} of the system) were studied. As a result, the following points have been concluded:

1) By increasing the airflow rate, the amount of moisture released from the desiccant material in the regeneration phase decreases by 60%.
2) Increasing the hot water flow rate increases the amount of moisture released from the desiccant by 34%, while the COP_{th} decreases by 57%.
3) In the process of removing moisture from the air, the amount of moisture removed decreases with the increase in airflow and low humidity. While the cooling capacity and COP_{th} increase.
4) Increasing the flow of cold water increases the humidity drawn from the air and reduces the temperature of the air entering the system.
5) The regeneration temperature negatively affects the COPth, as it decreases when the temperature increases from 45-65ºC because raising the water temperature requires more thermal energy.
6) Increasing the air temperature increases the covered heat exchanger efficiency in the regeneration stage, while the effectiveness decreases in the dehumidification stage.

Nomenclature

Q total	**Total cooling capacity**	**kJ**
$Q_{regeneration}$	Regeneration heat consumption	kJ
h_{in}	Enthalpy of inlet air	kJ/kg
h_{out}	Enthalpy air outlet to the heat exchanger	kJ/kg
$\dot{m}_w$	Mass flow rate of water	kg/s
Cp	specific heat capacity	J/K kg
$\dot{V}_{air}$	Air flow rate	m^3/s
$T_{w\ reg.inlet}$	Inlet water temperature heat exchanger covered with silica gel	°C
$T_{w\ reg.outlet}$	Outlet water temperature heat exchanger covered with silica gel	°C
ΔW	Moisture content difference	g/kg
$\mathbf{Q_{act}}$	Actual heat transfer	kJ
$\mathbf{Q_{max}}$	Maximum possible heat transfer	kJ

Greek Symbol

ϵ	Effectiveness of heat exchanger covered with silica gel

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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