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RESEARCH ARTICLE – MECHANICAL ENGINEERING

Experimental Study on Dehumidification by Silica Gel Blue Using Dehumidification System and Air-Conditioning

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Abstract

The growing issue of energy shortages has been exacerbated by the increasing demand for air conditioning in tropical regions. This has highlighted the need for supplementary methods to reduce the load on air conditioning systems and thereby lower energy consumption. The objective of this study is to evaluate the effectiveness of silica gel-Blue as a dehumidifying agent for removing moisture generated from sources such as human respiration, perspiration, and household activities like ironing. To address this problem, a dehumidification system was designed consisting of several shelves loaded with silica gel-blue to help absorb moisture. Experimental tests were conducted using a dehumidification system in conjunction with an air conditioning system, measuring its moisture absorption capacity and its impact on relative humidity and energy consumption. The results showed that relative humidity levels decreased to 33%, 29%, and 25% in June, July, and August, respectively, when using the combined system. The moisture absorption rates of silica gel-Blue were recorded as 83.39 g/h in June, 70.82 g/h in July, and 65 g/h in August. It was also found that approximately 750 g of silica gel-blue was required to remove the moisture produced by one person. Furthermore, the electrical energy consumption was reduced to 3.5 kWh with the dehumidification system, compared to 5.1 kWh without it. These findings confirm the efficiency of silica gel-Blue in humidity control and demonstrate its potential for reducing energy usage when integrated with air conditioning.

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Keywords: Renewable Energy; Adsorption Materials; Air Conditioning; HVAC Processes; Solar Energy.

1. Introduction

International energy demand has risen recently as a result of the expansion of the powerful global economy. Together, the United States, China, and India account for more than 70% of the world's energy demand. Most of this energy is used for cooling and heating applications [1]. Non-renewable energy sources have been and continue to be the world's primary source of energy for many years implying that renewables account for less than 10% of global energy consumption [2]. The significant rise in internal humidity caused by individuals breathing in the region, which results in an uncomfortably hot environment during the summer, is another significant issue with latent load. HVAC (heating, ventilation, and air conditioning) systems and humidifiers can help. On the other hand, sophisticated HVAC systems that control temperature and humidity are expensive and consume more energy than traditional air conditioners, which condense vapor by reducing the air temperature below the dew point to reach the desired humidity level [3]. Due to the stressful environment, this process causes moisture in the processed air to condense together with water drops and condensate. The method is acceptable, but it is always essential to raise the temperature to a comfortable level because it is always too low for human comfort [4]. The overall cooling load is made up of latent components of 30% to 40%, and in hot, humid climates, this percentage might even exceed 70%. Therefore, research has concentrated on developing strategies to reduce latent energy by reducing moisture in an environment with high humidity [5]. Adsorption materials are frequently used in adsorption processes to remove moisture from space. Adsorption systems can be fed with low heat sources such as solar energy or waste heat as one of the clean energy sources. Adsorption systems have the benefit of not having any moving parts, as well as not corroding or crystallizing. Additionally, an adsorption chiller's effectiveness is unaffected by variations in the temperature of the heat source, making them appropriate for solar applications [6]. One of the best adsorption materials, silica gel has a large specific surface area that makes it simple to absorb water, making it a superior drying agent [7]. Desiccant materials can be classified as either inorganic (such as zeolites, clay, silica gel-Blue, CaCl2, LiCl, or LiBr) or carbon-based (like graphite, activated carbon, carbon nanotubes, carbon molecular sieves, or pre-shaped carbon fibers) [8]. There are numerous studies on dehumidification; the one used in this study aims to get rid of moisture. For this, Kamel et al. [9] offer valuable insights into emerging systems and technologies designed for efficient moisture control. In a study by Alahmer et al. [10], silica gel-Blue and molecular sieve desiccants were utilized as drying materials. The moisture removal capacity of the two materials increased by approximately 2.065 g/kg of dry air and 5.71 g/kg of dry air, respectively.

Nomenclature & Symbols

A/C	Air-conditioner	p_{ws}	Saturation Pressure of Water Vapor of Moist Air
DS	Dehumidification System at Atmospheric Pressure	w	Humidity ratio
h_{gf}	Latent Heat of Evaporation	m_w	Mass of Water Vapor
q_l	Latent Load	m_a	Mass of dry air
RH	Relative humidity	mn	amount of water vapor
HVAC	Heating ventilating and Air Conditioning was the Humidity Ratio of the Saturated Moist Air		

Using silica gel-Blue, Mahmood et al. [11] have created an innovative moisture-absorbing material that, when integrated into walls and ceilings, effectively reduces indoor humidity levels. Simulation results demonstrated that this approach can significantly decrease humidity in heavily used indoor areas, presenting a sustainable alternative to conventional mechanical ventilation systems. In a study by Lopez-Carreon et al. [12], this review examines the core processes involved in moisture ingress and explores effective strategies for its mitigation. It highlights the primary mechanisms of water movement, including capillary action, vapor diffusion, and condensation, and underscores the significance of employing moisture-resistant materials along with hygrothermal simulation tools to manage and prevent moisture-related issues. The utilization of solar energy to remove moisture from a location using an adsorption process was highlighted by Yang and Zhao [13]. For the comparative investigation of moisture sorption and desorption characteristics, Singh et al. [14] used a variety of materials, including dried cow dung, coco peat, sawdust, and silica gel-Blue. After the experiment, it was discovered that silica gel has the highest moisture adsorption and sawdust has the lowest adsorption rate. Yari et al. [15] A non-invasive portable microwave radar system has been developed to detect moisture within building elements. This innovative technology enables the early detection of moisture problems in walls, roofs, and foundations, allowing for prompt corrective actions to prevent structural deterioration. Al-Samari et al. [16], Investigation on the viability of using geothermal energy for climate control in Iraq. However, when the geothermal system demonstrated its capability to offer the space's occupants a suitable level of air conditioning, the issue of a high level of humidity surfaced. Despite the growing body of research on moisture control and dehumidification using various adsorbent materials, most prior studies have focused either on theoretical analysis, simulation models, or experimental tests under controlled conditions without implementing practical integration with conventional HVAC systems in real-life environments. Furthermore, there is limited research addressing cyclic adsorption-based dehumidification in continuously occupied indoor spaces where humidity levels fluctuate significantly. While studies have explored the potential of silica gel and other desiccants, few have examined the operational efficiency and sustainability of periodically regenerated adsorption systems using silica gel-Blue in actual air conditioning setups. Therefore, this study presents a novel approach that combines a standard air conditioning unit with an integrated, cyclic dehumidification system utilizing silica gel-Blue. By replacing the saturated adsorbent material with a dry one every hour, this method maintains effective humidity control, improves indoor comfort, and offers an energy-efficient, practical alternative suitable for high-humidity environments.

2. Materials and methods

In this work, silica gel-blue was used as an adsorbent to remove moisture from the compartment.

2.1. Material preparation

Silica gel was prepared for experiments, for its ability to remove moisture with a diameter of 3-5 mm and it can adsorb up to 40% of its own weight in water due to its high pore area per unit volume, which can be as high as 450 m2/g [17]. Silica gel appears deep blue when dry and then turns red when wet. Additionally, silica gel-Blue is a polymeric structure of incompletely dehydrated colloidal silicic acid, with the formula (SiO2.nH20) and it is dried in a range of 50 ºC to 90 ºC [18]. The adsorbent material was weighed on an electronic compact scale before and after the removal of moisture. Specifications of the adsorbent material (silica gel-Blue) are shown in Table 1.

Table 1. Specifications of the adsorbent material (silica gel-Blue)

Color	Diameter size	Chemical formula
Blue	3-5 mm	(SiO2.nH20), [18]

2.2. Theoretical

According to the room's approximate 76.8 m^3 size and the 8 people who will be using it, the recommended amount of silica gel-Blue, estimated at 6 kg, was determined. According to this study, the moisture content was determined using Eq. (1), and the mass of water vapor was determined using Eq. (2) assuming a temperature of 25 ºC and a humidity of 40%. The same calculations should then be performed assuming a temperature of 25 ºC and a humidity of 60%. It was discovered that there was a 350 g difference in the mass of water vapor when the humidity was dropped from 60% to 40%. Considering that 150 g of moisture is absorbed for each 1 kg of silica gel-Blue, each side of the dehumidifying system needs 3 kg of silica gel-Blue, which means it needs 6 kg of silica gel-Blue for the entire dehumidification system. That is why the system was designed with these dimensions and measurements. The moisture content was calculated in Eq. (1) where (w) is the humidity ratio, (m_w) is the mass of water vapor in kg and (m_a) is the mass of dry air in kg. Eq. (1) is [19]:

$$w = \frac{m_w}{m_a} \tag{1}$$

For dry air and water vapor, the ideal gas equation and Dalton's rule apply where they can occupy the same volume at the same temperature where (P_{ws}) is the saturation pressure of water vapor of moist air in (*pa*) and (P_{at}) is atmospheric pressure in (pa). as given in Eq. (2) [19]:

$$w_s = 0.62198 \frac{p_{ws}}{p_{at} - p_{ws}} \tag{2}$$

The ideal gas where (*P*) is pressure in kPa, (*V*) is volume in (m^3), (m_a) is mass in kg, and (R) is gas constant in J/kg. K and (T) is temperature in K. as given in Eq. (3)[20]:

$$Pv = m_a R\,T \qquad (3)$$

By dividing the latent load by the latent heat of evaporation, which may be used to determine the amount of water vapor that is released by each individual it was obtain where (m_n) is amount of water vapor in kg/s, (q_l) is latent load in W and (h_{gf}) is latent heat of evaporation in kJ/kg. as given in Eq. (4) [20]:

$$m_n = \frac{q_l}{h_{gf}} \qquad (4)$$

The amount of water vapor produced by these eight individuals in the room was calculated. The latent load per office employee is 55 W, according to ASHRAE [21] when the temperature is 25.5 ºC and the difference between the specific enthalpy for water vapor (h_g) and the specific enthalpy for water liquid (h_f) is 2441.34 kJ/kg. It was found that the amount of water vapor produced by one person for an hour was 81.0 g/h, which means that the total mass of water vapor produced in the room for eight persons was 648 g/h after calculating (m_n) from Eq. (4).

2.3. Methodology

The main components of the dehumidifying system are a rotating drum, 24 racks, two fans, a transparent polymer housing, 6 sensors connected to the Arduino (the sensor specifications are shown in Table 2), and a computer that records humidity and temperature during experiments. The (DS) system consists of two identical parts, one of which is the part responsible for removing moisture from the space occupied by the space occupants, and it is considered the most important part of the system. In addition, the other half of the (DS) system is the solar system (drying system). After rotating the dehumidifying system so that the interior part (inside the room) is outside, the process of drying the adsorbent material begins when exposed to sunlight. Fig. 1(a) represents the experimental setup of the (DS) system. The two-ton refrigeration capacity air conditioner that was used in the experiment was used with a dehumidifying system to test the efficiency of their work together.

Table 2. Sensor specification

Data	Outputs both Temperature and Humidity through serial data.
Power supply	3.3 V to 5.5 V
Humidity range	(0– 100% RH)
Temperature range	(-40 ~ 80 °C)
Resolution or sensitivity	Humidity 0.1%RH; temperature 0.1°C)
Accuracy	Humidity ± 2% RH (Max ±5%RH); temperature ±0.5°C
Temperature measurement precision, Humidity hysteresis	±0.5 °C, Humidity ±1RH; temperature ±0.2 °C, ±0.5%RH/year

The rig specifications; the system was created as a rotating iron cylinder that was mounted in the experimental room's window and had a height of 140 cm and a diameter of 50 cm. The cylinder shape was chosen (rather than any other geometric shape) because it is simple to rotate and because it avoids angles that might be challenging to rotate, as shown in Fig. 1(b). The cylinder was divided in the middle by an iron piece. With a thickness of 2 mm, the cylinder was divided into two parts symmetrically and equal in shape and size. The cylinder is hermetically closed at the top, and in the middle of each top of the system, there is a fan that circulates the air inside the system and pulls the moisture from the bottom to pass through the silica gel to start the adsorption process. The dehumidification system is installed in the window of the experiment chamber. A humid environment is created inside the room using a moisture generation source that simulates the amount of moisture generated by 8 people who occupy the space. Install sensors at the top and bottom of the two symmetrical portions of the system (at the entry and exit).

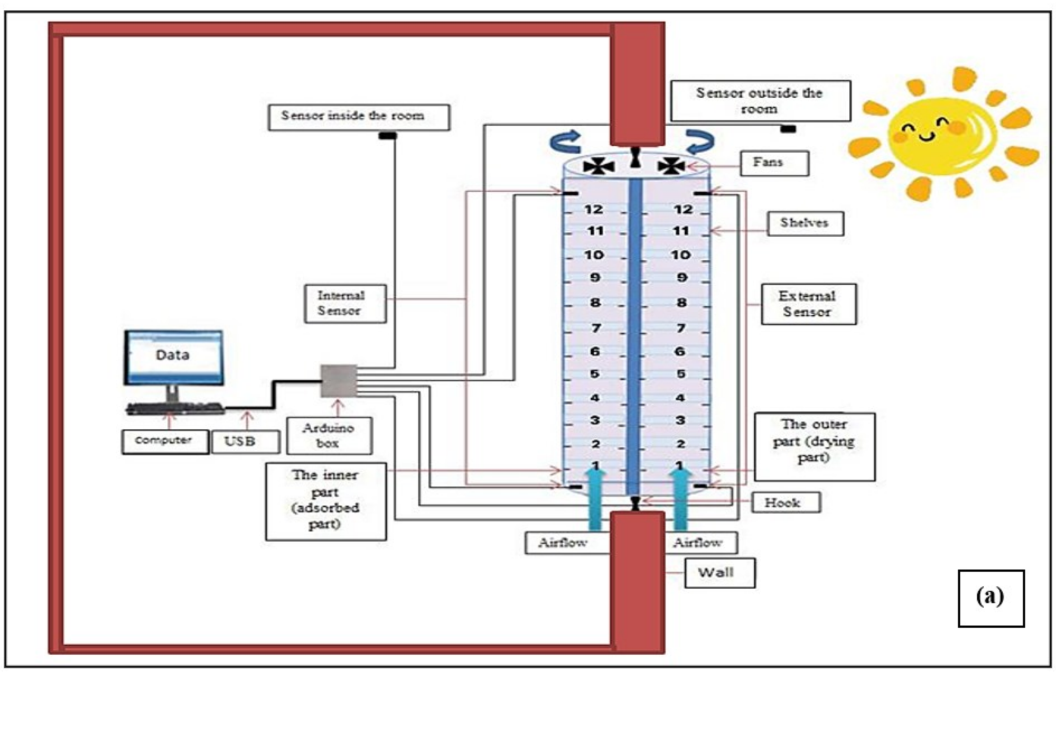

Fig. 1. (a) Schematic of the dehumidifier system, (b) The actual dehumidifier system

Two other sensors are also present; one is placed within the space to measure the humidity and temperature there, while the other is placed outside in a shaded location to measure the ambient temperature and humidity. The adsorbent material and the amount of water removed from the air conditioner were weighed before and after the experiment using an electronic scale. The dehumidification process starts after the fans and computer-related sensors are activated. The process is carried out by spinning the cylinder and exposing the wet adsorbent material to the sun for predetermined amounts of time. The experiments were conducted during the hot summer months (June, July and August) and it was measured. The maximum amount of moisture the material (silica gel-Blue) could adsorb, the rise in air temperature as a result of sorption, the length of time it took to desorb the moisture, the moisture added to the experiment, and the moisture removed.

3. Results and Discussions

In this section, the dehumidification system (DS) was integrated with the air conditioner, and the importance of silica gel was clearly demonstrated through its role in reducing the latent load by removing moisture. Several experiments were conducted in which the performance of (DS) was compared with an air conditioner split unit with a load of 8 persons, and the work of the air conditioner alone with the same load. The experiment was conducted in the harshest climatic conditions in the summer between 1:00 pm and 3:00 pm. In addition, it was calculated that the amount of water an air conditioner removes, which represents the amount of moisture removed from the space.

3.1. Effect of the adsorbent on the removal of relative humidity

The experiment was carried out using silica gel-Blue in the dehumidification process. Fig. 2 shows that this experiment was conducted during June for two hours, where the maximum temperature was 48°C and the minimum was 29°C. When using the split air conditioner, the maximum value of the humidity inside the room reached 40%, and then it began to gradually decrease until it reached 36%. When using the (DS) with the air conditioner, the process of dehumidifying was faster where the humidity decreased to 33%. The effect of temperature on the surroundings of the room appeared when the humidity was high when the air conditioner was used alone. The behaviour of temperature in the room is shown when this experiment was conducted in June. The temperature reached 33°C and decreased to 29°C when using the air conditioner only. While the temperature at the beginning of the experiment when using the (DS) with the air conditioner was 32°C and then decreased significantly to 26°C. This is evidence that (DS) when working with the air conditioner has overcome the heat produced by silica gel-Blue because it is an exothermic substance and even contributes to lowering the temperature as well.

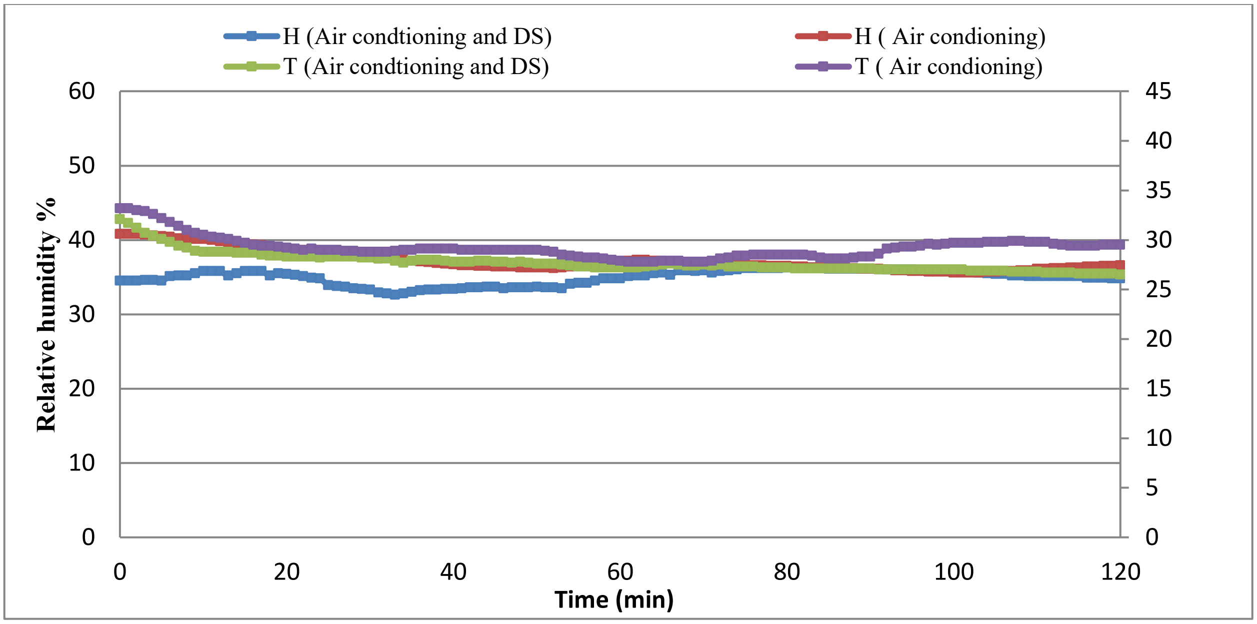

Fig. 2. Behaviour (DS) and air conditioner in dehumidifying and the change in temperature in June

Fig. 3 discusses the process of dehumidifying using the (DS) and the air conditioner in July. The same mechanism of work in the previous experiment, where the maximum temperature on the day of the experiment was 51°C and the minimum was 30°C according to the Iraqi meteorological organization. The highest value of the humidity inside the room when using the air conditioner reached 38% and then gradually decreased until it reached 32%. When using the (DS) with the air conditioner, the relative humidity decreased to 29%. The reason for the decrease in the humidity when compared to the month of June is that the month of July is considered higher in temperature and drier. In addition, this rise was evident even when there were 8 people occupying the space. The temperatures inside the room when using the (DS) with the air conditioner in July. The temperature when using the air conditioner reached 36°C, then it decreased to 30°C, but when using the (DS) with the air conditioner, the temperature was 32°C and then decreased to 25°C in July.

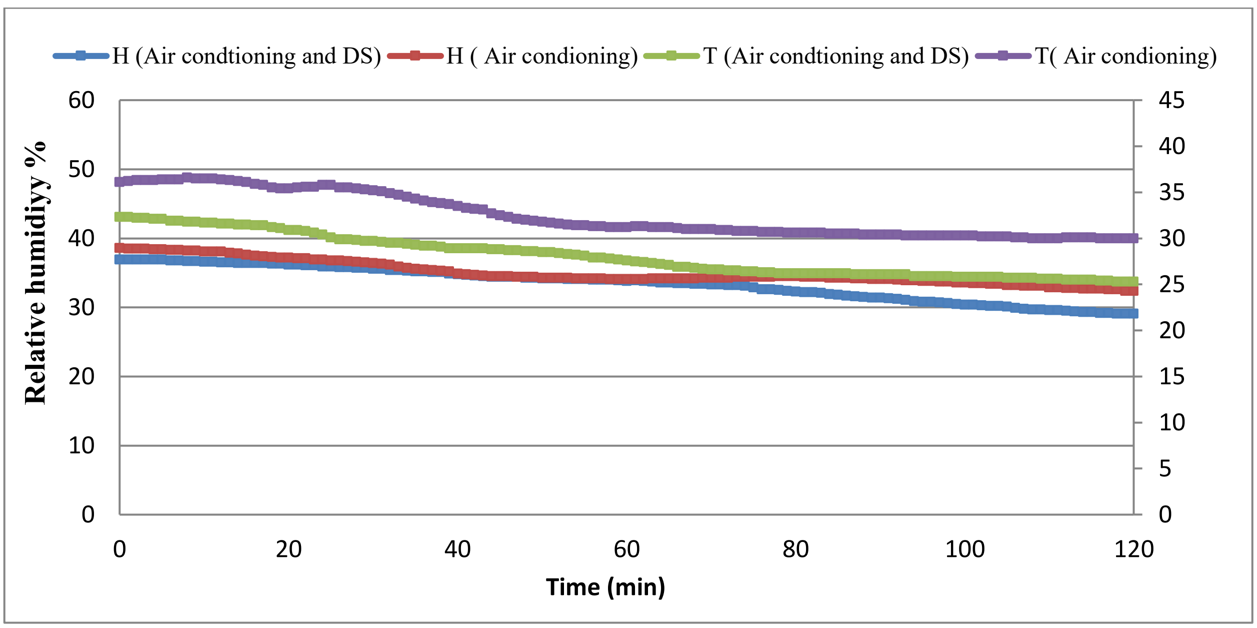

Fig. 3. Behavior (DS) and air conditioner in dehumidifying and the change in temperature in July

Fig. 4 shows the procedure of dehumidifying the same experiment in August. The dehumidification system with the air conditioner shows a clear effectiveness over the work of the air conditioner alone. The percentage of humidity when using the air conditioner reached 29% and decreased to 27%. While the relative humidity in the room decreased to 25% when using the (DS) with the air conditioner. The decrease in this percentage when compared to the previous months is because August in Iraq-Baqubah is characterized by a rise in temperature, offset by a rise in relative humidity. The temperature when using the air conditioner reached 33°C and decreased to 29°C, but when using the (DS) with the air conditioner, the temperature was 33°C and then decreased to 27°C. From the results, it was concluded that when the (DS) works with the air conditioner, there was a decrease in the temperatures inside the room. When using the (DS) alone, knowing the adsorption process generates a temperature of 2°C -3°C as mentioned previously.

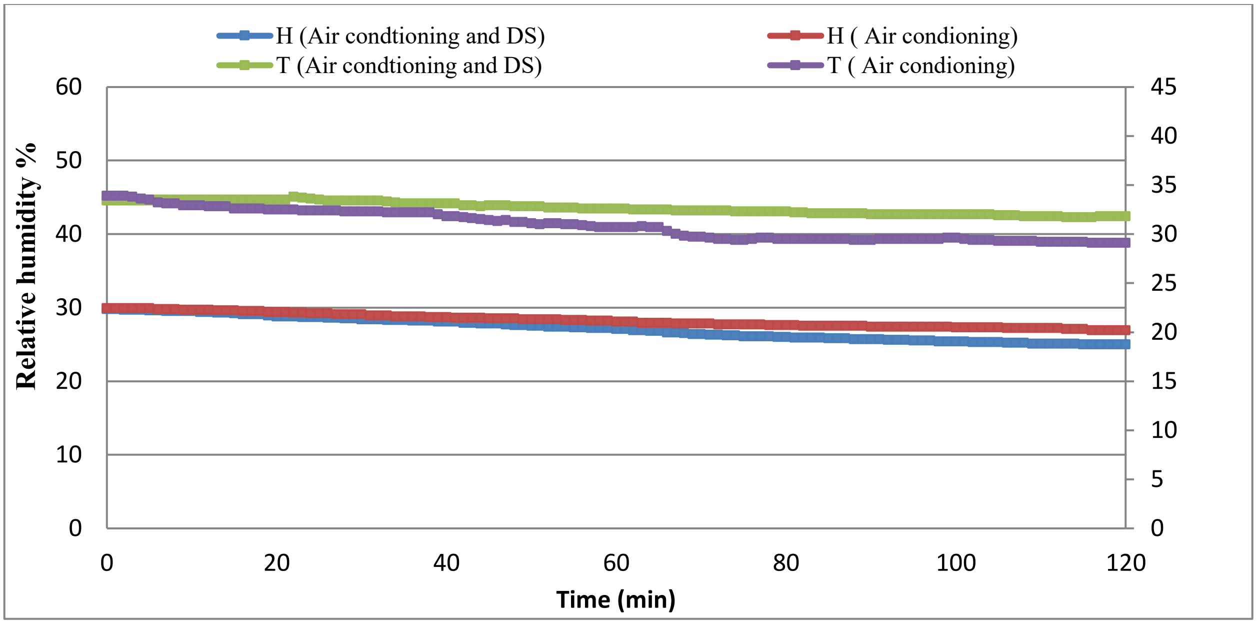

Fig. 4. Behavior of (DS) and the air conditioner in dehumidifying and the change in temperature in August

In Fig. 5(a) the amount of water vapor removed in June when using the split air conditioner was equal to 1404.03 g at a rate 68%. When using the (DS) with the air conditioner, the total amount of water was 658.49 g at a rate 32%. An average difference in the amount of water removed was 745.54 g. Fig. 5(b) shows that the amount of water removed during July when using the air conditioner was about 510 g at a rate 74%. When using the (DS) with the air conditioner the amount of water removed was 175 g at a rate 26%. The same experiment was repeated in August as shown in Fig. 5(c), the amount of water vapor removed when using the split air conditioner was equal to 950 g at a rate 56%. When using the (DS) with the air conditioner, the total amount of water was 750 g at a rate 44%. Where a decrease in the percentage of the amount of moisture appeared, the water collected during the work of the system with the air conditioner because this month is characterized by high relative humidity. However, the amount of water removed by the system and the air conditioner was still less than the amount of water when the air conditioner was working alone. From the previous forms, we conclude that when the (DS) works with the air conditioner, it works to reduce the load on the air conditioner, as it removes moisture as well. A sensitive electronic balance was used to calculate the weights of the adsorbed material, the specifications of the electronic compact scale are shown in Table 3.

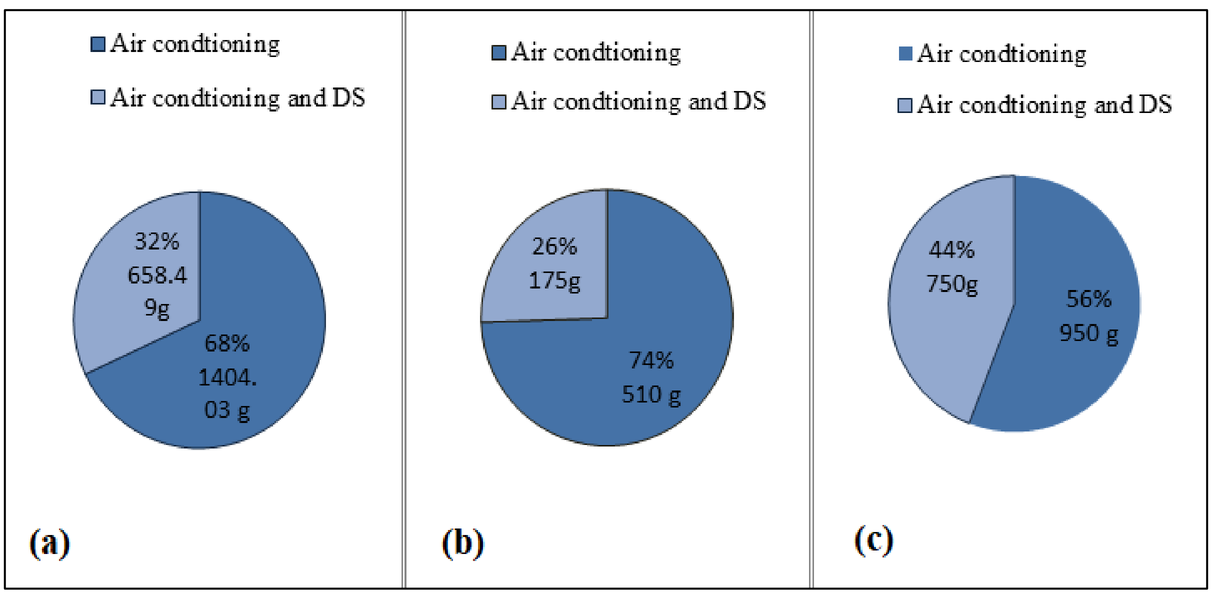

Fig. 5. Amount of water removed, (a) in June, (b) in July, (c) in August

Table 3. Electronic Compact scale specifications

Capacity	200g / 500g
Accuracy	0.01g (for 200g), 0.1g (for 500g)
Units	g/Oz/(for 0.1/0.2g accuracy)
Tare range	Tare full capacity
Auto off	60 seconds off
Operation temperature	5 – 35 °C
Display	LCD 5 digits

3.2. Comparison of the temperatures outside and inside the room

The large difference in temperature between the inside of the room when using the (DS) with the air conditioner and the temperature outside is apparent. Fig. 6 shows the temperature in June, when the temperature outside reached 42 °C and rises until it reaches its peak of 49 °C, corresponding to the temperature 32 °C inside the room and then decreases over time until it reaches 26 °C. The temperature in July is shown in Fig. 7 when using the (DS) with an air conditioner inside the room and the temperatures outside. The temperature inside the room was 32 °C and decreased until it reached 25 °C. In addition, the temperature outside the room reached 51°C.

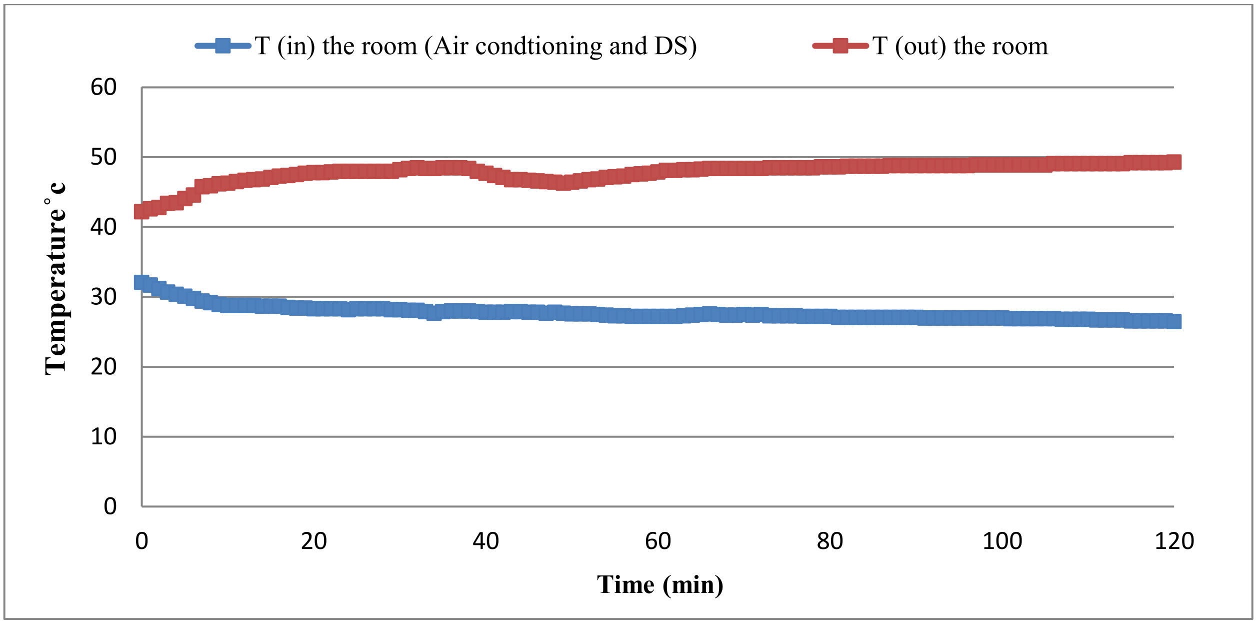

Fig. 6. Temperatures inside and outside the room in June

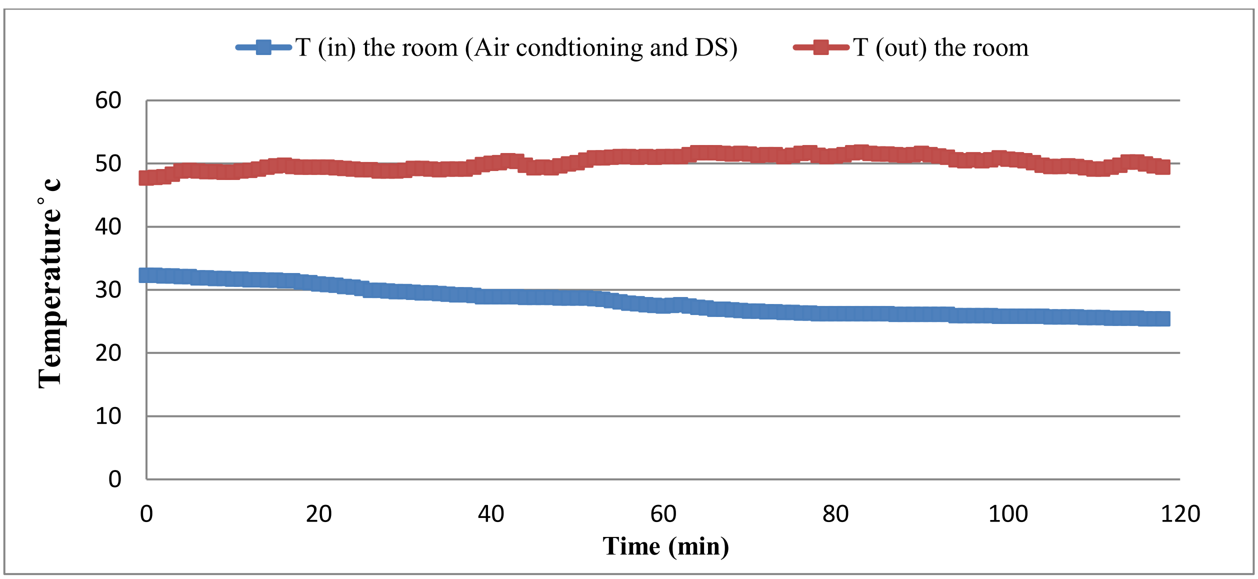

Fig. 7. Temperatures inside and outside the room in July

In August, the same previous experiments were conducted, where the temperature inside the room reached 33°C and decreased until it reached 27°C, but outside the room, the temperature was 52°C as shown in the Fig. 8. Fig. 9 shows the determination of the experimental conditions on the ASHRAE comfort chart when using the air conditioner without a dehumidifying system for two continuous hours during the peak summer temperatures. Where it is clear the relative humidity has decreased but it is out of the comfort zone, however the very low humidity helps people feel comfortable. Desiccant systems function by removing moisture from the air, thereby reducing indoor humidity levels. Lower humidity decreases the latent heat load, allowing the air conditioning (AC) system to operate more efficiently. This improved efficiency enables the AC to maintain lower temperatures while consuming less energy, significantly enhancing thermal comfort. The integration of air conditioning with desiccant dehumidification results in a more efficient and stable indoor thermal environment. This combined system ensures a steady and controlled decrease in indoor temperature, as reflected in the gradual downward trend observed in the temperature curve. The reduction in indoor temperature can be attributed to active heat removal by the air conditioning system, Humidity control achieved through the desiccant system, enhancing AC performance, and the synergistic operation of both systems, which sustains a continuous temperature decline. [22, 23].

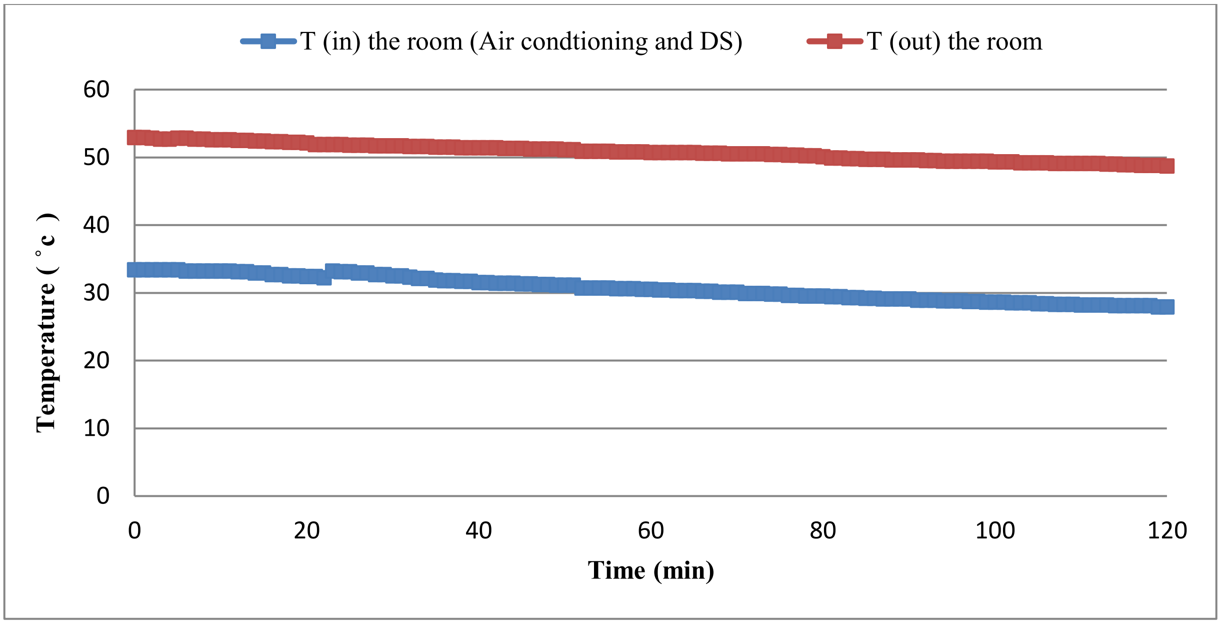

Fig. 8. Temperatures inside and outside the room in August

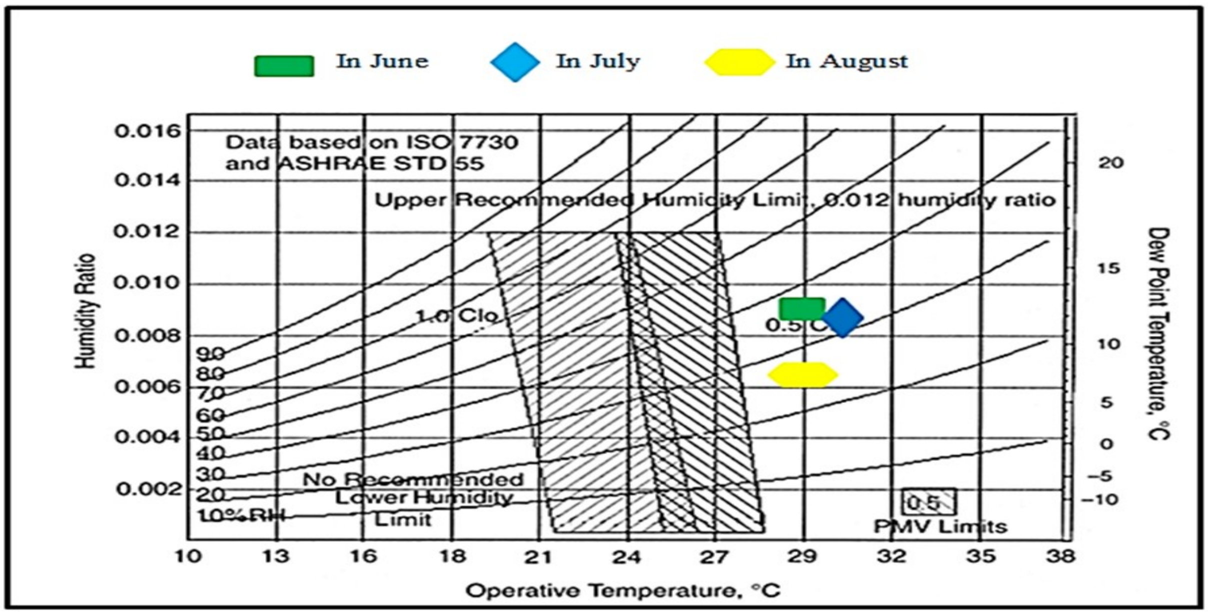

Fig. 9. ASHRAE comfort zones in summer when using air conditioning [24]

Fig. 10 shows the comfort zone when using an air conditioner with a dehumidification system using silica gel as an adsorbent. It is noted that complete comfort was obtained by providing a suitable temperature and humidity for the occupants of the space within only two hours. It was concluded that when using the dehumidification system with the air conditioner, it provided an ideal comfort for the occupants of the space, according to ASHRAE criteria to provide comfort conditions. However, there was a fundamental problem, namely, high relative humidity during the run of this system. So, to reach the comfort of the dehumidification system, which can be combined with the geothermal system, we will get a comfortable state that fits the standards of ASHRAE. Where the geothermal system contributes to lowering temperatures in the summer period, while the dehumidifying system that uses blue silica gel as an adsorbent as a dehumidifier, thus achieving maximum Convenience by using two systems that rely entirely on clean energy for their work, low cost and energy saving.

3.3. Electric power consumption of the image removal system

An experiment was conducted in September to observe the performance of the dehumidification system with the air conditioner and to calculate the performance factor for both cases. In the first case, the dehumidification system was operated with the air conditioner operating at a temperature of 27°C in the presence of a load consisting of 8 persons from 6:00AM to 2:00PM. Where the amount of cooling loads was calculated using the HAP program for a period of 8 hours from 6:00AM to 2:00PM and its value was found to be 16.6 kWh. While the amount of work input cooling in the presence of the air conditioner was only 5.1 kWh, its amount was 3.5 kWh when using the air conditioner with the dehumidification system. This means the latter consumes less electrical energy These results are realistic when compared with the results obtained by the researchers in [25]. Fig. 11 shows this value.

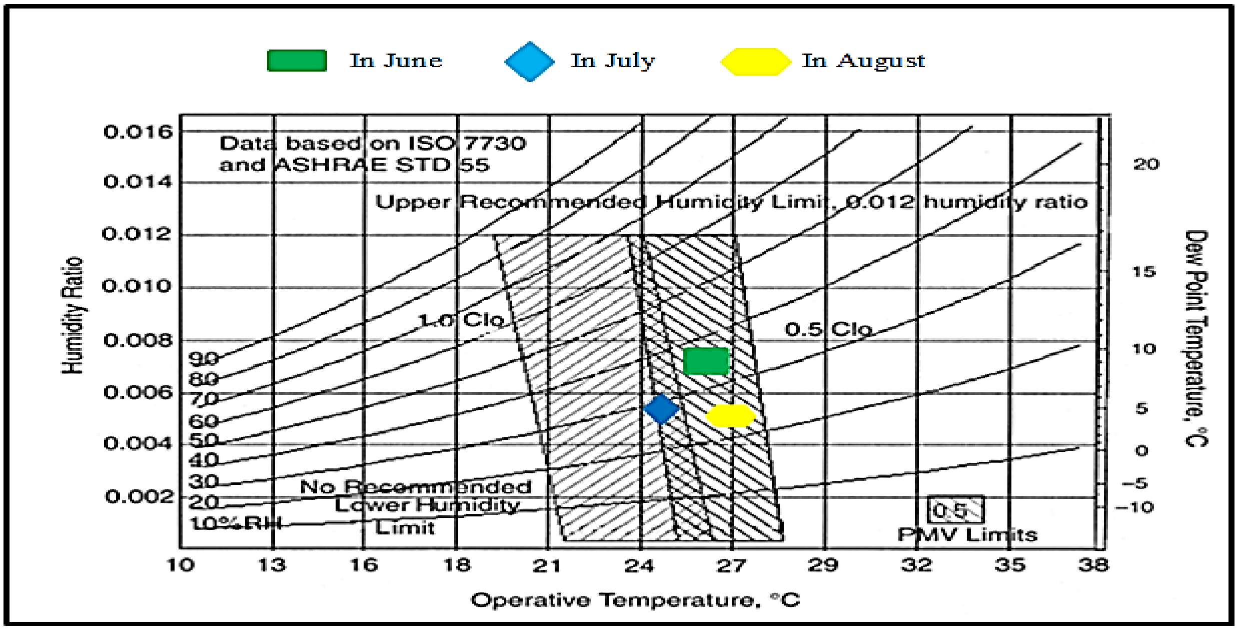

Fig. 10. ASHRAE comfort zones in summer when using air conditioning with (DS) [24]

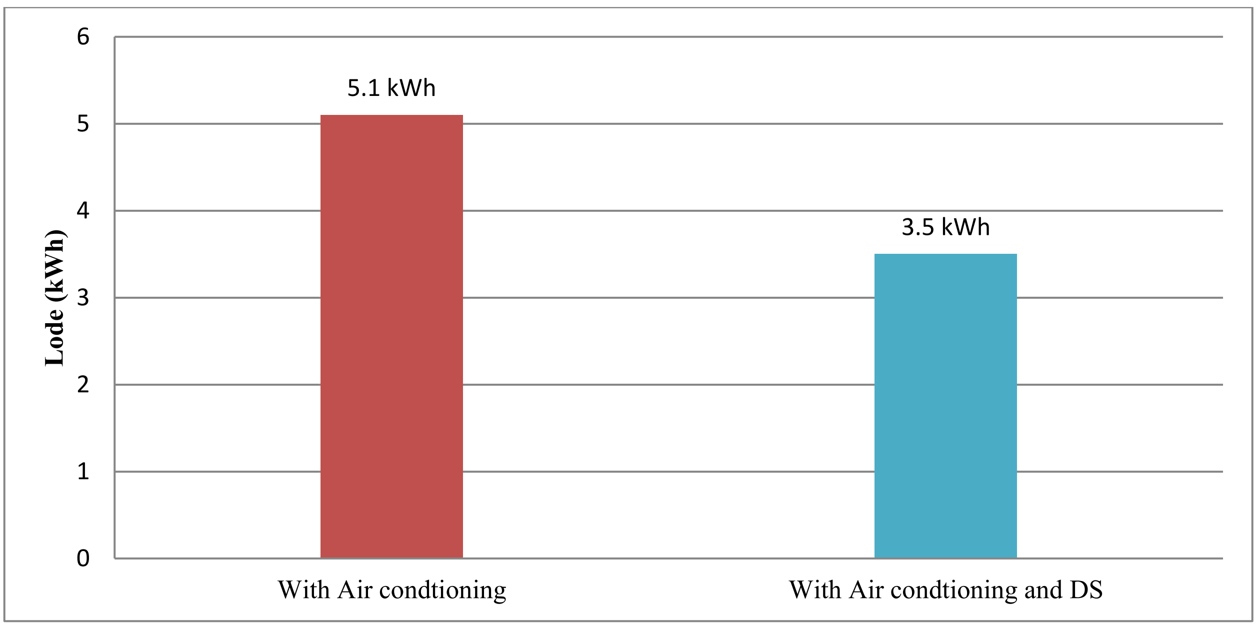

Fig. 11. Cooling load of air conditioner with and without DS

4. Conclusion

From this study the following important conclusions are drawn:

- The study demonstrated the feasibility of using absorbent materials to remove moisture from a specific space. When combined with an air conditioner, the dehumidification system proved its effectiveness in removing moisture during the summer, when temperatures dropped from 32°C to 26°C in June, from 32°C to 25°C in July, and from 33°C to 27°C in August.
- It was concluded after conducting practical experiments that it needs 750 g of silica gel-blue to remove the moisture generated by each person.
- The dehumidification system proved its efficiency when used with the air conditioner, as it contributed to alleviating the latent load (relative humidity) on the air conditioner to arrive at 33%, 29% and 25% in June, July and August respectively.
- The amount of water vapor removed by the air conditioner when used with and without the drying system was weighed, and it was found that the action of the air conditioning improved as a result of the reduced load on it.
- The amount of water vapor collected from the air conditioner after each experiment, when using the air conditioner combined with a dehumidification system, was 658.49 g, 175 g, and 750 g for June, July, and August, respectively. In contrast, when using the air conditioner alone, the amount of water vapor removed was 1404 g, 510 g, and 950 g for the same months.
- The amount of electrical energy consumed when using the dehumidifying system with and without an air conditioner was calculated and found to be equal to 3.5 kWh and 5.1 kWh respectively.

- By fixing the results on the ASHRAE chart for comfort conditions, it was found that when using the dehumidification system with the air conditioner, it reached the ideal state to provide comfort for the space occupants.
- The payback period for the cost of (DS) was calculated from what was saved from the cost of electrical energy consumption, and it was found that the cost would be paid within 28 months.

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