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A Comprehensive Assessment of Condenser Performance Enhancement Using Condensate Water and Its Impact on the Coefficient of Performance of Refrigeration Systems

Tamem Hamad Khalaf

College of Eng., Department of Mech. Eng., University of Tikrit, Tikrit, Iraq

Tamemaljboory@gmail.com

Maki Haj Zaidan

College of Eng., Department of Mech. Eng., University of Tikrit, Tikrit, Iraq

makihajzaidan@tu.edu.iq

Abstract

The purpose of this research is to investigate the effect of condensate water spray on the performance of a vapor compression refrigeration system (VCRS), particularly in terms of condenser efficiency. The condenser is a critical component that removes heat, and its performance has a direct impact on the coefficient of performance (COP), energy consumption, and efficiency. Under hot ambient temperatures, condensation pressure and compressor work increase, which reduces the efficiency of the VCRS. To improve condenser efficiency, condensate water collected from the evaporator surface is sprayed onto the condenser surface via a solar-powered pump. The spray water is evaporated, which provides evaporative cooling that reduces the condenser temperature. The experimental setup was carried out in Baiji,Salah Al-Din Governorate, Iraq, under hot climatic conditions to investigate the impact of condensate water spray on the condenser performance of a vapor compression refrigeration system.An experiment setup with a split-type air conditioner has been implemented with thermocouples, pressure gauges, and electrical measuring devices to measure the performance before and after the spray technique. The experiment showed that the performance has improved significantly after the modification. The average actual COP has improved from 2.37 to 3.42, which is an increase of 44%. The electrical power consumption has also reduced by 13.8%. The specific cooling effect has also improved by 22.2%, which indicates that the cooling capacity has improved significantly. The condenser cooling has also improved significantly during.It was also found that spray rate, ambient temperature, and humidity are significant factors that affect the performance of the system. The evaporative spray method was found to be a sustainable option as it is a cost-effective method that utilizes water obtained through condensation. The condensate water spray method is a viable option for reducing energy consumption, COP improvement, and thermal performance of refrigeration systems.

Keywords- Vapor Compression Refrigeration System (VCRS), Condenser Efficiency, Evaporative Cooling , Coefficient of Performance (COP) , Energy Consumption

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1-Introduction:

Vapor compression refrigeration systems (VCRS) are some of the most commonly used refrigeration systems for residential, commercial, and industrial applications due to the efficiency of the systems and the number of applications. Despite the popularity and efficiency of the refrigeration systems, the efficiency of the systems remains largely dependent on the efficiency of the condenser, which plays a vital role in the refrigeration process, transferring heat from the system to the surrounding environment. An increase in the temperature of the condenser or the surrounding environment results in a considerable decrease in the coefficient of performance (COP), which increases the consumption of the refrigeration systems (Dossat& Horan, 2001). In the last few years, considerable attention has been paid to developing simple techniques for improving the efficiency of the condenser, which can be achieved by utilizing the condensate water obtained from the evaporator coil for spraying the condenser.This is considered a form of partial evaporative cooling, as the evaporation of some of the water results in the reduction of the condensation pressure and hence an increase in the coefficient of performance of the system (Hammad& Al-Hadhrami, 2010). The advantages of using this technology include the fact that it does not require an additional water source, as it uses the water collected during condensation. This makes it more suitable for use in hot and dry climatic conditions, as it can be more effective compared to the efficiency of traditional cooling systems. The effectiveness of the use of this technology has been supported by many studies, as it has been found to have a positive impact on the efficiency of the system. Some studies have indicated that the use of this technology can lead to a reduction of 5-15% in the condensing pressure, as well as an increase of up to 10-25% in the coefficient of performance, depending on the type of system (Hernández et al., 2018; Al-Sulaiman, 2019). Spraying water on the air inlet of a compression refrigeration condenser lowers the air temperature by about 10°C, enhancing cooling capacity by up to 19% and improving the COP by 18%.(Zaidan et al.,2024).Vapor compression cooling systems in hot, dry climates (up to 48 °C and <20% humidity) often operate at high pressures using environmentally friendly refrigerants, leading to high energy consumption and lower COP; passing the air through a wet pad before the condenser reduces its temperature to around 11 °C, enhancing the cooling capacity by nearly 20%, improving COP by 15%, and reducing electricity consumption by up to 15%.(Zaidan et al.,2019) A two-stage evaporative cooling system was designed and tested using outdoor air, consisting of an indirect cross-flow aluminum heat exchanger (30×60×40 cm) and a direct cylindrical air-washing unit (45×60×3 cm). Outdoor air is drawn by a centrifugal fan, cooled sensibly in the heat exchanger, and then further cooled by direct evaporation in the air-washing unit. Experiments at Tikrit University showed optimal performance at airflow rates of 750 cfm (dry side) and 1000 cfm (wet side) with pipe diameters of 1–1.5 cm and lengths of 45 cm, achieving up to 80% improvement in evaporative cooling efficiency under hot and dry summer conditions.(Zaidan et al.,2019).

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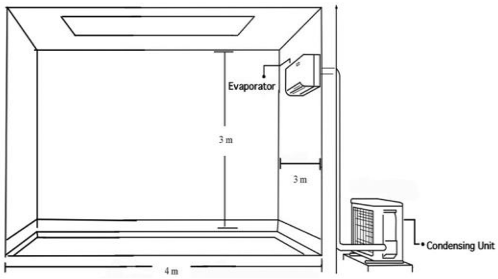

Fig. 1.The experimental room with the split-type air conditioner

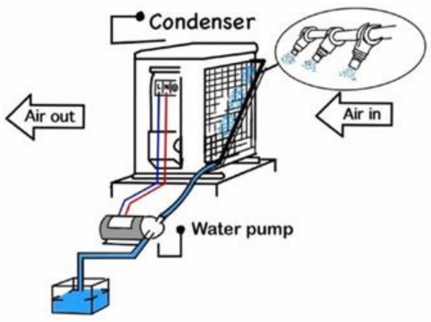

Fig. 2.The schematic diagram of the spraying system.

The vapor compression refrigeration cycle has the main components of the compressor, condenser, expansion valve, and evaporator. The condenser is the main component of the vapor compression refrigeration cycle. The efficiency of the condenser depends on the temperature difference between the refrigerant and the cooling medium. The cooling medium is normally air. However, in some areas with high temperatures, the use of air as the cooling medium increases the temperature of the condensed vapor and the pressure (Li et al., 2024). In order to address this, the use of condensate water spray has been investigated as an evaporative cooling mechanism. This method has been found to be effective, as the evaporation of water from the condenser surface absorbs latent heat, reducing the condensation temperature. This method is also found to be sustainable, as it does not require the use of external resources, and the efficiency can be increased with the increased amount of moisture removal from the evaporator. This has been investigated, and it has been found that the use of optimized spray rates improves the COP and reduces the condensation temperature (Ahmed & Khan, 2019). In another study, it has been found that the COP can be improved by 4–8%, along with the reduction of the load on the compressor (Wang, Yu, & Chan, 2020). In another study, it has been found that the efficiency of the heat transfer can be increased, along with the reduction of the load on the compressor (Rahman et al., 2021).An increase of ~6% COP and ~40% savings, depending on water distribution, was reported by Li et al. (2024). COP improvement was demonstrated by Hernández et al. (2025) using condensate water alone, thus making it a sustainable solution, especially in hot and dry environments. In conclusion, the use of condensate water spray is an effective and sustainable

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solution to enhance the condenser, reduce energy consumption, and increase COP, especially in high-temperature environments.

The purpose of this paper is to present an extensive systematic review of the scientific literature on the use of condensed water for spraying the condenser with the aim of improving the performance of vapor compression refrigeration systems, especially with respect to thermal mechanisms, application, studies, and models, as well as opportunities and gaps for further development.

Fig. 3.Thermocouple locations for measuring inlet and outlet temperature at the evaporator.

Fig. 4. The full cone spray nozzle used (left) and the drawing of the nozzle (right)

2.1Coefficient of Performance (COP) and Its Importance: The COP is a significant parameter for evaluating the efficiency of vapor compression refrigeration systems. It is defined as the ratio of the amount of heat extracted at the evaporator to the amount of energy input required (Sumeru, 2022). The COP of a vapor compression refrigeration system is affected by various parameters such as the temperature difference between the condenser and evaporator, operating pressures, refrigerant properties, and the efficiency of the refrigeration system itself (Hajidavaloo&Eghtedari, 2007; SYang et al., 2019).

2.2Condensed Water in Vapor-Compression Systems: During the operation of a vapor compression refrigeration system, water vapor contained within the air gets condensed on the cold surfaces of the evaporator and is usually discarded. The condensed water can be utilized to improve the efficiency of the refrigeration system by spraying it on the surfaces of the condenser or on the inlet air. This reduces the temperature and pressure of condensation, thus enhancing the COP of the refrigeration system. The refrigerant can also be subcooled using the condensed water, thus enhancing the cooling capacity of the refrigerant; studies show that COP is improved by as much as 21% for split-type R32 systems (Imbang et al., 2014).

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2.3 Methods to Improve COP: Various methods to improve COP involve reducing the condenser temperature and increasing the evaporator temperature using heat exchangers, water cooling, air cooling, and evaporative spray. The evaporative spray process involves the absorption of heat by the process of water evaporation, which leads to a reduction in the pressure of the condenser. It also leads to an increase in COP. Optimizing the water distribution system and the nozzles also help to improve the performance of the system (Rachman&Nesti, 2014; Yang et al., 2020; Ahmed et al., 2025). These methods, along with the condenser, help to improve the efficiency of the system (Stefaniak et al., 2025).

2.4. Analysis of Condensate Water Utilization: Condensate water can be collected in trays placed under the evaporator, and the water can be reused to spray the condenser coils. This method uses the evaporative cooling technique to reduce the surface or air temperature, thus increasing the COP, reducing the load on the compressor, and increasing the heat transfer efficiency (Harby et al., 2016; Kaneesamkandi, 2023). The advantages of this method are energy savings, reduction of external water consumption, and increasing sustainability, especially in arid environments. However, the drawbacks of this method are the chances of scale or settlement of particles on the condenser coils, thus the need for a proper spray system to be put in place (Leung et al., 2024).

3. Experiments and Modeling:

3.1.Equipment details

The experimental study was carried out by using a conventional split-type air conditioner as a main cooling source to test the performance of the condenser unit under various working conditions. As illustrated in the figure (1).To measure the temperatures, a data logger was employed to record the temperatures continuously, thus ensuring precise measurement of the temperatures during the experimental study. Thermocouples of Type K were placed at various points of the condenser and evaporator to measure the local temperatures precisely. Furthermore, a pressure gauge was used to measure the condensation pressure and the compressor outlet pressure with high precision, while a voltmeter and an ammeter were used to measure the voltage and current, thus enabling precise measurement of the power consumption of the system.

A collection flask for the condensate was installed at the bottom of the evaporator, which collected the condensed water droplets resulting from the condensation of the vapors. This collected water was then used for the experiments concerning the spray mechanism on the condenser. As shown in the figure (2). In order to transport the collected condensate from the collection flask to the condenser surface, a solar-powered water pump was used, which ensured the efficient use of renewable energy for the purpose of the experiment. Cotton was used for the purpose of holding the spray tubing, preventing leakage at the points of connection, and ensuring the uniform distribution of the collected condensate water on the condenser surface. This experiment ensured the evaluation of the impact of the condensate water spray on the efficiency of the condenser. As shown in the figure (3,4). The figure (5) shows the necessary measurement devices required to test, operate, and monitor the performance of a refrigeration system, including a manifold gauge and a clamp meter. A manifold gauge is a set of blue and red gauges, representing low and high pressures,

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respectively, connected to a system to measure pressures, identify the state of operation, and determine the temperatures of evaporation and condensation, as well as charging or recovering the refrigerant. In figure 6, a thermocouple temperature sensor is illustrated, attached to a component of the external air conditioner unit.The figure 7 shows a solar-powered device with a small photovoltaic panel, wiring, and mounting base, providing a renewable and independent energy source for outdoor applications such as sensors, lighting, or small pumps.

Fig. 5Measuring instruments including a manifold gauge for refrigerant pressure

Figure 6 Installation of a thermocouple sensor for temperature measurement on the external air conditioning unit.

Figure 7: Solar-Powered Device with Photovoltaic Panel and Mounting Base

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3.2.Experimental procedure

The methodology of the experiment included running a standard split-type air conditioner, which was connected to a data logger and Type K thermocouples to record the temperatures at the inlet and outlet of the condenser and evaporator sections of the air conditioner, respectively. Pressure gauges were placed at the outlet of the compressor section and the condenser section to record the pressures at these points, while voltage and current meters were employed to determine the power consumption of the system. During the experiment, the condensed water from the evaporator section was collected in a separate flask to ensure that there were no impurities in the system. The collected water was then sprayed on the condenser surfaces by a solar-powered pump.Cotton material was used to secure the tubing, prevent leakage, and ensure even coverage, while the spray rate was regulated to prevent excessive water from interfering with the system's performance and yet adequate water to achieve the desired effect of cooling. During the entire process of spraying, temperatures, pressures, and power consumption were monitored. After this process, the coefficient of performance (COP) was calculated before and after the condensate spray was applied, while the decrease in condenser temperature was analyzed to determine the thermal effect of the water used for spraying on the overall performance of the system.

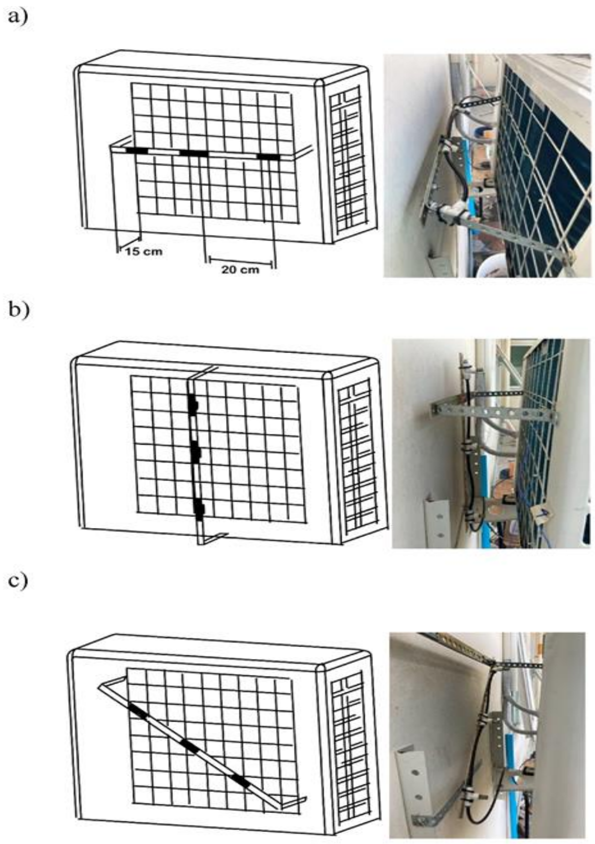

Fig. 7. Spray drying nozzles with the (a) horizontal, (b) vertical, and (c) diagonal configuration

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4.(Coefficient of Performance - COP)

$$COP = \frac{Q_{evap_{wop}}}{W_{work}}$$

Where:

- **Q_C**: Cooling capacity of the evaporator [W or kW]
- **W**: Electrical power consumed by the compressor [W or kW]

The cooling capacity is calculated after determining the amount of water evaporated from the wet pad. This value is then used to compute the dry-bulb temperature of the air exiting the wet pad (i.e., the temperature of the conditioned space) according to the following [29]:

$$Q_{cp} = \dot{m}_{wep} * h_{fg} \qquad \ldots\ldots\ldots\ldots\ldots\ldots.(3.28)$$

$$T_{Dop(theo)} = \left(\frac{(\dot{V_p} \times \rho_m \times Cp_m \times T_{Da}) - Q_{cp}}{\dot{V_p} \times \rho_m \times Cp_m}\right) \ldots\ldots\ldots\ldots\ldots \quad (3.29)$$

The amount of heat removed from the condenser is calculated using the following equation:

$$Q_{cond.wop} = \dot{m}_f * (h_2 - h_3) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.30)$$

$$Q_{cond.wop} = \dot{m}_a * Cp_a * \left(T_{Doc(theo)} - T_{Dop(theo)}\right) \qquad \ldots\ldots \quad \ldots\ldots(3.31)$$

$$T_{Doc(theo)} = T_{Dop(theo)} + Q_{cond.wop}/(\dot{m}_a * Cp_a) \quad \ldots \ \ldots\ldots\ldots\ldots(3.32)$$

The temperature of the air leaving the condenser, in the absence of a wet pad, is calculated using the following equation:

$$T_{Dao} = T_{Da} + Q_{cond.wop}/(\dot{m}_a * Cp_a) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (3.36)$$

All of these equations were implemented and programmed using a computer code written in **FORTRAN 90** to calculate the dry-bulb temperature of the air leaving the cooling pad and the air temperature exiting the condenser. These computed values were then compared with the experimental measurements obtained using thermocouple sensors.

5.Results and Discussion:

Figure 1 illustrates the theoretical and experimental values of the Coefficient of Performance (COP) of the refrigeration system before and after the applied modification, over the time period from 10:00 AM to 8:00 PM. From the results, there is a clear indication of improvement in the performance of the system after the modification. The average actual COP increased from 2.37 to 3.42 after the modification, indicating an improvement of about 44%. This shows a significant improvement in the thermal efficiency of the system, as a result of the applied modification. Similarly, the average theoretical COP increased from 2.77 to 4.10 after the modification, indicating improvement in the ideal performance of the

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thermodynamic cycle of the system. Therefore, the results confirm that the applied modification has a positive impact in optimizing the working conditions of the system, hence reducing the adverse effects of the system.

It was observed that the actual COP values were consistently lower than the theoretical values, as expected in real systems. Prior to the modification, the actual to theoretical COP ratio was about 85%, while after the modification, it was about 83%. These results can be attributed to the unavoidable losses in real systems, including:

- Non-ideal compressor efficiency
- Heat losses to the surrounding environment
- Pressure drops across system components
- Mechanical and electrical losses

Despite these differences, the close ratio indicates stable system performance both before and after the modification. The results also demonstrated that COP varies with operating time. Before the modification, the lowest COP values were recorded during midday, particularly between 1:00 PM and 3:00 PM, when the actual COP dropped to 2.05. This decrease was due to the rise in ambient temperature and the increase in thermal load on the system. After the modification, a significant improvement was observed during the same period, with the COP reaching a peak value of 3.75 at 2:00 PM. This enhancement is a clear indicator of the modified system's ability to operate efficiently under high thermal load conditions.

It was also shown that COP changes over time. Before the modification, the minimum COP values were recorded at midday, at a specific time between 1:00 PM and 3:00 PM, at which the actual COP took a minimum value of 2.05. This reduction occurred because of the increase in ambient temperature as well as the thermal load. After the modification, a remarkable improvement was recorded at the same time, reaching a maximum COP value of 3.75 at 2:00 PM. It should be noted that this improvement indicates the ability of the modified system to work efficiently under high thermal loads.

- Reduced electrical energy consumption
- Lower operational costs
- Improved overall system efficiency
- Enhanced energy utilization efficiency

From the experimental results, it can be concluded that the applied modification has a significant impact on the performance of the refrigeration system. It can be seen that actual and theoretical values of COP are significantly improved, thus increasing the efficiency of the system and reducing losses. At the same time, it can be noted that the system has a more stable performance, especially during peak thermal loads, thus proving the effectiveness of the applied modification in terms of system performance improvement.

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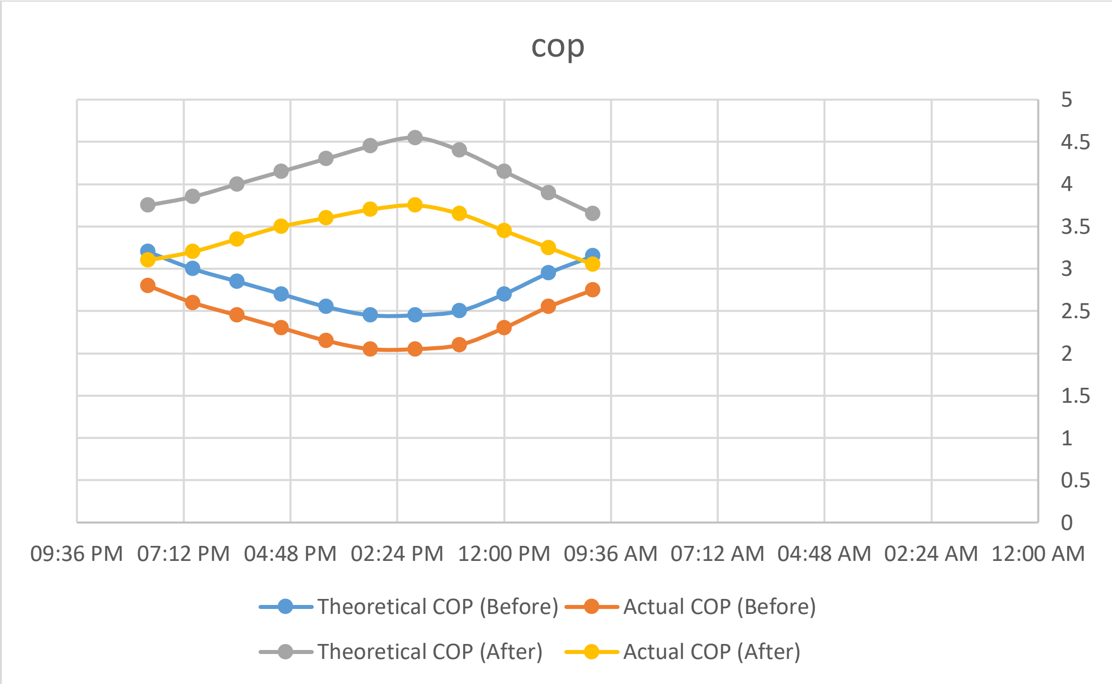

Figure (1).Comparison between theoretical and actual COP before and after modification over the daily operating period.

2-The results obtained as indicated in figure (2) show a marked improvement in the specific cooling effect (q) of the refrigeration system as a result of the applied modification. This shows a positive improvement in the thermal efficiency of the refrigeration system. The average actual cooling effect was improved from 138 before the modification to 168.7 after the modification, which is equivalent to a 22.2% increase, while the average theoretical cooling effect was improved from 158 to 206.5 after the modification, which is equivalent to a 30.7% increase. This shows that the modification resulted in a greater amount of heat being absorbed by the evaporator. It was also noticed that the actual cooling effect values were lower compared to the theoretical ones for all operating conditions, which is a common phenomenon for real systems due to losses, non-ideal processes, and the efficiency of the components. Moreover, the lowest actual cooling effect values were noticed before the modification, specifically during the afternoon, due to the increased thermal load and the high ambient temperature. After the modification, the ability of the system to maintain high cooling effect values was noticed, especially for severe operating conditions, with the highest value reaching 178 at 2:00 PM. In addition, the results obtained after the modification for the system's performance were more stable compared to the results before the modification, with the cooling effect value ranging over a higher interval compared to the results before the modification. Therefore, it can be confirmed that the modification has a positive impact on the thermal performance of the system, specifically by increasing the cooling effect and the efficiency of the heat absorption process, which improves the overall efficiency of the refrigeration system.

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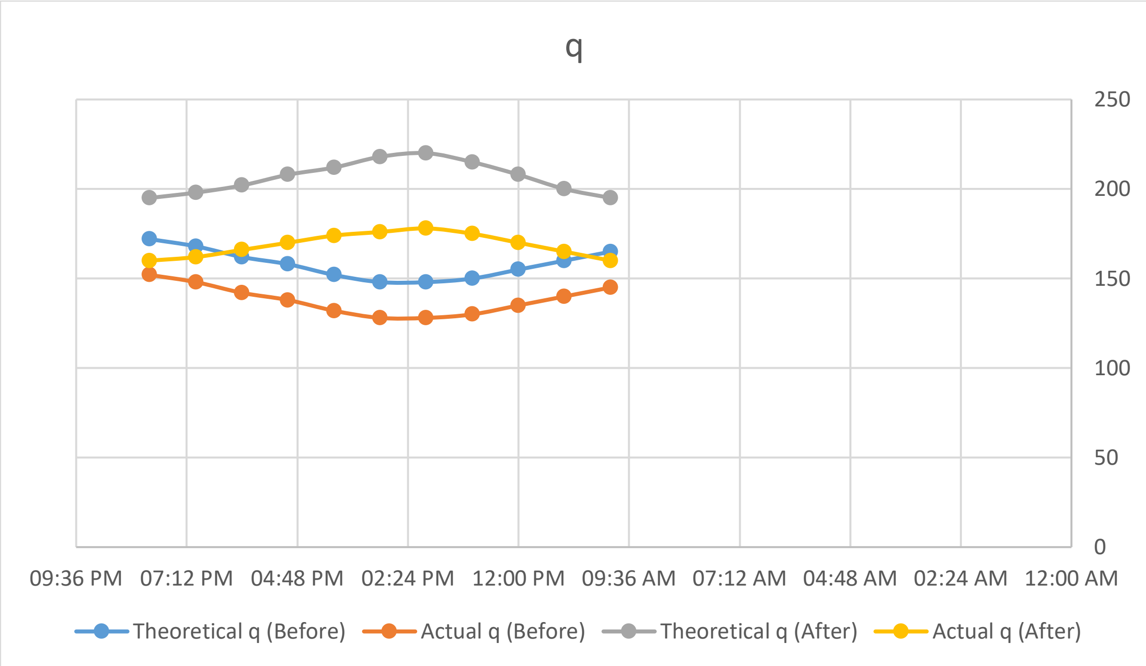

Fig2. **Comparison of Theoretical and Actual Specific Cooling Effect (q) Before and After Modification as a Function of Operating Time**

The results illustrated in Figure (3) show a clear reduction in the electrical power consumption of the refrigeration system after the applied modification, indicating an improvement in the system's energy performance. The average electrical power consumed decreased from approximately 2.17 kW before the modification to 1.87 kW after the modification, representing a reduction of about 13.8%. This decrease is attributed to improved compressor operating conditions and a reduced work requirement for completing the compression process due to the applied modification, which positively impacted the reduction in electrical energy consumption.It was observed that the highest power consumption before the modification occurred during the afternoon, reaching 2.3 kW at 2:00–3:00 PM, due to increased thermal load and higher ambient temperature, which required greater compressor work. In contrast, after the modification, a significant reduction in power consumption was recorded during the same period, reaching 1.92 kW, demonstrating the modified system's capability to operate more efficiently under high thermal load conditions.Furthermore, power consumption values after the modification showed relative stability and generally lower levels throughout all operating hours compared to the pre-modification condition. Overall, these results confirm that the applied modification led to a reduction in electrical power consumption and improved energy efficiency, consistent with the observed enhancements in both the coefficient of performance (COP) and the cooling effect, reflecting an overall improvement in the efficiency of the refrigeration system.

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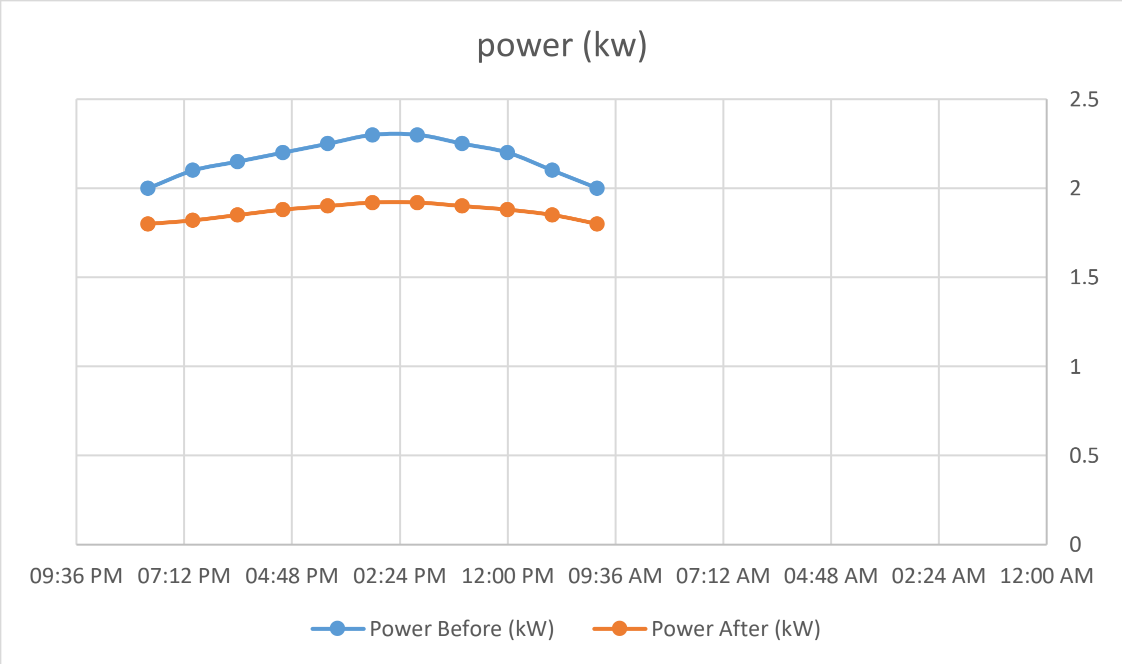

Figure (3).Variation of electrical power consumption with time before and after the modification.

The results obtained in Figure (4) indicate a clear relationship between the condensed water quantity (W_c) and the sprayed water quantity (W_s) during the operation period. It was found that the quantity of sprayed water was greater than the quantity of condensed water at all times of measurement, indicating the efficient role of the spray system in increasing the heat transfer and thus the efficiency of the condensation process. The maximum quantity of sprayed water was 1.2 L at 2:00–3:00 PM, during which time the ambient temperatures are the highest, indicating the need to increase the quantity of sprayed water to increase the efficiency of the cooling process in the condenser system. The minimum quantity of condensed water during the same period was 0.1 L, resulting from the increase in ambient air temperatures, which decreases the efficiency of the condensation process.As the ambient temperature decreased with the progression of the evening hours, a gradual reduction in the quantity of the sprayed water was observed, reaching a value of 0.85 L at 8:00 PM, whereas the quantity of the condensed water gradually increased, reaching its maximum value of 0.45 L. These results indicate that the rate of the water spray plays a vital role in enhancing the heat transfer conditions within the condenser, thus reducing the surface temperature of the condenser, which leads to the enhancement of the thermal performance of the system. It should be noted that the results obtained confirmed the inverse proportionality between the quantity of the sprayed water and the condensed water under the conditions of high ambient temperature.

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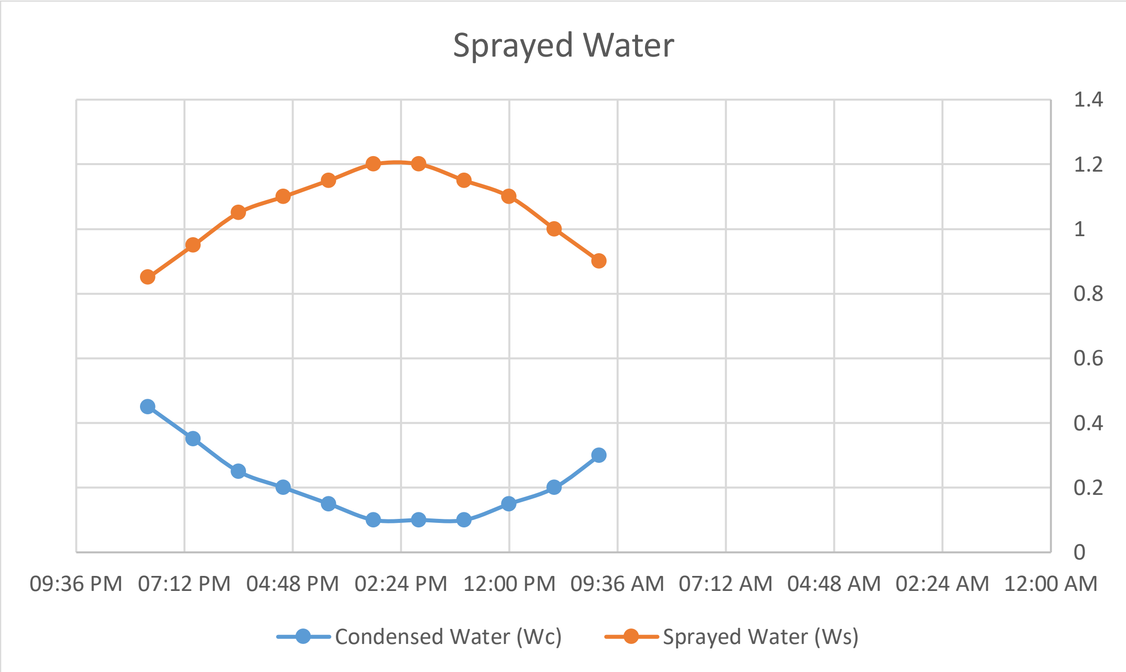

Figure (4).Amount of condensed material and amount of sprayed water.

5- By analyzing the daily climate data, it has been found that there is a definite pattern in the change in ambient temperature and relative humidity, which is very important for mechanical engineering, particularly for designing ventilation and air-conditioning systems and for thermal comfort analysis. The data have shown that the temperature is low in early morning hours and gradually increases, reaching its peak in the middle of the day and in the afternoon, i.e., between 2:00 and 3:00 p.m., when it reaches 44°C, and then gradually falls in the evening. On the other hand, relative humidity is high in the morning and gradually falls with the increase in temperature, reaching 15% during peak hours, and then again increases in the evening with the fall in temperature.

This inverse relationship between temperature and humidity is an instance of the widely known physical relationship whereby the relative humidity in the atmosphere decreases as the temperature increases, provided the amount of water vapor in the atmosphere remains constant. From an engineering viewpoint, the midday hours are the most stressful in terms of the heat and dryness in the atmosphere, while the evenings and nights are thermally stable with regard to relative humidity for the comfort of humans. The data can thus be used to investigate the local climate, the thermal performance of the environment, and improve the design of the mechanical systems for optimal thermal comfort.

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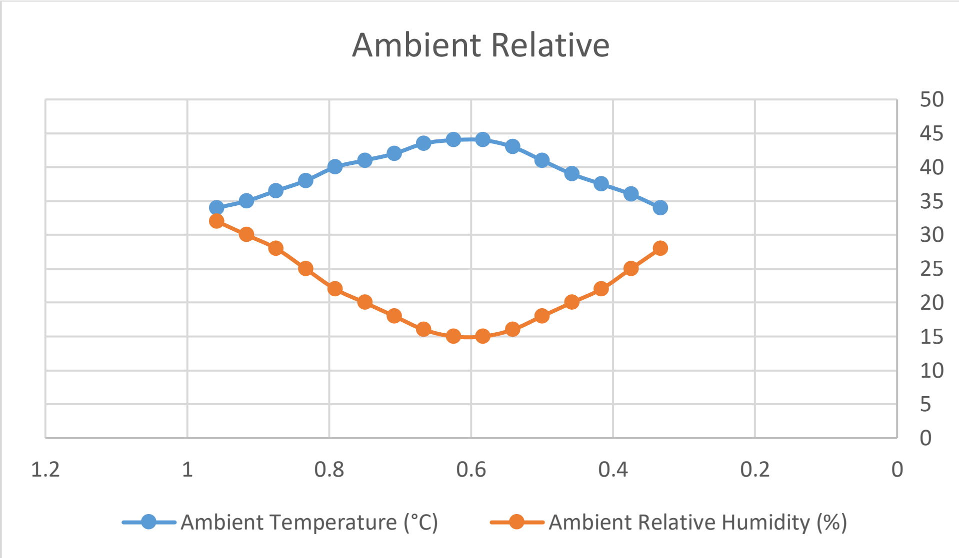

Figure (5) illustrates the variation of temperature and humidity throughout the day, facilitating a visual analysis of their inverse relationship.

Conclusions:

1. **Improvement of COP:** From the results presented above, there is an improvement in the actual and theoretical COP values after the modification. The average actual COP improved from 2.37 to 3.42, which is an improvement of around 44%. On the other hand, the theoretical COP improved from 2.77 to 4.10.
2. **Increase in Specific Cooling Effect (q):** As shown by the results above, there is an increase in the average actual and theoretical values of q from 138 to 168.7 and from 158 to 206.5, respectively, which shows that there is an improvement in the ability of the refrigerant to absorb heat from the evaporator.
3. **Reduction in Electrical Power Consumption:** From the results presented above, there is a reduction in the electrical power consumption from 2.17 kW to 1.87 kW by around 13.8%, which shows that there is an improvement in the performance of the compressor.
4. **Effectiveness of Condenser Water Spray:** There was a clear correlation between the sprayed and condensed water, which shows the effectiveness of the spray, leading to the enhancement of the efficiency of the process, especially with the increase in the ambient temperature.
5. **Impact of Climatic Conditions on Performance:** From the data collected, it was evident that the temperature and humidity had an inversely proportional effect, with the highest temperature and lowest humidity levels prevailing during the midday period, while the conditions were stable in the evening and at night.

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6. **Performance Stability after Modification:** There was increased stability with regard to the COP and the specific cooling effect, which shows the efficiency of the system, especially during the highest thermal load.

Recommendations:

1. **Adoption of Condensate Water Spray Technology:** It is recommended that the use of the water spray technology on the condenser in vapor compression systems can be adopted as an effective solution to improve the COP and reduce the energy consumption rate, especially in high-temperature conditions.
2. **Design of Controllable Spray System:** The design of the spray system can be made in such a manner that the flow of water can be adjusted according to the thermal requirements and the temperature conditions.
3. **Improvement of Insulation and Minimization of Losses:** The thermal and mechanical losses in the different components of the vapor compression systems, particularly the compressor and the condenser, need to be reduced in order to make the performance closer to the theoretical conditions.

4. Consideration of Daily Climate Analysis: Daily changes in temperature and humidity levels should be considered to ensure the stability of the refrigeration and ventilation systems, which provide thermal comfort to the users.

5. Monitoring Water Usage and Regular Maintenance: Maintenance of the condenser, along with the efficiency of water distribution, should be considered to ensure the effectiveness of the spray system. It should be ensured that the system does not face problems like scaling or condensation.

6. Expansion of Future Studies: It is recommended that further research should be conducted to consider the application of advanced evaporative cooling systems with the addition of other systems to make the system more energy- and water-efficient.

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