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Research Article

Theoretical study on combining the air-cooled condenser with evaporative cooling to enhance the Coefficient of Performance of multi-split air conditioning systems

Kien Quoc Vo*, Chi Hiep Le

ABSTRACT

This paper presents the results of theoretical study on enhancing heat exchange in multi-split air-cooled air conditioning condensers by combining it with the evaporative cooling method to increase efficiency and reduce electricity consumption. Based on thermodynamic calculations of humid air and refrigeration cycle calculations, this study results show that enhancing condenser cooling combined with evaporative cooling is highly effective. If the ambient humidity decreases by 10%, the air temperature leaving the condenser with evaporative cooling decreases by 1.8°C, and the COP (Coefficient of Performance) increases by an average of 6%. In the weather conditions of the southern provinces of Vietnam, the COP of the air conditioning system with enhanced condenser cooling through evaporative cooling increases by an average of 16% compared to the case without enhanced heat exchange. The cost savings for a 4HP multi-capacity air conditioning system working for an average of 8 hours is 4,000 VND. The lower the ambient air humidity, the more effective it is to enhance condenser cooling with air combined with evaporative cooling.

Key words: enhancing cooling, air cooled condenser, evaporative, multi-split, COP, energy saving

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INTRODUCTION

Multi-split air conditioning systems are widely utilized in office buildings, hotels, and villas. The advantage of this system is that it uses a common outdoor unit for multiple independent indoor units and saving installation space for outdoor units. In the current market, multi-split systems have two types of condensers: air-cooled and water-cooled.

An air-cooled multi-split system offers the benefit of a compact design and a lower initial investment cost. However, its drawback is a lower COP compared to a water-cooled multi-split system, as air has a significantly lower heat convection coefficient than water. The air exiting the condenser can be significantly hotter, depending on environmental conditions, typically 10 to 15°C higher than the inlet air temperature. The heat generated from outdoor units, combined with heat from other sources like factory emissions and vehicles, contributes to higher ambient temperatures in densely populated areas, a phenomenon known as the heat island effect.

The heat island effect leads to several negative consequences. Higher ambient temperatures cause the refrigerant's condensation temperature to rise, resulting in a lower COP. A lower COP means higher energy consumption, leading to increased operating costs and additional greenhouse gas emissions.

To lessen the influence of the urban heat island effect, improving the energy performance of HVAC systems is essential. One possible solution involves lowering the temperature of the discharged air from air conditioners' outdoor units.

Recognizing the benefits of enhancing the condenser cooling, recent research worldwide has yielded the following findings:

Youbi-Idrissi et al [1] conducted calculations on air-cooled air conditioning systems combined with water spraying. The research results indicate that compared to air-cooled systems alone, air conditioning systems with air cooling and water spraying can increase productivity and cooling efficiency by 13% and 55%, respectively. Additionally, the research reveals an optimal threshold for water spraying to achieve maximum efficiency.

Hajidavalloo et al [2] focused on enhancing the efficiency of air-cooled air conditioning systems combined with evaporative cooling for condenser heat dissipation. Their study shows that, incorporating evaporative cooling into condenser heat dissipation significantly enhances the system's performance. As the ambient temperature rises, the performance improvement rate also increases. The research also demonstrates a 20% reduction in energy consumption and a 50% increase in system efficiency.

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Tissot et al[3]conducted theoretical and experimental research to enhance air conditioning performance by spraying water onto the condenser for air cooling. The researchers recorded condensation pressure, refrigerant condensation temperature, as well as the ambient conditions (temperature and humidity) upstream and downstream of the condenser. The findings reveal that applying moisture to the condenser surface enhances the overall COP of the air conditioning system by 28.9% when the ambient air temperature is 308K and the humidity is 19.7%.

Boulet et al[4] conducted experimental research on enhancing heat exchange in condenser units using air and small droplets of water. The findings demonstrate that introducing water into the airflow directed at the condenser unit improves heat exchange significantly. The maximum heat flux density achieved can be up to 3.5 times greater when comparing cases with and without water spraying.

In a study related to cooling the condenser by the evaporative cooling method, Chien et al[5] investigated the water spray distribution and collection efficiency of the nozzle in a chiller's evaporative condenser. Their results suggest that the spray hole's cross-sectional area and the flow rate are key factors influencing the uniformity of the sprayed water.

Ketwong et al[6] explored the direct evaporative cooling technique for generating for air cooling under hot-dry and hot-humid weather conditions. Their study examined the impact of water supply temperature, wet-bulb temperature, and the water-to-air mass ratio. The findings indicated that in hot-humid conditions, when the water supply temperature is lower than the wet-bulb temperature, increasing the water-to-air mass ratio leads to a reduction in outlet air temperature. In contrast, under hot-dry conditions, if the water supply temperature exceeds the wet-bulb temperature, decreasing the mass ratio is necessary to achieve lower air temperatures.

Lee et al[7] presented a study on the heat exchange mechanism of a falling film over a horizontal circular tube bundle. Their findings indicated that when the air velocity reached 2 m/s, the average heat transfer coefficient across four tube locations could reach up to 5.0 kW/m^{2}K, given a water flow rate of 5 liters per minute and a heat flux of 30 kW/m^{2}K.

Naveenprabhu et al[8] carried out an experimental investigation on the condenser efficiency of a water chiller using cooling pads composed of jute, cotton, and coconut fibers. The study evaluated heat rejection by varying the placement of the cooling pad relative to the heat exchanger and fan. The findings revealed that positioning the pad in the airflow path between the fan and the chiller enhanced the heat removal efficiency for all three pad types by maximizing evaporative cooling effects. Among them, jute pads demonstrated the highest performance, achieving a cooling efficiency 23.5% greater than cotton pads and 47.1% higher than coconut fiber pads. Placing the straw cooling pad between the fan and the chiller resulted in a 76.5% improvement in water cooling rate compared to the position of the pad in front of the fan and chiller, and an 11.8% improvement compared to the position of the pad behind the fan and chiller

In an experimental study conducted by Yang et al[9] on an air conditioner using an evaporative cooling system in the form of spray, the experimental results showed that the application of the evaporative cooling system, such as spraying, had a significant impact on improving the device's efficiency and the enhancement rate increased as the outside temperature rose. By utilizing the evaporative cooling system in hot conditions, passive skills could be reduced by up to 22%, and the COP could improve by approximately 42.6%.

In another experimental study aimed at improving the COP of an air conditioning system using evaporative condensation equipment, conducted by Wang et al[10], the results showed that pre-cooling the air with evaporative equipment reduced the saturation temperature by 2.4°C to 6.6°C. This also increased the refrigerant flow rate entering the system. Consequently, the rise in liquid mass flow within the evaporative equipment led to a COP improvement ranging from 6.1% to 18%, while compressor power consumption decreased by up to 14.3%.

A numerical study on the thermal performance of an evaporative cooling condenser was presented by Jahangeer et al[11]. They developed a comprehensive model and performed finite difference techniques for simulations. The study focused on a finless condenser tube with airflow through it, while fine water sprays were introduced at the top. The flow rate was adjusted to achieve film thicknesses of 0.075, 0.1, and 0.15 mm. The results indicated that the overall heat transfer coefficient from the wall to the air could reach up to 2000 W/m^{2}K when incorporating evaporative cooling. The numerical findings were validated through comparisons with existing experimental and theoretical data, showing strong agreement.

An experimental study and performance optimization of a two-stage air conditioning system incorporating an evaporative condenser were conducted by Atmaca et al[12]. The results obtained showed that the COP improved by 10.2%–35.3%, while the cooling capacity improved by 5.8%–18.6%, and total energy consumption was reduced by 4%–12.4%. Additionally, the system's COP, cooling capacity, and power consumption were significantly influenced by ambient temperature and relative humidity.

Yang et al [13] performed experimental study on the combination of evaporative cooling method for air-cooled condenser. Their results demonstrated that compressor power consumption decreased, while the COP of the air-cooled chiller improved by 4%–8% with the implementation of spray evaporative cooling. This system also contributed to electricity savings of 2.37%–13.53% in the air-cooled chiller. Further efficiency gains could be achieved by optimizing the spray cooling mode, such as adjusting water flow based on cooling demand and strategically positioning the spray nozzles.

Aiming to mitigate the heat island effect and enhance the COP of air-cooled condenser air conditioning systems, this paper presents a theoretical study on improving condenser cooling performance in multi-unit air conditioning systems by integrating evaporative cooling under the climatic conditions of southern Vietnam.

RESEARCH METHODOLOGIES

Figure 1 illustrates the influence of the condensing temperature on the compressor's work and cooling capacity of the air conditioning cycle. With constant evaporation temperature, higher condensing temperature increases compression work (process 1-2) and reduces cooling capacity (process 4-1) leading to a decrease in COP of cycle 1-2-3-4 and vice versa, when condensing temperature decreases, compression work will decrease (process 1-2') and increase cooling capacity (process 4'-1) leading to an increase in COP of cycle 1-2'-3'-4'. For air-cooled systems, the condensing temperature depends heavily on the air temperature and the airflow rate entering the condenser unit. With a constant airflow rate for condenser cooling, if the air temperature is low, the condensing temperature of the refrigeration cycle will be low, and vice versa. If the airflow rate for condenser cooling is increased while keeping the air temperature constant, it will result in a decrease in the condensing temperature and an improvement in the COP of the air conditioner. However, it will also increase the power consumption of the condenser fan. Based on economic and technical analyses, air conditioner manufacturers have determined the optimal airflow rate for condenser cooling for various capacity ranges. Therefore, to increase the COP of an air-cooled air conditioner without significantly increasing the fan energy consumption in condenser, the only viable option is to control the air temperature for condenser cooling.

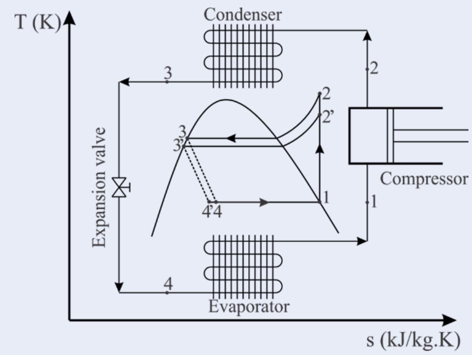

Figure 1: Effect of condensing temperatureon compressor work and cooling capacity

The air temperature for cooling the condenser unit depends on environmental conditions, which are external factors that we cannot control. However, we can adjust the air temperature within a localized range. The simplest way to lower the air temperature within a localized range is by using the evaporative cooling method. The lowest achievable air temperature through evaporative cooling is the wet-bulb temperature, which corresponds to the temperature and relative humidity of the environment. The lower the environmental humidity, the lower the wet-bulb temperature. In this approach, the temperature of the water used for evaporative cooling has minimal impact on the wet-bulb temperature.

To apply evaporative cooling to the air used for cooling the condenser unit, a misting system must be installed at the inlet of the air-cooling section. This approach not only reduces the temperature of the air leaving the condenser, thereby increasing the COP of the air conditioning system, but also enhances the convective heat transfer coefficient of the surrounding air. As a result, the overall performance and efficiency of the condenser unit are significantly improved.

The water used for evaporative cooling of air has a very low flow rate, so it can use domestic water or condensed water from evaporative devices. Condensed water from the air conditioning unit has the advantage of low temperature but the disadvantage of low flow rate, so for two-unit air conditioners, using condensed water is not feasible. Therefore, to make the most of the condensate from the air conditioner evaporators, a multi-split air conditioning system is very suitable.

Surveying a multi-split air conditioning system using R32 refrigerant gas with a capacity of 4 HP; the cooling airflow of the outdoor unit is 50m^3/minute. The outdoor unit can connect with up to 5 indoor units simultaneously. When all 5 indoor units operate simultaneously, the cooling capacity of each unit is 2kW at a current intensity of 13.9A, and the maximum capacity of the outdoor unit is 13kW.

Assumptions:

- The refrigerant compression process is an adiabatic process.
- The refrigerant vapor entering the compressor is

1. The room temperature to be maintained is 26°C.
2. The outdoor air temperature ranges from 30°C to 40°C
3. The water temperature is 3°C above the wet-bulb temperature of the ambient air.
4. After humidification, the air becomes fully saturated with moisture at 100% relative humidity.

Within the condenser unit, the refrigerant transfers heat to the surrounding air and undergoes phase change into a liquid. Based on heat transfer principles, the refrigerant's condensing temperature in the outdoor unit must be 8–10°C higher than the temperature of the exiting air. Under the climatic conditions of the southern region, air-cooled air conditioning systems typically operate with a condensing temperature ranging from 50°C to 55°C.

Implementation Method:

- Apply the principles of moist air to determine the water spray flow rate and the air temperature following evaporative cooling.
- Use the energy balance equation at the condenser unit to compute the air temperature leaving the condenser and subsequently estimate the refrigerant's condensing temperature.
- Calculate the COP for the regular cycle and the combined water and air cooling cycle.
- Calculate the operating costs of both approaches.

The equation for the mass balance of substance when humidifying air:

$$G_1 + \triangle d = G2 \quad (1)$$

The energy balance equation:

$$G_1.I_1 + \triangle d.r = G_2.I_2 \quad (2)$$

The humidity content of moist air:

$$d = \frac{0,622.p\_v}{1 - p\_v} \quad (3)$$

Pressure of water vapour in saturated air:

$$P_{sat} = 0,004516 + 0,000718.t - 2,649.10^{-6}.t^2 + 6,944.10^{-7}.t^3 \quad (4)$$

Enthalpy of moist air:

$$I = 1,006t + (2501 + 1,84t)d \quad (5)$$

Where:
-G: mass flow rate of moist air [kg/s]
-d: humidity content of moist air [(kg vapour)/(kg dry air)]
-I: enthalpy of moist air [kJ/kg]
-pv: vapour water pressure of moist air [bar]
-psat: saturated pressure of vapour water in moist air [bar]
-r: latent heat of water (kJ/kg)
-t: temperature of moist air [oC]

RESULTS AND DISCUSSIONS

In practical working conditions with an incoming air temperature for cooling of 35°C and a desired room air temperature of 26°C, the corresponding vaporization and condensation pressures of R32 refrigerant are 9 bar and 32 bar, respectively.

Using the EES software to calculate the enthalpy at various points on the theoretical air conditioning cycle with the given operating parameters, the following findings were recorded:

- The condensing temperature of the R32 refrigerant is 50.8°C.
- The COP of the cycle is 4.2.

In maximum capacity mode (with a maximum outdoor unit capacity of 13 kW) and based on an airflow rate through the outdoor unit of 50 m3/minute, considering the air flowing through the outdoor unit as a heating process, the theoretical temperature of the air leaving the outdoor unit is determined to be 46.5°C. The temperature difference between the condensation temperature and the air leaving the outdoor unit is 4.3°C.

When the outdoor unit air is humidified to saturation, its temperature reaches the wet-bulb temperature, at which the relative humidity is 100%. By applying an iterative method, the wet-bulb temperature is determined to be 30°C, resulting in the cooled air temperature after humidification reaching 41.4°C.

Assuming the temperature difference between the refrigerant's condensing temperature and the cooling air temperature at the condenser outlet remains constant, the refrigerant's condensing temperature under combined air and evaporative cooling conditions will be 45.7°C. Correspondingly, the refrigerant's condensation pressure will be 28.41 bar. Under these conditions, the theoretical COP of the air conditioning system is calculated to be 4.922.

Performing a similar analysis with varying input parameters within the specified range, the results are illustrated in the following figures:

a. Effect of inlet air temperature and humidity on the temperature of air exiting the condenser

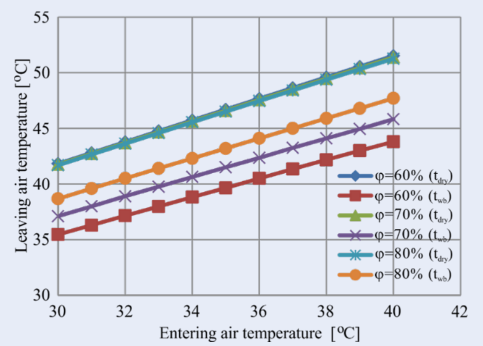

Figure 2: Effect of entering airtemperature and humidity on the air temperature leaving the condenser

The calculation results presented in Figure 2 indicate that as the air temperature before entering the condenser varies, the air temperature leaving the condenser changes linearly with the entering air temperature. The effect of the air's relative humidity before entering the condenser on the exiting air temperature is negligible. Within the condenser, where the air absorbs heat, the heat transfer process primarily involves sensible heat exchange.

Furthermore, the results in Figure 2 demonstrate that when evaporative cooling is applied to the condenser's cooling air, the air temperature leaving the condenser is significantly lower compared to conventional air cooling. Specifically, if the ambient air humidity is reduced by 10%, the air temperature exiting the condenser under evaporative cooling conditions decreases by an average of 1.8°C.

b. Effect of cooling air temperature on COP

The calculations presented in Figure 3 show that as the cooling air temperature rises, the COP of the air conditioning system decreases in an approximately linear manner. Under conventional air cooling, the COP remains relatively stable regardless of changes in the relative humidity of the incoming air.

However, when evaporative cooling is applied to the air used for condenser cooling, the relative humidity of the incoming air significantly impacts the COP. Specifically, lower relative humidity leads to a higher COP. The calculations further reveal that a 10% reduction in ambient air humidity results in an average COP increase of 6% when the condenser is cooled using a combination of air and evaporative cooling.

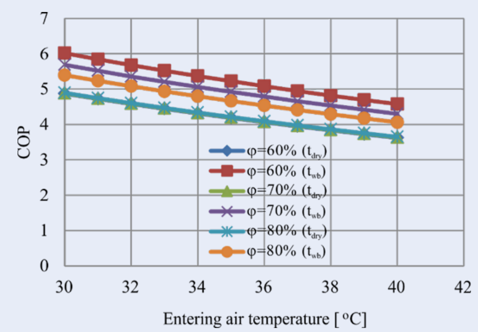

Figure 3: Effect of entering airtemperature on COP

The calculations in Figure 4 reveal that as the ambient air's relative humidity decreases, the increase in COP when combined with evaporative cooling is higher, and vice versa. When the incoming air temperature for cooling rises, the increase in COP when combined with evaporative cooling also increases. This can be easily explained as follows: when the cooling air temperature increases, the COP of the air conditioner decreases. When cooled by evaporative cooling, the air temperature decreases, enhancing the cooling efficiency of the condenser. However, when the relative humidity of the cooling air is higher, the increase in COP with respect to air temperature is insignificant. Under weather conditions in southern Vietnam, the average increase in COP with evaporative cooling is 16%.

c. Effect of cooling air temperature and relative humidity on spray water flow rate.

The calculations in Figure 5 demonstrate that as the cooling air temperature increases, the flow rate of sprayed water required for the air to reach saturation also increases. When the humidity of the cooling air is lower, the flow rate of sprayed water needed for saturation is higher. The calculation results align with theory because as the air temperature rises, the vapor pressure of air also increases, and at lower humidity levels, the vapor pressure of water vapor in the air is lower. Under the weather conditions in Ho Chi Minh

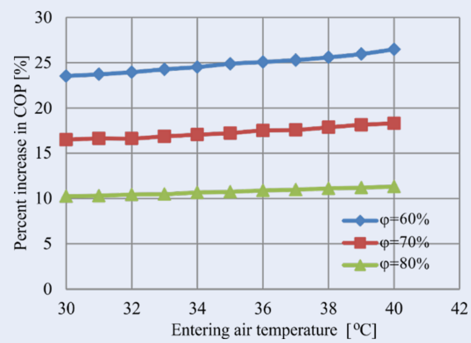

Figure 4: Effect of entering airtemperature and relative humidity on the COP of the condenser.

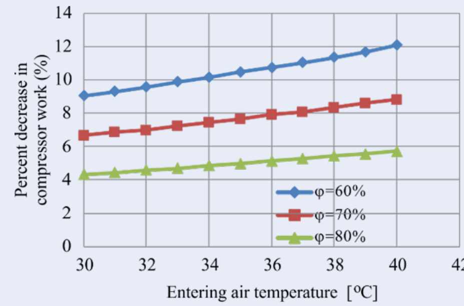

Figure 6: Effect of entering air temperature and relative humidity on compressor work

City, the amount of sprayed water per unit air conditioner capacity varies in the range of 1-2 kg/h. This water flow is negligible and easily manageable.

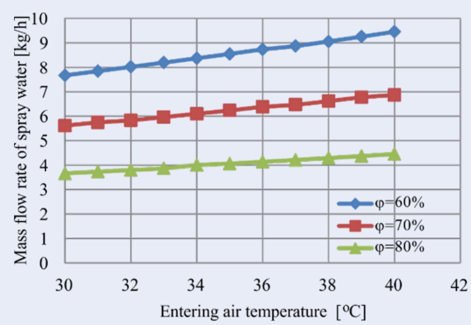

Figure 5: Effect of entering air temperatureand relative humidity on spray water flow

d. Effect of entering air temperature and relative humidity on compressor work.

Based on the calculated COP of the air conditioner for two cases: normal air cooling and combined with evaporative cooling, the compressor work for both cases has been determined. The difference in compressor work between these two cases is depicted in Figure 6. The results presented in Figure 6 indicate that when the humidity of the cooling air is low, the difference in compressor work between the case with moisture injection and the case without moisture injection is higher, and vice versa. This result demonstrates that in harsh climatic conditions, cooling the condenser air by combining it with evaporative cooling provides a significant efficiency advantage. In the weather conditions of Ho Chi Minh City, the percentage reduction in compressor work when the condenser is cooled in combination with evaporative cooling varies in the range of 5-10%.

e. Effect of entering air temperature and relative humidity on operating cost savings

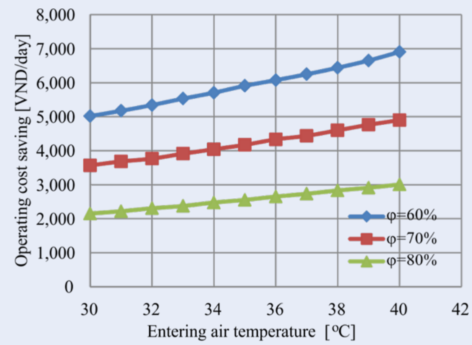

Figure 7: Effect of entering airtemperature and relative humidity on operating cost savings

Based on the results of calculating the difference in compressor work between the two cases of cooling the condenser with normal air and cooling combined with evaporative cooling, the amount of energy saved was determined. Assuming the system's operating time per day is 8 hours and the average domestic electricity price is 2014 VND/kWh, the economical operating costs are also determined. Based on the spray water flow, corresponding DC water pump capacity and the price of domestic tap water of 5,300 VND/m3, the cost to operate the evaporative cooling system is also determined. The calculation results presented in Figure 7 show that the cost savings depend heavily on the relative humidity of the air surrounding the condenser. The lower the air humidity, the higher the savings and vice versa. In addition, ambient air temperature also has a significant influence on operating costs. The higher the ambient temperature, the lower the operating cost of an air conditioner incorporating evaporative cooling compared to normal air cooling. With the mentioned multi-type air conditioner, if the environmental humidity is 70%, the cost saved when operating 8 hours/day is an average of 4,000 VND/day.

CONCLUSION

The calculation results indicate that enhancing the cooling of the condenser unit through a combination with evaporative cooling is highly effective. Cooling the condenser unit with the evaporative cooling method has contributed to an increase in the air conditioner's COP, consequently reducing the amount of electrical energy consumption. Additionally, the outlet air temperature from the condenser has also significantly decreased, contributing to the reduction of the impact of heat island. The specific results achieved are as follows:

-The ambient air's relative humidity decreases by 10%, the air temperature leaving the condenser in case the air is evaporatively cooled drops by an average of 1.8°C.

- The ambient air's relative humidity decreases by 10%, the COP increases on average by 6% when the condenser is cooled by air in combination with evaporative cooling.

- The amount of sprayed water per unit air conditioner capacity varies in the range of 1-2 kg/h.

- The percentage drop in compressor energy consumption when the condenser is cooled in combination with evaporative cooling varies in the range of 5-10%.

In the climate conditions of Vietnam, with the average ambient temperature of the hottest month being 35oC and the average humidity being 70%, the improvement in COP and power consumption of the compressor by the method of cooling the condenser with air combined with evaporative cooling is 16% and 7% respectively. This result is similar to the previous research results of Wang [10].

With the positive outcomes achieved by the enhanced condenser cooling method using evaporative cooling, it can be concluded that this approach is highly suitable for the weather conditions in Southern Vietnam. Especially during the hot season when ambient air temperatures are very high, the energy efficiency gains are substantial. In addition to enhancing performance, the condenser cooling method combined with evaporative cooling also helps address electricity shortages during the summer. The evaporative cooling of air for condenser cooling does not affect the existing system, has a simple structure, and is cost-effective, making it easy to implement.

Currently, the research results are based on theoretical calculations with fixed assumptions, so these results may not reflect the actual conditions. To confirm the benefits of combining air-cooled condenser cooling with evaporative cooling on energy saving ability, it is necessary to conduct experimental studies in the future.

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COMPETING INTERESTS

The authors wish to confirm that there are no known conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome.

AUTHORS' CONTRIBUTIONS

The first author (Kien Quoc Vo) conceived the research idea and conducted the research, the second author (Chi Hiep Le) participated in reviewing and helping to draft the manuscript. The authors read and approved the final manuscript.

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Bài nghiên cứu

Nghiên cứu lý thuyết về việc kết hợp dàn ngưng giải nhiệt gió với làm mát bay hơi để nâng cao hệ số hiệu suất của hệ thống điều hòa không khí multi-split

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TÓM TẮT

Bài báo này trình bày kết quả nghiên cứu lý thuyết về việc tăng cường trao đổi nhiệt trong dàn ngưng giải nhiệt gió multi-split bằng cách kết hợp với phương pháp làm mát bay hơi nhằm tăng hiệu suất và giảm điện năng tiêu thụ. Dựa trên các tính toán nhiệt động lực học của không khí ẩm và tính toán chu trình làm lạnh, kết quả nghiên cứu cho thấy việc tăng cường làm mát dàn ngưng kết hợp với làm mát bay hơi có hiệu quả cao. Nếu độ ẩm môi trường giảm 10%, nhiệt độ không khí ra khỏi dàn ngưng với làm mát bay hơi giảm 1,8°C và hệ số hiệu suất (COP) tăng trung bình 6%. Trong điều kiện thời tiết của các tỉnh miền Nam Việt Nam, hiệu suất làm mát (COP) của hệ thống điều hòa không khí với dàn ngưng tăng cường làm mát bằng bay hơi tăng trung bình 16% so với trường hợp không có trao đổi nhiệt tăng cường. Chi phí tiết kiệm được cho một hệ thống điều hòa không khí đa công suất 4HP hoạt động trung bình 8 giờ là 4.000 đồng. Độ ẩm không khí xung quanh càng thấp thì việc tăng cường làm mát dàn ngưng bằng không khí kết hợp với làm mát bay hơi càng hiệu quả.

Từ khoá: tăng cường làm mát, dàn ngưng giải nhiệt bằng không khí, bay hơi, máy lạnh multi-split, hệ số hiệu suất COP, tiết kiệm năng lượng

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