UDC: 621.5

Air-conditioning condenser integrated with a spray system utilizing condensate water

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Abstract: Recycling the condensate water is environmentally friendly routine for energy saving in modern buildings. Aiming at the waste cold utilization of condensate water, a novel spray system employing the cold water as substance was proposed to cool the condenser. The condensate water forms thin liquid film which is crushed into tiny droplets later in the nozzle. Carried by the condensing air, the spray droplets are easy to deposit on the surface of condenser exchanger. And thus the evaporation can take place over the hot surface homogeneously. With this facility, the condensate water can be well recycled during the usage of air conditioning. In this way, it can prevent the condensate water from environment pollution. And this facility is helpful for energy saving and CO_2 emission, as well as good economic return.

Key Words: Condensate water, spray, heat exchange, energy saving

1. Introduction

As increasing constantly of the energy need globally and rapid consumption of non-renewable energy, the energy supply is becoming tense. From the view of resource consumption, 1/6 of resource consumption in the world relating directly to construction industry, the construction energy consumption totally accounts for 27.6% of total energy consumption. In the construction energy consumption, the energy consumption used in Heating Ventilation and Air Conditioning (HVAC) accounts for 30%-50% [1]. Air conditioner operated in summer, when the surface temperature of an evaporator is lower than the dew-point temperature of the ambient air, vapors in the air will be condensed to form water film on the surface of the evaporator. And the condensate water results from the constant heat and mass transfer of the air around the film and the water film. With the concept of the energy saving and emission reduction, the condensate water draws more and more attentions.

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There are two ways using the condensate water: one is to use it as water resource: one is as the supply for units of the cooling tower. Another is to use it as sanitary water in public places, such as the airport lounges [2-3]. But in recent years, the development of split type air conditioner in China is rapid. The condensate water produced by this air conditioner has large refrigerating capacity. The condensate water needn't discharge into the air, and it can be used to pre-cool the air which is into the condenser. It's good for the heat rejection of condenser and lower the energy consumption in the operation.

Some researchers have been conducted for the energy saving and utilization of the air condensate water [4-8]. The solution that the condenser is cooled to lower the temperature of outdoor unit by the condensate water is a mature technology of the utilization of the condensate water. Simple equipment, effective energy saving and good economic benefits are advantages of this technology. There are three major methods cooling the condenser by condensate water, including spraying method, wet membrane method and the method of adding a condenser. The spraying method is to collect condensate water into a collection plate. By using a control system of water level, when the water level is up to the preset height, the condensate water is elevated and sprayed with the condenser. Water evaporation absorbs a lot of heat, increasing heat rejection. The refrigeration effect of the system enhanced obviously, saving the energy, especial the electric energy. The disadvantage that the volume of condensate water is small will lead the discontinuous and unsteady operation of the air conditioner system. Wet membrane method is to put up the breathable non-woven fabric on the two side of the condenser, adding the area of heat transfer. When condensate water is sprayed with the condenser, it will cool the whole surface of condenser in the evaporation process, increase the heat rejection and enhance the refrigeration effect, achieving the goal of saving energy. The method only needs simple equipment, but has a great effect of saving energy. Adding the additional condenser is to add an evaporative condenser in series before the air cooled condenser of initial air conditioner system. The temperature is reduced by the evaporating of the condenser water sprayed with condenser. Another method is adding an assistant condenser, i.e. setting another condenser as assistant for the origin air-cooling condenser in the air conditioning system. Via the evaporation of spray condensate water, the temperature of the condenser is decreased. Compared with the spray and wet film, all the cooper pipe and fins in the condenser are made of anticorrosion materials thus can avoid the erosion on aluminum fins caused by condensate water.

Chen Nan et al. [13] made a comparison about the capacity of condensate water among different climate, and it was found that the capacity of condensate water is larger in South and East of China, resulting in a better energy-saving efficiency. Zhao Tao et al. [14] proposed three prototypes for condensate water usage. It was proved that adding the small pump to spray condensate water cooling condenser was the most efficient way for better heat exchange. The COP is improved and the cooling capacity is increased as well. Chen En, Yu Jing et al. [15-19] carried out a calculation of capacity of water for split-type air conditioner. And the variation of COP is analyzed due to using the cold water to cool condenser. Besides, it was practically applied technology to use the condensate water to cool the condenser in Germany in 1996. And some relative patents has also been published in the US. Charles L. Michael [20] invented a facility to clean the condensate water for drinking. Kevin Teller [21] introduced several patents concerning recycling condensate water for cooling condenser during 1992 to 1997. The working principles were briefly introduced and a novel invention for using the waste cold of condensate water was also proposed.

In all, it is a concerning topic to combine the air conditioning system with building energy saving. As for the present work, a prototype to cool the condenser with spray under ultralow cold water flowrate is proposed. And the results indicated that the usage of this facility gave rise to lower energy consumption and CO_2 emission.

2. System design

2.1 The calculation of condensate water

2.1.1 The Assumptions for calculation

A split-type air conditioner was taken as an example which brand is KFR72W/E1(72553L1)C1-N3 in the room 215 of Power building, Chongqing University. We calculated the production of condensate water that the air conditioner generated in operating condition in summer.

To simplify the calculation, some assumptions was made as below:

(1) The influence of building structure and placement on cooling load is negligible;

(2) The air conditioner runs steady in operating condition;

2.1.2 The parameters

(1) The parameters of air conditioner

The main parameters of air conditioner are as shown in Table 1:

Table 1 Operating parameter of the selected air conditioner

Cooling capacity （W）	heating capacity（W）	Circulating flow (m^3/h)	rated power（W）
7200	8200	1150	2410/2530

(2) Outdoor air parameters

According to The design manual of heating air conditioning and we take outdoor meteorological condition in Chongqing into account. Outdoor air parameters are as shown in Table 2.

Table 2 Outdoor air properties

atmospheric pressure（hPa）	dry-bulb temperature （℃）	wet bulb temperature （℃）	average daily temperature（℃）	Outdoor air speed（m/s）
991.2	36.5	27.3	33	2.4

(3) Indoor air properties

According to the design manual of air conditioner, indoor air properties are as listed in Table 3:

Table 3 Indoor design parameters

temperature（℃）	relative humidity（%）	air speed（m/s）
24-28	40-65	≤0.3

According to the Tables, set indoor air parameters :t_N =24℃，ψ_N=60%。

(4) Fresh air ratio

Due to the frequent going in and out of the office, opening or closing windows and doors, accordingly, the fresh air ratio was set at 10%

2.1.3 The calculation of condensate water

1). Cooling load

According to the air conditioning type, the refrigerating capacity is rated as 7200 W, in the process of actual operation, in order to simplify the calculation, regard the indoor cooling load as the rated refrigerating capacity calculation directly, Q = 7200 W.

2). Humidity load

Humidity load is derived from the moisture gain of the room, And the moisture gain of the room is depend on it's using properties. The moisture gain of the lab consist of moisture gain from occupant, food, fresh air and opening water surface etc.

(1) Moisture gain from occupant

There are 9 man and 3 women in the lab, moisture gain from a woman is 84% of a man, so moisture gain from occupant:

$$m_1 = \frac{1}{1000} n\psi g = 1.847 kg/h \tag{1}$$

n —— The number of people indoor;

ψ —— Clustering coefficient, 0.96;

g —— Moisture gain from a man per hour, taken as: 167 g/h;

(2) Moisture gain from food

According to the literature, moisture gain from food is about 10 g/h per person, consequently, the moisture gain from food is m_2:

$$m_2 = 0.12 kg/h \tag{2}$$

(3) Moisture gain from fresh air

The fresh air penetrate in the lab through the windows and the doors, the fresh air is 10% percent of the circular air rate, actually, fresh air volume is 115 m^3/h, consequently, the moisture gain from fresh air is m_3:

$$m_3 = \rho G'(\mathrm{d_w} - \mathrm{d_c}) = 0.969\,\mathrm{kg/h} \tag{3}$$

(4) Moisture gain from opening water surface

The moisture gain from opening water surface is calculated as followed:

$$m_4 = Fg' = 0.0013 kg/h \tag{4}$$

Where:

F —— the evaporation surface area of the water channel, unit: m^2;

g' —— evaporation capacity per square meter, unit: kg/m^2·h.

Humidity load in the lab：

$$m = \sum_{i=1}^{4} m_i = 2.973 kg / h \tag{5}$$

3). The calculation of condensate water

According to temperature and humidity parameter of air indoor and outdoor, confirming the state points N, W indoor and outdoor. Confirm the mixed state point C according to the fresh air ratio. The air at mixed state point C was cooling and dehumidification through the air cooled heat exchanger, and intersects the relative humidity lineψ=90%-95% at L, L point is the point of ventilation state, the cooled air is supplied into the room, subsequently cooling and dehumidifying the air indoor, and then reached at state point N along the heat moisture ratio line ε, latterly mixed with fresh air at state point C. The air treating processes indoor circulate like this, and the psychrometric chart of this process is showed as figure 1.

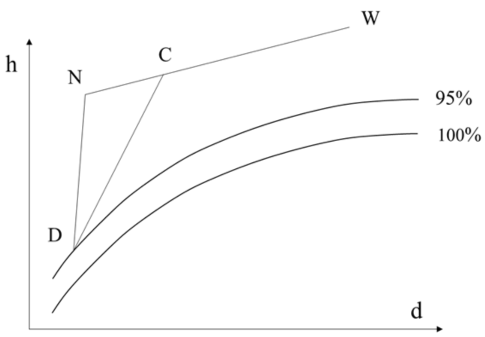

Fig 1 the psychrometric chart in the air treating process

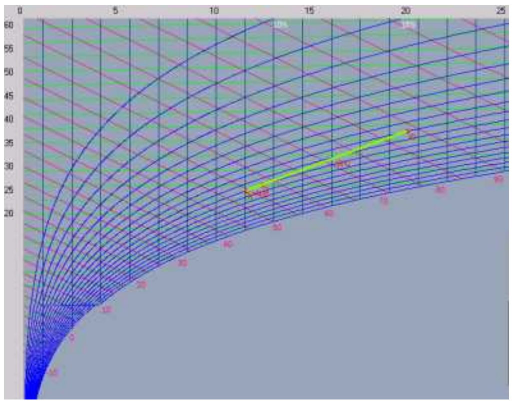

Fig 2 the psychrometric chart

Outdoor state point W: it is determined by the dry-bulb temperature t_W =36.5℃, wet bulb temperature t_{SW} =27.3℃, checking the psychrometric chart(Fig 2) and confirming the enthalpy value h_W and moisture content $d_{W,}$ respectively h_W =88.09 kJ/kg, $d_{W=}$ 19.94 g/kg.

Indoor state point N: according to the given indoor temperature t_N=24℃, relative humidityψ_N =60%, checking the psychrometric chart(Fig 2) and confirming the enthalpy value h_N and moisture content $d_{N,}$ respectively h_N =53.71 kJ/kg, $d_{N=}$ 11.58 g/kg.

Mixed state point C: according to the mixed theory of two different state of air, mixed state point locate on line NW, and fresh air ratio k satisfy:

$$k = \frac{h_C - h_N}{h_W - h_N} \tag{6}$$

$$k = \frac{d_C - d_N}{d_W - d_N} \tag{7}$$

Take the date into the terms above to confirm the enthalpy value h_C and moisture content d_C, respectively h_C =57.148 kJ/kg, d_{C}= 12.416 g/kg.

The mixed air from indoor and outdoor is bring in air-condition, and then is treated latterly supplied into the lab, along the heat moisture ratio line ε reached at indoor state point N, moisture ratio ε:

$$\varepsilon = \frac{Q}{m} = \frac{7.2 \times 3600}{2.973} = 8825.3kJ / \text{kg} \tag{8}$$

In the psychrometric chart, across indoor state point N draw moisture ratio ε intersects the relative humidity lineψ=95% at L, confirming point L: moisture content d_{L}=9.99 g/kg，density ρ=1.183 m^3/kg.

According to moisture content balance: the quantity of condensate water from air-condition is M:

$$M = \rho G(\text{d}_\text{C} - \text{d}_\text{L}) = 3.042\,\text{kg/ h} \tag{9}$$

Finally: the quantity of condensate water from air-condition in summer is: 3.042 kg/h.

2.2 Design of spray system

To guarantee the spray droplets to deposit on the condenser uniformly, twelve nozzles are arranged in this system. Thus the flowrate in each nozzle can be derived as following:

$$q = \frac{M}{N} = \frac{3}{12} = 0.25L / h \tag{10}$$

where q is the flowrate in each nozzle, M is the total water flowrate, and N is the nozzle number.

For the flowrate in each nozzle is quite low, a peristaltic pump (FB-RDB6) is employed to spray periodically under a range of 1.25 mL/min-650 mL/min, cf. Figure 3.

Figure 3 the diagram of peristaltic pump

Figure 4 the diagram of mini-type fan

It's difficulty to spray the cold water in single liquid phase due to ultralow flowrate and low pressure of peristaltic pump. Thus air assistant spray was taken into consideration. A min-type fan was set to blast air into the nozzle, thus crush the liquid film into fragments. A fan (WS7040-24-8) was selected (Fig 4), which provide a wind pressure as high as 6 kpa. Considering the pipe resistance, the final pressure was reduced to 3-4 kpa. Additionally, by slotting the cold water pipe inserted in the nozzle, a liquid film with 0.05 mm in thickness was obtained. Thereafter, air blasting happened to the thin film for better spray atomization. According to the force balance on the liquid film, the film would break up into pieces as external force overcomes the viscous force and surface tension, which is descripted as:

$$\frac{\sigma}{\delta} < P_{air} \tag{11}$$

Where σ is surface tension, δ is the liquid film thickness, and p_{air} is air pressure provided by fan. Then substitute the data into the equation as below:

$$\frac{\sigma}{\delta} = \frac{0.0731}{0.00005} = 1462Pa < 3000Pa \tag{12}$$

A conclusion can be arrived that the spray is technically practical. Moreover, the spray atomization is implemented due to the variation of surface tension and aerodynamics. The spray mode can be classified as the first wind-induced spray. According to the theory, the droplets size is in the same magnitude of liquid jetting. Thus the droplet size is predicted as 0.05 mm as well.

2.3 The prototype of system

As shown in Figure 5, a micro spray system based on condensate water, which contain water system and air system. Water storage tank, peristaltic pump and water pipe, all of them made up the water system. Water storage tank, cover with insulation layer that used for preventing condensate water exchange heat with the environment, is used to collect condensed water. Condensate via the water piping to spray nozzle by the driving of the pump; Air system include draught fan and air piping. The air outside is pump to the nozzle by the fan before mixed with condensate water, then mixture of air and condensed water would transfer heat with refrigerant of High temperature and high pressure through the fin.

Key component of the system is spray nozzle, just as shown in Figure 6. Condensate water is pumped into nozzle via the water piping, at the end of which is designed to be flat with fistulous internal structure, making condensate water well atomized and distributed in the mixing chamber. When air through the air piping to the chamber and crash the spray of condensate water into smaller droplets. It would improve the heat transfer coefficient and increase the refrigeration capacity under combined effect of the improving of air flow rate and the evaporation of the recycling condensate water, so as to achieve the effect of energy conservation and emissions reduction.

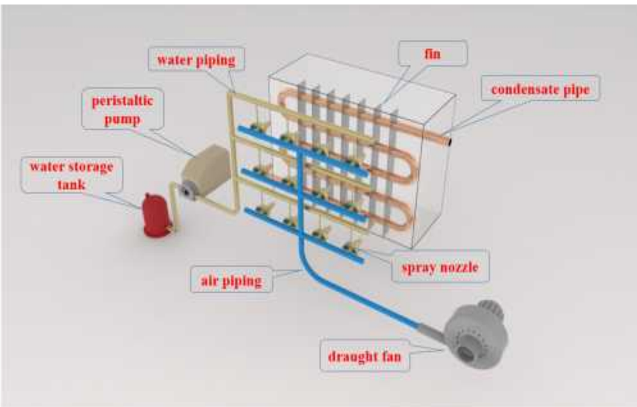

Figure 5 the overall system diagram

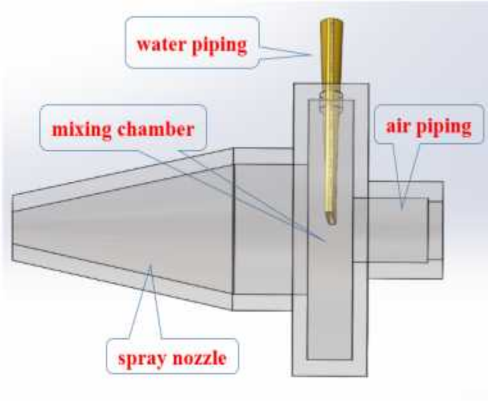

Figure 6 schematic diagram of spray nozzle

3. Efficiency calculation

The efficiency calculation of the system has been carried out in order to ensure the designed system was economical and reliable. As an example, the refrigerating capacity was 7200W, power rating was 2410 W.

The operating condition were as follows: Outdoor environment temperature was 36.5℃, the controlled indoor temperature was 26℃, condensation temperature was 50℃, evaporation temperature was 5℃, subcooling temperature was 5℃, Superheating temperature is 2℃. Without consideration of pressure drop and flash evaporation in the Refrigerant flow process, the refrigerant working medium was R22.

The refrigeration cycle of P-h was shown in Fig 7. The calculated COP was as follows:

$$COP = \frac{h_2 - h_1}{h_s - h_2} = \frac{408.62 - 256.31}{439.08 - 408.62} = 5.00 \quad (13)$$

The flow rate of R22 was:

$$q_m = \frac{7200}{408.62 - 256.31} = 47.27 g/s \quad (14)$$

As shown in Figure 8. When spray wasn't adopted, all the heat of condenser was used to heat air, on the enthalpy wet graph was a straight up line point 1 to point 2. It can be figured out:

$$Q = G(h_2 - h_1) \quad (15)$$

When spray was adopted, condenser heat dissipating capacity was divided into two parts: the evaporation latent heat of the air condensing water Q_{water}, the heat used to heat the air Q_{air}. The air in the condenser can be considered as a constant moisture content heating process, as shown in Fig 8, point 1 to point 3, then the heated air absorbed the vapored air condensing water at a constant temperature, the state of the mixed turned into point 4. The process on the psychrometric chart was point 3 to point 4. It can be figured out:

$$Q = Q_{water} - Q_{air} \quad (16)$$

$$Q_{water} = M_{water} - h_{latent} \tag{17}$$

$$Q_{air} = G(h_3 - h_1) \tag{18}$$

$$Q_{water} = G(h_4 - h_3) \tag{19}$$

In the mentioned formula, Q was total heat exchange amount; Q_{water} was heat exchange mount of air condensing water; Q_{air} was heat exchange mount of air; M was mass flow rate of air condensing water; K was coefficient of heat transfer; A was heat transfer area of condenser. It can be concluded that the increase of Q_{water} give rise to the decrease of Q_{air}, when the heat exchange amount was constant. The heat exchange area and the coefficient of heat transfer remain unchanged, hence Δt decreased, result in the decreasing of condensing temperature. The calculating result showed that the condensing temperature decreased about 2.85℃.

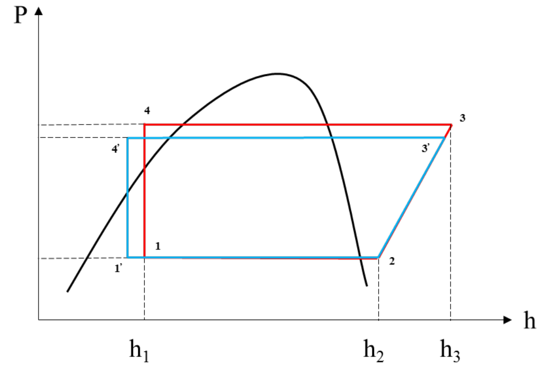

Figure 7 Refrigeration cycle comparison before and after adding spray

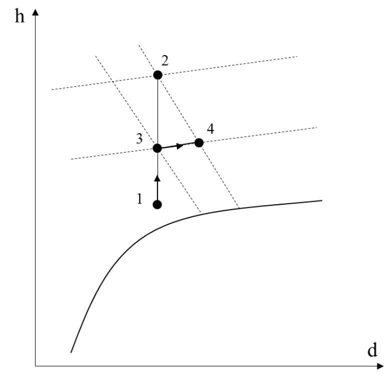

Figure 8 Enthalpy wet figure of the heating processes of the cooling air

As shown in Figure 8. The refrigerating cycle were 1-2-3-4 before spray system was added. The condensing temperature decreased after spray system was added, and the refrigerating cycle turned into 1'-2-3'-4'. Checked the pressure-enthalpy chart of R22, it can be calculated as follows:

$$COP_1 = \frac{408.62 - 256.31}{439.08 - 408.62} = 5.00 \tag{20}$$

$$COP = \frac{h_2 - h_1}{h_s - h_2} = \frac{408.62 - 252.85}{437.69 - 408.62} = 5.36 \tag{21}$$

The main calculation results were shown in Table 4:

Table 4 Systemic changes before and after adding spray

	Refrigerating capacity (kJ/kg)	Compression work (W)	COP
No spray	7200	1439.84	5.00
Spray	7363	1374.14	5.36

Varies	↑2.2%	↓4.5%	↑7.2%

For example, the rated power of the air conditioner was 3 kW. It is supposed to work for 10 hours a day, 120 days a summer and thus, the electricity consumption was worth RMB 3600. Adopting the proposed method, subtracted the electricity consumption of pump and fan which was approximately equal to 60 W, 181 yuan electricity charges can be saved each year. The cost was RMB 340 each unit, the cost can be recovered in 1.87 year. In 2014 china building have energy consumption was 1.25×1017 kJ, If all the household air conditioner adopted the proposed air-conditioning condenser integrated with a spray system utilizing air condensing water in this work, the benefits were as follows:

1. Energy-saving benefit: If the air conditioner energy consumption took up half of the total energy consumption, 1.16×10^{12} kW·h energy can be saved, equivalent to about 1.42×10^{8} t of standard coal.

2. Emissions Benefits: The saving electricity is generated by coal, if the power generation efficiency is 36%, about 3.96×10^{8} t standard coal can be saved, about 1.07×10^{9} t emissions were reduced.

3. Economic benefit: If electric charge was 0.5 yuan per kilowatt-hour, throughout the year China can save about RMB 58 billion.

4. Conclusion

1. When refrigerating capacity is 7200 W and relative humidity of outdoor air is 48.9%, it is about 3 kg/h available air conditioning condensate water would be obtained;

2. After will be uniformly the condensate film, recycled air atomization, available size of small droplets is about 0.05 mm after distribution of the liquid film homogeneously and using the air to make condensate water atomization;

3. The micro spray system would lead to the reducing the condensation temperature of air conditioning system and the increasing of refrigerating capacity. Consumption of the compressor power would be also reduced. All of these result in the increasing refrigeration system COP.

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