Air conditioning fresh air unit with solar air collector and evaporative cooler

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Abstract. Fresh air load accounts for about 30% of air conditioning energy consumption. This paper introduced an air conditioning fresh air unit which combines solar air collector with indirect evaporative cooler. In summer, indirect evaporative cooler was used to precool fresh air, circulating water was used as spray water and the condensed water was used as supplement; in winter, solar air collector was used to preheat fresh air, and indirect evaporative cooler was used as sensible heat exchanger of primary air. The results of energy consumption calculation and analysis show that compared with the traditional fresh air handling unit, the energy saving of the air conditioning fresh air unit was 36.9% in summer and 64.0% in winter. The static investment payback period of the air conditioning fresh air unit was 3.7 years and the initial investment recovery period was 4.7 years.

1. Introduction
HVAC energy consumption accounts for about 60% of building energy consumption, while fresh air load accounts for about 30% of air conditioning energy consumption [1].

In recent years, indirect evaporative cooling had attracted extensive attention. Compared with traditional mechanical refrigeration, indirect evaporative cooling has following advantages: using natural cold source, environmentally friendly, simple structure, low initial investment and operation cost[2]. Peterson and Hunn built an evaporative cooling system to provide pre-cooled mixed air for the air conditioning system. They found that the composite system can reduce about 12% of the traditional air conditioning load[3]. Xiang Huang combined evaporative coolers with mechanical refrigeration systems to precool fresh air in summer. When the fresh air ratio was 20%, the operation load of system can be reduced by 10%[4].

Solar energy is a kind of renewable energy. The heat utilization of solar energy has two ways: solar water collector and solar air collector. Solar air collector had more advantages than solar water collector in places with hot air demand, because the solar air collector doesn’t need the secondary heat exchange of water. Bing Zhang improved cop of heat pump unit by connecting solar air preheater in series in front of heat pump evaporator[5]. Ping Jiang designed a new type of solar air collector with high efficiency. Under the air volume of 0.00613m³/s and solar radiation intensity of 611.484w/m², the highest instantaneous heat collection efficiency was 71.73%[6].

The air conditioning fresh air unit combines solar air collector with indirect evaporative cooler to reduce energy consumption of fresh air treatment. In summer, indirect evaporation cooler was used to cool the air, and surface cooler was used to supplement the cooling capacity. In winter, solar air collector was used to preheat the air, and the surface cooler was used to supplement the heat. It was worth mentioning that the spray water in the indirect evaporative cooler was provided by tap water and
the indoor air was used as secondary air of indirect evaporative cooler. What’s more, the condensate water was used to supplement the spray water and reduce the temperature of the spray water, which can reduce the energy consumption of fresh air treatment.

2. Composition and operation principle of air conditioning fresh air unit

2.1 Composition
The air conditioning fresh air unit was composed of solar air collector, indirect evaporative cooler, water tank, surface cooler, fresh air unit air supply fan, filter and water pump. Figure 1 showed the structure of the unit.

![Figure 1 Structure of air conditioning fresh air unit](image)

1. Inlet of fresh air in winter; 2. Solar air collector; 3. Axial flow fan; 4. The first air valve; 5. Inlet of fresh air inlet in summer; 6. Second air valve; 7. Inlet section; 8. Filters; 9. Indirect evaporative cooler; 10. Spray pump of indirect evaporative cooler; 11. Water tank; 12. Inlet of secondary air of indirect evaporative cooler; 13. Heat exchanger of indirect evaporative cooler; 14. Water distributor; 15. Outlet of secondary air of indirect evaporative cooler; 16. Surface cooler; 17. Air supply fan of fresh air unit; 18. Inlet pipe of cold (hot) water; 19. Outlet pipe cold (hot) water; 20. Exhaust pipe of secondary air indirect evaporative cooler; 21. Exhaust fan of indirect evaporative cooler

2.2 Operation principle
In summer, fresh air enters the inlet section from the inlet of fresh air. After passing through the filter, fresh air entered the indirect evaporative cooler. At this time, the water in the water tank was driven by the water pump enters the water distributor to spray the secondary air flow passage. When the secondary air discharged from the room flows through the water film, the secondary air was cooled. After absorbing the heat of primary air, the secondary air was heated and the primary air was cooled. Driven by the indirect evaporative cooling exhaust fan, the secondary air was discharged out of the room finally. The remaining cooling capacity required of fresh air was provided by the surface cooler.

In winter, driven by the axial flow fan, the primary air entered the inlet section after the air was heated in the solar air collector. When the primary air temperature was higher than the indoor air, the primary air will be sent into the room. If the primary air temperature was lower than the indoor exhaust air temperature, the primary air will be sent into the indirect evaporative cooler for heat exchange with the secondary air. At this time, the indirect evaporative cooling heat exchanger becomes the fresh air heat recovery device. Finally, the primary air will be sent into the room and the secondary air was discharged out of the room. The remaining heat required of the fresh air was provided by the surface cooler.
In spring and autumn, the fresh air unit can be used according to the demand of users.

3. Design and calculation of air conditioning fresh air unit

Taking Hangzhou as a reference geographical location for using fresh air units. Outdoor calculated temperature of air conditioning in summer $t_1$ was 35.6°C; outdoor calculation temperature of air conditioning in winter $t_4$ was -2.4°C; outdoor wet bulb temperature of air conditioning in summer was 29.0°C; outdoor relative humidity of air conditioning in winter was 82%; outdoor air enthalpy in summer $h_1$ was 94.3kJ/kg; outdoor air enthalpy in winter $h_4$ was 3.5kJ/kg.

In summer, the indoor design temperature $t_{NX}$ was 26℃, the relative humidity was 60%, and the enthalpy value $h_{NX}$ was 58.4kJ/kg; in winter, the indoor design temperature $t_{ND}$ was 18℃, the relative humidity was 55%, and the enthalpy value $h_{ND}$ was 36.3kJ/kg. The air density $\rho$ in winter and summer was 1.3kg/m³.

A building with an air conditioning fresh air unit can accommodate 50 people and the per person fresh air demand was 30m³/h. Therefore, the total fresh air volume was 1500m³/h. In calculation, the air volume of primary air $L_1$ and secondary air $L_2$ were regarded as equal.

3.1 Indirect Evaporative Cooler

3.1.1 Summer

In summer, moisture content of outdoor air $d_1$ was 22.8g/kg; relative humidity of outdoor air was 61%; dew point temperature of outdoor air was 27.0°C; temperature of indoor air $t_{NX}$ was 26℃; wet bulb temperature of indoor air $t_{SNX}$ was 20.3℃. If circulating water was used to spray, the spray water temperature was equal to the wet bulb temperature of secondary air. However, the circulating water in indirect evaporative cooler was supplemented by condensate water, the spray water temperature will be lower than the wet bulb temperature of secondary air. The ratio of circulating water and condensate water determines the final temperature of spray water. In the indirect evaporative cooler, the best range of water gas ratio was 0.2-0.5. When the water gas ratio was 0.2, the circulating water volume was 390kg/h[7]. The proportion of volume of condensate water circulating water was about 1:15, so the spray water temperature was about 20°C.

According to the temperature of the spray water and the indoor exhaust air, the wall temperature of the indirect evaporative cooler was lower than the dew point temperature of the primary air. Consequently, the primary air was cooled and dehumidified when passing through the indirect evaporative cooler. It has been proved that when the indoor air was used as the secondary air and the relative humidity of the primary air was 60%, the cooling efficiency of the indirect evaporative cooler will decrease with the increase of the dry bulb temperature of the primary air. When the dry bulb temperature of primary air rose from 27℃ to 36℃, the cooling efficiency of the indirect evaporative cooler decreases from 0.65 to about 0.54[8]. Thus, the cooling efficiency of indirect evaporative cooler was assumed to be 54%.

The cooling efficiency $\eta$ of the indirect evaporative cooler was as follows:

$$\eta = \frac{t_2 - t_{SNX}}{t_1 - t_{SNX}}$$  \hspace{1cm} (1)

In the formula, $t_2$ was dry bulb temperature of outlet of primary air in summer. $t_{SNX}$ was temperature of spray water.

It can be found that the temperature of primary air outlet dry bulb $t_2$ was 27.2℃. At this time, the relative humidity of primary air was 90%, $h_2$ was 80.0kJ/kg.

Thus, the cooling capacity of fresh air born by indirect evaporative cooler was 7.7kW.

$$Q_z = \frac{L_1 \rho (h_1 - h_2)}{3600} = 7.7kW$$
3.1.2 Winter
In winter, the indirect evaporative cooler can be regard as the sensible heat exchanger. Sensible heat exchange efficiency $\varepsilon$[9] was 55%. Temperature of secondary air $t_{nd}$ was 18℃.

The sensible heat exchange efficiency $\varepsilon$ of primary air and secondary air was as follows:

$$\varepsilon = \frac{t_s - t_e}{t_s - t_{nd}}$$  \hspace{1cm} (2)

3.2 Solar air collector
The calculation formula[10] of solar air collector was as follow:

$$Q_T = \frac{I_0 \mu f \eta}{1000}$$  \hspace{1cm} (3)

In the formula, $\eta$ was the thermal efficiency of solar air collector, $Q_T$ was the heat collection of solar air collector, $I_0$ was the solar radiation intensity in horizontal plane, $\mu$ was angle correction factor, $f$ was the collecting area of solar air collector.

The enthalpy of indoor air in winter $h_{ND}$ was 36.6kJ/kg, and the temperature of indoor air $t_{ND}$ was 18℃. If the solar air collector bore all the fresh air load, the required heat of the solar air collector $Q_T$ can be calculated according to the following formula.

$$Q_T = \frac{L_1 \rho C_p (t_{nd} - t_4)}{3600}$$  \hspace{1cm} (4)

In the formula, $C_p$ was specific heat capacity of air at constant pressure.

Thus, $Q_T$ was 11.1kW according to the formula(4).

The average solar radiation intensity of Hangzhou in winter $I_0$ was 317W/m²[11]. What’s more, $\mu$ was 0.8 and $\eta$ was 65%[12-13]. According to formula(3), the collector area of solar air collector was 68 m². However, due to the allowable installation area of solar air collector was limited in the actual project, 22m² was taken as the actual installation area of solar air collector.

3.3 Surface cooler
3.3.1 Cooling capacity of surface cooler in summer
After precooling by indirect evaporative cooler, the cooling capacity of the primary air bore by the surface cooler in summer was 11.7kW.

$$Q_1 = \frac{L_1 \rho (h_s - h_{in})}{3600} = 11.7kW$$

3.3.2 Heat capacity of surface cooler in winter
The total number of winter days in Hangzhou was 90 days. 75%, 50% and 25% of the average daily solar radiation intensity in Hangzhou was taken as the dividing point of each section. Table 1 showed the distribution of daily average solar radiation intensity of Hangzhou in winter[11].

| Daily average solar radiation intensity $I$ (W/m²) | Day (d) | Proportion of total winter days (%) | Average value(W/m²) |
|--------------------------------------------------|---------|-----------------------------------|---------------------|
| $\geq$317                                         | 43      | 47.8                              | 425.3               |
| 317 $\geq$ $I \geq$238                           | 12      | 13.3                              | 279.4               |
| 238 $\geq$ $I \geq$159                           | 6       | 6.7                               | 195.9               |
| 159 $\geq$ $I \geq$79                            | 15      | 16.7                              | 112.2               |
| 0                                                | 14      | 15.6                              | 0                   |
When the average solar radiation intensity was 425.3w/m², the heat provided by solar air collector was 4.9kW according to formula(3). In winter, the temperature of outdoor air \( t_4 \) was -2.4℃. After heated by solar air collector, the temperature of primary air \( t_5 \) was 6.6℃. Since the heat exchange efficiency of the sensible heat exchanger was 55%, the temperature of primary air outlet \( t_6 \) was 12.9℃ according to formula(2).

Therefore, the heat capacity of the primary air bore by the surface cooler in winter was 2.8kW.

\[
Q_2 = \frac{L \cdot \rho \cdot C_p \cdot (t_{nd} - t_o)}{3600} = 2.8kW
\]

Similarly, when the daily average solar radiation intensity was 279.4, 195.9, 112.2 and 0W/m², the heat capacity of the primary air bore by the surface cooler in winter was 3.5, 4.0, 4.4 and 5.0kW respectively.

4. Economic benefit analysis of air conditioning fresh air unit

4.1 Initial investment in equipment
The price of traditional fresh air unit with 1500 m³/h fresh air volume was about 3600RMB. The indirect evaporative cooler, exhaust fan, water pump and solar air collector was added in the new type of air conditioning fresh air unit as new components. The price of solar air collector was 3960RMB. The material area of indirect evaporative cooler was about 3m²[7], and the price of the indirect evaporative cooler was 1350RMB. The power of exhaust fan with 1605m³/h air volume was 0.031kW and the price of exhaust fan was 500RMB. The power of water pump with 0.6m³/h water volume was 0.1kW and the price of exhaust fan was 200RMB.

The total investment of new components of air conditioning fresh air unit was 6010RMB, thus the total investment of air conditioning fresh air unit was 9610RMB.

4.2 Operating expenses

4.2.1 Traditional fresh air unit
The cooling capacity of the primary air bore by the fresh air unit in summer \( Q_3 \) was 19.4kW

\[
Q_3 = \frac{L \cdot \rho \cdot (h_i - h_{nx})}{3600} = 19.4kW
\]

If COP of water chilling unit in summer was 3, the power consumption per hour was 6.5kW·h. The heat capacity of the primary air bore by the fresh air unit in winter \( Q_4 \) was 11.1kW. If COP of water chilling unit in winter was 4, the power consumption per hour was 2.8kW·h.

4.2.2 Air conditioning fresh air unit
The cooling capacity of the primary air bore by the indirect evaporative cooler in summer was 7.7kW, and the power consumption per hour was 0.2kW·h. After precooling by indirect evaporative cooler, the power consumption per hour caused by surface cooler was 3.9kW·h. Therefore, the total power consumption per hour of the new fresh air unit in summer was 4.1kW·h.

When the average solar radiation intensity in winter was 425.3w/m², the heat capacity of the primary air bore by the surface cooler in winter was 2.8kW, and the power consumption per hour was 0.7 kW·h. Similarly, when the daily average solar radiation intensity was 279.4, 195.9, 112.2 and 0W/m², the power consumption per hour was 0.9, 1.0, 1.1, 1.2kW·h respectively. If the unit work at night, the power consumption per hour was 1.2kW·h.

The fresh air unit works 12 hours a day (8 hours in the day, 4 hours in the evening) and the price of electricity is 0.56RMB/kW·h. What’s more, the fresh air units works 90 days in winter and summer respectively. Table 2 showed the power consumption and charge of traditional fresh air unit and new
type of air conditioning fresh air unit in winter and summer.

Table 2 Electricity consumption and charge of two kinds of fresh air units

| Daily average solar radiation intensity (W/m²) | Summer | Winter |
|----------------------------------------------|--------|--------|
| | Day (d) | Power consumption (kW·h) | Charge (RMB) | New | Tradition | New | Tradition | New | Tradition | New | Tradition |
| 425.3 | 43 | 445.7 | 249.6 |
| 279.4 | 12 | 142.4 | 79.8 |
| 195.9 | 6 | 2479.7 | 76.4 | 142.4 | 114.2 |
| 112.2 | 15 | 206.4 | 115.6 |
| 0 | 14 | 114.2 | 203.8 |
| Sum | / | 2479.7 | 76.4 | 142.4 | 114.2 |

Compared the traditional fresh air unit with the new type of air conditioning fresh air unit, we found the air conditioning fresh air unit can save 2592kW·h and 1451.5 RMB in summer. The energy saving rate was 36.9%; in winter, energy saving of the air conditioning fresh air unit was 1949.2kW·h and the cost saving was 1091.5RMB. The energy saving rate was 64.0%. Thus, the air conditioning fresh air unit can save 4541.2kW·h and 2543RMB in one year.

The payback period of air conditioning fresh air unit was analyzed by NPV (Net Present Value) method, and the discount rate was 8%. Table 3 showed the accumulated NPV of air conditioning fresh air unit.

Table 3 The accumulated NPV of air conditioning fresh air unit

| The end of year t | 0 | 1 | 2 | 3 | 4 | 5 |
|------------------|---|---|---|---|---|---|
| Expenditure (RMB) | -9610 | / | / | / | / | / |
| Income (RMB) | / | 2543 | 2543 | 2543 | 2543 | 2543 |
| NPV flow (RMB) | -9610 | 2543 | 2543 | 2543 | 2543 | 2543 |
| Cumulative NPV flow (RMB) | -9610 | -7067 | -4524 | -1981 | 562 | 3105 |
| Discount coefficient | 1 | 0.926 | 0.857 | 0.794 | 0.735 | 0.681 |
| Discounted value of net flow (RMB) | -9610 | 2354.8 | 2179.4 | 2019.1 | 1869.1 | 1731.8 |
| Accumulated discounted value (RMB) | -9610 | -7255.2 | -5075.8 | -3056.7 | -1187.6 | 544.2 |

According to table 5, the static investment payback period and the dynamic investment recovery period could be calculated.

Therefore, the static investment payback period was 3.7 years and the dynamic investment recovery period was 4.7 years.

5. Conclusion
(1) Compared the traditional fresh air unit with the new type of air conditioning fresh air unit, the air conditioning fresh air unit can save 2592kW·h and 1451.5RMB in summer. The energy saving rate was 36.9%; in winter, the energy saving of the air conditioning fresh air unit was 1949.2kW·h and the cost saving was 1091.5RMB. The energy saving rate was 64.0%. Thus, the air conditioning fresh air unit can save 4541.2kW·h and 2543 RMB in one year.

(2) The air conditioning fresh air unit with 1500m³/h new air volume was taken as an example. Under the ideal operation condition, the incremental investment of the new fresh air unit was 6010RMB and the cost saving was 2543RMB in one year. What’s more, the static investment payback period was 3.7years and the dynamic investment payback period was 4.7years.
Acknowledgments
I would like to extend my heartfelt thanks to a host of people, without whose assistance the accomplishment of this thesis would have been impossible. I am also grateful to my students and many other colleagues, whose valuable suggestions and instruction has benefited me a great deal. I owe a lot to my family as well for their consistent support.

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