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Operation Modes and Energy Analysis of a New Ice-Storage Air-Conditioning System

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Abstract: Based on the idea of temperature and humidity independent control, a new air-conditioning system is presented, which combines ice storage air-conditioning system and capillary radiation air-conditioning. And the ground-source is also applied to provide high temperature for the cold source for capillary radiation air-conditioning. The air-conditioning system is characterized by power load peak load shifting, reducing energy consumption and providing good thermal comfort. Taking an office building in Hangzhou area as an example, the experiment is developed by calculating building load, designing air-conditioning schemes and making cold storage strategy. In order to compare with conventional air-conditioning system, energy consumption has been analyzed. The results show that the ice storage air-conditioning system has advantages in energy conservation.

Keywords: Air-conditioning, Ice-storage, Capillary radiation system, Energy, Project, Temperature and humidity independent control, Operation

1. INTRODUCTION

The operating cost of ice storage technology can significantly be reduced by making full use of peak and valley price difference, which has very strong competitive power of cold source selection in district cooling [1-5]. Based on temperature and humidity independent control, a radiation air-conditioning system was presented, which combined roof radiation and displacement ventilation system [6-8]. Compared with conventional air-conditioning system, it has a lot of advantages, for example, energy saving, low operation cost, no sense of blowing and low noise, etc. At present, there are many scientific literatures [9-12] that are about ice storage and radiation air-conditioning, but most of them address the issue as two systems independent of each other. There is no research that combines the ice storage with radiation air-conditioning technology. If we can combine these two techniques, the “peak load shifting” of ice storage air-conditioning can not only be used but also the high comfort and low energy consumption characteristics of the radiation air-conditioning can be made full use of. The development of ice storage air-conditioning system has important research value and practical significance.

Nakano Yukio [13] proposed a kind of radiant cooling system integrated with ice storage system. When summer, cooling system uses ice as a cooling medium, ice is made and stored in the ice storage tank during the night. 3 ~ 4 °C cold water is obtained from the ice storage tank and supplied to each air-conditioning unit, when needed for cooling during the daytime. Low temperature and humid air are produced by the air-conditioning unit and sent to the metal radiant plate between the roof and the ceiling of the room. Radiation panel get cold by convection. Indoor heat is reduced by the cooling radiation panel through radiation. The cold air temperature is risen by convective heat transfer and then into the room from the ceiling and terminal window for elimination of all indoor residual humidity and heat. However, because the temperature of the air in the ceiling (10 ~ 11 °C) is low, so it is easy for condensation to form on the surface of metal plate by radiation which affects the service life. In addition, the load of indoor is fully assumed by fresh air of new system and its energy-saving characteristics are not significant. So based on the idea of temperature and humidity independent control, a new air-conditioning system was presented in the article.

2. ICE STORAGE AIR-CONDITIONING SYSTEM

Ice storage air-conditioning system is made up of the ice storage system and capillary radiation air-conditioning system. The ice is made and stored by double working unit in off-peak hours in the night time. In the peak period of daytime, low temperature of the ice is used for making chilled water, the cooling capacity of cool fresh air dehumidification and a portion of the capillary radiation. With the displacement ventilation, dedicated outdoor air system maintains a higher air quality, indoors. In addition, buried soil pipe heat exchangers are provided by the system, which provide major capillary radiant cooling using the free abundant underground earth cold source. Fig. (**1**) is the ice storage air-conditioning system diagram. It mainly consists of three subsystems: the ice storage system, dedicated outdoor air and

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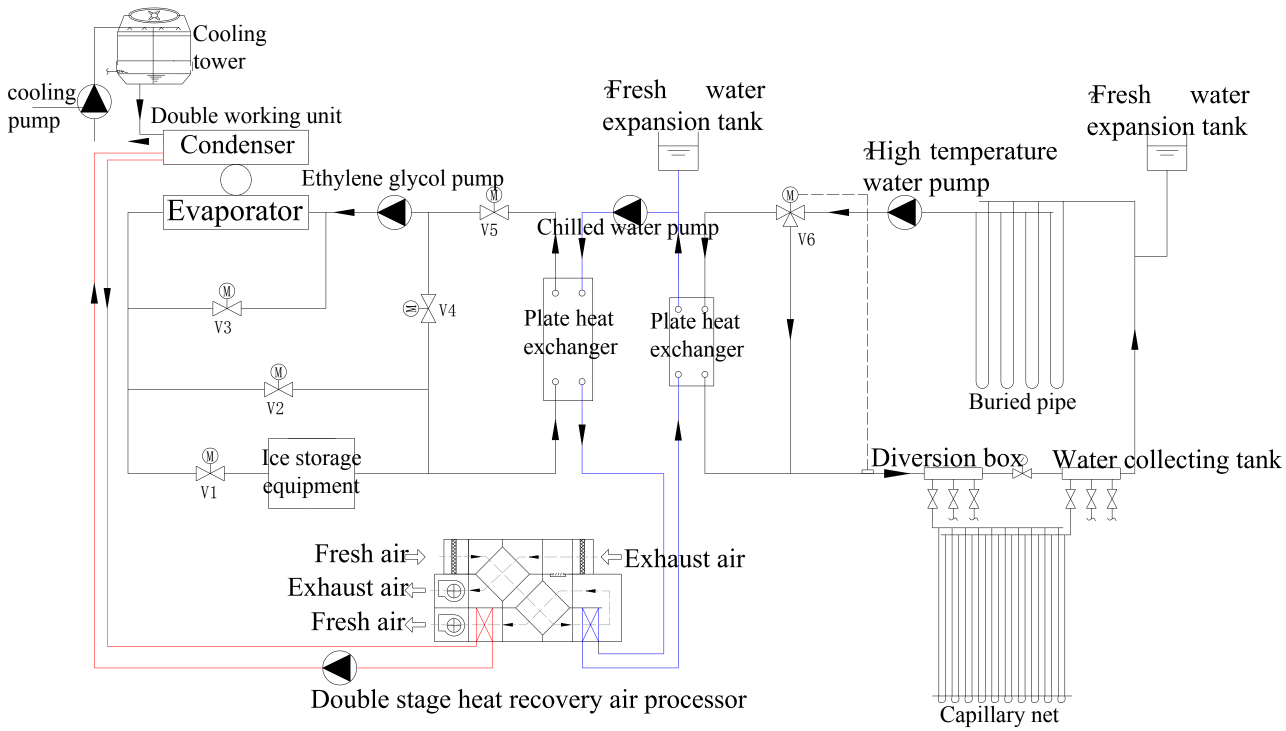

Fig. (1). Schematic diagram of air-conditioning system.

Table 1. The valve state under the different modes.

Modes	V1	V2	V3	V4	V5	Ethylene Glycol Pump	Cooling Water Pump	Chilled Water Pumps
Ice storage	open	close	close	open	close	start	start	stop
Melting ice	regulating	regulating	open	close	open	start	stop	start
Refrigerator	close	open	close	regulating	open	start	start	start
Combined	regulating	regulating	close	close	open	start	start	start

dehumidification system, and capillary radiation cooling system.

Ice storage system is mainly composed of some devices, for example, double working unit, ice storage tank, ethylene glycol pump and the plate heat exchanger that is connected to the next level system. The condensation side of the double working unit is equipped with cooling tower and heat recovery unit. The condensation heat can be recycled by heat recovery unit and reheat the refrigeration dehumidification system of fresh air at low temperatures. The upstream series is a host and the host priority mode is adopted in this system, which can make the water return with higher temperature, which first passes through the refrigeration unit to keep the high efficiency and good energy saving of the unit. At the same time, it can also reduce the ice storage tank capacity and initial investment. There are four operation modes: ice storage mode, melting ice cooling mode, refrigerator cooling mode, refrigerator cooling combined melting ice cooling mode. The state of valves and pumps under the different modes are shown in Table **1**.

1) Ice storage mode

According to the principle of the optimization of the ice storage system, ice should be made at off-peak electricity with double working unit, making full use of lower local price. During the double working unit running at full capacity, the low temperature of ethylene glycol solution is utilized as a refrigerant. Operation efficiency of double working unit is lower under the working mode of ice storage and the ethylene glycol solution is cycled between the refrigeration unit and the ice storage tank. Double working unit automatically stops when the ice storage tank meets the quantity requirement of the ice storage.

2) Melting ice cooling mode

Melting ice cooling mode mainly is used during the transition season of smaller load. Cooling load is borne by the melting ice. The ice is stored by refrigeration unit during the off-peak hours of night.

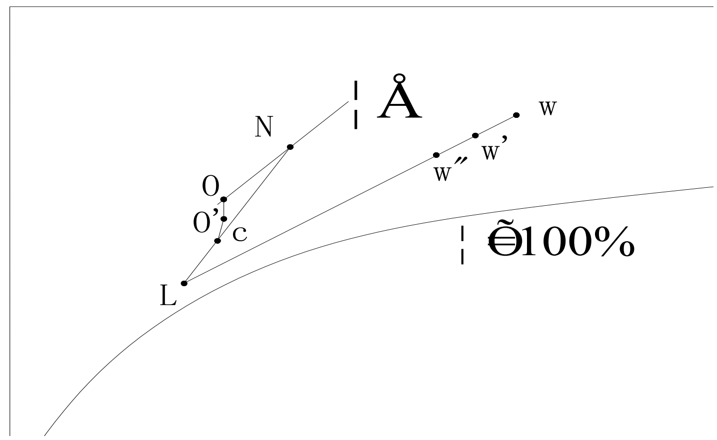

Fig. (2). Schematic of the air handling process.

3) Refrigerator cooling mode

This mode is used only for specific period, such as the ice storage tank failure or maintenance.

4) Refrigerator cooling combined melting ice cooling mode

Combined cooling work mode is open, when the air-conditioning cooling load is large. In order to meet the requirements of air-conditioning load and try to reduce operational costs of the electric power system, the cooling load is provided by the refrigeration unit and ice storage tank. Ethylene glycol solution flows into the refrigeration unit evaporator side and the coil inside the ice storage tank, when refrigeration unit is under air-conditioning condition. The temperature decreases and the low temperature solution flow into the heat exchanger and reduce the temperature.

In order to meet the cooling load demand, an optimized method to melt the ice is needed. Therefore, when the refrigeration unit priority strategy is adopted, the refrigeration unit runs at full capacity. The process and the running time of the refrigeration unit are controlled by system optimization control scheme. The ice melting cooling capacity is equal to the total cooling load minus the refrigerator cooling capacity. The cooling capacity changes with the change of the hourly load and refrigerator machine running number.

Radiant cooling system is mainly made up of the capillary net radiation, water divider, catchment device, high temperature cooling water pump, buried pipe loop, the plate heat exchanger and expansion water tank. The capillary network is installed on the interior ceiling. Water at 17 °C ~ 19 °C was used as the cold source and heat was transferred by radiation. Radiation cooling only affects indoor sensible heat cooling load.

Fig. (**2**) is the schematic diagram of the air-conditioning system. The system principle diagram shows the double stage heat recovery air processor is used for processing exhaust and fresh air in the handling process. The cooling capacity of the door ventilation is recycled by fresh air in the first level of heat recovery unit and the state is changed from W to W '. The cold capacity that makes W' to W "comes from "the loss of the mixed air changed from C to O'. Fresh air W" changes into apparatus dew point L after cooling and dehumidification. Then, with the new and exhaust air mixed, supply of air C is obtained by introducing indoor ventilation. In order to achieve indoor air state point O, it is important that the air heats at O', and by introducing pre-cooling fresh air and condensation heat, O' changes to O. The air handling process of the system makes full use of the indoor ventilation and the heat of condensation of the unit and is good for solving the energy problem of fresh air pre-cooling and reheating process.

3. ENERGY SAVING ANALYSIS

Based on an office building in Hangzhou of China, the ice storage air-conditioning system and conventional air-conditioning system were designed. The project has six floors and is 25.1 m high. The building mainly includes offices, clubs, reception halls, restaurants and lounge rooms. Project is located in Hang Zhou, which is in the east longitude 120°26', north latitude 30°10'. Total construction area of the building is 6800 m^2 and air condition covers an area of 6150m^2. It is required that the summer cooling can achieve and satisfy the requirement of human body comfort. Design parameters of indoor and outdoor are: outdoor dry bulb temperature of air-conditioning in summer is 35.70°C, relative humidity is 80%; indoor air temperature in summer is 26°C, relative humidity is 60%. Cooling time is 07:00~18:00, for the building as an office. By calculation, the hourly load of the day is obtained, as shown in Fig. (**3**). Configuration of ice storage air-conditioning system is shown in Table **2**.

3.1. The Determination of Operating Plan

Based on the building load characteristics, equipment capacity, the unit numbers, the local peak and off-peak price and other comprehensive designs and analysis, the strategy of ice storage system was designed and the optimum operation scheme was selected. In order to quantitatively analyze ice storage air-conditioning system energy saving, it needs to be compared with conventional air-conditioning system for energy consumption in cooling season. With 100% load,

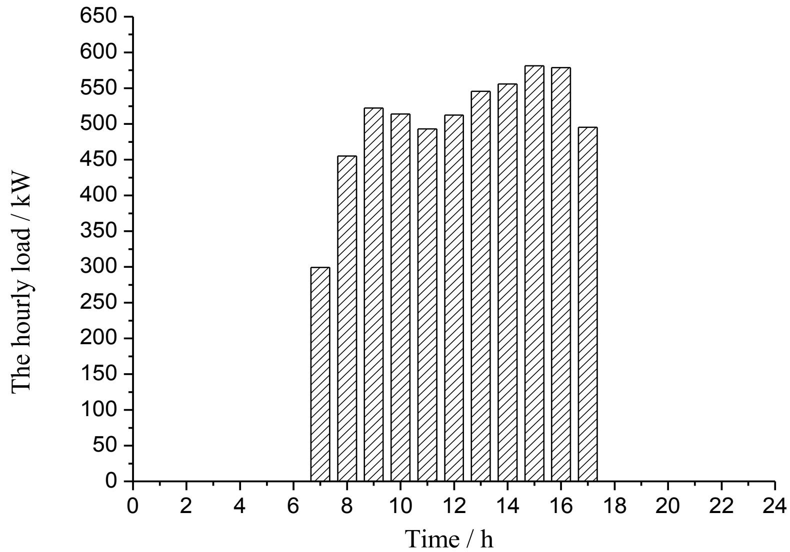

Fig. (3). Diagram of hourly load.

Table 2. List of main equipment of air- conditioning system of ice storage combined with capillary network.

Order	Device	Specifications	Numbers	Power(kW)	Operating Power(kW)
1	Double working unit	Air-conditioning mode 197kW/ Ice storage conditions 130kW	2	38/37	76/74
2	Ice storage equipment	Ice storage heat capacity 594HT	1		
3	Ethylene glycol pump	Flow 30m^3/h,Lift 24m	5	4	12/16
4	Plate heat exchanger	Heat exchanger 581.5kW,The heat exchange area 105m^2	1		
5	Plate heat exchanger	Heat exchanger 69.7kW,The heat exchange area 18m^2	1		
6	Chilled water pump	Flow 28m^3/h,Lift 20m	5	3	12
7	Cooling tower	Flow 50m^3/h	2	1.5	3
8	Cooling water pump	Flow 25m3/h,Lift 20m	5	3	12
9	Capillary net	Capillary 3.35×0.5mm	4832m^2		
10	Radiant cooling pump	Flow56.3m^3/h, Lift 21m	5	5.5	22
11	Buried pipe	Deep 80m	50		
12	Air processor	Air volume 3000m^3/h	1	1.1,0.55	1.65
13	Air processor	Air volume 5000m^3/h	2	1.5,1.1	5.2
14	Air processor	Air volume 7000m^3/h	2	2.2,1.5	7.4
15	Air processor	Air volume 8000m^3/h	1	3.0,1.8	4.8

75% load, 50% load, 25% load as the basis for comparison. Table **3** shows the electricity prices in Hangzhou city at different times of the day.

Operation strategy under each load can be determined by the following formula:

$$Q_{total} = \lambda \sum_{i=1}^{24} q_i \tag{1}$$

$$Q_{take} = 0.97 \times Q_{storage} \tag{2}$$

Table 3. Time-of-use electricity price in Hangzhou.

Period of Time	Time	Differential Power Price /RMB	Constant Power Price /RMB
Valley time	23:00-05:00	0.368	0.98
Flat time	05:00-17:00	0.736	0.98
Peak time	17:00-23:00	1.104	0.98

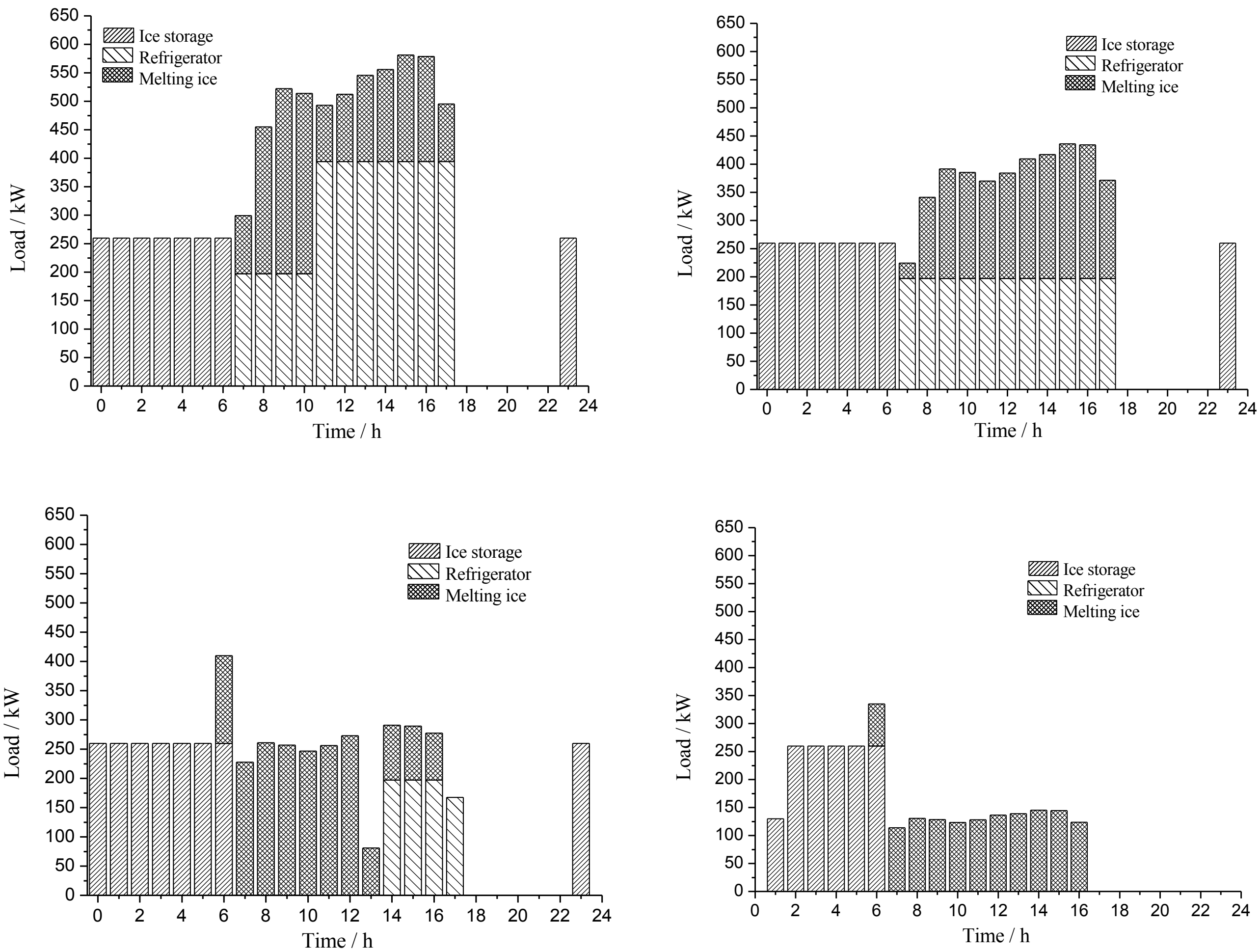

Fig. (4). Operation strategy map under four kinds of load rate.

$$Q_{\text{Refrigerator}} = Q_{total} - Q_{take} \tag{3}$$

$$N = \frac{Q_{\text{Refrigerator}}}{q_c} \tag{4}$$

Where, Q_{total} is the total cooling load throughout the day, kWh; Q_{take} is the maximum capacity of ice cold, kWh; $Q_{\text{Refrigerator}}$ is the cooling capacity that is provided by refrigerator daily, kWh; λ is part load rate with 100%, 75%, 50% and 25%. N is equivalent to full load operation of the number of refrigerator.

According to the change of the design load and partial hourly load, using the above method, the load was distributed. Fig. (**4**) is operation strategy of ice storage air-conditioning system under different loads. When the load is 100%, there are three kinds of operating modes:

A. Double working unit to make ice (23:00~ 07:00 the next day, 8 hours in total), the maximum energy needed to make ice for full capacity is 2080 kWh, and the two double working units operate to store ice at full capacity.

B. One of the double working units on air-conditioning mode and ice melting for cooling (07:00 ~ 10:00, 3 hours in total);

C. Two of double working units on air-conditioning mode and ice melting for cooling (10:00 ~ 18:00, 8 hours in total).

Table 4. List of main equipment of traditional air-conditioning system.

Order	Device Name	Specifications	Power /kW	Operating Power /kW
1	Conventional unit	Refrigerating capacity 415kW, Chilled water flow $71m^3/h$, Cooling water flow $85m^3/h$	78	156
2	Frozen water pump	Flow $43m^3/h$,Lift 24m	5.5	22
3	Frozen water pump	Flow $45m^3/h$,Lift 16m	4	16
4	The cooling tower	Fan diameter 1500mm×2,Flow $190m^3/h$	11	11
5	Air processor	$35000m^3/h$	16	96

D. When the load is 75%, there are two kinds of operating modes:

E. Double working unit to make ice (23:00~ 07:00 the next day, 8 hours in total) the maximum ice storage capacity is 2080kWh, the two double working units operate to store ice at full capacity.

F. One of double working units on air-conditioning mode and ice melting for cooling (07:00 ~ 18:00, 11 hours in total).

G. When the load is 50%, there are four kinds of operating modes:

H. Double working unit to make ice (23:00~ 07:00 the next day, 8 hours in total), the maximum ice storage capacity is 2080kWh, the two double working units operate to store ice at full capacity.

I. Ice melting for cooling (07:00 ~ 14:00, 7 hours in total)

J. One of double working units on air-conditioning mode and ice melting for cooling (14:00 ~ 17:00, 3 hours in total).

K. One of double working units on air-conditioning mode of 85% load and ice melting for cooling (17:00 ~ 18:00, 1 hours in total);

L. When the load is 25%, there are two kinds of operating modes:

M. Double working unit to make ice (23:00~ 07:00 the next day, 8 hours in total), the maximum ice storage capacity is 2080kWh, the two double units operate to store ice at full capacity;

N. Ice melting for cooling (07:00 ~ 18:00, 11 hours in total).

3.2. Energy Consumption

Table **4** is the main equipment for conventional air-conditioning system. For the comparison of the energy consumption of the two systems, the annual electricity consumption calculation is needed and the number of operational days air system in different loads. Therefore, in this paper, the operational days of the air-conditioning system were assumed. Hangzhou is located in the south of Yangtze River and summer is hot. Cooling time is approximately from mid-May to early October, for about 140 days, which included 100% load for 30 days, 75% load for 40 days, 50% load for 45 days and 25% load for 25 days. With 100% load, 75% load, 50% load and 25% load is the basis for comparison of the operating energy consumption of the daily, the entire cooling season of ice storage air-conditioning system and conventional air-conditioning system in summer, as shown in Tables **5** and **6**.

The advantage of energy-saving of the ice storage air-conditioning system relative to the conventional air-conditioning system is obvious. By calculation, energy consumption of ice storage air-conditioning system in cooling season only is 68.98% of conventional air-conditioning system energy consumption and saves 91790kWh, annually.

In addition, the operating hours and the electrical consumption of the ice storage air-conditioning system and conventional air-conditioning system are significantly different. Due to the impact of price, the running cost of the two systems has a great difference. The operational daily energy consumption of the entire cooling season of ice storage air-conditioning system and conventional air-conditioning system is compared and shown in Tables **7** and **8**.

The calculation of data in the table shows that, the economic advantages of ice storage air-conditioning system over the conventional air-conditioning system are obviously. The running cost of cooling season only is equivalent to 50.1% of conventional air-conditioning system and about RMB 144600 is saved. However, the initial investment of ice storage air-conditioning is more than the conventional air-conditioning system, which is mainly reflected in ice storage equipment, capillary network, the capillary network installation and buried pipe heat exchanger manufacturing. If the ice storage air-conditioning system can be reasonably designed, then the main factors influencing the investment payback period of the air-conditioning system are the difference of peak and off-peak prices. It can be seen from the above analysis that the investment payback period is significantly impacted by the difference of peak and off-peak prices.

CONCLUSION

(1) Based on the ideas of independent temperature and humidity control, a kind of ice storage air-conditioning system was proposed in this paper; the system consists of three

Table 5. The comparison of daily power consumption.

Load	Ice Storage Air-Conditioning				Conventional Air-conditioning
	The Valley kWh	Flat Section /kWh	The Peak /kWh	The total /kWh	The Total /kWh
100%	840	1565	156.5	2561.5	3050
75%	840	980.5	98	1918.5	2288
50%	840	521	77.9	1438.9	1789
25%	577.5	275.5	27.6	880.6	1290

Table 6. The comparison of cooling seasonal total power consumption.

Load	Days	Ice Storage Air-Conditioning		Conventional Air-conditioning	
		Daily Consumption /kWh	Total Power Consumption /kWh	Daily Consumption /kWh	Total Power Consumption /kWh
100%	30	2561.5	76845	3050	91500
75%	40	1918.5	57555	2288	91520
50%	45	1438.9	43167	1789	80505
25%	25	880.6	26418	1290	32250
The total	140	203985		295775	

Table 7. The comparison of daily operating cost between two kinds of air- conditioning system.

	Ice Storage Air-Conditioning				Conventional air-conditioning
	The Valley/RMB	Flat Section/RMB	The Peak/RMB	The Total/RMB	The Total /RMB
100% load	309	1151.5	172.8	1633.3	2989
75% load	309	721.6	108.2	1138.8	2242
50% load	309	483.5	85.9	878.4	1753
25% load	212.5	202.8	30.4	445.7	1264

Table 8. The comparison of cooling seasonal total operating cost between two kinds of air- conditioning system.

Different Load	Days	Ice Storage Air-conditioning		Conventional Air-conditioning	
		Daily Cost /RMB	The Total /RMB	Daily Cost /RMB	The Total /RMB
100%	30	1633.3	48999	2989	89670
75%	40	1138.8	45552	2242	89689.6
50%	45	878.4	39528	1753	78894.9
25%	25	445.7	11142	1264	31605
The total	140	145221		289859.5	

subsystems: ice storage system, fresh air dehumidification system and capillary radiation cooling system.

(2) The composition and working principle of the system was described in the paper. The system has the “peak load shifting” of ice storage system and high comfort and low energy consumption of radiation air-conditioning system. High temperature cold source was provided by buried pipe for capillary radiation cooling.

(3) Energy consumption of ice storage air-conditioning system and conventional air-conditioning system was analyzed based on an engineering example. With 100% load, 75% load, 50% load, and 25% load is the basis for comparison. Results show that: the advantages of ice storage air-conditioning system in energy saving are obvious.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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