Experimental Investigation of Direct Expansion Dynamic Ice-on-coil Storage System Used in Residential Buildings

Maoyu Zheng Fanhong Kong Zongwei Han
PH.D. Professor
Doctoral Candidate
School of Municipal & Environmental Eng, Harbin Institute of Technology
Harbin P. R. China, 150090
tian12388@sohu.com

Wei Liu
Master
Planning and Designing Institute of Telecommunication
Guang Dong P. R. China, 510630
LW@gpdi.com

Abstract: The reduction in electricity consumption of an ice-storage system in the daytime leads to financial savings for building owners and extension savings for a power plant and national economy. Great advancements have been made in domestic ice-storage systems due to the bigger peak-to-valley differences of electricity used in residential buildings. However, there are still some shortcomings that affect its widespread applications. The paper reports on an experimental investigation on a domestic direct expansion dynamic ice-on-coil storage system that overcame the disadvantages of static and dynamic ice-storage system. It is concluded that periodic ice moving avoids the increased heat resistance that creates a decreased evaporating temperature. Due to a better heat exchanger ability caused by the larger surface of sheet ice, steady and low chilled water temperature was directly extracted from an ice storage tank. The longitudinal and axial fin-added coils improved the COP of the refrigerating unit and ice-packing factors.

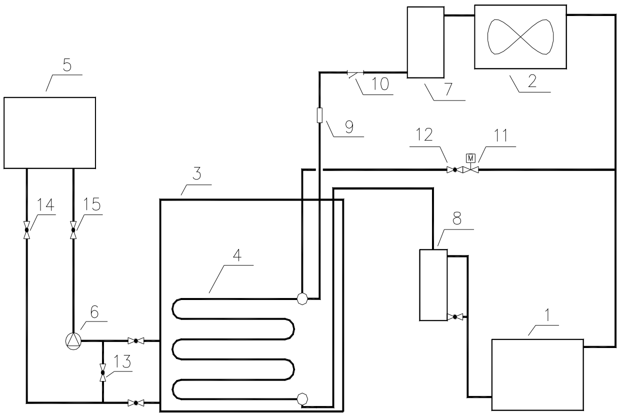
Keyword: Direct expansion dynamic ice-on-coil storage; Longitudinal fins; Ice-packing factor

1. INTRODUCTION

The electricity consumption of ice-storage system in night with cheap price during summer months is a economical and healthy solution to air-conditioning for building's owner with less electricity cost and government with decreasing investment on power plant due to peak-to-valley effect. With the developing of economy and increasing of living level, more and more air-conditioners were used in residential buildings, which made bigger and bigger peak-to-valley different. So it is need to develop pint-sized ice-storage system to meet the demand. Although the simplicity and convenient controlment of static ice-storage system. It is difficult to overcome its increasing heat resistance and decreasing COP. More important, it is difficult to be pint-sized to meet domestic ice-storage system. As for dynamic ice-storage system, due to its difficult controlment and instability of ice slurry transport that need deeply studied, it is difficult to obtain wide acceptance of residential owners[1]. This work focuses on the experiment investigation on a direct expansion dynamic ice-on-coil storage system, aiming at the greater penetration of pint-sized ice-storage system into Chinese market.

In previous research, it was found that a number of ice crystals in the shape of thin leaf were formed on the interface and were removed due to the buoyancy force acting on the ice. The removed ice, which rose toward the surface of solution, was ascertained to be liquid like ice continuously without the deposition of an ice layer on the cooled plate [2][3]. Through a number of methods have been examined to remove ice, the experiment was done on a new method to remove ice, which was most important period of a dynamic ice-storage system.

The objective of this experiment is to provide a dynamic ice-thermal storage system through investigating and analyzing the operation characteristics of the direct expansion dynamic ice-on-coil storage system aiming at economizing on electricity of residential building.



1－compressor 2－condenser 3－ice storage tank 4－evaporator
5－user 6－circulation pump 7－liquid receiver 8－suction trap
9－thermostatic expansion valve 10－filter 11－solenoid valve 12～15－ball valve

Fig.1 Schematic diagram of experimental apparatus

2. EXPERIMENTAL THEORY AND METHOD

2.1 Experimental Setup

This system combined the advantages of static and dynamic ice-storage system and overcame the disadvantages of them. Fig.1 shows the schematic diagram of experimental setup. Experimental apparatus consisted of a ice-storage tank, a refrigerant cycle, a chilled water cycle and a test section. The heart of the experiment system is the ice-storage tank. It had the dimensions 1170×580×1140mm inner volume. To reduce the heat flux to the surrounding environment, polystyrene foam with 50mm in thickness was used as insulant outside the tank. In order to observe the processes of ice making and ice moving clearly, a observation window was set on one side of the tank. Six serpentine finned tubes bundle (in fig.4) in parallelity with same spacing was used as evaporator in tank. The coils were aluminum made, 21mm in outer diameter and 19mm in inner diameter, with 18mm height fins including longitudinal and radial. The heat conductivity coefficient of aluminum is 202 W·m^{-1}·k^{-1}. A liquid receive was installed before the thermostatic expansion valve and immediately after the condenser to avoid the gaseous refrigerant into the expansion valve. In order to avoid the liquid refrigerant into the compressor,. a suction trap was installed before the compressor and immediately after the evaporator.

The processes of the experiment are as follows:

On ice-making mode, turned off the valves 11,12,13,14 and 15 and shut the circulation pump 16. The flow of the refrigerant is shown in Fig.2:

The heat absorbing of refrigerant in evaporator made the water temperature decreased. When it decreased to about 273 K, the ice appeared outside the evaporator coil. Once the thickness of ice was up to the mark (about 5-8 mm), turned on the valves 11 and 12 to make the compressor exhaust flow into the evaporator 4 directly. The high temperature gaseous refrigerant and the fins cutting made the ice outside evaporator coil move to float on the water. On ice-melting mode, turned on the valves 14, 15 and the circulation pump 6 to operate the cold-discharged cycle. The chilled water from users changed heat with the ice floating on the water to lower temperature and then flowed back to users by pump 6. The system can operate on ice-making mode while it was operating on cold-discharged mode, that is, the ice-making and ice-melting mode can be coinstantaneous.

2.2 Measurement

The important parameter temperature was

measured by THERMODACⅢ digital voltmeter using self-made copper-constantan thermocouples. With this purpose, twelve thermocouples were used. Three of them were arranged on the fin with step of 6 mm throughout the fin height and on the tube as showed in fig.3. Four thermocouples were used to measure the temperature of different depth in water as arranged in fig.4. In addition, the inlet and outlet temperatures of refrigerant and chilled water were measured.

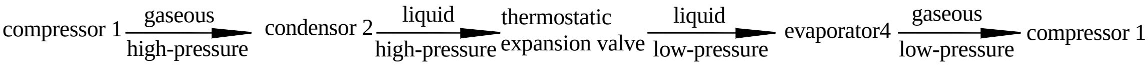
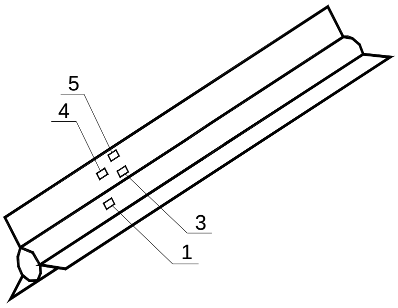


Fig. 2 The flow chart of refrigerant on ice-making mode

The measured error was estimated to be no more than 0.1 K for the temperatures, 0.5 mm for the coordinates of thermocouples on fin and 10 mm for thermocouples in water in tank.

The volume V_i of ice formation in tank was measured using the relation of density difference between water and ice as follow formula, which was detected as a change Δh in the height of the water surface in tank.

$$\rho_w V_{w0} = \rho_w V_{W1} + \rho_i V_i \tag{1}$$



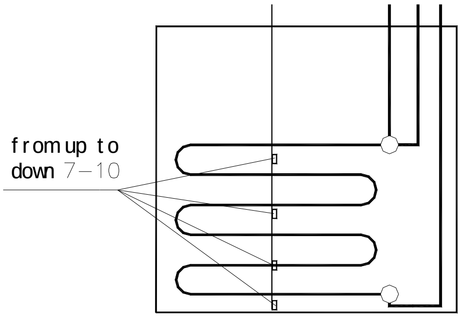
1-surface temperature of coil

3-surface temperature of fin (3mm from the bottom)

4-surface temperature in the middle of fin

5-surface temperature of fin (3mm from upper)

Fig.3. Distribution of measuring points



7-measuring point 680mm from the bottom

8-measuring point 420mm from the bottom

9-measuring point 150mm from the bottom

10-measuring point 70mm from the bottom

Fig.4. Distribution of measuring points

$$V_{w0} = a \times b \times h_0 - V_{pg} \tag{2}$$

$$V_{w1} = a \times b \times h_1 - V_{pg} - V_i \tag{3}$$

$$V_i = \frac{\rho_w}{\rho_w - \rho_i} \times S \times \Delta h \tag{4}$$

Where ρ_w and ρ_i denote the density of water and ice, respectively. V_{w0} and V_{w1} denote the water volume before and after ice making, respectively. h_0 and h_1 denote the water depth in tank before and after ice making, respectively. V_{pg} denotes the volume of evaporator that under the water. S is the horizontal section area of inner tank. The Δh was measured by ruler whose measurement error is 1 mm, and the thickness of slice ice was measured by micrometer with a measurement error of 0.01mm.

The volume flow rate of chilled water was measured by volumetric flowmeter whose measurement error is 0.001 m^3 and a stop-watch with the scale factor 0.1 s. The electricity power was measured by ammeter.

The experiment was done in building energy-saving laboratory of Harbin Institute of Technology in china in Apr, 2005.

2.3 Preparation

Before the starting of the experiment, the following procedures should take place:

* Pressure should be applied to the interior of the pipes in order for any leak to be found and sealed.

* If there are no leaks after pressure measurement, the system should be filled with

refrigerant.

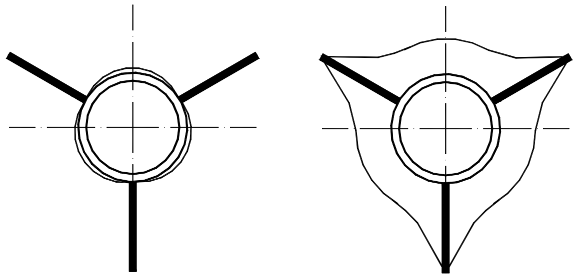
＊ Thermocouples and measuring instruments should be arranged. It needs to notice that the thermocouples arranged in water and on pipes should be insulated with them with a lamella of nonconductor outside it.

The determination of optimum operation conclusion will introduce later. The following experiment and discussion were done under the condition of three longitudinal fins evaporator and natural convection on ice-making and ice-moving mode.

3 THE EXPERIMENTAL RESULT AND DISCUSSION[4]

3.1 Ice-making Mode

The Fig.5 shows the fin's influence on the shape of ice formation. The longitudinal fins cut the ice formatted outside the pipe. On the prophase of ice formation, the wall temperature of fins was not low enough to format ice. There was only thin ice on tube as showed in Fig.a. With the time went on, the wall temperature of fins decreased, and the ice appeared on fins. The cut view of ice shape was as showed in Fig.b.



(a)prophase of ice formation (b) anaphase of ice formation

Fig.5 The cutaway view of ice formation shape

Fig.6 shows the ice thickness variation on ice thermal storage mode. Though the present measurement is not accurate enough, it presents that the ice-thickness almost linearly increases, and the ice thickness growth rate is almost constant at 0.2mm per minute. It is known that the ice growth rate will decrease with the decreasing heat conductivity of the deposited ice layer, and it will increase with the degree of refrigerant undercooling. The evaporating temperature, in the present experiment, decreased with the decreasing heat conductivity. Moreover, with the increasing of ice layer thickness, the heat exchanging surface area increased. Therefore, within the short time of ice making, the effect of them maybe canceled with each other. It can be noted that the characteristic of the constant ice growth velocity is a distinctive feature in the present ice formation phenomenon.

The temperature on coil and in water had the similar tendency as shown in Fig.7 and in Fig.8. During the period of latent heat storage, the temperatures on fin fluctuated 273 K, but the wall temperature of coil fluctuated obviously with various ice-storage cycles. The wall temperature of coil would increase sharply after ice moving and then would have a downside on next ice-making cycle. The water temperature versus time is shown in Fig.8. The curved line fall steeply at beginning, then changes to fall slowly and remains level off at last. The three periods are sensible heat storage period, transient period and latent heat storage period as we called. As the initial temperature was 8℃ at the sensible heat storage period, all the refrigerating capacity was used to cool down the water, and it made the water temperature decrease sharply. At the transient period, the curve falling slowly was due to that not all the refrigerating capacity was used to decrease water temperature. By this we mean that only some refrigerating capacity was used to decrease water temperature, the others are used to freeze. After this period was the latent heat storage period, the refrigerating capacity was mainly used for freezing, and the water temperature remained steady.

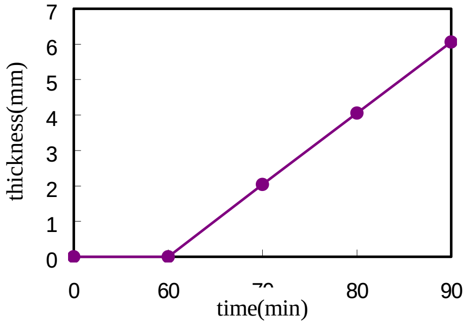


Fig.6 The ice-thickness variation curve on ice-making mode

3.2 Ice-moving Mode

On ice-moving mode the high-temperature refrigerant from the compressor flowed into the evaporator directly resulting in the ice moving from the coils. The inlet temperature of refrigerant was high up to 45 ℃ and the temperature after ice-moving was still higher than 30℃ as shown in Fig.9. The difference of inlet and outlet temperature kept up higher than 30℃. It was proved that the heat of high temperature refrigerant from compressor was enough to move the ice. The ice moving would be easier if joined the mechanical vibration.

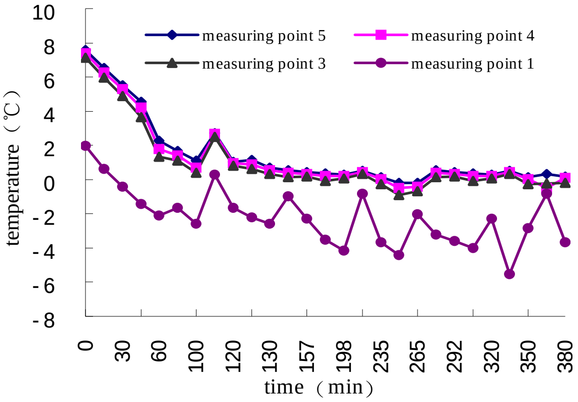


Fig.7 The temperature variation on fins and coils

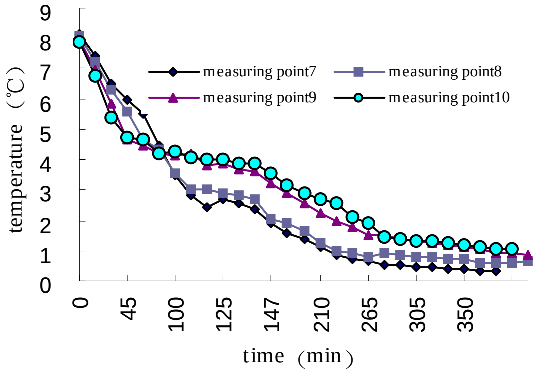


Fig.8 The temperature variation on ice-storage mode

When on ice-moving time, there would have a sharp increasing of refrigerant temperature as shown in Fig.10, however, after a few minutes of ice moving, the temperature will drop to below 0℃ and the evaporating temperature was always higher than 266 K and it changed periodically with the periodic ice-moving. For static ice-on-coil storage system, the thicker ice layer led to lower evaporating temperature, moreover, the refrigerating efficiency would decrease. However, in this system, the periodic ice-making avoided them and a high refrigerating efficiency was obtained. This manner of ice moving is a special characteristic of the present system different from other ice-storage systems.

3.3 Ice-melting Mode

On ice-melting mode, the chilled water changed heat with ice floating above the tank directly, and the inlet and outlet temperature of chilled water are important parameters for air-conditioning system. In the present experiment, the time of chilled water outlet temperature lower than 2℃ was 4.5h long as shown in Fig.11, which was latent heat discharged period, and after, comes the sensible heat discharged period, the temperature increased rapidly to 279 K within 1.5h. The cold-discharged rate was estimated based on the temperature different of the inlet and outlet temperature, which is expressed by.

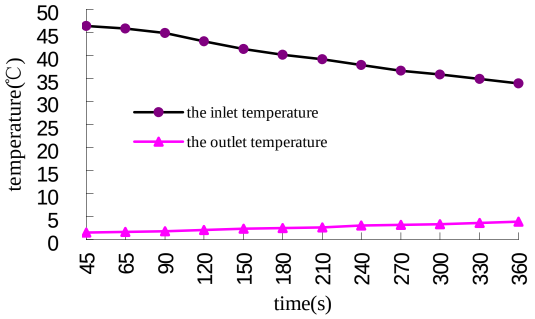


Fig.9 The in-let and out-let temperature of refrigerator

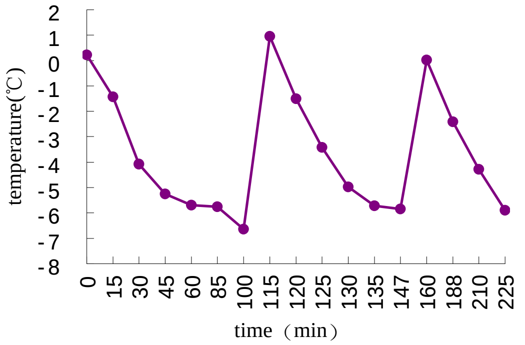


Fig.10 The evaporating temperature variation

$$q = \rho_w v c_p \left(t_i - t_o \right) \tag{5}$$

where q denotes the cold-discharged rate. t_i and t_o

denote the inlet and outlet temperature of chilled water. c_p denotes the specific heat of water at constant pressure. v denotes the volume flow rate of chilled water. The Fig.12 shows the cold-discharged rate and amount. During latent heat discharged period, the cold discharged rate and the outlet temperature remained steady even at the end of period, and about 75% of cold was discharged during this period. The floating slice ice, with large interface surface with water, made the cold-discharged rate large and steady. It can be noted that the characteristic of large and steady cold-discharged rate is a distinctive feature in the present cold-discharged phenomenon.

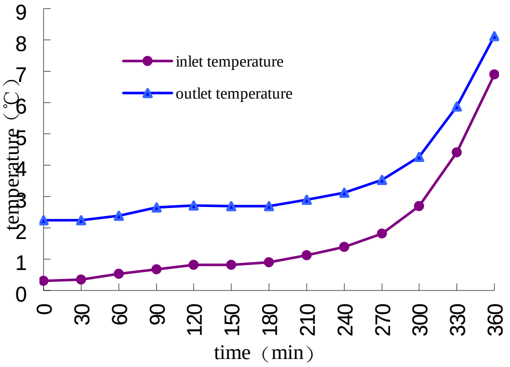


Fig.11 The in-let and out-let temperature variation curve

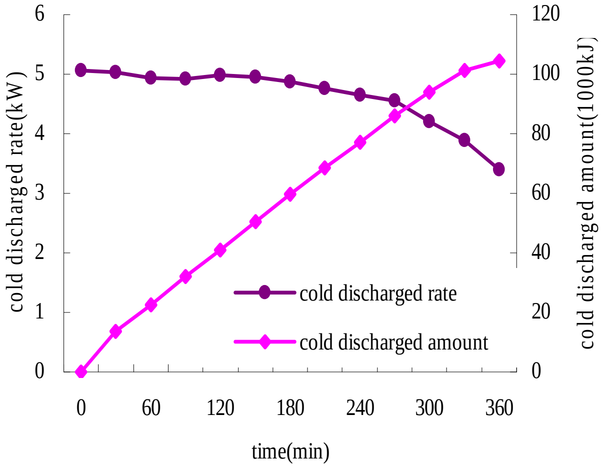


Fig. 12 The cold discharged rate and amount

5. CONCLUSION

In the present experiment, the ice making, ice moving and ice melting phenomena of direct expansion dynamic ice-on-coil storage system were investigated. The following conclusions can be drawn:

1. The ice-thickness growth was almost linear with time within the short time of ice-making mode.

2. Due to the cutting on ice, adding longitudinal fins on coils make it feasible to format and remove ice on static coils periodically.

3. The relatively high evaporating temperature and periodic ice moving made a high COP and high ice-making capacity.

4. On ice melting mode, a low chilled water outlet temperature and a large cold discharged rate can be obtained even at the end of cold discharged period, which were important parameters of ice storage air-conditioning system.

From the result, we can see that this system remove all the aforementioned disadvantages of previous static and dynamic ice-storage system, providing great possible using for residential buildings. Another is that it has highest degree of reliability to meet the daytime load of air-conditioning

To improve the building user’s living quality, the last but not the least, the system could be installed easily and conveniently, and have minimal maintenance requirement. Furthermore, the operation of the proposed ice-storage system is very simple. The administrator of a building, with switched-off, can open the system and switch the refrigerating unit at night, and close it to start the chilled water cycle at morning. Others as conversion between ice making and ice moving, and the end determination of ice-thermal storage period is controlled automatically.

REFERENCES

[1] Ruzhu Wang, Guoliang Ding. Latest Refrigeration and Air Conditioning Technology[M]. Science Publishing Company. 2002,159-160. (In Chinese)

[2] Hirata T, Nagasaka K, Ishikawa M. Crystal Ice Formationof Solution and Its Removal Phenomena at Cooled Horizontal Solid Surface, Part I: Ice Removal Phenomena[J]. Int Journal of Heat and Mass Transfer 2000(43):333～339

[3] Hirata T, Kato M, Nagasaka K, Ishikawa M. Crystal Ice Formation of Solution and Its Removal

Phenomena at Cooled Horizontal Solid Surface Part II: Onset of Ice Removal Condition[J]. Int Journal of Heat Mass Transfer 2000,43:757～769

[4] Fanhong Kong. Experimental Research of Home Air-conditioning Ice Storage System [D]. Harbin: Harbin Institute of Technology, 2005. (In Chinese)