

Research Progress of Evaporator Surface Frost Suppression Technology

Qi Cui^{1,*}, Jing Liu¹, Weiwei Shi¹, Ying Wang², Tao Yuan²

¹ School of Civil Engineering, Henan Polytechnic University, Jiaozuo, 454003, China

² China Academy of Building Research Co., Ltd., Beijing, 100013, China

* Corresponding author: Qi Cui (Email: 1757742431@qq.com)

Abstract: Frosting of the evaporator leads to the increase of its thermal resistance and the reduction of system COP, which affects the safe use and efficient operation of air source heat pump. This paper summarizes the common evaporator frost suppression methods researched by scholars at home and abroad, and classifies the frost suppression methods into four categories: changing the inlet air parameter of the evaporator, modifying the surface of the evaporator, optimizing the structure and design of the evaporator and applying an external electromagnetic field to the evaporator, and overviews the progress of the research on the four frost suppression methods and makes an outlook to provide references and proposals for the further development of evaporator frost suppression technology of the air source heat pumps.

Keywords: Frosting of the evaporator; Air source heat pump; Evaporator frost suppression methods; Evaporator frost suppression technology.

1. Introduction

Air source heat pumps are widely used because of their high efficiency, energy saving, and environmental protection advantages, but the surface of the evaporator of the air source heat pump is prone to frosting when the ambient air temperature is low and the relative humidity is high. [1] Frosting of the evaporator will not only reduce the efficiency of the air source heat pump, but also reduce the efficiency of the heat pump. Evaporator frost will not only reduce the heat transfer performance of the system, and increase energy consumption, if not timely defrosting, but also cause system blockage, affecting the normal operation of the system, and in serious cases, will lead to refrigeration unit can not run normally. Studies have shown that the accumulation of frost layer in the air conditioning system will reduce the heat transfer efficiency of the heat exchanger by 50% to 75%. [2]. Solving the evaporator surface frost problem is of great significance for the further development of air source heat pump, promoting energy saving and emission reduction policy, and realizing the goal of "carbon peak, carbon neutral". At present, the existing defrosting methods mainly include electric heating defrosting, reverse cycle defrosting, hot gas bypass defrosting, and energy storage defrosting. These defrosting methods require additional energy consumption, and the defrosting process requires the unit to be shut down, which cannot ensure the continuous operation of the system and affects the stability of temperature and humidity on the use side. Therefore, there is an urgent need to explore a method to delay the evaporator frost, so that the frost phenomenon at the beginning of the evaporator operation is effectively suppressed. For nearly 20 years, scholars at home and abroad have proposed a series of methods to inhibit the evaporator frost, this paper is divided into four categories of these methods: change the inlet air parameters of the evaporator, the evaporator surface modification, optimization

of the structure and design of the evaporator, the imposition of an external electromagnetic field. These four types of frost suppression methods are summarized as shown in Figure 1.

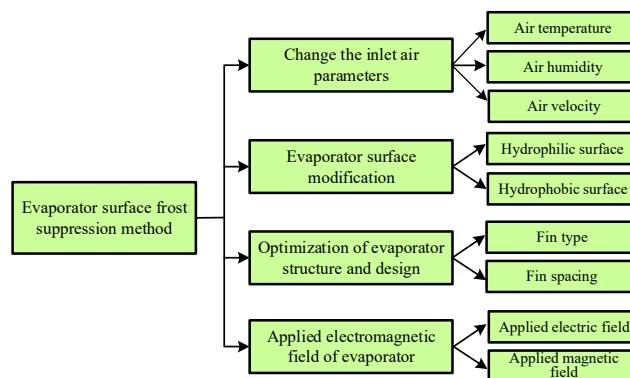


Figure 1. Classification of evaporator frost suppression methods

2. Changing Evaporator Inlet Air Parameters

Incoming air temperature, relative humidity, and air flow rate are the main parameters affecting the evaporator frost. When the wet air flows into the evaporator, if the evaporator surface temperature is lower than the dew point temperature of water vapor, the water vapor will undergo a phase change in the evaporator surface condensation for droplets, with the evaporator temperature is further reduced, lower than the three-phase point temperature of the water, droplets will be frozen into the frost crystals, frost crystals continue to grow to form a frost layer attached to the surface of the evaporator, affecting its heat transfer. Therefore, changing the evaporator inlet air parameters can effectively inhibit its surface frost.

2.1. Preheating air temperature

Preheating air temperature at the inlet of the evaporator is a simple and effective method of frost suppression, Kwak et al. [3] Installed an electric heater at the outdoor evaporator inlet and tested its frost suppression effect, the experimental results showed that the heating capacity and COP of the air source heat pump system equipped with an electric heater increased by 38% and 57%, respectively, compared with the conventional air source heat pump at the outdoor dry and wet bulb temperatures of 2 °C and 1 °C, but the electric heater consumed too much energy and was not economical in the

experimental process. Huang et al. [4] designed a heat recovery system as shown in Figure 2. The system can recover the heat released from the external surface of the compressor and use it to preheat the air temperature at the inlet of the evaporator. Tests of the system found that the frost suppression effect is obvious and does not need to consume additional energy, which helps to delay the frost on the surface of the evaporator and improve the performance of the air source heat pump system. However, the problem of uneven temperature and pressure distribution and mass flow rate fluctuation exists during the experiment, and further improvement is needed if it is to be put into use.

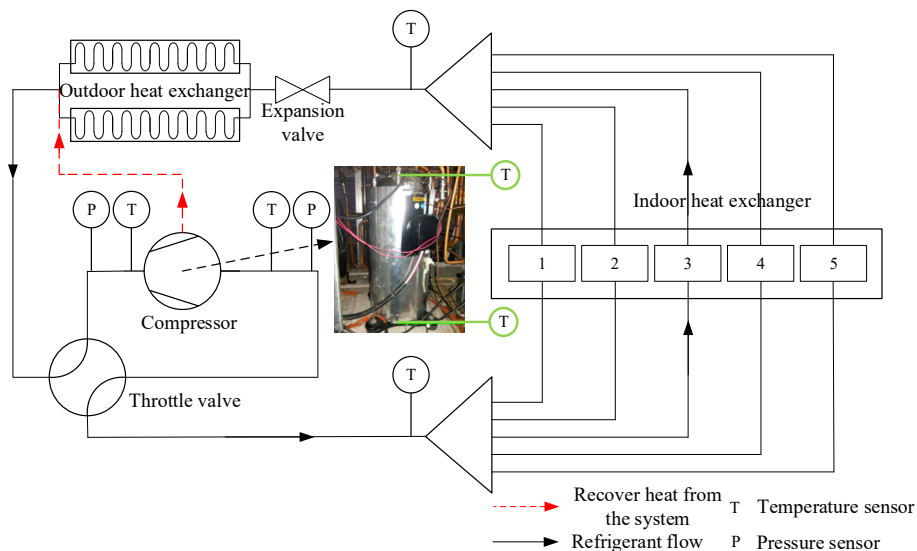


Figure 2. Principle of heat recovery air source heat pump system [4]

2.2. Reduction of relative humidity

The relative humidity of the inlet air is an important parameter affecting the evaporator frost, Xing Zhen [5] studied the law of change of frost layer thickness on the evaporator surface with time under different relative humidity, and the effect of different relative humidity on the frost layer thickness is shown in Figure 3. The figure can be seen, the relative humidity from 65% only increased by 10%, the frost layer thickness but a sharp increase, it can be seen, the relative humidity of the evaporator surface frost has a huge impact. Therefore, frosting can be suppressed by reducing the relative humidity of the air.

Currently, scholars mainly use desiccants to absorb the moisture in the wet air so as to reduce the relative humidity of the air, Zhang et al. [6] proposed a frost-free air source heat pump system with an integrated solid dehumidifier, as shown in Figure 4. The system adds a heat exchanger coated with desiccant to the ordinary air source heat pump system, which can dehumidify the incoming air before sending it to the air heat exchanger to achieve the effect of frost suppression. The system is paired with both adsorption and desorption modes, which allows for the reuse of the desiccant, thus realizing the frost-free operation of the system. However, the system requires air ducts and dampers, resulting in an increase in system size and cost.

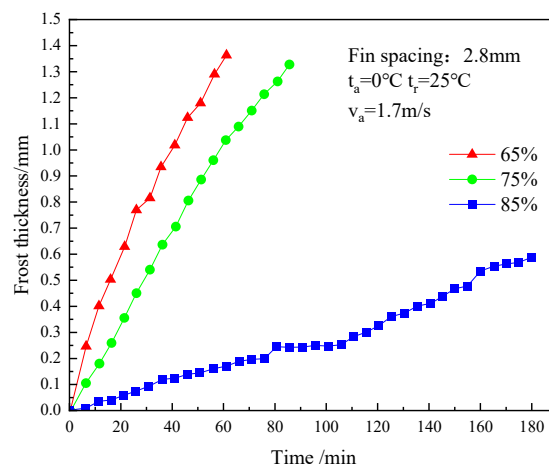


Figure 3. Effect of different relative humidity on the thickness of frost layer [5]

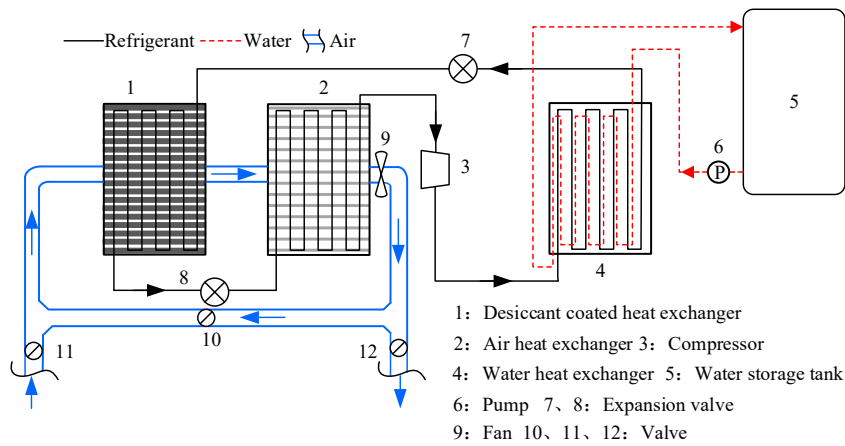


Figure 4. Frost-free air source heat pump water heater system schematic diagram [6]

Compared with solid desiccant dehumidification systems, liquid dehumidification systems are characterized by low solution regeneration temperature requirements and renewable energy can be provided by low-grade heat sources. In this regard, Li et al. [7] proposed a new frost-free air source heat pump system with the help of desiccant solution to absorb moisture and exchange heat with air, as shown in Figure 5, according to which a theoretical model is

established and experimental validation is carried out, and the results show that the system operates more efficiently than the traditional air source heat pumps in the winter and does not need to be defrosted regularly. However, a multi-stage regeneration process is designed in this system, and the regeneration process is more complicated than conventional regeneration, and the required cost is larger, therefore, this system is not put into use.

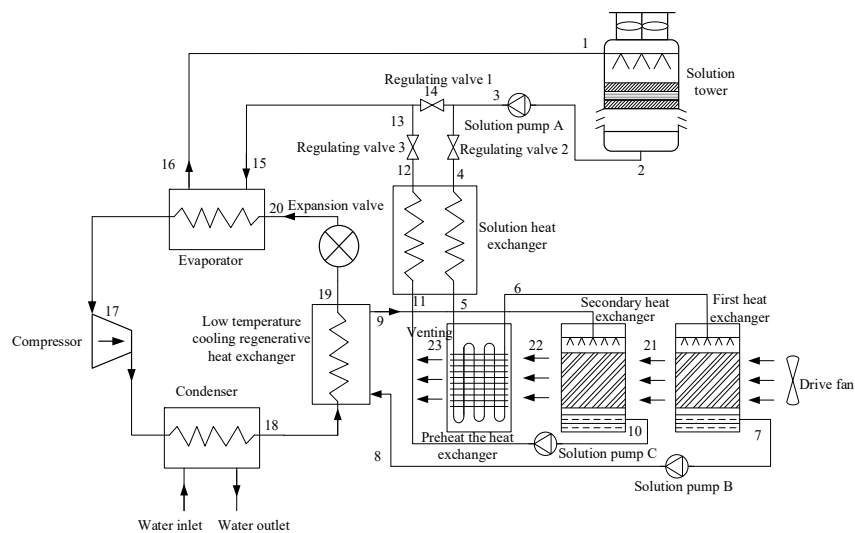


Figure 5. Schematic diagram of the new frost-free air source heat pump system [7]

Zhang et al. [8] proposed a frost-free air source heat pump system with integrated liquid desiccant dehumidification, which utilizes LiCl solution to absorb the moisture in the wet air, and at the same time the absorbed water is used to humidify the room. Experiments on this liquid desiccant system were carried out in a low-temperature and high-humidity environment, and the results show that the system ensures both frost-free operation of the evaporator and a comfortable level of humidity in the room, and the coefficient of performance of its humidification system is 30% to 40% higher than that of Conventional humidification system. However, the system solution regeneration process is direct contact, easy to bleed liquid phenomenon, causing serious pollution to the indoor environment.

2.3. Changing the air flow rate

Regarding the influence of inlet air flow rate on the frost suppression effect of evaporators, many scholars at home and

abroad have carried out research, but the research results are not the same. Sen et al. [9] concluded through experimental research that the smaller the air velocity through the inlet of the evaporator, the more serious the evaporator frosting. Wu Jinyu et al. [10] studied the effect of inlet air flow rate on evaporator frosting under the experimental condition of $-20\text{ }^{\circ}\text{C}$. The experimental results show that under the same conditions of temperature and humidity, the amount of frosting increases with the increase of the inlet air flow rate, and the increase is approximately linear. Guo Xianmin et al. [11] conducted an in-depth study on the influence of inlet air flow rate on evaporator frosting, taking into account the interaction between the operating parameters of the system and the air flow rate in the evaporator frosting process. The experimental results show that in the early stage of frosting, the growth rate of the frost layer thickness on the evaporator surface accelerates with the reduction of the inlet air flow rate, but in the late stage of frosting, the larger the air flow rate is,

the faster the growth rate of the frost layer is.

3. Evaporator Surface Modification

At present, the frost suppression mechanism of evaporator surface modification is mainly through changing the morphology and adhesion of water droplets on the cold surface, so that liquid water is not easy to condense on the surface to achieve the purpose of frost suppression. According

to the surface wettability theory, solid surfaces can be divided into hydrophilic, hydrophobic, and superhydrophobic surfaces. The hydrophilicity of a surface is generally categorized according to the size of the static contact angle of the surface, as shown in Figure 6. The contact angle of hydrophilic surfaces is less than 90° , the contact angle of hydrophobic surfaces ranges from 90° to 150° , and the contact angle of superhydrophobic surfaces ranges from 150° to 180° .

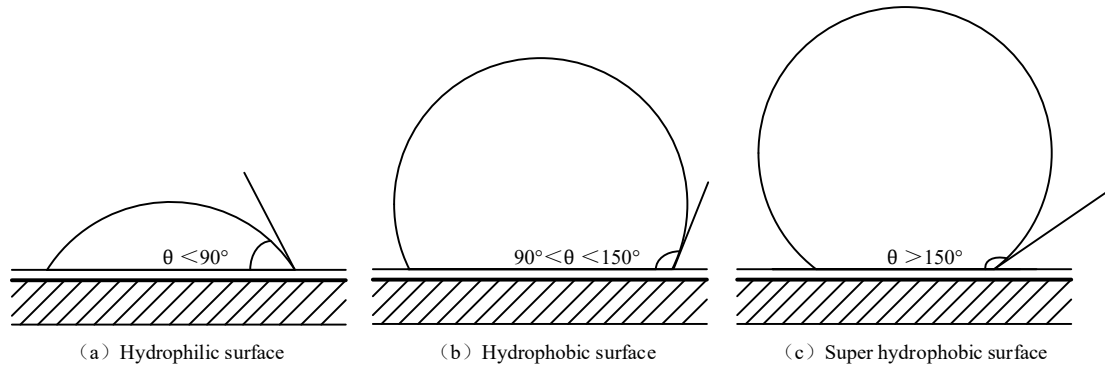


Figure 6. Classification of hydrophilic surfaces

3.1. Hydrophilic coating

The use of hydrophilic coatings to retard evaporator frost first began in the 1980s. In 1989, Highgate [12] demonstrated that hydrophilic coatings were able to maintain water droplets on cold surfaces at -20°C without freezing, and then Okoroafor et al. [13] conducted frosting experiments on hydrophilic-coated surfaces and ordinary surfaces. The experimental results show that the thickness of the frost layer on the surface coated with hydrophilic coating is reduced by 10-30% compared with the normal surface, but the thickness

of the coating is 0.7 mm, and the reusability is poor, and if it is coated on the surface of the evaporator, it will greatly reduce its heat transfer performance. Huang Lingyan et al. [14] developed a strong hydrophilic coating, the thickness of the coating is only 0.05 mm, which will be sprayed onto the surface of the copper plate and the uncoated surface for frost experimental research, the experimental results are shown in Figure 7. The figure can be seen before the experimental period of 80 min, coated with a good effect of frost suppression of its surface without frost formation, frost layer thickness of 0.

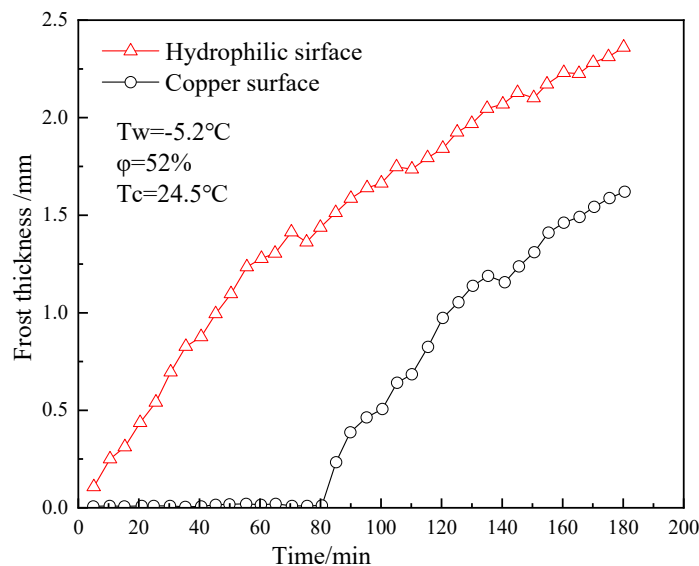


Figure 7. Frost suppression effect of two types of surfaces [14]

Liang et al. [15] found that although the hydrophilic coating can inhibit evaporator frosting, its wettability is so good that a large amount of water is retained on the evaporator fins after melting the frost, which greatly shortens the secondary frosting time. Ma Qiang [16] studied the process of defrost drainage and cyclic refrosting on ordinary, hydrophilic

and hydrophobic surfaces he found that in the process of defrosting and liquid discharge, the residual liquid water on the hydrophilic surface is irregular in shape, the contact angle is very small, and the liquid discharge is discharged in the form of a film and for the longest time, and in the process of recycling and refrosting, the residual liquid water freezes

within 2 min, and the surface is frosted very quickly again.

3.2. Hydrophobic coating

Compared with hydrophilic coatings, the frost inhibition of hydrophobic coatings is more widely studied, and many scholars have been inspired by the "Lotus Effect" and started to conduct the preparation and research of lotus leaf-like hydrophobic surfaces. Sommers et al [17]. analyzed the frosting experiments on uncoated, hydrophilic and hydrophobic coated surfaces. the experimental results showed that, compared with the uncoated surfaces, the frost density of the hydrophobic surfaces decreased by 37%~41%, while the frost density of the hydrophilic surfaces increased by 20%~26%. Zhou Yanyan et al. [18] compared the frost formation on the surface of aluminum sheets with different contact angles at -28.5 °C. The comparison of the amount of frost formation on aluminum sheets with different contact angles is shown in Figure 8. The larger the contact angle, the less the amount of frost on the surface. With the extension of time, the amount of frost on the aluminum surface at each contact angle gradually increases, but the smaller the contact angle, the faster the increase; the larger the contact angle, the slower the increase.

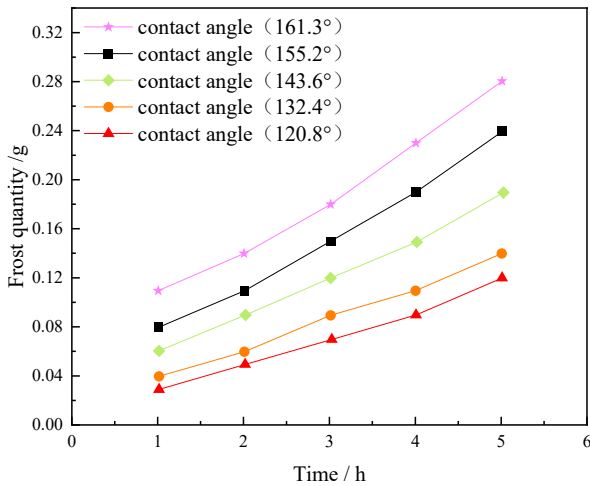


Figure 8. Comparison of the amount of frost formation at -28.5°C for aluminum sheets with different contact angles [18]

Liu et al. [19] used a hydrophobic coating on an evaporator and investigated frost formation on the evaporator surface of an air-cooled refrigerator sprayed with a hydrophobic material (contact angle of 106.5°) versus a bare aluminium evaporator surface (contact angle of approx. 78°) over a period of 480h. The results showed that the initial frost formation on the evaporator was reduced by about 16.9% and the secondary frost formation was reduced by about 22.9%. Fan et al. [20] studied the frost characteristics of hydrophilic fins, conventional fins and superhydrophobic fins evaporator under the condition of ambient temperature of -10 °C and relative humidity of 90%, and the experimental results are shown in Figure 9, after 60 min of frost, the frost amount of superhydrophobic fins is reduced by 18% and 38.6% than that of hydrophilic fins and conventional fins, and the attenuation rate of heat exchanged by the heat exchanger is also the lowest.

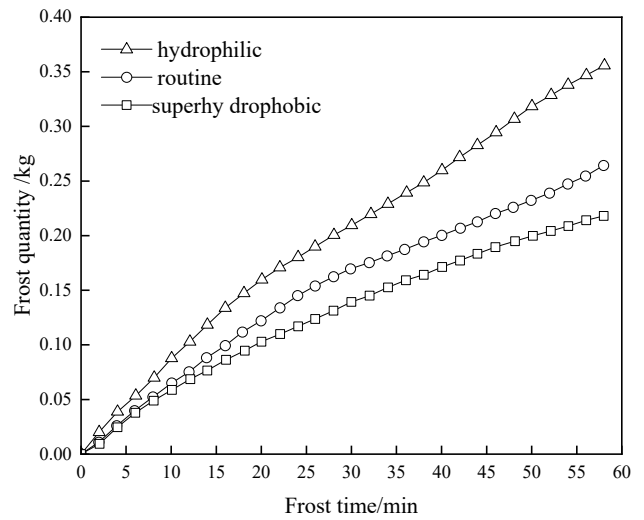


Figure 9. Variation of the amount of frost on the surface of fins of different evaporators with time[20]

4. Optimization of Evaporator Structure and Design

Adjusting the evaporator structure and design can improve the heat transfer performance of the evaporator to a certain extent and play a role in suppressing evaporator frosting. Cheng Weihong et al. [22] used the distribution parameter method to model the evaporator and calculated the effect of different fin spacing on the evaporator frost, and concluded that increasing the fin spacing can delay the evaporator frost. Park et al.[23] conducted an experimental study on evaporator frosting with equal-pitch and sequentially increasing-pitch louvered fins, and found that unequal-pitch louvered fins inhibit frosting significantly, and the thermal performance is 21% higher than that of equal-pitch louvered fins. However, the larger the evaporator fins are not the better, K et al.[24] experimentally investigated the effects of fin spacing of 1.41 mm, 1.59 mm and 1.81 mm on the frost suppression performance of the evaporator. The results showed that the heat exchanger with fin spacing of 1.59 mm had the most obvious frost suppression effect and the highest total heat transfer coefficient. Zhang et al. [25] investigated the performance of parallel flow serpentine fin, parallel flow parallel fin and round tube waveform fin evaporators under frost conditions. The results showed that the round tube waveform fin evaporator had the longest operating time and the parallel flow parallel fin evaporator had the shortest operating time. Xie Fulin et al.[26] investigated in detail the effect of different fin types (smooth fins, corrugated fins and slit fins) on the evaporator surface frosting through experiments with a temperature of 0 °C, a relative humidity of 70%, and an inlet wind speed of 1.7 m/s at the evaporator. The results were shown that the surface frosting rate of corrugated fins and slit fins is much larger than that of smooth fins.

5. Applying External Electromagnetic Fields

The evaporator frost process is actually wet air in the water vapor migration on the surface of the evaporator, condensation process, due to the water molecules have a strong polarity, in the frost process if the application of external electromagnetic field will have an impact on the migration process of water molecules, affecting the frost.

Based on this, a large number of scholars have begun to study the effect of applied electromagnetic field on the evaporator frost suppression.

5.1. Imposed electric field

Schaefer was the first to discover that an applied electric field causes changes in the shape and size of the formed frost crystals[27] After that, Maybank et al[28]. carried out an in-depth study and found that the frost crystals formed on the cold surface after the application of electric field would become more fragile and easy to fall off, and their shapes would be more elongated and would grow towards the electrode side. Munakata et al[29] investigated the effect of applied electric field voltage on frost formation on cold surfaces. The results showed that the amount of frost on the surface decreased significantly at a voltage of 7.5 kV, and then increased when the voltage was further increased. Blanford et al.[30] analyzed the effect of the magnitude of the applied electric field current on the evaporator frost. The experimental results showed that: when the current size of 5 μA , the surface frost amount reduced to 20% of the original; when the current size increased to 120 μA , the surface frost amount but increased to 100% of the original.

The results of the above scholars show that the applied electric field will delay the amount of frost on the evaporator and cold surfaces, but some scholars found that the applied electric field does not inhibit the frost, Zhang Xinhua et al.[31] tested the frost inhibition performance by applying an electric field to a hydrophilic surface. The experimental results showed that the applied electric field not only does not inhibit the formation of the frost layer on the hydrophilic surface, but also promotes the growth of the frost layer. Dalvi et al.[32] found that although the applied electric field had an effect on the size and shape of the generated frost crystals, it had no effect on the frost formation rate and the amount of frost formation. It can be seen that the use of applied electric field to inhibit evaporator frost needs more in-depth research.

5.2. Imposed magnetic field

Magnetic fields can change the physicochemical properties of water and have an effect on the phase change process of water, which in turn has an effect on the evaporator surface frosting. Gou Yujun et al.[33] conducted an experimental study on the magnetic surface frost phenomenon and compared it with the ordinary surface frost. The experimental results showed that: due to the role of the magnetic field, the magnetic surface generated frost crystals more sparse, loose, similar to the shape of the needle, but did not carry out an in-depth study of the. Mok et al.[34] investigated the process of solution freezing under the action of an applied magnetic field, and came up with results similar to those of Yujun Gou on the effect of magnetic field on frost crystals, and further concluded that an applied magnetic field would retard frosting. Li Jiacun et al.[35] investigated the effect of cold surfaces with different magnetic properties on frosting. The results showed that when the magnetic properties were in the range of 0-350 mT, the magnetic field could effectively inhibit the frosting process on the cold surfaces, and the frost crystals that had been formed on the magnetic surfaces were easier to remove compared with the non-magnetic surfaces; however, when the magnetic properties are in the range of 350-400 mT, the presence of magnetic field promotes the frosting on the contrary. Mengmata et al.[36] studied on the crystallisation characteristics of bare copper surface under weak AC

magnetic field (0-6mT). The experimental results showed that the degree of crystallization supercooling increased with the increase of magnetic field strength, which prolonged the crystallization time to a certain extent, which provided a reference for the study of frost suppression by the additional magnetic field of the evaporator.

6. Conclusion and Outlook

This paper summarizes the evaporator frost suppression methods explored by scholars in recent years and reviews the research progress of changing the evaporator inlet air parameters, evaporator surface modification, optimizing the structure and design of the evaporator, and applying external electromagnetic field. However, in order to realize the safe use and efficient operation of air source heat pumps, the author believes that in-depth research is needed in the following aspects.

(1) change the evaporator inlet air parameters: preheat the evaporator inlet temperature can inhibit frost, but most of the methods need to consume extra energy and low efficiency, recovery of waste heat will be used for the evaporator inlet warming not only energy saving but also can play a role in the effect of frost inhibition will become the future direction of the research; the use of desiccant to reduce the humidity of the air inlet of the evaporator can play an obvious effect of frost inhibition, but the continued use of desiccant leads to its dehumidifying. However, the continuous use of desiccant leads to its dehumidification ability to reduce, renewable desiccant dehumidification system in the actual use of some problems, need to be further improved; change the evaporator inlet air flow rate to inhibit the effect of frost in the early stage of frost and the later is not consistent, need to be more in-depth study.

(2) evaporator surface modification: hydrophilic coating and hydrophobic coating although both play a good frost inhibition effect, but there are some problems, hydrophilic coating evaporator first frost defrost will be due to its hydrophilic nature, the fin surface will retain a lot of water, and will soon be frost again; hydrophobic coating evaporator in the ultra-low temperature evaporator surface temperature, it will promote the frost and frost layer growth more dense. Therefore, it is still to be explored whether it is feasible to use both of them to inhibit evaporator frosting.

(3) Optimize the structure and design of the evaporator: Although changing the fin spacing and fin type of evaporator can achieve the effect of frost suppression, the size of fin spacing and the selection of fin type should be determined according to the experimental environment.

(4) Apply external electromagnetic field: the voltage, current and polarity of the external electric field will have a certain effect on the frost layer, but there is no unanimous conclusion on whether it promotes or inhibits frost; the effect of the external magnetic field on the frost suppression will be changed with the change of the magnetism, sometimes instead of promoting the frost, the magnetic poles of the magnetic layer of the underlying causes of the impact of the frost layer of scholars did not carry out a profound study.

References

- [1] Wang Fenghao, Ma Longxia, Wang Zhihua, et al. Research status and prospect of defrost control methods for air source heat pumps[J]. Journal of Refrigeration,2021,42(05):27-35.

- [2] Cui J, Li W Z, Liu Y, et al. A new model for predicting performance of fin-and-tube heat exchanger under frost condition [J]. *International Journal of Heat and Fluid Flow*, 2011, 32(1): 249-260.
- [3] Kwak K, Bai C. A Study on the Performance Enhancement of Heat Pump Using Electric Heater under the Frosting Condition: Heat Pump under Frosting Condition [J]. *Applied Thermal Engineering*, 2010, 30(6/7): 539-543.
- [4] Huang B, Jian Q, Luo L, et al. Experimental study of enhancing heating performance of the air-source heat pump by using a novel heat recovery device designed for reusing the energy of the compressor shell[J]. *Energy Conversion and Management*, 2017, 138: 38-44.
- [5] Xing Zhen. Research on frost layer growth characteristics of finned tube heat exchanger [D]; Tianjin University of Commerce, 2016.
- [6] Zhang L, Fujinawa T, Saikawa M. A New Method for Preventing Air-source Heat Pump Water Heaters from Frosting [J]. *International Journal of Refrigeration*, 2012, 35(5): 1327-1334.
- [7] Li Y G, Chen G M, Tang L M, et al. Analysis on Performance of a Novel Frost-free Air-source Heat Pump System [J]. *Building and Environment*, 2011, 46(10): 2052- 2059.
- [8] Zhang L, Hihara E J, Saikawa Michiyuki. Combination of Air-Source Heat Pumps with Liquid Desiccant Dehumidification of Air [J]. *Energy Conversion and Management*, 2012, 57: 107-116.
- [9] Senshu T, Yasuda H, Kuroda S, et al. Heat pump performance under frosting conditions (I): Heat and mass transfer on cross-finned tube heat exchangers under frosting conditions[J]. *ASHRAE Trans.*, 1990, 96:324-329.
- [10] Wu JY, Chen JP. Numerical simulation and experimental study of evaporator frost characteristics under low-temperature conditions[J]. *Cryogenic Engineering*, 2008(01):33-37.
- [11] Guo Xianmin, Wang Dongli, Chen Yiguang, et al. Effect of outdoor heat exchanger head-on wind speed on frost characteristics of air-source heat pumps[J]. *Journal of Chemical Engineering*, 2012, 63(S2):32-37.
- [12] Highgate D, Knight C, Probert S D. Anomalous 'freezing' of water in hydrophilic polymeric structures [J]. *Applied Energy*, 1989, 34(4): 243-259.
- [13] Okoroafor E U, Newborough M. Minimising Frost Growth on Cold Surface Exposed to Humid Air using Cross-Linked Hydrophilic Polymeric Coatings [J]. *Applied Thermal Engineering*, 2000, 20:737-758.
- [14] Huang, Lingyan, Liu, Zhongliang, Wang, Jingteng, Liu, Yaomin, Gou, Yujun. Experimental study of water resistance of frost inhibiting coatings[J]. *Journal of Engineering Thermophysics*, 2009, 30(09):1537- 1539.
- [15] Liang C, Wang F, Lu Y, et al. Experimental and theoretical study of frost melting water retention on fin surfaces with differed surface characteristics[J]. *Experimental Thermal and Fluid Science*, 2016, 71:70-76.
- [16] Ma Qiang. Experimental and simulation study of cold surface frosting in low temperature and high humidity environment [D]; Tsinghua University, 2015.
- [17] Sommers A D, Riechman A, Truster N L, et al. Densification of frost on hydrophilic and hydrophobic substrates- examining the effect of surface wettability[J]. *Experimental Thermal and Fluid Science*, 2016, 75:25-34.
- [18] Zhou Yanyan, YU Zhijia. Study on the anti-frost properties of aluminum-based superhydrophobic surfaces[J]. *Journal of Chemical Engineering in Higher Education*, 2012, 26(06):929-933.
- [19] Liu Mengmeng, Wang Xianzhong, Huang Yegui, etc. Experimental study on the frost suppression performance of hydrophobic coated evaporator[C]//China Household Electric Appliances Association. Proceedings of China Household Electric Appliances Technology Conference 2021. *Journal of Electrical Appliances*, 2021, 1:175-181.
- [20] Fan Laifu, Cao Xianqi, Dai Jingjing, Wen Xiantai, Wang Feng. Experimental study on the frost suppression/defrosting performance of superhydrophobic heat exchangers[J]. *Journal of Hebei Engineering University (Natural Science Edition)*, 2020, 37(04):87- 93.
- [21] Li liyan, Liu Zhongliang, Zhao Ling-Qian, LI Yan-Xia. Study on frost suppression at the early stage of frosting without liquid nucleus formation[J]. *Journal of Engineering Thermophysics*, 2019, 40(01):198-203.
- [22] Cheng Weihong, Yao Yang, Ma Minliang. Influence of structural parameters of air-side heat exchanger of air-source heat pump on frost characteristics [J]. *Journal of Shenyang University of Architecture (Natural Science Edition)*, 2006, 03: 458-461.
- [23] Park J-S, Kim D R, Lee K-S. Frosting behaviors and thermal performance of louvered fins with unequal louver pitch [J]. *International Journal of Heat and Mass Transfer*, 2016, 95(499-505).
- [24] Kim K, Lee K-S. Frosting and defrosting characteristics of surface-treated louvered-fin heat exchangers: effects of fin pitch and experimental conditions [J]. *International Journal of Heat and Mass Transfer*, 2013, 60(505-511).
- [25] Zhang P, Hrnjak P S. Air-side performance evaluation of three types of heat exchangers in dry, wet and periodic frosting conditions [J]. *International Journal of Refrigeration*, 2009, 32(5): 911-921.
- [26] Xie Fulin, Guo Xianmin, Guo Xinwei, et al. Experimental study on the effect of fin structure on the frost characteristics of heat exchangers [J]. *Journal of Refrigeration*, 2021, 42(03): 51-58.
- [27] Schaefer V. Project cirrus general electric research laboratory[J]. Schenectady, New York, Final Report, 1953: 52-53.
- [28] Maybank J, Barthakur N N. Growth and Destruction of Ice Filaments in an Electric Field [J]. *Nature*, 1967, 216(5110): 50-52.
- [29] Munakata T, Yabe A, Tanasawa I. Effect of Electric Fields on Frosting Phenomenon, F, 1993 [C].
- [30] Blanford, Ohadi M, Dessiatoun S V. Compound air-side heat transfer enhancement in a cross-flow refrigerant-to-air heat exchanger, F, 1995 [C].
- [31] Zhang Xinhua, Liu Zhongliang, Wang Jingteng, et al. Influence of surface properties of vertical plate on frost layer growth under electric field [J]. *Journal of Refrigeration*, 2006, 03: 54-8.
- [32] Dalvi-isfahan M, Hamdami N, Le-bail A, et al. The principles of high voltage electric field and its application in food processing: a review [J]. *Food Research International*, 2016, 89(48-62).
- [33] Gou Yujun, Liu Zhongliang, Liu Yaomin, et al. Experimental study on the effect of magnetic field on the frosting process on cold surfaces [J]. *Journal of Engineering Thermophysics*, 2009, 30(03): 465-467.
- [34] Mok J H, Choi W, Park S H, et al. Emerging pulsed electric field (PEF) and static magnetic field (SMF) combination technology for food freezing [J]. *International Journal of Refrigeration*, 2015, 50(137-145).

[35] LI Jiachun, Yujun Hou, Yida Li, et al. Visualization of icing and frost suppression on magnetic cold surfaces [J]. *Cryogenic Engineering*, 2021, 06): 51-57.

[36] Meng Minata, Liu Bin, Shan Liangliang, et al. Crystallization characteristics of bare copper surface under weak AC magnetic field [J]. *Journal of Refrigeration*, 2020, 41(03): 153-159.