Research on the Frosting Rule and Frost Suppression Strategy
of Air Source Heat Pump in Guiyang, China

Ruiyong Mao¹, Yaxin Yang¹*, Peng Pei², Xuerui Yang³, Maojun Tian¹, Cheng Hu¹ and Weiping Yang¹

¹College of Civil Engineering, Guizhou University, Guiyang, China, ²College of Mines, Guizhou University, Guiyang, China ³Guizhou Construction Science Research Station Institute Limited Company of CSCEC, Guiyang, China

*Correspondence Email: yangyaxin0307@163.com

Abstract: In order to solve the serious frosting problem of air source heat pump in high humidity area in winter, a set of air source heat pump was tested and studied. The experimental results showed that the frost condition in winter in study area started when the outdoor temperature was less than 6℃ and the relative humidity was more than 75%. The blocking experiment proved that frost formation was beneficial to the operation of the unit when the blocking degree was less than 10%. Furthermore, by extending the initial time of frosting, a new method of frost suppression was proposed, which extended the initial time of frosting by 22 minutes. In the high humidity area, air source heat pump was recommended to be used for heating when it is above 8℃ in winter, while the staged frost suppression was considered when it is below 6℃ to improve the performance of air source heat pump.

1 Introduction
Air source heat pump is widely used in winter heating in Guiyang, but the humidity in winter is generally high in this area, which makes the operation of air source heat pump easily frosted. Frequent defrosting has adverse effects on indoor comfort, unit energy efficiency and service life. Liu and Wu [1] pointed out that frost density and frost thermal conductivity were the main parameters to study frost formation, but the influencing factors were complex. Dong and Shen [2] established a new energy flow model by introducing thermal resistance and thermal potential to analyze and optimize the equipment. Yao Yang et al. [3] considered the influence of refrigerant two-phase flow on the model, and established the distributed parameter models for outdoor evaporator and outdoor air side of air source heat pump respectively. Then, it was concluded that the axial power of compressor and air side heat exchange decreased with the increase of relative humidity. Frost density and frost thickness are both time functions. In the calculation of frost amount, it is considered that the constant frost density will cause the unit to misjudge defrosting due to the inaccurate calculation of frost amount. Gong et al. [4] established the frost layer, the refrigerant side and the outside air side models of the evaporator, and simulated the frosting process. However, the modeling is a quantitative analysis, and the coefficients which vary from place to place cannot be determined uniformly. In recent years, through the related thermodynamic software, new frosting models have been established. Ye and Lee [5] proposed a new frosting model considering the influence factors of the heat exchange decrease caused by the increase of frost amount,

[121x60]Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd
and suggested that the condensed water should be drained in time or the fan power should be increased to improve the air side heat transfer efficiency. Chung et al. [6] established the frost growth rate model under different frosting conditions through the improved \( \varepsilon - \) NTU method, and derived the corresponding performance changes.

Due to the significant difference between Guiyang and other regions in the frosting rules caused by the special geographical and climatic environment and few experimental studies on the frosting conditions of air source heat pump, it is necessary to carry out the research on effect of frosting on the unit performance under actual winter conditions in double-high regions (high moisture content and high relative humidity) represented by Guiyang, and put forward corresponding frost suppression methods to solve the discomfort caused by frequent defrosting.

2 Introduction to the test

2.1 Test overview
In this experiment, a 3400W air conditioning unit was tested for frosting in winter.

2.2 Test object
The test object is an office of a college in Guiyang equipped with an air source heat pump. The performance and parameters of heat pump is shown in Table 1 and 2.

| Performance parameters of the air source heat pump | parameters          |
|--------------------------------------------------|---------------------|
| rated power                                      | 1100W (200W-1250W) |
| rated current                                    | 5.08 (0.92A-5.77A)  |
| refrigerant                                      | R410A/830g          |
| theoretical SEER value                           | 4.5                 |
| heating capacity                                 | 3400W (700W-3600W)  |
| Max. working pressure at discharge / suction side| 4.2/1.5MPa          |

| Structural parameters of heat exchanger          |
|--------------------------------------------------|
| heat exchanger                                   |
| fin spacing                                      | mm                  |
| tube spacing                                     | mm                  |
| pipe diameter                                    | mm                  |
| length                                          | mm                  |
| pipe diameter                                    | mm                  |
| tube row number                                  |                     |
| liquid separation number                         |                     |
| heat transfer area                                | m²                  |
| evaporator                                       |                     |
| condenser                                        |                     |

3 Test process

3.1 Test method
The distribution of measuring points is shown in Figure 1. Under different temperature and humidity conditions, tested parameters include: the temperature and pressure at the inlet and outlet of the compressor, the pressure before and after the capillary, the temperature and humidity at the inlet and outlet of the condenser, the temperature and humidity at the inlet and outlet of the evaporator, the wall temperature of the evaporator pipeline, the flow before the evaporator, and the air speed at the inlet and outlet of the outdoor unit and indoor unit.

3.2 Frost amount test
The relationship between frost amount and air moisture content was analyzed by measuring frost
amount. The measurement of frost amount were divided into two parts: one was the collected defrosting water; the other was the calculation of defrosting water film adhering to the fin surface.

3.3 Frost blocking process test
The winter temperature in Guiyang is mainly 4℃ to 6 ℃, and the humidity range is mostly 75% to 85%. On the background, the air inlet speeds of outdoor unit under different frosting degree were tested to compare with that without frosting. Take the wind speed as 10% - 90% of the original initial wind speed as the blocking degree standard, that is, 10% of the wind speed corresponds to 90% of the blocking degree, and so on.

3.4 Frost suppression experiment
The heating cables were fixed on the main refrigerant separation pipe to raise the wall temperature of the evaporator, thereby prolonging the initial frosting time and suppressing frost.

Table 3 Frosting conditions of different outdoor temperatures

| working condition | temperature range (℃) | relative humidity RH(%) | moisture content d(g/kg) |
|-------------------|------------------------|--------------------------|--------------------------|
| A                 | 6-8                    | 70%-80%                  | 5.31                     |
| B                 | 4-6                    | 70%-80%                  | 5.201                    |
| C                 | 2-4                    | 70%-80%                  | 4.31                     |
| D                 | -1-2                   | 70%-80%                  | 3.505                    |

4 Results analysis and discussion

4.1 Dynamic performance analysis

4.1.1 Unit performance test under the same humidity and different temperature. The test conditions are shown in Table 3. The frosting tests of air source heat pump were carried out for each condition, and the effect of frosting on the unit performance are shown in Figure 2 to Figure 4.

![Figure 1 Distribution of measuring points](image)

1 compressor; 2 gas-liquid separator; 3 liquid accumulator; 4 evaporator; 5 capillary; 6 drying filter; 7 condenser; 8 four-way reversing valve

![Figure 2 and Figure 3](image)

(a) under condition A (b) under condition B
4.1.2 Unit performance test under the same temperature and different humidity. The test conditions are shown in Table 4.

It can be seen from Figure 2 that in the frosting condition the performance change curve of the unit fluctuates greatly, and the system is unstable. It can be concluded that:

1) No matter what the temperature range, the heating capacity $Q_k$ always increases sharply after the unit is started, and then decreases when the system is stable until the evaporator begins to frosting. In the early stage of frosting, the heat exchange surface area of the fins are increased by the frost layer, so the heating capacity of the unit is increased. Then, with the increase of frost layer thickness, the heat conduction resistance increases; with the increase of frost amount, the fin channel is blocked, which hinders the heat exchange between fins and the outside air, so the heat exchange decreases slowly.

2) Compared with the heating capacity, the change of compressor power is more stable and gentle. But, the overall trend is identical.

3) The change trend of COP is similar to that of heating capacity.

In order to get the most suitable application range of air source heat pump in Guiyang, performance parameters in each frosting temperature were compared. The compressor has the best performance within the temperature range of 6℃ to 8 ℃ (Figure 3 and figure 4).
From Figure 5 and 6, it can be concluded that under the same temperature and different relative humidity, the operation time of unit is: $t_H < t_G < t_F < t_E$. It can be seen that the relative humidity of outdoor environment directly affects the speed of frosting, and then affects the operation time of unit.

Figure 5 shows that in the early stage of frosting, it is helpful to heat exchange of the unit, and the heating capacity reaches the peak value. After that, the increase of frost layer affects the heat exchange of the unit, and the heating capacity decreases. When the unit runs to 28min / 33min / 39min / 54min respectively under each working condition, it enters into high frequency state, and the heating capacity begins to increase. The time of entering high frequency state in condition E is 26 min earlier than that in condition H, and the unit operation time is shorter. The faster frosting, the more frequent defrosting, the lower the heating capacity. When the frosting enters into the later stage, the heating capacity decreases until the temperature difference between the inlet and outlet of the indoor unit drops below 7℃, and then defrosting. The difference of operating time between condition E and condition H is 28 min, which shows that the moisture content is also an important factor affecting frosting speed.

![Figure 5. Heating capacity curve with time under different frosting conditions](image)

![Figure 6. COP curve with time under different frosting conditions](image)

It can be seen from Figure 6 that COP of condition E is 1.01 lower than that of condition H on average. Frequent frosting results in short operation time of the unit, low heating capacity and low COP. High relative humidity and moisture content in Guiyang result in rapid frosting and frequent defrosting.

### 4.2 Experiment on the influence of frost blocking

According to Figures 7 and 8, the evaporator surface temperature is the highest in the upper the second row and the lowest in the middle the fourth row. Because the fan is blowing the fourth row in the middle of the evaporator, the temperature distribution is high on both sides and the middle is low, so the fourth row in the middle is frosted first; the air temperature around the second row and the fourth row in the upper part is slightly higher than the fourth row in the middle, so it is frosted later.

| Working condition | Temperature range (℃) | Relative humidity RH(%) | Moisture content d(g/kg) |
|-------------------|------------------------|-------------------------|--------------------------|
| E                 | 2-4                    | 50%-60%                 | 2.92                     |
| F                 | 2-4                    | 60%-70%                 | 3.45                     |
| G                 | 2-4                    | 70%-80%                 | 3.98                     |
| H                 | 2-4                    | 80%-90%                 | 4.52                     |

From Figures 5 and 6, it can be concluded that under the same temperature and different relative humidity, the operation time of unit is: $t_H < t_G < t_F < t_E$. It can be seen that the relative humidity of outdoor environment directly affects the speed of frosting, and then affects the operation time of unit.

Figure 5 shows that in the early stage of frosting, it is helpful to heat exchange of the unit, and the heating capacity reaches the peak value. After that, the increase of frost layer affects the heat exchange of the unit, and the heating capacity decreases. When the unit runs to 28min / 33min / 39min / 54min respectively under each working condition, it enters into high frequency state, and the heating capacity begins to increase. The time of entering high frequency state in condition E is 26 min earlier than that in condition H, and the unit operation time is shorter. The faster frosting, the more frequent defrosting, the lower the heating capacity. When the frosting enters into the later stage, the heating capacity decreases until the temperature difference between the inlet and outlet of the indoor unit drops below 7℃, and then defrosting. The difference of operating time between condition E and condition H is 28 min, which shows that the moisture content is also an important factor affecting frosting speed.
The difference between the initial wall temperature and the environment temperature is not significant. When the blocking degree is 20% to 70%, the temperature gradually decreases until the blocking degree is 90%. The frost layer basically covers the temperature sensing probe and the temperature drops suddenly. The channel of fins is blocked by frost and can't exchange heat with the outside. The thermal efficiency of indoor unit drops sharply, and then defrosting.

Figures 9 and figure 10 show the temperature drop extremely from without frost to 10% blocking degree. The temperature of the fourth row in the middle is relatively gentle when the blocking degree is 20% to 40%; while, the temperature of the fourth row in the upper is 20% to 60%. Therefore, it can be considered to suppress frost in stages to improve the performance of the unit, namely first frosting, first suppressing.

Figure 11 show that the heat capacity and compression ratio increase slightly from starting up to 10% blocking degree. Since frosting is a phase change process and the frost layer will increase the fins surface areas, heat transfer capacity increases. The surface temperature and heating capacity of the frost layer increase after the blocking degree reaches 40%. This is because the self-protection device of the unit sends a signal and automatically changes to high frequency. With the increase of the operation time of the unit, the performance of the compressor drops sharply. When the blocking degree is 100%, defrosting is needed. The compressor power decreases uniformly with the increase of frost amount. With the increase of blocking degree, the change trend of COP is similar to that of heating capacity.
4.3 Performance of frost suppression and non frost suppression
For the staged frost suppression method, the frost suppression experiment was performed on the working conditions in Table 3, and the performance parameters were compared with the non-frost suppression conditions. As shown in figure 12, frost suppression experiments were performed by opening three heating cables. The results are shown in Figures 13 and figure 14. This experiment was carried out in an artificial environment room.

The heat capacity by frost suppression is about 1.15 times as much as that of non frost suppression. In the initial frosting period, the heat exchange effect is obviously enhanced. In the middle and late period of frosting, its heating capacity gradually decreases. At the end of frosting, unit is out of service and defrosting. In order to prevent the continuous increase of frost, start up the heating cables after the initial frosting period. Frost suppression experiments were performed by opening three heating cables in the following order: the second row in the middle → the lower pipe → the second row in the upper. The initial time of frost suppression is about 22 minutes longer than that of non frost suppression. The wall temperature will increase by starting up the heating cables, which is helpful to suppress the growth of frost. Under all working conditions, the heat transfer effect of frost suppression is better than that of non frost suppression.

5 Conclusion
Experiments on frosting of air source heat pump caused by temperature and humidity in Guiyang were conducted, and the following conclusions were drawn:

(1) Temperature affects the speed of frosting, and the moisture content determines the frost amount. In high humidity areas, a large amount of frost generated per unit time which cause frequent defrosting.
However, with the decrease of outdoor temperature, the moisture content and the amount of frosting decreases, and the whole heating cycle will not produce too much frost.

(2) The frosting conditions in Guiyang should meet environment temperature ≤6℃ and RH≥75% simultaneously. Temperature between 6℃ to 8℃ is the uncertain zone of frosting condition, and the frosting instability will transition to the condensation condition. The elution of condensed water will increase the heat exchange efficiency of the unit. It can be concluded that it is favorable to the run of air source heat pump when the temperatures is higher than 8℃ in high humidity area.

(3) When the degree of frost blocking is 10%, the unit's performance is optimal in all aspects. The initial frosting is helpful to heat exchange. Because of the time inconsistency of frost covered finned tubes, it is considered to be a staged frost suppression method.

(4) It is efficiency to wind the heating cables around the main channel of the outdoor unit evaporator to suppress frosting, which can extend the initial frosting time for about 22 minutes. This method can improve air source heat pump application in high humidity areas.

Acknowledgements
This study is supported by the fund of the Department of Science & Technology of Guizhou Province (Grant No. [2016] 1408), Science and Technology Project of Guizhou Province(Grant No. [2018] 5781), and Science and Technology Project of Guizhou Province(Grant No. [2018] 1039).

References
[1] Liu Y, Wu Q. Summary of frost formation mechanism and heat pump defrosting technology [J]. Energy saving technology, 2018, 36 (3): 195-200.
[2] Dong W, Shen G. Energy flow model research and optimization of evaporative cooling system [J]. Energy saving technology, 2019, 37 (3): 213-220.
[3] Yao Y, Jiang Y, Ma Z. Frosting rule of air side heat exchanger of air source heat pump chiller and water heater [J]. Journal of Harbin University of technology, 2012, 34 (5): 660-662.
[4] Gong G, Tang J, Lv D, et al. Research on frost formation in air source heat pump at cold moist conditions in central-south China[J]. Applied Energy,2013,102:571-581.
[5] Ye H Y, Lee K S. Performance prediction of a fin-and-tube heat exchanger considering air-flow reduction due to the frost accumulation[J]. International Journal of Heat and Mass Transfer,2013,67:225-233.
[6] Chung Y, Yoo J W, Kim G T, et al. Prediction of the frost growth and performance change of air source heat pump system under various frosting conditions[J]. Applied Thermal Engineering, 2019, 147:410-420.