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Experimental Study on Frost Characteristics of Variable Pitch Finned-Tube Heat Exchangers#

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ABSTRACT

The efficient use of energy and sustainable development is the eternal development theme of today's era. Finned-tube heat exchangers are widely used in various systems, and the heat transfer efficiency and operating performance have an important impact on the energy consumption of the system. When finned-tube heat exchangers are running at low temperature, the phenomenon of surface frosting often occurs. The generation of frost layer will worsen the heat transfer performance, and defrosting also needs additional energy consumption, resulting in a waste of energy. This paper conducted an experimental study on the frosting characteristics of a finned-tube heat exchanger with variable fin spacing, built a test platform for the frosting performance of the finned tube heat exchanger, and analyzed the effects of air temperature, relative humidity and wind speed on the frosting characteristics of the finned-tube heat exchanger with variable fin spacing. The experimental results show that the increase of air temperature, relative humidity and wind speed will promote frost formation.

Keywords: finned-tube heat exchanger, frost, heat and mass transfer

NONMENCLATURE

Abbreviations	
Fr	Frost
Fs	Frost surface
Symbols	
T	Temperature
RH	Relative humidity
WS	Wind speed

1. INTRODUCTION

With the development of the times, the global energy demand continues to grow, the efficient use of energy and sustainable development is the eternal development theme of today's era. "Heating and cooling accounts for about half of global energy consumption, mostly from inefficient use of fossil fuels or biomass, and accounts for more than 40% of global energy carbon emissions," according to the IEA's "Renewable Energy Policy in the Energy Transition Era - Heating and Cooling." Finned-tube heat exchangers are widely used in heating and cooling systems. During the operation of the system, frosting on the surface of heat exchangers often occurs. With the accumulation of frost layer on the surface of the finned-tube heat exchanger, the heat transfer performance of the heat exchanger will be seriously deteriorated, in addition, in order to maintain normal operation, additional heat has to be consumed for defrosting, resulting in additional energy consumption, which causes a waste of energy.

Frost formation is a complex heat and mass transfer process, which is closely related to environmental parameters, such as air temperature, humidity, speed, and the characteristics of heat exchangers, such as fin spacing, shape, surface characteristics. Na and Webb[1] explored the mass transfer mechanism of frost layer and proposed that water vapor in wet air is in a supraturated state on the surface of frost layer. Liu et al.[2,3] found that the growth of frost layer in the initial stage increases the heat exchange area of the heat exchanger and promotes heat tranfer. Neal[4] and Lee et al.[5] put forward the heat and mass transfer equation of frost layer, which lays a foundation for the establishment of frost formation model. In practice, the variable pitch finned-tube heat exchanger is widely used, and the experimental research on the frosting characteristics of finned-tube heat exchanger under complex working conditions has theoretical guiding significance for optimizing the operation of the system and reducing energy consumption.

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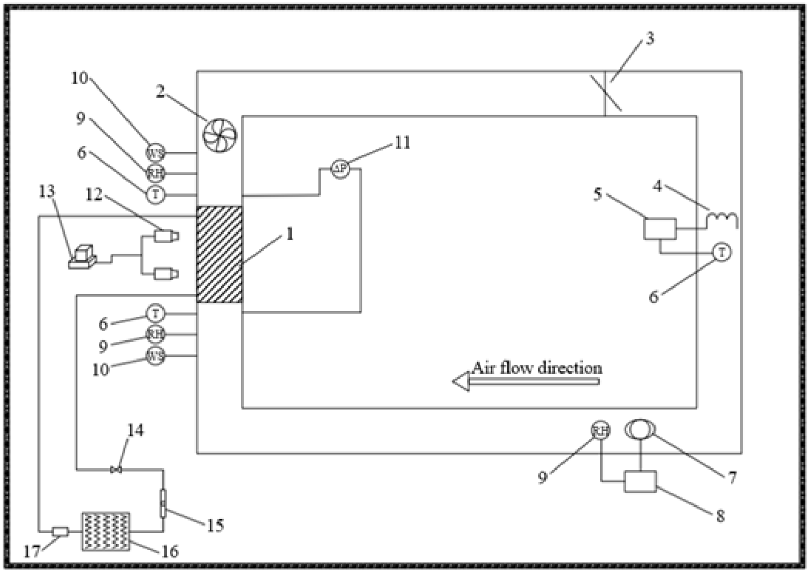
2. EXPERIMENTAL SYSRE



1 Finned-tube evaporator 2 Fan 3 Damper 4 Electric heater 5 Electric heater controller 6 Temperature sensor 7 Humidifier 8 Humidity controller 9 Humidity sensor 10 Wind speed sensor 11 Pressure drop sensor 12 CCD high-speed camera 13 Image acquisition system 14 Throttle valve 15 Dryer filter 16 Condenser 17 Compressor

Fig. 1 Experiment system

In this paper, a finned-tube heat exchanger frost-forming performance test platform is established. The frost-forming performance of the finned-tube heat exchanger under frost-forming conditions are studied, and the influence of air temperature, humidity and flow rate on the frost-forming performance of finned-tube heat exchanger with variable pitch is explored.

The experimental system is shown in Fig. 1. The frost-forming performance test system of finned-tube heat exchanger is composed of refrigeration circuit and air circuit. The refrigeration circuit consists of a compressor, a condenser, a filter dryer, a throttle valve and a finned-tube heat exchanger for testing. The refrigerant used in the experiment is R600a. The air circuit is a closed loop, driven by the fan to carry out forced circulation flow in the loop, when the air flows through the finned-tube heat exchanger, the moisture in the air forms a frost layer on the surface of the heat exchanger, and the low temperature and low humidity air continues to flow. Then, after electric heating, humidifier humidification cycle back to the heat exchanger, through the controller adjustment, so that the air temperature and humidity through the loop stable at a certain set value.

The parameters measured in the experiment include air temperature, relative humidity, wind speed, pressure drop of the heat exchanger, etc. The arrangement of measuring points of each parameter is indicated in Fig. 1. T-type thermocouples are used for air temperature measurement, with a relative error of ±0.2℃. All thermocouples are calibrated by standard thermometers with an accuracy of ±0.1℃. The relative humidity of the air is measured using a 4-20 mA humidity sensor with an error of ±1.5%. The air velocity is measured by a 4-20 mA micro wind speed sensor with a measuring range of 0-10 m/s and an error of ±0.02%. Air pressure drop measurement using 4-20 mA differential pressure transmitter, measuring range 0-100 Pa, error ±2 Pa. The real-time monitoring data of temperature measuring points, wind speed measuring points, humidity measuring points and pressure drop measuring points are recorded by data acquisition recording equipment.

During the experiment, an image acquisition system is set up, a CCD high-speed camera is used to collect real-time images, the main camera is 4800 W pixel, and the light filler lamp is used to fill light. The image acquisition system calculates the frost thickness according to the calibration distance.

After the frost forming process, the heat exchanger is defrosted with hot air at 40℃ and the defrosting water is collected. The remaining water droplets in the evaporator are wiped with cotton. The defrosting water is measured by Ohouse high precision electronic balance (accuracy 0.01 g).

A variable pitch finned-tube heat exchanger is used in the experiment, which is composed of copper coils and aluminum fins. There are 2 rows and 18 columns (1-18 from top to bottom). Finned-tube evaporator has three kinds of fins with different spacing.

3. RESULTS AND DISCUSSION

3.1 Effect of air temperature on frosting performance

The frosting characteristics of the variable pitch finned-tube heat exchanger are studied under the air temperature of 2℃, 5℃ and 8℃ with the air relative humidity of 70% and the wind speed of 1.5 m/s.

In the frost forming process, the temperature difference between the wet air and the cold surface provides the heat transfer driving force for the frost forming process, and the greater the temperature difference, the greater the heat transfer driving force for the frost forming process.

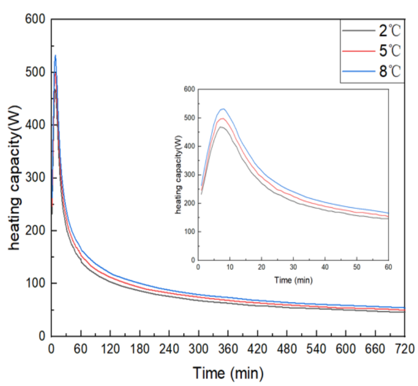


Fig. 2 Effect of temperature on heating capacity

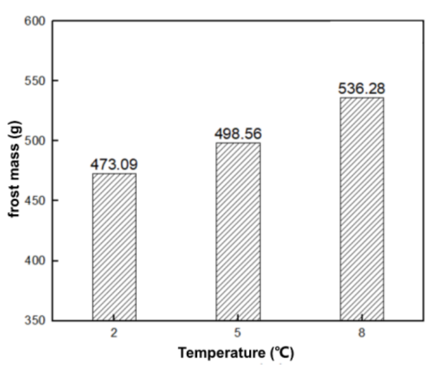


Fig. 3 Effect of temperature on frost mass

Fig. 2 shows the heat exchange of finned-tube evaporator under different air temperature conditions. It can be seen from the figure that the heat exchange of evaporator shows a trend of first increasing and then declining. With the increase of temperature, the maximum heat exchange that the evaporator can achieve also increases. The increase of temperature increases the heat transfer temperature difference between the wet air and the cold surface of the evaporator, provides a greater heat transfer driving force for the frost formation process, enhances the heat transfer between the wet air and the evaporator surface, and therefore promotes the frost formation process. Fig. 3 shows the frosting amount of finned-tube evaporator under different air temperature conditions. It can be seen from the figure that with the increase of air temperature, the frosting mass of evaporator presents a linear increase trend.

Fig. 4 shows the pressure drop of finned-tube heat exchanger during the frosting process under different air temperature conditions. According to the pressure drop change curve, the pressure drop of evaporator presents a continuous rising trend with the progress of frosting process. The maximum pressure drop achieved is 20.8 Pa, 26.9 Pa and 33.2 Pa, respectively. The increase of temperature promotes the frost formation process, and the increase of the pressure drop speeds up, and the maximum pressure drop is also increased.

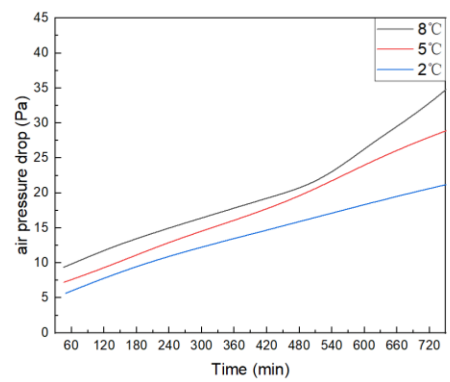


Fig. 4 Effect of temperature on air pressure drop

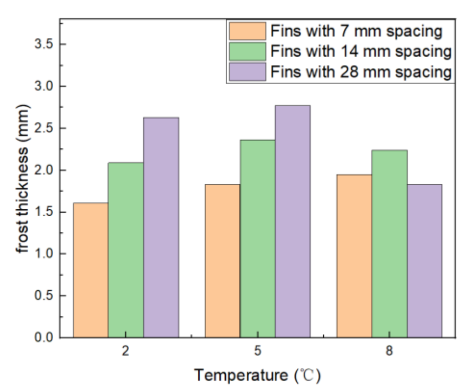


Fig. 5 Frost thickness of different fin spacing

Fig.5 shows the comparison of frost layer thickness of finned tube heat exchanger with different spacing under different air temperature conditions. It can be seen from the figure that air temperature has an effect on the frost layer thickness and frost layer distribution. In the frosting experiment, the flow of wet air is first through the lower part of the heat exchanger with fin spacing of 28 mm, then through the middle with fin spacing of 14 mm, and finally through the upper with fin spacing of 7 mm. With the increase of temperature, the frost thickness of the 28 mm large-spacing fins and 14 mm medium-spacing fins increased first and then decreased, while the frost thickness of the upper 7 mm small-spacing fins gradually increased, and the difference of the thickness between different spacing fins gradually decreased. When the air temperature rises, the temperature difference between the air and the surface of the heat exchanger increases, which promotes the heat transfer process and the thickness of the frost layer increases. However, the experimental condition of the air temperature tested in the experiment is higher than the melting point of the frost layer. When the temperature rises further, the melting effect of the frost crystal is greater than the frost formation effect promoted by enhanced heat transfer. It shows that the thickness of frost layer begins to decrease, and then the cooled wet air continues to flow through the upper part, which shows that the increase of temperature difference strengthens the frost formation process at low temperature.

3.2 Effect of air humidity on frosting performance

The frosting characteristics of finned-tube heat exchanger are studied under the conditions of air temperature of 2℃ and wind speed of 1.5 m/s. The relative humidity of air is 60%, 70% and 80%, respectively.

Fig. 6 shows the heat transfer of finned-tube heat exchanger under different relative humidity conditions. It can be seen from the figure that with the increase of relative humidity, the heat transfer of evaporator decreases, but the change of air relative humidity has less impact on the heat transfer of evaporator than the change of temperature. Moreover, with the increase of humidity, the time when the heat transfer performance begins to decline is advanced. It shows that high humidity can promote frost formation. In the process of frost formation, the partial pressure of water vapor in the wet air provides the driving force of mass transfer, and the partial pressure of water vapor is linearly positively correlated with the relative humidity. Therefore, the greater the relative humidity of the wet air, the greater the mass transfer driving force during the frost formation process, and the more water vapor in the wet air into frost phase. Fig. 7 shows the frosting mass of finned-tube heat exchanger under different air relative humidity conditions. It can be seen from the figure that with the increase of air relative humidity, the frosting mass of finned-tube evaporator also increases.

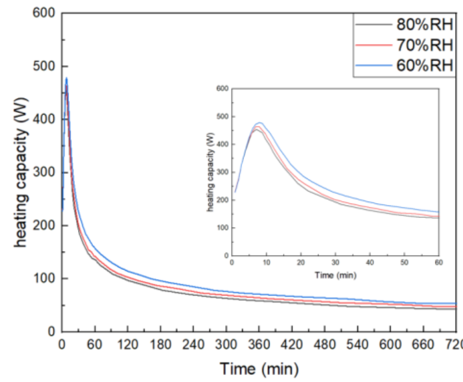


Fig. 6 Effect of humidness on heating capacity

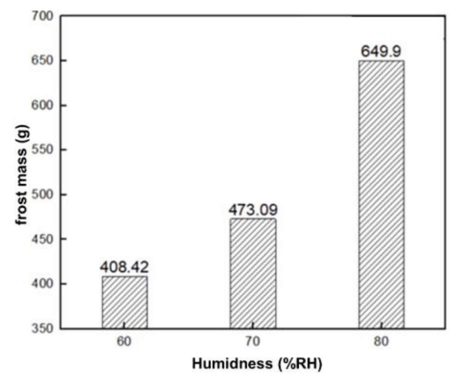


Fig. 7 Effect of humidness on frost mass

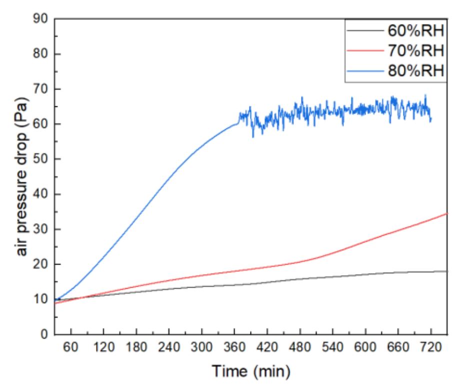


Fig. 8 Effect of humidness on frost mass

Fig.8 shows the change of air pressure drop of finned-tube heat exchanger during frost formation under different relative humidity conditions. According to the pressure drop change curve, the increase rate of evaporator pressure drop increases significantly with the increase of air relative humidity. Under the operating condition of 70% relative humidity, the pressure drop of the evaporator can reach 33.2 Pa, while under the experimental condition of 80% relative humidity, when the experimental system runs for 6h, the pressure drop of the evaporator has reached about 65 Pa, the ultimate air pressure drop of the finned tube heat exchange. Subsequently, the pressure drop of the evaporator fluctuates around the ultimate pressure drop. That is, when the heat exchanger runs for 6h under the condition of 80% relative humidity, the flow channel is blocked, and the system performance is seriously reduced.

Fig. 9 shows the comparison of frost layer thickness of finned tube heat exchanger with different spacing under different air relative humidity conditions. When the air relative humidity is 60%, 70% and 80% respectively, the frost thickness of the lower 28 mm large-spacing fins increases with the increase of air relative humidity. The relative humidity has an exponential effect on the frosting thickness of the lower fin, which are 1.97 mm, 2.63 mm and 4.16 mm, respectively. With the increase of relative humidity, the difference of frost thickness on the surface of fin with different spacing increases, and the phenomenon of frost non-uniformity becomes more obvious.

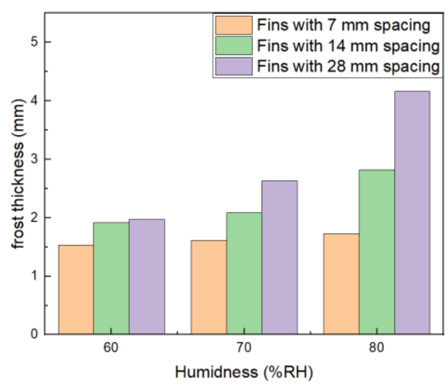


Fig. 9 Frost thickness of different fin spacing

3.3 Effect of wind speed on frosting performance

The frosting characteristics of finned-tube heat exchanger are studied under the conditions of air temperature of 2℃, relative humidity of 70% and wind speed of 1.0 m/s, 1.5 m/s and 2.0 m/s, respectively.

Figure 10 shows the heat transfer of finned-tube heat exchanger under different wind speed conditions. It can be seen from the figure that with the increase of wind speed, the heat transfer increases.

Figure 11 shows the frosting mass of finned-tube heat exchanger under different wind speed conditions. With the increase of wind speed, the frosting mass increases. On the one hand, the increase of wind speed enhances the heat transfer of heat exchanger and provides greater heat transfer driving force for the frost formation process; on the other hand, the circulation of air in the loop is accelerated, and more water vapor enters the heat exchanger to frost on the surface.

Fig. 12 shows the air pressure drop of finned-tube heat exchanger during frost formation under different wind speed conditions. With the increase of wind speed, the increase of air pressure drop speeds up, and the maximum pressure drop achieved also increases, indicating that the increase of wind speed promotes frost formation.

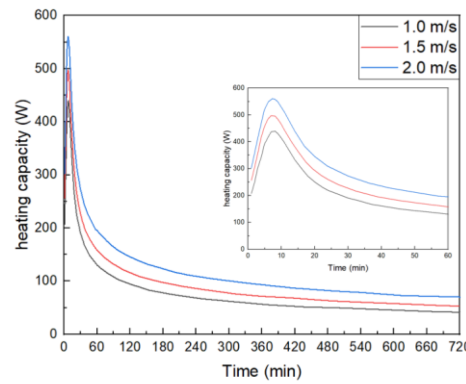


Fig. 10 Effect of wind speed on heating capacity

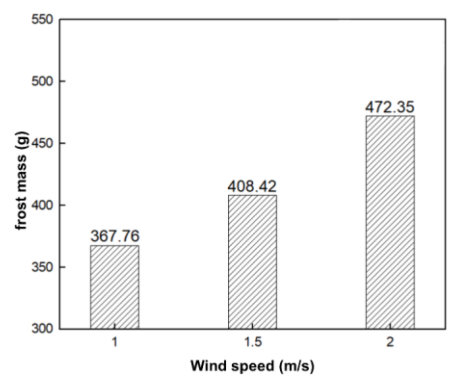


Fig. 11 Effect of wind speed on frost mass

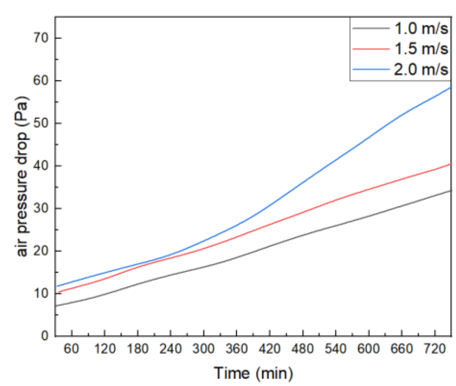


Fig. 12 Effect of wind speed on air pressure drop

Fig. 13 shows the comparison of frost layer thickness of finned tube heat exchanger with different spacing under different wind speed conditions. With the increase of wind speed, the frost thickness decreases, and the difference in frost thickness on the surface of finned-tubes heat exchanger with different fin spacing decreases. Water vapor that phase changes is not easy to adhere to the surface of the frost layer to grow outwards, but with the increase of wind speed, evaporator heat transfer and frosting mass are increased, so the density of the frost layer is increased under the frosting condition of high wind speed.

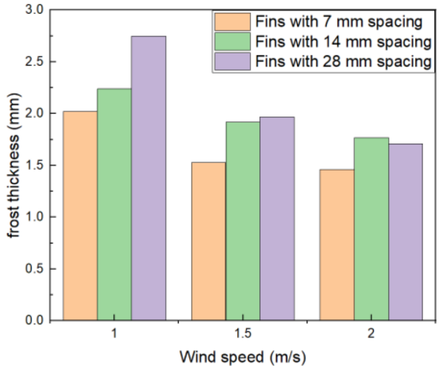


Fig. 13 Frost thickness of different fin spacing

4. CONCLUSION

In this paper, the frosting performance test of variable pitch finned-tube heat exchanger is carried out, and the experimental results are analyzed. The effects of air temperature, relative humidity and wind speed on frosting performance of variable pitch finned-tube heat exchanger under frosting condition are studied, and the following conclusions are obtained:

(1) The increase of air temperature increases the temperature difference between the air and the heat exchanger surface, which provides a greater heat transfer driving force for the frost formation process. Under the frost formation condition, with the increase of air temperature, the heat transfer, frost formation mass and air pressure drop increase. The frost layer thickness on the surface of variable spacing fins is not uniform.

(2) The increase of the relative humidity of the air provides a greater driving force for mass transfer in the frost forming process. With the increase of relative humidity in the frost forming condition, the heat transfer of the evaporator decreases, and the heat transfer decay time is advanced; The thickness of the frost layer on the surface of the lower fins increases exponentially, and the frost formation non-uniformity on the surface of the different spacing fins increases.

(3) The increase of wind speed enhances the convective heat transfer between the heat exchanger and the air. Under frosting conditions, with the increase of wind speed, the heat transfer, frosting mass and air pressure drop of the evaporator increase. The thickness of frost layer on the surface of fin with different spacing decreases. The higher the wind speed, the higher the density of frost layer.

ACKNOWLEDGEMENT

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