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A Natural Wind Defrosting, Nano-coated Antibacterial Self-cleaning Energy-saving Health Air-cooled Refrigerator

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ABSTRACT

The air-cooled frost-free household refrigerator is popular in the market because of its large size and frost-free size. However, the evaporator defrost process consumes a large amount of electrical energy to limit the wide spread of this refrigerator, at the same time because of its structural problems, resulting in its evaporator, air duct can not be artificially cleaned, leading to the growth of bacteria, pollution of food storage. This research has developed a self-cleaning energy-saving health refrigerator that uses indoor natural wind defrosting, ultra-hydrophilic nano-titanium dioxide coating photocatalytic sterilization and sterilization. After experimental comparison, under the same operating time of the same operating conditions, the refrigeration mode saves 1.5%, the defrost process saves 95%, reduces the amount of frosting by 23%, the temperature changes of the freezer is less than 7 ℃, and the desterilization rate of nano-coated reaches 80%.

1. INTRODUCTION

The Air-cooled frost-free refrigerators are recognized by the industry as an inevitable trend in the development of refrigerators due to their unique large capacity, multi-temperature zone and automatic defrost. It uses the evaporator fan to make the refrigerating chamber and the freezing chamber return to the evaporator and exchange heat with the evaporator. During this cooling process, the water vapor in the air condenses on the surface of the evaporator, and then the evaporator runs for a longer time, the frost layer is getting thicker, so that the flow resistance of the heat resistance and the process air increases, the air flow is reduced, the evaporation temperature decreases, reducing the performance of the evaporator heat exchanger. Therefore, when the frost layer on the surface of the evaporator reaches a certain thickness, regular defrosting is required.

Domestic and foreign scholars have studied refrigerator defrosting related process comprehensively. Liu *et al.* (2018) designed a new defrosting technology - bypass cycle defrosting system using compressor casing thermal storage (BCD-CCTS), and used the heat storage package to store the waste heat of the compressor casing for heating the

defrosted refrigerant. The experimental results show that BCD-CCTS reduces defrosting time by 65%–77% and defrosting power consumption by 89%–92% compared with 180–419 W EHD. (Liu *et al*., 2018)
Fernando *et al*. (2011) studied the distribution of frost layer on the refrigerator evaporator by establishing a mathematical model of frost layer distribution, two electric heaters with different powers were designed to defrost the upper and lower tubes of the evaporator, which improved the defrosting efficiency.(Fernando *et al*. ,2011)
Song *et al*. (2012) preheated the frost with the air coming back from refrigerating chamber for a single air-cooled refrigerator evaporator, optimizing the return air time and air volume, reducing defrosting power consumption by 27% and the whole power consumption by 6.7%. (Song *et al*. 2012)
Cheng *et al*. (2008) optimized and optimized the distribution and power of the defrosting heater, the location of the defrosting sensor, the defrosting control rules and the control parameters by experimental analysis of automatic defrosting design for frost-free room in multi-temperature zone refrigerator, thus achieving a good automatic defrosting performance. (Cheng *et al*., 2008)
Zhou *et al*. (2014) conducted a design study on the principle and device of the heat storage defrosting cycle using compressor waste heat as the heat source, carried out relevant experimental verification on the air conditioner product, and found that the air conditioner has improved low temperature heat, defrosting time and comfort. Because of the special structure of the compressor heat storage tank, the compressor can be quickly started after defrosting in a low temperature environment, and the heating time is 3 minutes ahead of the ordinary machine. (Zhou *et al*., 2014)
Li *et al*. (2014) proposed a method of adding a miniature strong electric field ionization discharge device in the freezer of the refrigerator. The electrolyzed water generates hydroxyl radicals to kill bacteria and molds in the refrigerator, decompose the odorous substances that have been produced, and finally degraded to CO2、H2O and trace inorganic salts. This can greatly extend the storage time of food and provide a higher guarantee for food safety. (Li *et al*., 2014)
Xuan *et al*. (2015) sterilizes the air in the refrigerating chamber by installing an ultraviolet LED lamp in the refrigerator to purify the food storage environment (Xuan *et al*., 2015). Huang *et al*. (2002) photocatalytic film made on ceramics, after 30 minutes of UV irradiation, the sterilization rate of E. coli can reach 90%. (Huang *et al*., 2002)
Domestic and foreign scholars have studied refrigerator defrosting related process comprehensively. It can be seen from the research of refrigerator defrosting technology in recent years that the frost layer is one of the important factors affecting the performance of air-cooled refrigerators. However, the current research on refrigerator defrosting technology is mostly focused on the improvement of refrigerator defrosting control mode or heater position distribution. New defrosting methods are rarely proposed. It is attributed to the simple structure of the electric heating defrosting system in the existing defrosting methods, but its energy consumption is large and the safety is poor; Since the frost layer of the air-cooled refrigerator is on the evaporator in the air duct, the natural convection defrosting takes a long time, which will greatly increase the temperature in the refrigerator compartment and cause the freshness of food to decrease; The hot gas defrosting effect is good, but it increases the complexity of the refrigeration pipeline and reduces the system reliability; the ultrasonic defrosting power is small and does not affect the operation of the refrigeration system, but the ultrasonic generation equipment is added, and it is easy to cause secondary frosting in the drain hole. The hot gas defrosting effect is good, but it increases the complexity of the refrigeration pipeline and reduces the reliability of the system; the ultrasonic defrosting power is small and does not affect the operation of the refrigeration system, but the ultrasonic generation equipment is added, and it is easy to cause secondary frosting in the drain hole. Regarding the heat storage defrosting technology, it is currently mainly used in the winter operating conditions of air conditioners as a method of auxiliary thermal refrigerant defrosting. Although this method has a certain reference effect, due to the structural difference between refrigerators and air conditioners, its final application to refrigerator working conditions is not yet mature, so currently there is no energy-saving defrosting method that is very suitable for refrigerator working conditions to replace electric heating. And the current research on the sterilization of the inside of the air-cooled refrigerator is mainly to sterilize the storage room, so as to ensure the food storage environment. However, the evaporator and air duct of air-cooled refrigerators are narrow and airtight. The use of electro-defrosting efficiency is low and the temperature rise is large. Therefore, bacteria are easy to breed, which will contaminate the food in the refrigerator and seriously affect health. However, there are few studies on the sterilization of evaporators and air ducts at present.
This study designed a self-cleaning energy-saving healthy air-cooled refrigerator that uses natural wind defrosting and nano- TiO_2 coating sterilization. Experiments show that compared with ordinary air-cooled refrigerators, the refrigerator saves electricity 1.5% in cooling mode, 95% in defrosting process, 23% in frost reduction, and the freezing compartment temperature rises below 7 ℃ under the same working conditions. At the same time, the nano coating has a sterilization rate of 80%.

2. Workflow of self-cleaning energy-saving healthy air-cooled refrigerator

Modified the Shanghai Soy refrigerator (BCD268WEGV) as shown in Fig.1.

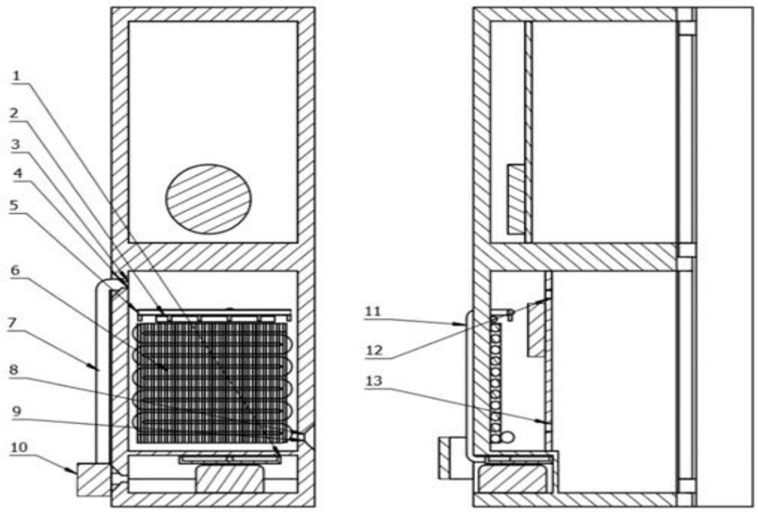


Figure 1: Self-cleaning energy-saving healthy refrigerator
1,Water pump & liquid tank;2,ultraviolet LED;3,Introducing natural wind throttles;4, Introducing natural wind tuyeres;5,spray device;6, Coating evaporator;7, Introducing natural wind duct;8, Leading natural wind throttles;9, Leading natural wind tuyeres;10, Fan;11, Water pipe;12, Circulating air inlet;13, Circulating air outlet.

2.1 refrigeration working flow

The refrigeration process of this refrigerator is the same as that of a normal air-cooled refrigerator. When cooling, 3, 8, and 10 in Fig.1 are closed, and the refrigerator transports the cooling capacity to the storage room under the driving of the original fan.

2.2 defrosting working flow

When defrosting, the compressor stops. 3, 8, and 10 in Fig. 1 are opened, so that the natural wind in the room passes through the compressor chamber under the driving of the fan. the wind passes through 7 and blows from 3, 4 to 6 to perform forced convection heat exchange. 6 has super hydrophilicity under the 2 irradiation, so that the water droplets attached to the surface of the evaporator are quickly flattened into a water film and slipped, and the defrost water is filtered back to 1 through the sieve. When the temperature sensor near the evaporator reaches 7 ℃, the defrosting operation ends, 3、 8 and 10 close, the compressor runs normally, and the refrigerator begins normal cooling.
When the frost on the fins cannot be removed within 20 minutes by relying only on natural wind defrosting, 1, 10 will be opened together. At this point, 1 extracts the auxiliary defrost reagent from the reservoir, pumps the reagent from 11 to 5 and sprays it onto the surface of 6 to achieve the auxiliary defrosting function. When the temperature of the temperature sensor near the evaporator reaches 7 ℃, 3 and 8 is closed, the compressor is started, the defrosting operation is finished, and the refrigerator starts to cool.
After the defrosting work is finished, the ultraviolet LED is turned off together.

3. Experimental apparatus and method

3.1 Experimental apparatus

As shown in Fig. 1, the project is modified for the Soy refrigerator (model: BCD 268WEGV), the modified refrigerator is used as the testing machine, and the unmodified refrigerator is the original machine. New equipment for the test machine includes two dampers, one pump, one ultraviolet LED, and one fan. The types and parameters of these items are as follows: FBZA-1750-6; AC220-240V and 4.5W; E14 and 5.5W; TD801512O1 and 8.5W.

The data acquisition system includes: temperature controller, humidity controller, thermocouple, temperature parameter collector, and power meter. Their specific models and related parameters are as follows: Seamanton UT35A and -5 ~ 60 ℃ ±0.3 ℃; Seamanton STH-TW1-RTH2 and 40% ~ 93% RH ± 3% RH; US Omega Φ0.3T type And ±0.5 ℃; ±0.1 ℃; 0.2-level single-phase electrical parameter measuring instrument 8710C and ±0.001W.

3.2 Experimental method

3.2.1 Measuring the characteristics of suppressing frosting

Under the condition that the indoor ambient temperature is 16 ℃, the refrigerator compartment load is 5.8 kg, and the freezer compartment load is 3.8 kg, the original machine and the test machine are all stopped after 5 hours of operation. After the frost layer on the evaporator surface is naturally melted, the volume of defrost water is measured.

3.2.2 Measurement of defrosting time and defrosting power

All testing procedures of this project are carried out in the Refrigeration Standards Laboratory of China Household Electrical Appliances Research Institute, and strictly comply with the relevant provisions of GBT 8509-2016. The temperature of the freezer compartment was set to -18℃, and the temperature of the refrigerator compartment was 4℃. In the experiment, the control variable method is adopted, the running time of the refrigerator (5h) is the same as the running load, and the experimental environment conditions are changed: 6℃ represents the winter indoor temperature (no heating area in winter), 16℃ represents the spring and autumn indoor temperature, and 32℃ represents the summer indoor environment temperature. At the same time, in order to increase the frosting amount and make the defrosting effect more obvious, 1L of 95℃ hot water was placed in the freezer compartment before the experiment to increase the humidity inside the refrigerator.

Under the above conditions, the defrosting time and defrosting power of this refrigerator under different ambient temperatures were measured. Among them, the flag for determining the end of the defrosting operation is that the middle surface of the evaporator reaches 7 ℃.

3.2.3 Measuring the characteristics of inhibiting bacteria

Because nano-TiO2 is bactericidal in the presence and absence of ultraviolet radiation, and ultraviolet light can effectively kill E. coli colonies[11-12]. Therefore, for Escherichia coli and Staphylococcus aureus, the following comparative tests were set up: ①aluminum plate coated with nano-TiO2 + ultraviolet irradiation;②aluminum plate coated with nano-TiO2 + no light; ③ordinary aluminum piece + ultraviolet irradiation;④ordinary aluminum Piece + no light.

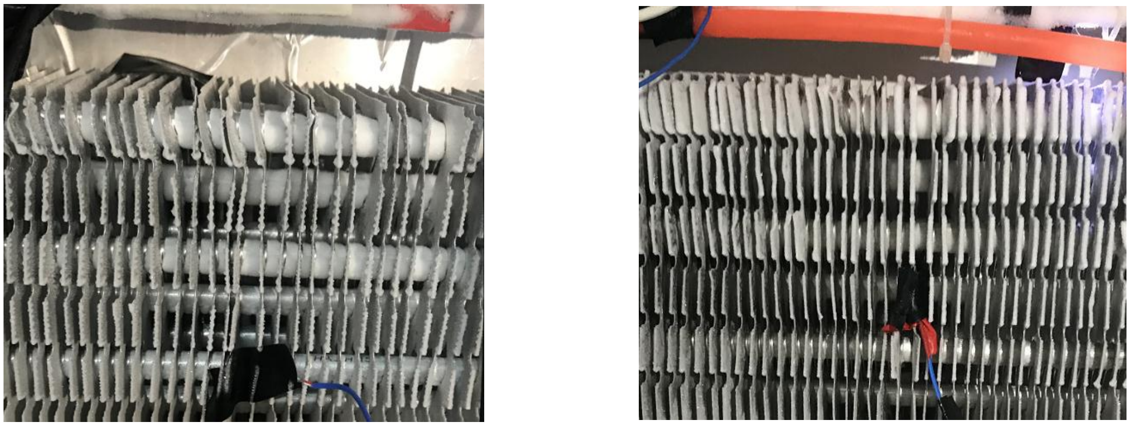
The above four groups of experiments were inoculated with the same concentration of E. coli and Staphylococcus aureus dilutions (each group consisted of 6 identical aluminum pieces, 3 of which were inoculated with E. coli and 3 were inoculated with Staphylococcus aureus). At 5 ℃, the experiments of ① and ③ after inoculation were irradiated with ultraviolet light for 7 min, and the experiments of ② and ④ were treated with no UV lamp for the same time. After incubation at a constant temperature for 20 h, the final colony growth was observed to compare the antibacterial ability of the aluminum sheets under different experimental conditions.

The above experiments were carried out under clean and sterile conditions.

4. Result and discussion

4.1 Analysis of frost suppression performance

After the original machine and the test machine were operated for 5 hours under the same working conditions, the frosting effect on the surfaces of the evaporator were as shown in Fig. 2. The frost layer on the surface of the original evaporator is dense, and obvious dendritic ice crystals appear on the top of the fins; the frost layer on the surface of the evaporator of the test machine is evenly distributed, the texture is loose, and the thickness of the frost layer is lower than that of the original machine. According to the relevant operation in 3.2.1, 57 ml of the original machine defrosting water and 44 ml of the test machine defrosting water were obtained.



a) Original machine b) Testing Machine

Figure 2: Frost on the surface of the evaporator

The comparison of the above figures shows that the nano-titanium dioxide coating can effectively reduce the amount of frost and improve the refrigeration efficiency of the refrigerator. The experiment obtained that the energy consumption of the uncoated healthy refrigerator was 0.483 KW ħ under the condition of 16 ° C, 5.8 kg of the refrigerator compartment load, and 3.8 kg of the freezer compartment load; under the same working conditions, The energy consumption of the coated healthy refrigerator is 0.376 KW ħ and the energy saving is 1.5%. The power recorded in the experiment is shown in Fig. 3.

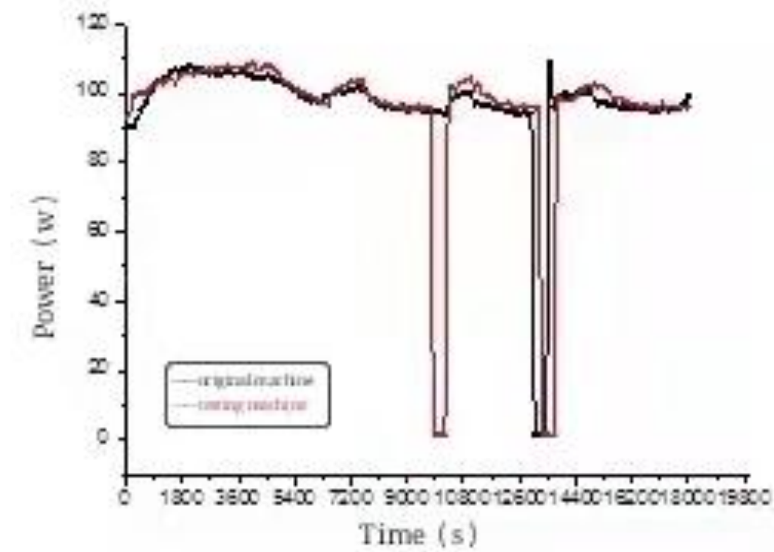


Figure 3: Power comparison chart

4.2The effect of natural wind defrosting

4.2.1The temperature of evaporator surface

As shown in Fig. 4, when the ambient temperature is 6 ℃, the surface temperature of the evaporator increases rapidly with time in the pre-defrost period, and the surface temperature fluctuates during the late defrost. When the defrost operation reaches 960s, the surface of the evaporator still does not reach 7 ℃. When the ambient temperature is 16 ℃, the surface temperature of the evaporator grows smoothly with time. When the defrosting work is carried out to 780s, the surface temperature of the evaporator reaches 7 ℃; when the ambient temperature is 32 ℃, the temperature increases rapidly, and the defrosting takes 150s. The evaporator surface reached 7.69 ℃.
From this, it can be concluded that the higher the ambient temperature, the shorter the defrosting time; the 7 ℃ and below is not suitable for natural wind defrosting alone.

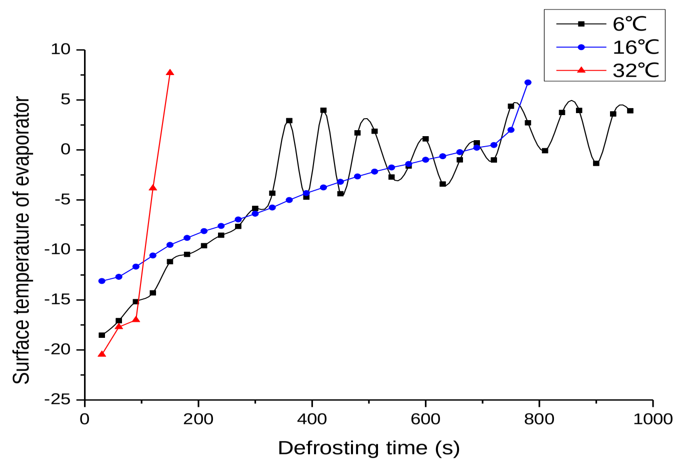


Figure 4: Surface temperature of evaporator

4.2.2The temperature of freezer compartment
It is experimentally found that the maximum temperature of the original electromechanical heating defrosting freezer is 11.7 ℃ when the ambient temperature is 16 ℃. When the ambient temperature is 6 ℃, 16 ℃, and 32 ℃, the maximum temperatures of the freezer compartments using natural wind defrosting are 3.79 ℃, 6.93 ℃, and -4.6 ℃, respectively, which are lower than the freezing chamber temperature when electric heating defrosting is used ,such as fig.5 shows. Therefore, the use of natural wind defrosting can effectively reduce the temperature rise of the freezer compartment during defrosting, and is more conducive to food storage than electric heating defrosting.

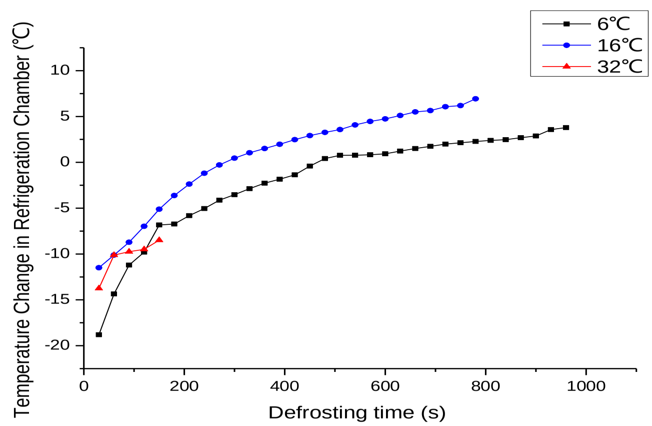


Figure 5: Freezer temperature change graph

4.2.3The energy consumption
At ambient temperature of 6 °C, 16 °C, 32 °C, natural wind defrosting and original electromechanical heating defrosting comparative experiments. Under the same running time, operating conditions and running load, the total time of the original electromechanical heating defrosting is 23min, including 13min electric heating, 10min shutdown, the total energy consumption of electric heating defrosting work is 183600J. Natural wind defrost at an ambient temperature of 6 °C, the energy consumption is only 4.4% of electric heating defrost, which can effectively reduce the energy consumption of electric heating defrost. The specific data is shown in Table 1.

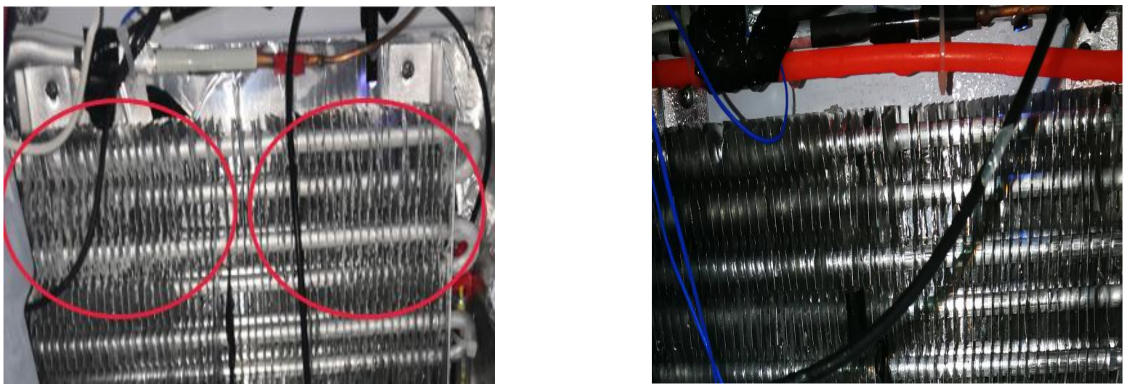
Table 1. Energy consumption of natural wind defrosting

Ambient temperature(℃)	**Defrosting time(min)**	**Energy consumption(J)**
6	16	8160
16	13	6630

32	2.5	1275

4.2.4The analysis of natural wind and auxiliary defrosting effect

According to the experimental standard of GBT 8509-2016, the experimental conditions are: ambient temperature is 16 °C, refrigerator compartment load is 5.8 kg, freezer compartment load is 3.8 kg, and the running time is 5 h. Under the experimental conditions, when the surface temperature of the evaporator reached 7 °C, the defrost was stopped, and the effect of the two refrigerators after defrosting was as shown in Fig. 6. After electric heating defrosting, there is residual frost layer on the surface of the evaporator, while natural wind defrosting is more thorough, and the surface of the evaporator is clean and has no frost layer.



a) Original machine defrosting renderings b) Defrosting effect diagram of testing machine

Figure 6: Effect picture after defrost

4.2.5The analysis of natural wind and auxiliary defrosting effect

When the ambient temperature is 6 ℃, only the natural wind defrosting time is long and the defrosting effect is poor. Taking the limitations of natural winds in low temperature environments into account, this refrigerator is designed with an auxiliary defrosting system. The following experiment was conducted to test the effect of the auxiliary defrosting system.

At an ambient temperature of 6℃, the natural wind defrost system and the auxiliary defrost system are simultaneously turned on, and the auxiliary defrost reagent is sprayed for 15 seconds and then turned off. The entire defrost operation took 8 minutes and the maximum temperature in the freezer was 1.4 ℃. Therefore, the auxiliary defrosting system can effectively solve the problem of poor defrosting effect by natural wind only in the low temperature environment, and improve the defrosting speed.

4.3 The analysis of bacteriostasis

According to 3.2.3, the number of colonies of E. coli and Staphylococcus aureus after different treatments is shown in Table 2 and 3.

Table.2 The number of E. coli colonies

group number	**aluminum plate coated with nano-TiO_2 + ultraviolet irradiation**	**aluminum plate coated with nano-TiO_2 + no light**	**ordinary aluminum piece + ultraviolet irradiation**	**ordinary aluminum Piece + no light**
1	1	5	2	13
2	0	4	1	12
3	1	5	1	9

Table.3 The number of Staphylococcus aureus colonies

group number	**aluminum plate coated with nano-TiO_2 + ultraviolet irradiation**	**aluminum plate coated with nano-TiO_2 + no light**	**ordinary aluminum piece + ultraviolet irradiation**	**ordinary aluminum Piece + no**

				light
4	1	6	2	5
5	1	5	3	7
6	2	5	2	8

As shown in Table 2 and 3, aluminum sheets coated with nano-TiO2 have good antibacterial properties under ultraviolet light. According to six experimental data, it can be seen that compared with ordinary aluminum sheets without any treatment, aluminum sheets with nano-TiO2 coating have an average decontamination rate of 80 % under ultraviolet light, which can effectively decompose bacteria and organic matter., not limited by the low temperature environment.

5. Conclusions

In this study, the effect of natural wind defrosting in air-cooled refrigerators at different season temperatures was adopted. The addition of nano-titanium dioxide coating on the surface of the evaporator to eliminate bacteria and frost was the innovation of this research. The auxiliary defrosting system solves the problem that the natural wind defrosting effect is not good when the indoor temperature is low. This study solves the problem of high energy consumption, low efficiency, long time, and elevated freezing room temperature when using electric heating defrosting. Experiments have shown that using this technology has the following advantages:

(1) Shorten the defrosting time. At 6 ℃, the natural wind and the auxiliary defrost system work together for 8 min. The natural wind defrost time is 13 min at 16 ℃, and the natural wind defrost time is 2.5 min at 32 ℃, while the average time of electric heating defrost is 23min.

(2) Saving defrosting power consumption. At 6 ℃, the natural defrosting power consumption of the natural wind and the auxiliary defrosting system is 4150J, the natural wind defrosting power consumption is 6630J at 16 ℃, and the natural wind defrosting power consumption at 12 ℃ is 1275J. The average defrost energy consumption of electric heating defrosting is 183600J.

(3) Reduce the amount of frost and reduce the energy consumption of refrigeration. After 5 hours of operation under the same working conditions, the energy consumption of the uncoated refrigerator was 0.483 KW ћ, and the energy consumption of the refrigerator after coating was 0.376 KW ћ, saving 1.5%.

(4) Antibacterial. In this study, a nano-titanium dioxide coating was added to the surface of the evaporator and irradiated with ultraviolet light. The average sterilization rate of the system was 80%.

(5) Ventilation and odor removal. The natural wind defrosting circulates the air inside and outside the refrigerator to reduce odor.

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