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Research on Quick-freezing Device with Ultralow Temperature Water Medium under Negative Pressure and Quick-freezing Method

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Abstract

This paper puts forward a quick-freezing method by putting the ultralow temperature medium into a negative pressure. Through the experiment, it indicated the speed and quality to refrigerating water under the condition of negative pressure. Based on that, it designed a quick-freezing device. Meanwhile this paper researched on how to quick-freeze products in bags by adopting this device. After being testified by the experiment, it proved that this device had improved the quick-freezing efficiency and the refrigerating effect.

Keywords: *negative pressure, ultralow temperature, quick-freezing method*

1. Introduction

According to the processing technology and quality requirement of frozen foods, frozen foods should have the following characteristics: the freezing temperature of frozen food should be below -30℃ or even lower; the ice crystal formation in the process of freezing food should be small, the size should be less than 100 microns; the time of generating through the maximum crystallization when food is frozen should not be exceeded 30 minutes[1]; the center temperature after food is frozen should be below -18℃; after the food is frozen, the circulation, including storage, transportation, sales and so on[2], the temperature of the above should be -18℃.Foods with the above characteristics at the same time can be called frozen food. As we know, frozen food industry in China was started in 1970's, which was mainly about the exported frozen meat, frozen seafood, vegetables and some other primary products. Low temperature freezing treatment can maintain the maximum color flavor of food as well as nutrition, which can inhibit microbial activity, so as to ensure the frozen food original taste and edible safety[3][4]. Moreover, a lot of frozen foods can be eatable only by microwave heating or by simple cooking, which is very convenient. In addition, the frozen food can control the content of fat, calories and cholesterol according to the different raw materials, so as to meet the needs of different consumers. Compared with the production cost of canned foods, its energy consumption is 30% lower, with high production efficiency as well. Owing to the characteristics of frozen food such as healthy and safe, convenient and delicious, with nutrition and low cost, the frozen food has developed rapidly both at home and abroad[5-6].

Through quick-freezing the food in bags, such as shrimps, meat, fish and others, as well as the pharmaceuticals, such as blood, seminal fluid and others, the quality could be kept to the maximum[7~10]. The principle of quick-freezing is transferring heat by

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adopting the medium convection or contact, which could transfer the heat energy from the frozen products quickly and lower the temperature rapidly. On account of the heat transfer in food and pharmaceuticals in bags is low in speed, the low-temperature cold store that takes cold air as medium is able to ensure low-temperature storage but with not good quick-freezing effect, people use fan to promote the cold airflow among frozen products for the sake of improving the quick-freezing effect[11]. Some people invent the method of heat transferring by contacting, which is putting the frozen products between the evaporator [12]. Also some people use quick-freezing evaporator to pre-refrigerate the quick-cold liquid, when it reaches to the target temperature of quick-freezing, put the food into refrigerator. Besides, some patents proceed with gradient ultrahigh pressure disposal according to the characters in various aquatic products, and do quick-freeze by coordinating with the variation of temperature [13-14].

The effect of heat transfer in the substance has close relationship with the heat transfer coefficient and temperature difference. The sequence of heat conductivity coefficients among water, ice and air is water＞ice＞air. Although the effect of heat transfer is good when take water as the medium, under normal pressures, the common liquid water will freeze under 0℃, it will lose fluidity and could not be preceded with convective heat transfer. In the meantime after the water turns into ice, the heat conductivity coefficient reduces, so normally people use heat water to unfreeze [15], rather than use cold water to quick-freeze. However, when put the water under negative pressure or into NaCl aqueous solution with certain concentration, it could maintain unfrozen under 0℃, it still has fluidity and could be preceded with convective heat transfer. In addition, along with the increase of vacuum degree or NaCl concentration, the temperature of freezing point to water will reduce. When the vacuum degree reaches to 10kPa, the water is still fluid under -25℃; when the NaCl concentration reaches to 35%, the freezing point to NaCl aqueous solution will reduce to -20℃. Such the big temperature difference between cold water or NaCl aqueous solution and the frozen products, together with the fluidity and large heat conductivity coefficient, as well as convective heat transfer could be realized, making it the ideal medium for quick-freezing [16-17].

All of the above-mentioned techniques are trying to reach the target of quick-freezing, but due to the cold air is slow in transferring heat, and the frozen products will be slower after being frozen, those measures are not perfect in improving the effect of quick-freezing[18]. Combined with the previous research results, this paper put forward the concept of freezing water medium of ultra-low temperature under negative pressure. Through the experiment, it proved that this method is feasible. Meanwhile a set of quick-freezing device of water medium with ultralow temperature was designed, and the refrigerating effect was improved indeed.

2. Experimental Research on Refrigerating With Ultralow Water Medium under Negative Pressure

Food freezing process exists great deal of heat conduction problems, no matter it is the spherical food, or slab shape food, the freezing process can be generally through the following three stages: the first stage, the temperature of the sample is decreased rapidly from the initial temperature until the surface temperature reaches the freezing point; the second stage, the phase transition occurs at the surface, from the outside surface to the inside center, so as to complete the phase change; the third stage, the temperature of sample continues dropping to the final frozen temperature[19]. The above freezing time of these three phases can correspondingly be included: Pre-cooling time, the time that the material consumed from the initial temperature to the freezing point; Freezing time, the consumed time that the water in the material is all frozen from the freezing point; Sub-cooling time, the consumed time that material is from the complete freezing temperature to the final frozen temperature. From this process, it can be seen that the surface of food is the first thing to complete being frozen, while the factor that influenced freezing time and freezing efficiency is mainly about making the center of frozen goods to achieve the target temperature[20-21].

It takes the common tap water as the research object. See the below Figure1 for the refrigerator, in this picture, there are closed container 4 and open container 6, inject 3L water into these two containers. 1 is the vacuum pump; adjust its pressure to 0.9MPa. The pressure gages that could monitor the changes of pressure are installed on the top of vacuum pump and closed container 4.

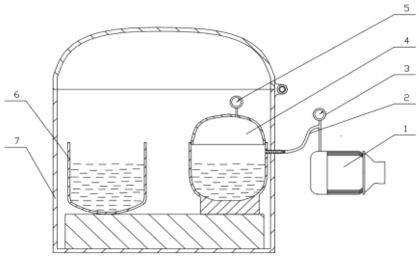

Figure 1. Experimental Schematic Diagram of Freezing with Ultra Low Temperature Water under Negative Pressure

After starting the vacuum pump, the pressure inside of closed container 4 will reduce gradually, in the meantime the temperature of water that is used during the experiment will reduce gradually. The variable values to the temperature could be recorded through the installed digital thermometer [22]. Table 1 is the temperature values recorded during the experiment.

Table 1. Temperature Values during the Experiment

Time（min）	Temperature inside of the refrigerator（℃）	Temperature inside of container 6（℃）	Temperature inside of container 4（℃）
0	6.0	13.0	13.0
15	-9.5	8.9	11.8
30	-12.5	5.1	10.3
45	-13.3	3.7	9.3
60	-14.9	1.9	7.3
75	-16	1.7	5.5
90	-16.8	0.4(starts to freeze)	4.2
105	-17.6	0.7	3.8
120	-17.5	0.8	3.1
135	-17.7	0.7	1.9
150	-18.1	0.7	1.2
165	-17.2	0.80.7	0.9（starts to freeze）
180	-17.7	0.7	0.7
195	-18.0	0.7	0.9
210	-17.8	0.7	0.7
225	-18.1	0.7	0.9
240	-17.9	0.7	0.7

From the above experimental data we can see, at the beginning stage , the temperature of container 4 and container 6 falls quickly, when time goes, the temperature of container 6 is decreased significantly faster than the temperature of container 4, after 90 minutes, it can reach the freezing temperature firstly [23]. After the frozen state is occurred, the temperature of container 6 can maintain the basic stability, namely 0.7℃, until the temperature of ice-chest reached the center temperature, namely, around -18℃. The reduction rule of temperature dropping inside container 4 is similar with container 6 ,however the temperature is decreased slowly, after reaching the freezing temperature, the temperature is also stable at 0.7℃, which shows the temperature distribution within container 4 is much even, the temperature difference between inside and outside of the frozen goods is smaller [24].

Seeing from this table, after putting the open container 6 and vacuum container 4 into a same refrigerator, the water in 6 is the first to start freezing (after 90 minutes past). The water in 4 starts to free until 165 minutes past, which explains that, the negative pressure could delay the time for freezing water. If adopt this method to freeze shrimp roe or other food, frozen time could be prolonged and refrigerating effect could be improved.

3. Freezing Method of Using Ultralow Temperature Water Medium under Negative Pressure and Developing Refrigerating Device

3.1. Introduction of the Device

Ultralow temperature refers to the scope of temperature ranging from -40～-80℃ during the process of food processing and industrial production. This temperature range is widely used in the frozen storage of high-grade aquatic products (such as tuna) , the storage and production of drug, the storage and processing of special food , the conservation of low temperature biology (such as the seed of rare species), as well as the performance test of electronic components in the low temperature. In addition, it can also provide the cold environment that is needed for testing properties of materials at low temperature, such as the low temperature impact test for pipeline welding at low temperature of ethylene liquefying device between -46～-58 ℃ and so on. The refrigeration methods of obtaining ultralow temperature in practice are mainly including two -stage compression refrigeration cycle, cascade refrigeration cycle and auto cascade refrigeration cycle system and so on. Among them, the cascade refrigeration is the mainly method to obtain the low temperature. The results showed that the different time intervals have different effects on the overall energy consumption of cascade system: the longer time interval can result in high grade road and waste a lot of energy; while the appropriate time interval can reach the high level loop energy consuming with moderate effect, which also can achieve the purpose of dropping the temperature of the low level loop rapidly; if it is in a short time interval, it needs to ensure that low temperature level can exhaust pressure in a safe range, otherwise it is not feasible to start in such short time interval.

Based on previous research, this paper put forward a quick-freezing device, which could produce ultralow temperature water, and do quick-freeze by taking the ultralow temperature water of constant circulation as medium. Meanwhile it proposed the quick-freezing method by using this device on food in bags, medicinal and pharmaceutical substances. The refrigerating device was designed as shown in Figure 2.

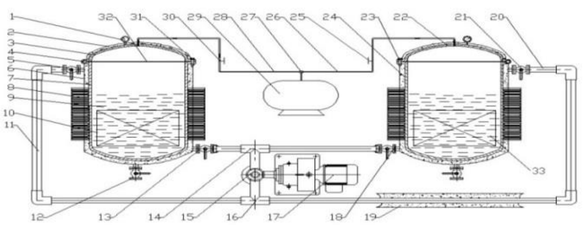

Figure 2. Schematic Diagram for the Quick-freezing Device with Ultralow Temperature Water Medium

1-pressure gage, 2-thermal-protective coating of the tank cover, 3-A tank cover, 4-hinge, 5-liquid inlet valve for A tank, 6-thermal-protective coating for tank’s body, 7-A tank body, 8-evaporator, 9-refrigerating liquid with ultralow temperature, 10-frozen product of the first bag, 11-liquid inlet pipe for A tank, 12-raffinate discharging valve, 13-liquid outlet valve for A tank, 14-the first T-branch pipe, 15-pump, 16-the second T-branch pipe, 17-motor, 18-fluid outlet valve for B tank, 19-thermanl-protective coating for the pipe, 20-fluid inlet pipe for B tank, 21-fluid inlet valve for B tank, 22- B tank cover, 23-lock bolt for B tank, 24- B tank body, 25-the second air valve, 26-the second exhaust tube, 27-T exhaust tube, 28-the first exhaust tube, 29-vacuum pump, 30-the first air valve, 31-lock bolt for A tank, 32-seal ring, 33- frozen product of the second bag

3.2. Operation Mode of the Device

This quick-freezing device with ultralow temperature water medium is mainly adopted the conclusions from above-mentioned experiments. Normally when the water temperature reaches to 0℃, the water will not flow or freeze. This device could allow the circulated water not get freezing under -20℃, thus ensure the optimal refrigerating effect inside of the container and improve the quality of the frozen products. The operating procedures are as follows.

a) Fill the refrigerating fluid (9) into B tank body (24), put the first bag product that waits to be froze (10) into A tank body (7), close A tank cover (3), lock and seal the A tank body (7) and A tank cover (3) with the lock bolt for A tank (31);

b) Open the first air valve (30), exhaust air from A tank body (7) by using vacuum pump (29) via the first exhaust tube (28) until reach to the vacuum degree 5kPa-80kPa;

c) Open the fluid inlet valve for A tank (5) and fluid outlet valve for B tank (18), close fluid outlet valve for A tank (13) and fluid inlet valve for B tank (21), start the pump (15). Pump the refrigerating fluid (9) into A tank body (7) until it fully submerges the frozen product in the first bag (10);

d) Open fluid outlet valve for A tank (13), close fluid outlet valve for B tank (18), self-circulate the refrigerating fluid (9) in the A tank body (7);

e) Open fluid outlet valve for B tank (18), close the fluid inlet valve for B tank (21), pump all of the refrigerating fluid (9) into A tank body (7), close the fluid outlet valve for B tank (18);

f) Open B tank cover (22), put the second frozen product in bag (33) into B tank body (24), close the B tank cover (22), lock and seal B tank body (24) and B tank cover (22) with lock bolt for B tank (23);

g) Open fluid inlet valve for B tank (21), pump the refrigerating fluid (9) into B tank body (24) until it fully submerges the frozen product in the second bag (33);

h) Open the fluid outlet valve for B tank (18), self-circulate the refrigerating fluid (9) in the B tank body (22), take away the heat of the frozen product in the second bag (33);

i) When the frozen product in the first bag (10) reaches to -5℃- -25℃, close the fluid inlet valve for A tank (5), open fluid inlet valve for B tank (21), pump all of the refrigerating fluid (9) into B tank body (24);

j) Stop exhausting air, loosen lock bolt for A tank (31), open A tank cover (3), take out the frozen product of the first bag (10), transfer it to preserve in refrigerating chamber under normal low temperature, put the new frozen product into A tank body (7);

k) When the frozen product in the second bag (33) reaches to -5℃- -25℃, close the fluid inlet valve for B tank (21), open fluid inlet valve for A tank (5), pump all of the refrigerating fluid (9) into A tank body (7);

l) Stop exhausting air, loosen lock bolt for B tank (23), open B tank cover (22), take out the frozen product of the second bag (33), transfer it to preserve in refrigerating chamber under normal low temperature, put the new frozen product into B tank body (24);

m) Circulate as per above-mentioned, when all of the frozen products that need to be froze have been finished frozen, pump (15) and vacuum pump (29) stop working, open the raffinate discharging valve (12), discharge the refrigerating fluid (9), close all of the valves.

The mentioned refrigerating fluid (9) is water or NaCl aqueous solution with mass percent 5%-35%.

3.3. Experiment and Result

Take procambarus clarkia in bag as the research object, fix the vacuum degree of the device to 20Ka, and carry out the experiment as per the above-mentioned procedures. Procambarus clarkia, also called crayfish, is China's traditional export aquatic food. The total national output in 2013 reached up to 60 tons, of which 2.7 tons were exported. 70% of the crayfish in the European markets came from China. Currently, crayfish is exported by transporting it in boxes after it is frozen quickly. The exported products of Procambarus clarkii are mainly including shelled shrimp and frozen shrimp. So far, the problems existed in the freezing technology are mainly as follows, such as the time of reaching freezing temperature is too long, the temperature of frozen center is decreased but the distribution of the frozen time is uniform, the energy consumption is high during the freezing process and so on. All these problems can cause the problem that the quality of frozen products is not high, which can bring great economic loss to food processing enterprises. In the process of quick-freezing, the temperature is strictly required, and the center temperature of the product is usually 15℃ below zero. The quality of the quick-frozen food depends on the freezing speed. When the food is being frozen, the shorter time it takes to generate the zone of maximum crystallization, the better the quality of the frozen food is. The frozen crayfish were provided by Hubei Laker Aquatic Products Co., Ltd. The average weight of the crayfish is about 30 grams, and the average body length is about 11cm. The processing flow for a whole crayfish is as shown in Figure 3.

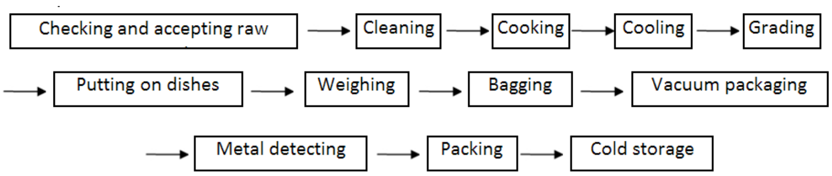

Figure 3. Schematic Diagram of the Processing Technology for Freezing Cooked Crayfish

Frozen goods will be treated as internal heat source, including sensible heat before freezing and after freezing latent heat and the sensible heat of the total cooling load, and thus calculate the cooling load per unit volume, namely the source term.

Frozen goods cooling load calculation formula:

$$q = \frac{G}{3.6T}\left[C_{hc}\left(t_1 - t_{hd}\right) + q_{dq} + C_{hd}\left(t_{hd} - t_2\right)\right] \qquad W$$

Internal heat source： $Q=\frac{q}{V} \quad (W/m^3)$.

where：

G —the number of goods， kg ；

T —freezing time of goods， h ；

C_{hc}, C_{hd} —heat capacity of frozen goods above / below freezing point of specific， $kJ/(kg\cdot°C)$ ；

t_1, t_2 —initial temperature and cooling end temperature of frozen goods， $°C$ ；

V —Single frozen goods volume， m^3 ；

Taking the above shrimp products as the experimental objects, making freezing experiments in the cold storage of Hua Zhong Agricultural University, during the process of experiment, we can monitor and record temperature, especially in the center of frozen food and other locations, we can have temperature monitoring and comparison. This experiment shows that the temperature distribution of frozen shrimp products is uniform by using ultralow temperature water device, which can overcome the problem of uneven freezing temperature and improve the quality of frozen shrimp products.

The results indicate that under -20℃, the water inside of the device is still in flow condition, which is not frozen. According to general refrigerating temperature standard for frozen food, when the center temperature to the frozen product reaches to -18℃, it reaches to the refrigerating effect. So this device has really improved the refrigerating quality and the freezing effect.

4. Conclusion

This paper put forward a quick-freezing device with ultralow temperature water medium and the method. Composing by two tank containers, pumps, valves, water pipes, vacuum pumps, air valves, exhaust pipes and others, this device reached to the quick-freezing effect through negative pressure or adding salt into water, reducing the freezing point of the water, producing ultralow temperature refrigerating fluid, making the ultralow refrigerating fluid circulate among the frozen products in bag. In the meantime this paper designed a quick-freezing device with ultralow temperature water medium, which could be used for quick-freezing cray, fish and other sea food, as well as the pharmaceutical products like blood. The experiment results showed this device was featured by quick-freezing and low energy consumption.

The proposal of this freezing method can solve the technical problems such as the uneven temperature of frozen products by using the common freezing method, the designed ultralow temperature water cooling device can be used for having freezing experiment on Procambarus clarkii and other common frozen foods, which also can bring innovation of technology for the frozen industry of shrimp products, so as to improve the frozen quality and frozen efficiency of shrimp products. Moreover, it also can improve economic benefits for shrimp products enterprises, especially shrimp exported enterprises.

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