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Performance test and numerical optimization of the golden Pomfret quick freezer

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Abstract. Liquid nitrogen (LN₂) quick freezer could make full use of most of latent heat and sensible heat of LN₂ to freeze food. Pomfret is prone to spoilage, which could be quickly frozen by LN₂ quick freezer after harvesting. In this paper, a LN₂ quick-freezer is designed to freeze the golden Pomfret by the cold N₂ at -80 °C and 1.5m/s. Test results of temperature field and velocity field show there is a good temperature uniformity in the freezer, and the velocity field can be more uniform and stable when a top baffle is adopted. The velocity field in the freezer is studied by CFD simulation with different deflectors installed at the top of the freezer. Simulation results show that most of the field have a uniform air volume with the arc deflectors, which can meet the requirements of the golden Pomfret quick freezing.

1. Introduction

Food quick freezing refers to the process in which food is rapidly frozen in a low temperature environment to make sure the cells form extremely small ice crystals and the cell tissue will not be damaged for preserving the raw juice and food aroma [1]. The quick freezer can quickly freeze food. Conventional quick freezers are cooled mechanically [2], whose temperature is generally above -30 °C. During the process of quick freezing, the air velocity should be controlled within a specific range and should not be too high (up to 20 m/s [3]). It is difficult to achieve vitrification of food cells. Grujic et al. stated that meat is best frozen at freezing rates more than 3.33 cm/h [4]. Bevilacqua et al. proved that in meat samples frozen with a characteristic freezing time (t_c) less than 23 min, intracellular ice crystals formed; whilst in samples with $t_c > 23$ min, they were intercellular [5]. Liquid nitrogen (LN₂) could be employed for food freezing [6], which could make full use of most of latent heat and sensible heat of LN₂ [1]. Temperature (temperature uniformity and control accuracy [7]) and velocity field are important parameters of the freezer. The golden Pomfret has very delicious meat [8], but its shelf life is very short and it is easy to deteriorate. The quality of golden Pomfret is reduced due to the action of microorganisms, external environment and enzymes during the circulation process. With the improvement of living standards, more attention is paid to the freshness of aquatic products [9]. The golden Pomfret cells can be quickly frozen with LN₂ quick freezing technology, so as to prevent the corruption and extend the shelf life. In this paper, a LN₂ quick-freezer was designed based on the quick-freezing process of golden Pomfret, which was tested on temperature and velocity field. The velocity field was optimized by installing different deflectors at the top of the freezer. The CFD simulation optimization and test results showed the quick freezer could meet the requirements of the golden Pomfret freezing.

2. Design of the quick freezer

According to the theory of “Food Polymer Science” (Schmidt and Marles [10], L. Slade and H. Levine [11]), water and aqueous solutions forms a glassy solid at a high freezing rate under the quick freezing process. Using cold N₂ as the medium, water in the fish cells can be frozen because of forced convection heat transfer. The following design of quick freezer based on the process parameters of the golden Pomfret quick-freezing.



2.1 Quick freezing process of golden Pomfret

Freezing rate is affected by the convective heat transfer coefficient, which is mainly determined by freezing temperature and velocity of cryogenic flow [3]. Experiments of the Pomfret frozen under different temperatures and N_2 velocity were made. The rate of freezing was calculated as the ratio of the distance from the surface to the food thermal center and the freezing period which elapsed from the moment when the surface temperature was 0°C until it reached -10°C in the thermal center [4]. The results of -80°C and 1.5 m/s are obtained, whose freezing curve is shown in Figure 1. The freezing rate is 3.64 cm/h ($>3.33\text{ cm/h}$ [4]) here. Meanwhile, the characteristic freezing time is 15 min ($<23\text{ min}$ [5]). Therefore, the golden Pomfret will be in good product quality after being frozen by the cold N_2 at -80°C and 1.5 m/s . This process parameters can be used as the design target of the quick freezer.

2.2 Structure design of the quick freezer

The refrigeration system including 4 parts (Figure 2): LN_2 tank, LN_2 transmission system, quick freezer and control system. The LN_2 transfer system connects LN_2 tank and the freezer, reducing cold energy loss with vacuum insulation technology. The freezer is made of double stainless steel with advanced insulating layers, where the golden Pomfret is frozen. Temperature and cooling can be controlled by the amount of LN_2 dispersed into the chamber. LN_2 flows into the distributor to disperse uniformly and then vaporize into nitrogen gas to exchange heat with the golden Pomfret under the role of fan rotation. In this way, freezer could make full use of most of latent heat and sensible heat of LN_2 . The relative hot nitrogen gas will be discharged to the atmosphere from the exhaust port [12].

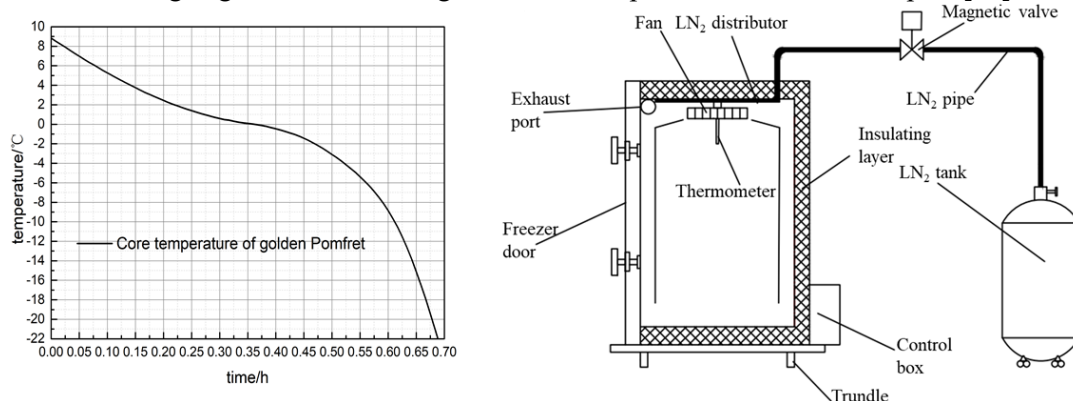


Figure 1. The freezing curve of the golden Pomfret **Figure 2.** Refrigerating system of the freezer

The structure of the freezing chamber is shown in Figure 3. A vortex fan is installed at the top of the freezer to circulate the cold N_2 . In order to make the flow field more uniform, the irregular quadrilateral deflector is installed at the top of the freezer, as shown in Figure 4. The freezing chamber size is $2 \times 1 \times 1\text{ m}$. The top fan spinning speed is 1400 r/min .

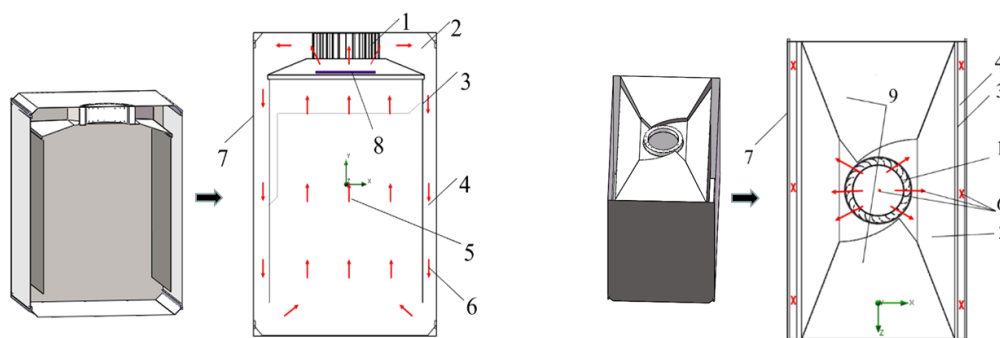


Figure 3. Internal structure diagram **Figure 4.** The deflector at the top of the freezer
(1-fan; 2-cold air outlet; 3-channel baffle; 4-side flow path; 5-freezing chamber; 6-cold air flow direction; 7-device housing; 8-top baffle; 9- deflector)

3. Performance test

Good temperature field and velocity field help avoid large variations in cooling rate between different parts of the freezer and leads to a more consistent product quality. The temperature field mainly includes two indicators: temperature uniformity and system temperature control accuracy. Good temperature uniformity and small temperature fluctuation can avoid cold shock to the golden Pomfret. High temperature control accuracy means that the temperature of the freezing chamber is sensitive and the temperature is more accurate [7]. Furthermore, only if the cold N_2 velocity in the freezing chamber is equal or greater than 1.5 m/s can the golden Pomfret be frozen quickly in good quality.

3.1 Performance test of temperature field

3.1.1 Temperature uniformity

The temperature was measured by the 9-point method. 9 points (C, T_1 , T_2 , T_3 , T_4 , D_1 , D_2 , D_3 , D_4) in the quick-freezer are shown in Figure 5. The left side is the freezer door. Place the PT100 probe at 9 points and connect the thermometer data terminal to the computer outside the freezing chamber. Run the quick-freezer, setting the temperature of the freezer as -80°C . After the freezing chamber reaches -80°C , record the temperature in the quick freezer for 30 min. The results shows that the temperature fluctuation range is $79.57\sim 82.50^\circ\text{C}$. Small temperature fluctuation and great temperature uniformity can satisfy the quick freezing requirement of the golden Pomfret.

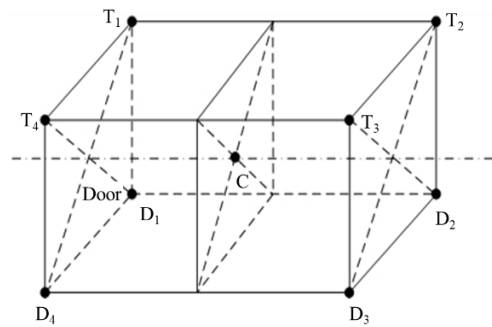


Figure 5. Distribution of 9 points for velocity and temperature measurement in the freezer

3.1.2 System precision test of the quick freezer

Table.1 System precision test results of the quick freezer

	Setting temperature / $^\circ\text{C}$	Standard temperature / $^\circ\text{C}$	Indicator temperature / $^\circ\text{C}$	Indication error
Thermometer system check	-80	-79.59	-80.10	-0.6
Recorder system check	-80	-79.59	-80.34	-0.75

The temperature measurement system accuracy requirement of the food freezer is $\pm 1.0^\circ\text{C}$ in the national standard [7]. Table 1 shows that the indication error: $|-0.6| < |\pm 1.0|$, $|-0.75| < |\pm 1.0|$. Therefore, the accuracy of the quick freezer meets the technical requirements.

3.2 Performance test of velocity field

In order to make the internal velocity field of the chamber more uniform, adding a top baffle under the air inlet of the fan was considered, as shown in Figure 3. The distribution of the velocity field in the freezer is measured with and without the top baffle respectively. The cold N_2 velocity was measured by the 9-point method, and the 9-point distribution was the same as in Figure 5. Place the anemometer probe at 9 points. Place the anemometer display outside the quick-freezer. The anemometer is calibrated in the standard wind tunnel calibration system before leaving the factory. After running the quick-freezer until the anemometer display being stable, read and average the velocity value at each point. The result is shown in Figure 6.

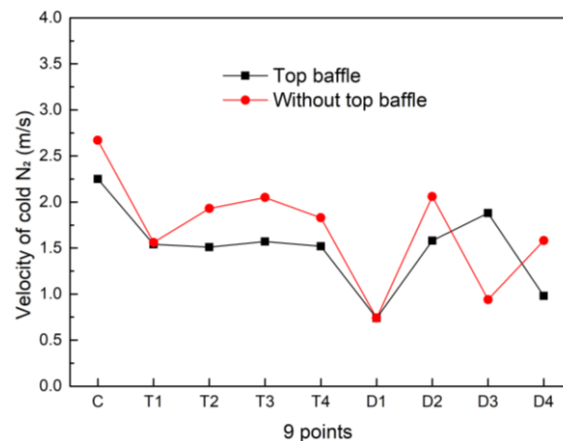


Figure 6. Cold N₂ velocity measurements at different positions of the quick freezer

According to the above data, the average N₂ velocity of the freezing chamber is 1.51 m/s and the variance is 0.1742 when there is a top baffle; the average velocity of the freezing chamber is 1.71 m/s and the variance is 0.3106 without the top baffle. Obviously, the velocity field is more uniform and stable when there is a top baffle. Most of the points meet the velocity requirements of the golden Pomfret frozen: the velocity of C, D₂, D₃, T₁, T₂, T₃ and T₄ are more than 1.5 m/s. It must be noted that cold N₂ velocity at points D₁ and D₄ is less than 1.5 m/s. Therefore, the velocity field inside the freezing chamber needs to be further optimized.

4. Quick freezer optimization

The key to optimizing the velocity field in the freezing chamber is the structural design of the deflector at the top of the freezer. The CFD simulation is used to calculate the velocity field when there is no deflector, irregular quadrilateral deflector, trapezoidal deflector and arc-shaped deflector. The CFD model is shown in Figure 3 and 4, including freezing chamber, a vortex fan, the deflector. The wall of the freezer regard as insulating. Energy conservation and N-S equation are taken into consideration. The velocity field near the inlet and outlet of the fan are shown in Figure 7.

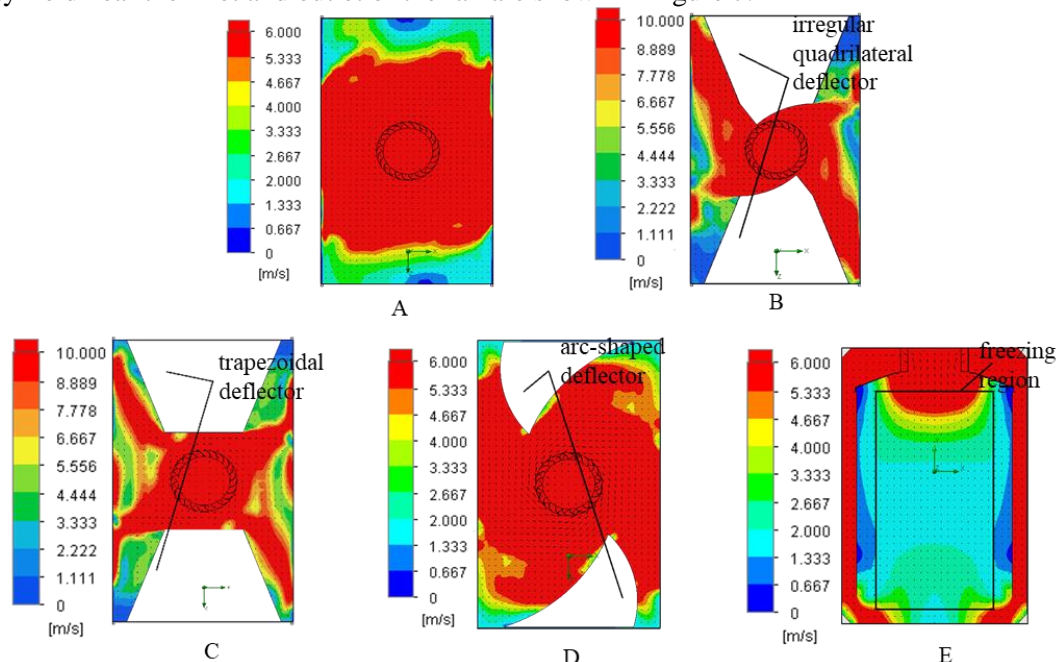


Figure 7. Velocity field near the inlet and outlet of the fan under different deflectors (A: no-deflector; B: irregular quadrilateral deflector; C: trapezoidal deflector; D: arc-shaped deflector; E: Freezing chamber velocity field under arc-shaped deflectors)

Following conclusions can be drawn from Figure 7. (A) The velocity uniformity is poor when there is no-deflector: the velocity tending to zero on upper left, lower left, upper right and lower right. (B) Result of the irregular quadrilateral deflector shows that N_2 is concentrated on the upper left and lower right. N_2 volume is little on the lower left and upper right, which leads to the N_2 velocity is less than 1.5 m/s at D_1 and D_4 consistent with the results of Table 2. (C) Trapezoidal deflector leads to velocity distribution is uneven near the inlet and outlet of the fan. (D) Most of the field have a uniform air volume when there are two arc deflectors relatively. Figure 7 (E) shows that the velocity field uniformity is better in the large freezing region of the freezing chamber under two arc deflectors. Therefore, the velocity field in the freezing chamber is more uniform under the arc deflector.

5. Conclusion

LN_2 quick freezer offers most of cold energy to freeze the golden Pomfret in high freezing rate. In this paper, a LN_2 quick-freezer was designed to freeze the golden Pomfret by the cold N_2 at -80°C and 1.5 m/s. Performance test on temperature and velocity field showed there was a good temperature uniformity ($79.57\sim 82.50^\circ\text{C}$) in the freezer. The velocity field was more uniform and stable when there was a top baffle. The velocity field in the freezer was simulated by CFD when different deflectors were installed at the top of the freezer. It tended to that most of the field had a uniform air volume when there were arc deflectors. Finally, the improved quick-freezer could quick freezing the golden Pomfret in good quality.

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Acknowledgments

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