

## Research Article

### Numerical Simulation of the Gas Flow Field in the Cold Storage and Freezing Process of *Procambarus Clarkii*

<sup>1</sup>Li Shuo, <sup>1</sup>Wang Shucai, <sup>2</sup>Cheng Fang and <sup>1</sup>Xia Gaobing

<sup>1</sup>College of Engineering, Huazhong Agricultural University, Wuhan 430070,

<sup>2</sup>College of Biosystem Engineering and Food Science, Zhejiang University, Hangzhou 310058, China

**Abstract:** The aim of this study is to find the temperature field distribution in cold storage and the influence factors of freezing time through the finite element technology. Taking an freezer in the laboratory as the research object, the inside flow environment was simulated by using the CFD simulation software, the unsteady numerical simulation of *procambarusclarkii*'s freezing process and frozen time were made simultaneously. Using this simulation method, the freezing process was simulated with different design parameters, the results show that there is an optimal fan position and supply velocity to make the cold storage has its best temperature field, so as to get the ideal frozen effect and frozen time. The research provides reference for optimization design of cold store.

**Keywords:** Frozen, numerical simulation, optimization design, *procambarusclarkii*

## INTRODUCTION

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 Li and Xie (2009). And proper air distribution in the freezing chamber can freeze faster and reduce energy consumption. According to the survey, currently the air distribution in most freezing rooms of cold refrigerators is improper or not proper enough. Due to the special physical environment in the freezing chamber, it is difficult to obtain the information of the freezing time for the food and the characteristic of the air distribution, but Computational Fluid Dynamics (CFD) can solve this problem. In China, Xie *et al.* (2005) have used the  $k-\epsilon$  model and the SIMPLE algorithm to conduct numerical simulation and experimental validation of the gas field in the refrigerator and obtained the regularity of the field distribution in the refrigerator. Sun *et al.* (2014) have studied air motion in the apple refrigerating chamber). In foreign countries, Moureh and Flick (2004) have conducted numerical computation and experimental validation of the flow field in the trailer loaded with goods with the FLUENT software.

However, little research has been done on the structure of the cold storage room for crayfish and its influence on the flow field both at home and abroad. Our research team cooperated with China's largest crayfish processing and export company Hubei Laker Aquatic Products Co., Ltd, obtained the parameters of the actual structure of the company's crayfish

refrigerator and designed the refrigeration test device for crayfish by using the resources of the aquatic product laboratory of Huazhong Agricultural University. In this study, we have used CFD to simulate the freezing process of crayfish and studied the influence of freezing conditions on freezing effect by changing freezing conditions.

## MATERIALS AND METHODS

**Physical model:** In this study, a certain refrigerator of Hubei Laker Aquatic Products Co., Ltd is the object of our study, whose internal dimensions (length×width×height) are 4.5×3×2.5 m and whose walls and door are made of polyvinyl chloride sandwich panels 0.15 m thick. There are two air coolers in the refrigerator, located diagonally at the bottom. The return air inlet is located at the back of the air cooler. The computational domain is the inner space of the refrigerator. The centrifugal fan is used to force air circulation. The order of Reynolds number magnitudes is about 106, which is turbulent flow and heat transfer in limited space (Xie *et al.*, 2005). There are three supporting poles in the refrigerator, which are left out for the purpose of simplifying the model. In order to simplify the calculation and make it convenient to do experiments, we use the freezing device in the laboratory to do experiments, whose dimensions (length×width×height) are 0.5×0.3×0.25 m. UG software is used for 3-D modeling. ANSYS software is used for mesh generating. The unstructured meshing

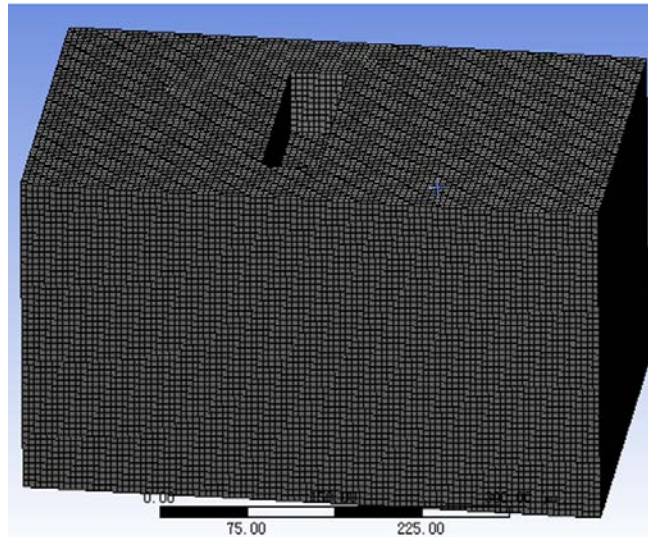


Fig. 1: The geometric model and meshing of the refrigerator

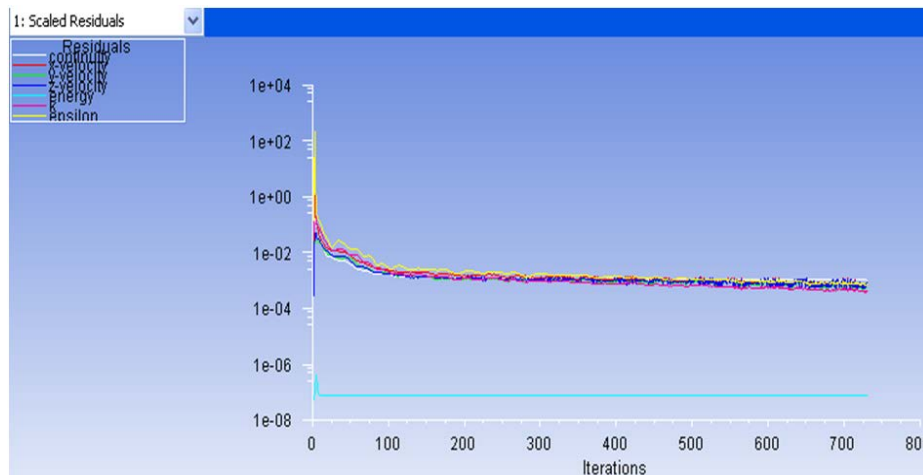


Fig. 2: The iterative curve

method is used. The mesh quality is less than 0.8 skewness, the geometric model and meshing of the refrigerator are as shown in Fig. 1 and 2.

**Mathematical model:** For the convenience of analog simulation, we make the following suppositions about the refrigerator to be studied (Yaohua *et al.*, 2012; Wang *et al.*, 2010):

- The supporting poles and pipelines have no influence on the flow field
- The air in the refrigerator is incompressible and conforms to Boussinesq supposition
- The gas in the refrigerator is Newtonian fluid
- The inner wall surface of the refrigerator is thermal insulation with good seal
- The air flow in the refrigerator is steady turbulent flow

According to the above conditions, we use the standard k-ε model and mature classical SIMPLE algorithm to simulate the air flow structure in the refrigerator and the general governing equation in the finite volume method in this study, whose simplified form is:

$$\text{div}(\rho u \phi) = \text{div}(\Gamma \text{grad } \phi) + S \quad (1)$$

where,

- ρ : Fluid density, kg/m<sup>3</sup>
- u : Fluid velocity vector, m/s
- φ : Generalized variable
- Γ : Generalized diffusion coefficient corresponding to φ
- S : Generalized source item corresponding to φ

For corresponding relations in different equations, see Table 1.

Table 1: The variables, diffusion coefficients and the source terms in each governing equation

Equation $\phi$ $\Gamma$	S
Momentum equation in X direction	$u \eta + \eta_t \cdot \frac{\partial p}{\partial x} + \frac{\partial}{\partial x} (\eta_{\text{eff}} \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y} (\eta_{\text{eff}} \frac{\partial v}{\partial x})$
Momentum equation in Y direction	$v \eta + \eta_t \cdot \frac{\partial p}{\partial y} + \frac{\partial}{\partial x} (\eta_{\text{eff}} \frac{\partial u}{\partial y}) + \frac{\partial}{\partial y} (\eta_{\text{eff}} \frac{\partial v}{\partial y})$
Momentum equation in Z direction	$\omega \eta + \eta_t \cdot \frac{\partial p}{\partial z} + \frac{\partial}{\partial x} (\eta_{\text{eff}} \frac{\partial u}{\partial z}) + \frac{\partial}{\partial z} (\eta_{\text{eff}} \frac{\partial v}{\partial z})$
Energy equation for turbulent flow K	$\eta + \frac{\eta_t}{\sigma_k} \rho G_k - \rho \epsilon$
Energy dissipation equation for turbulent flow $\epsilon$	$\eta + \frac{\eta_t}{\sigma_\epsilon} \frac{\epsilon}{k} (C_1 \rho G_k - C_2 \rho \epsilon)$
Energy equation	$T \frac{\eta}{\rho_r} + \frac{\eta_t}{\sigma_T} 0$

Table 2: The coefficients in the model

$C_\mu$	$C_1$	$C_2$	$\sigma_k$	$\sigma_\epsilon$	$\sigma_T$
0.09	1.44	1.92	1.00	1.30	0.9~1.0

In the table:

$$G_k = \frac{\eta_t}{\rho} \left\{ 2 \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 \right] + \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial w}{\partial x} \right)^2 + \left( \frac{\partial w}{\partial y} \right)^2 \right\}$$

$$\eta_{\text{eff}} = \eta + \eta_t; \eta_t = \rho C_\mu k^2 / \epsilon$$

where,

$v$  and  $\omega$  = Respectively the velocity vectors in the directions of X, Y and Z, m/s

$K$  = The turbulence energy,  $m^2/s^2$

$\epsilon$  = The dissipation rate,  $m^2/s^3$

$T$  = The temperature,  $^\circ\text{C}$

$\eta$  = The fluid dynamic viscosity,  $\text{kg}/(\text{m}\cdot\text{s})$

$\eta_t$  = The turbulent flow viscosity coefficient

The empirical constant in the model  $K$ - $\epsilon$  uses classic recommended value, Table 2.

### Boundary conditions and initial conditions:

According to the dimensions of the refrigerator, we can obtain its Reynolds number, which is over 105, so the model is a high Reynolds number turbulent model (James *et al.*, 2007). In the  $k$ - $\epsilon$  model, the flow is supposed to be complete turbulent flow, the effect of the molecular viscosity is ignored and the Reynolds number in the area close to the wall surface is very low, so it can be treated using the method of standard wall function. In order to simplify the model, we suppose: the initial temperature of the food is consistent, the density of the food does not change in the freezing process, each item of the food is of the same nature and the freezing temperature remains unchanged.

The velocity inlet conditions are used for the inlet, the turbulence intensity is set at 5%, the velocity at 3 m/s and the hydraulic diameter of every air inlet is 0.5 cm. The pressure outlet conditions are used for the outlet, thermal insulation walls are used and the goods are made into porous media. Our research focuses on the analysis of the freezing effect on crayfish.

Therefore, we analyze the goods in the refrigerator by taking them as a whole. Although the goods in the refrigerator are not objects that do not let air in, we can see from the researches of our predecessors that the air flow in the goods is very small, so we can deem the temperature of the storage box of the crayfish as the temperature of the crayfish bodies. 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.

## RESULTS AND DISCUSSION

**Numerical simulation:** In our research, we used ANSYS software to mesh the model and imported the meshing file to FLUENT software. When we analyzed and calculated the flow field in the refrigerator, we set boundary conditions and initial conditions according to the above-mentioned requirements and used difference control volume method to discrete the governing equation. We used SIMPLE algorithm to solve the equations of the velocity field and temperature field. The convergence precision of the energy equation is  $10^{-8}$  and that of the other equations is  $10^{-3}$ . The process of freezing food itself is a complicated process. It occurs within a certain temperature range not at a certain temperature. The definition of the freezing time that the International Institute of Refrigeration accepts is the time that it takes the food to be frozen from the initial temperature to the specified central temperature (Wang *et al.*, 2010). In our research, the initial temperature of the crayfish was  $15^\circ\text{C}$  and our calculation ended when the central temperature of the frozen crayfish body dropped to below  $-18^\circ\text{C}$ . The physical property parameters are the monomer density  $1300 \text{ kg}/\text{m}^3$ , specific heat  $3.5 \text{ kJ}/(\text{kg}\cdot^\circ\text{C})$  and the thermal conductivity  $0.5\text{W}/(\text{m}\cdot^\circ\text{C})$ .

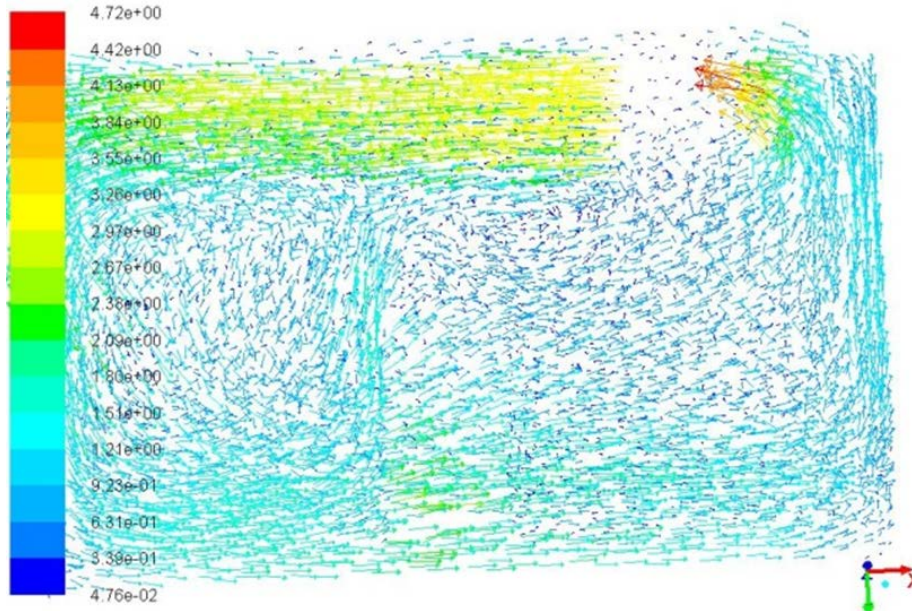
Shown in Fig. 3 for the cross section of the distribution of the velocity field, it can be more clearly seen the speed of the size of the direction changing law,

especially around the goods, revealed a typical swirling airflow distribution, it will transfer to temperature and the effects of frozen goods.

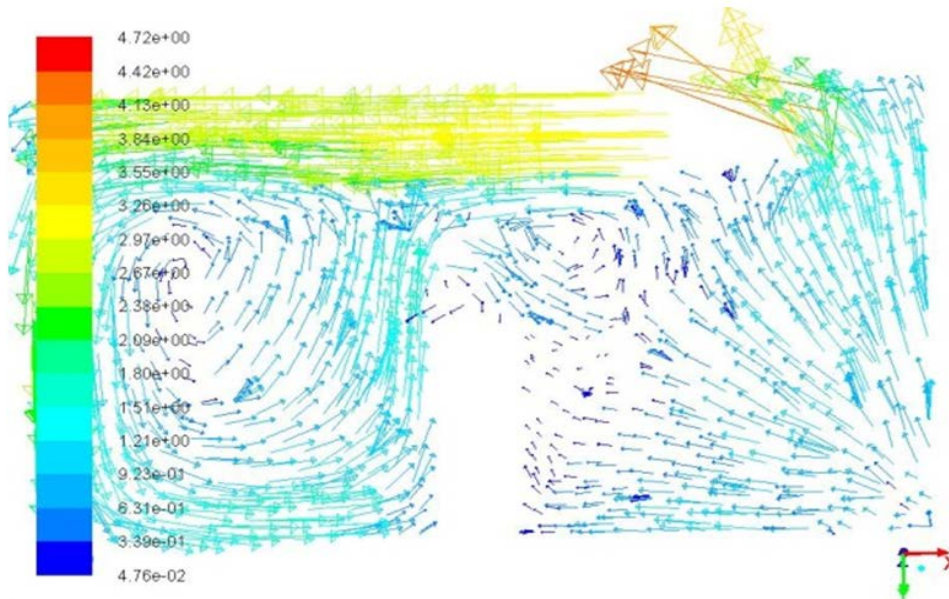
From the results of the study, goods have more influence on flow field of the cold storage of goods, simulation show that the swirl flow field, the whole flow field showed a trend of disorder, uniformity, the windward side wall of the goods kona significantly lower temperature, the goods the upper temperature is

lower, suggesting we have cold storage should be set in the storehouse board insulation, enlargement of the rolls of cold air flow, reduce the stay of the goods under the hot air.

The process of freezing crayfish is mainly convection heat transfer. The distribution of the airfield in the refrigerator determines the homogeneity of the temperature to a large extent. From Fig. 3, we can see that there are distinct rotational flow areas on both

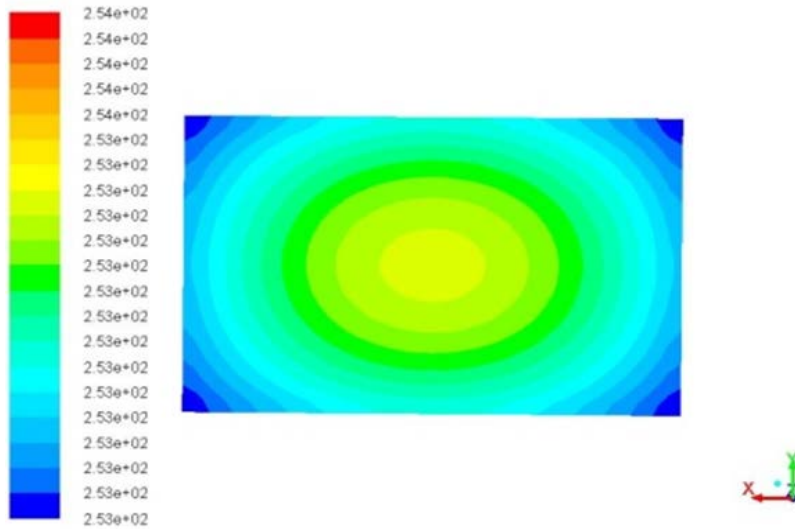


(a) The velocity field distribution over the cross section in the refrigerator

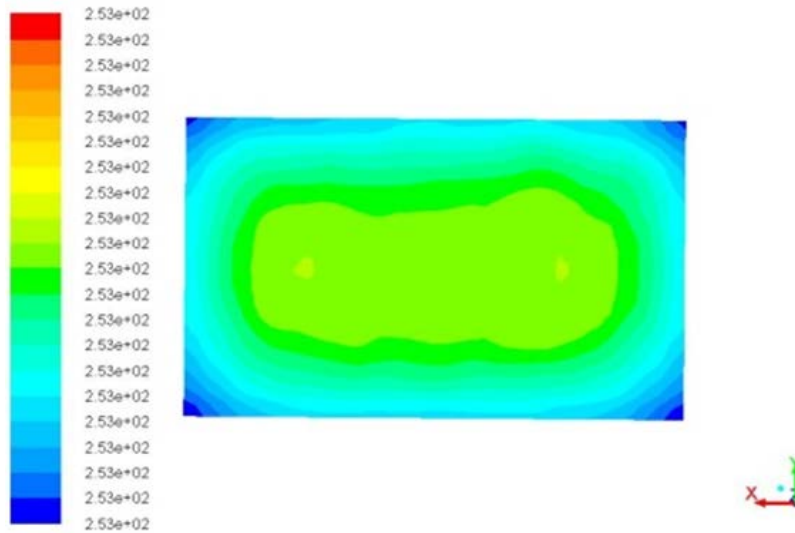


(b) The velocity field distribution over the longitudinal section in the refrigerator

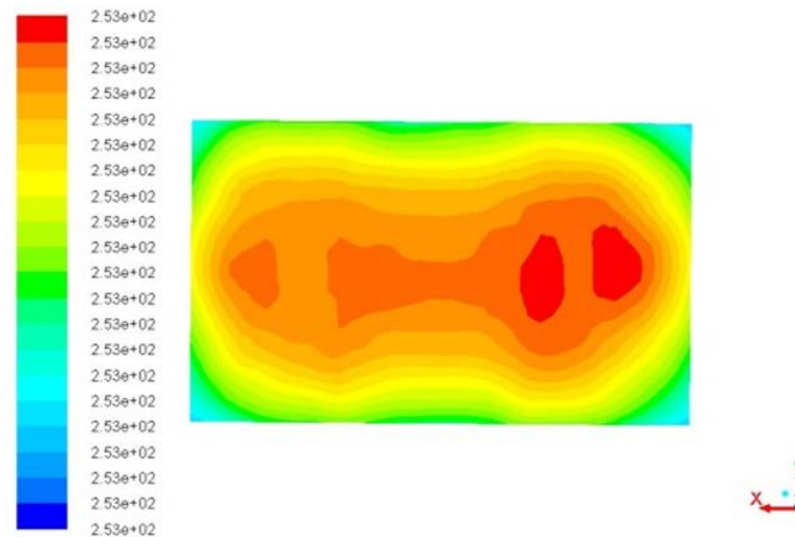
Fig. 3: The velocity field distribution in the refrigerator



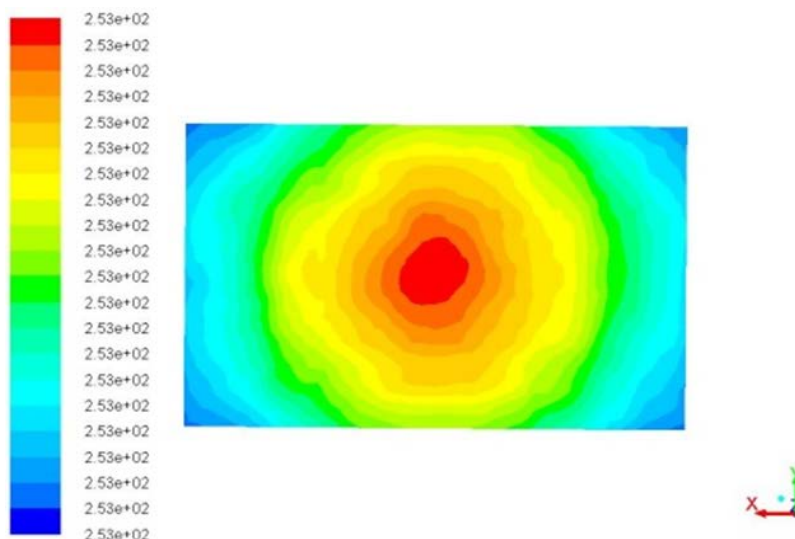
(a) Frozen to 100s



(b) Frozen to 400s



(c) Frozen to 1200s



(d) Frozen to 800s

Fig. 4: Temperature field on the longitudinal section when crayfish are frozen to 100, 400, 800 and 1200s

the cross section and the longitudinal section, which is determined by the locations of the fans and the air blowing angle. There is distinct wall flow on the four walls in the refrigerator. The wind blown out of the fans located in the two diagonal angles converge in the center. As the wind velocities and directions are different, distinct rotational flow is formed, which is consistent with the actual flow characteristic.

From Fig. 4, we can see that as there is drastic heat exchange when the crayfish begin to be frozen, the temperature drops significantly. When the freezing goes on, it becomes steady. After the crayfish are frozen to 1200s, we can see clearly that the freezing begin to extend from all around to the center. Thus ends the simulation of the freezing process.

**The influence of changing design parameter on the freezing time:** Based on the simulation of the actual freezing process in the company's refrigerator, we analyzed the influence of the fan locations and the air supply velocity on the freezing time of food by changing the locations of the fans and the air supply velocity in order to find the optimal freezing quality and freezing time.

Based on the model as shown in Fig. 1, by changing the speed of air blowing and respectively simulating temperature fields with wind velocities such as 5, 7 and 10 m/s, we know that the increase of the speed of air blowing can accelerate the freezing speed and reduce the freezing time. Moreover, with the increase of the speed of air blowing, the reduction of freezing time becomes steady, which is consistent with the conclusion of predecessors' researches, so we will say no more about it in this study (Li and Xie, 2009; Xie *et al.*, 2014).

Based on predecessors' research, supply air way, goods storage way and the speed of the supply air will

influence on cold storage, such as temperature and speed, but after simulation found that the speed of air supply generally have certain influence to refrigerate or freeze time, but has no effect on temperature field distribution of the basic. Therefore, in this case the results can be used for the actual operation, for the specific parameters of cold storage, behind the actual model is set up, in order to calculate the more accurate results, comparing the simulated data and experimental data shows a more accurate.

## CONCLUSION

We have learnt the rules of temperature field distribution and the rules of the freezing time of crayfish by conducting numerical simulations of the airflow field and the freezing process of crayfish in a specific refrigerator. We have found the ways to improve the freezing quality reduce freezing time and optimize the refrigerator by validating the results of analog computation by doing analog computation on freezing time again by changing some design parameters:

- The whole flow field is a large center recirculation region, backflow zone speed compared with the other area is small and its position is in the cold area of cold storage, the goods against the cold.
- There are close to the boundary of the flow in a flow trend of cooling fan inlet airflow have rise trend of convergence and then gradually spread. In addition, present in every corner speed decreases.
- A cold storage central district is the temperature of the goods storage area is not the lowest place, but rather on the high side, this related to condole type air supply way.

- The speed of air supply has certain influence to refrigerate or freeze time, but has no effect on temperature field distribution of the basic. Therefore, in this case the results can be used for the actual operation.

#### **ACKNOWLEDGMENT**

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