ISSN : 0974 - 7435 Volume 10 Issue 16

2014

BioTechnology
An Indian Journal

FULL PAPER
BTAIJ, 10(16), 2014 [9313-9320]

Numerical simulation and experimental validation of the freezing process of procambarus clarkia

Li Shuo[1*], Wang Shucai[1], Cheng Fang[2], Zou Shengbi[3], Xia Gaobing[1]
[1]Cllege of Engineering, Huazhong University, Wuhan 430070, (CHINA)
[2]College of Biosystem Engineering and Food Science, Zhejiang University, Hangzhou 310058, (CHINA)
[3]Hubei Lake Group, Qianjiang 433116, (CHINA)

ABSTRACT

Taking an actual freezer as the research object, the inside flow environment was simulated by using the CFD simulation software, the unsteady numerical simulation of procambarus clakii's freezing process and frozen time were made simultaneously. The results of simulation were verified by experiments, the results show that the simulation datas fitted the experimental datas well, the maximum temperature difference between the experimental data and the simulation results was 3℃. Using this simulation method, the freezing process was simulated again 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

Procambarus clakii; Frozen; Numerical simulation; Optimization design.

INTRODUCTION

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. 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[1]. 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 Jing et al have used the k-εmodel 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[2]. Sun Haiting et al have studied air motion in the apple refrigerating chamber[3]. Zhao Chunjiang et al have studied numerical simulation of spatial distribution of the temperature field inside the compartment of the refrigerator truck[4]. Guo Jiaming et al have studied the influence of the structure of refrigerated transport carriage on the flow field and stated that the flow field in the "differential pressure type" carriage is even[5]. In foreign countries， J.Moureh et al have conducted numerical computation and experimental validation of the flow field in the trailer loaded with goods with the FLUENT software[6]. Zertal-Menia et al have conducted numerical simulation of the air flow in the refrigerator truck and corresponding validation tests[7]. Rodriguez-Bermejoa et al have conducted analog computation and experimental study of the temperature field of the refrigerated container[8]. Chourasia et al have conducted two-dimensional simulations of the temperature field and airflow field in a potato cold storage in India and the water loss of the potatoes and the relative humidity in the storage[9].

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 article, we have used CFD to simulate the freezing process of crayfish, recorded the freezing time, used the test device to do corresponding validations, and studied the influence of freezing conditions on freezing effect by changing freezing conditions.

THE ESTABLISHMENT OF THE CFD MODEL

Physical model

In this article, a certain refrigerator of Hubei Laker Aquatic Products Co., Ltd is the object of our study, whose internal dimensions (length×width×height) are 4.5m×3m×2.5m, and whose walls and door are made of polyvinyl chloride sandwich panels 0.15m 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. Its structure is shown in Figure 1. 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[2]. 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 2.0m×1.5m×1.2m. UG software is used for 3-D modeling. ANSYS software is used for mesh generating. The unstructured meshing method is used. The mesh quality is less than 0.8 skewness.

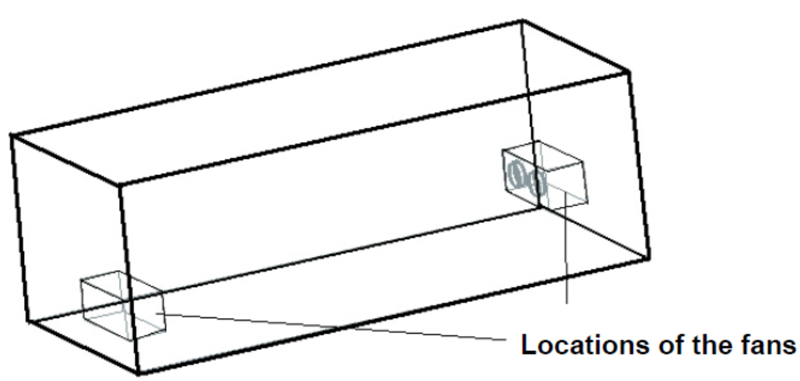


Figure 1: The geometric model of the refrigerator and the locations of the fans

Mathematical model

For the convenience of analog simulation, we make the following suppositions about the refrigerator to be studied[10,11]:

(1) The supporting poles and pipelines have no influence on the flow field;
(2) The air in the refrigerator is incompressible and conforms to Boussinesq supposition;
(3) The gas in the refrigerator is Newtonian fluid;
(4) The inner wall surface of the refrigerator is thermal insulation with good seal;
(5) The air flow in the refrigerator is steady turbulent flow.

According to the above conditions, we use the standard k-εmodel 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 article, whose simplified form is:

div (ρuφ)=div (Γgradφ)+S **(1)**

where, ρ—fluid density, kg/m^3 ; u—fluid velocity vector, m/s ; φ—generalized variable; Γ—generalized diffusion coefficient corresponding toφ; S—generalized source item corresponding toφ. For corresponding relations in different equations, see TABLE 1.

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

Equation	φ	Γ	S
Momentum equation in X direction	u	$\eta+\eta_t$	$-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\eta_{eff}\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\eta_{eff}\frac{\partial v}{\partial x}\right)$
Momentum equation in Y direction	u	$\upsilon\ \eta+\eta_t$	$-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\eta_{eff}\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial y}\left(\eta_{eff}\frac{\partial v}{\partial y}\right)$
Momentum equation in Z direction	ω	$\eta+\eta_t$	$-\frac{\partial_p}{\partial_z}+\frac{\partial}{\partial_x}\left(\eta_{eff}\frac{\partial_u}{\partial_z}\right)+\frac{\partial}{\partial_z}\left(\eta_{eff}\frac{\partial_v}{\partial_z}\right)$
Energy equation for turbulent flow	K	$\eta+\frac{\eta_t}{\sigma_k}$	$\rho G_k-\rho\epsilon$
Energy dissipation equation for turbulent flow	ε	$\eta+\frac{\eta_t}{\sigma_\epsilon}$	$\frac{\epsilon}{k}(C_1\rho G_k-C_2\rho\epsilon)$
Energy equation	T	$\frac{\eta}{P_r}+\frac{\eta_t}{\sigma_T}$	0

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

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

Where, v andω are respectively the velocity vectors in the directions of X, Y, and Z, m/s; K is the turbulence energy, m2/s2; εis the dissipation rate, m2/s3; T is the temperature, □; η is the fluid dynamic viscosity, kg/(m·s-1); η_t is the turbulent flow viscosity coefficient.

According to the general control equation $k-\varepsilon$, sources S_k and S_ε are defined as

Where:

$$S_k=\tau_{ij}^R\frac{\partial u_i}{\partial x_j}-\rho\varepsilon+\mu_t P_B$$

$$S_\varepsilon = C_{\varepsilon 1}\frac{\varepsilon}{k}\left(f_1\tau_{ij}^R\frac{\partial u_i}{\partial x_j} + \mu_t C_B P_B\right) - C_{\varepsilon 2} f_2 \frac{\rho\varepsilon^2}{k}$$

$$P_B = -\frac{g_i}{\sigma_B}\frac{1}{\rho}\frac{\partial\rho}{\partial x_i}$$

$$f_1 = 1 + \left(\frac{0.05}{f_\mu}\right)^3$$

$$f_2 = 1 - \exp\left(-R_T^{\ 2}\right)$$

$$\mu_t = f_\mu\frac{C_\mu\rho k^2}{\varepsilon}$$

$$f_\mu = \left[1 - \exp\left(-0.025R_y\right)\right]^2\left(1 + \frac{20.5}{R_T}\right)$$

$$R_T = \frac{\rho k^2}{\mu\varepsilon} \qquad R_y = \frac{\rho\sqrt{k}\,y}{\mu}$$

u_i ——the velocity components;

x_i 、 x_j ——coordinate component, m/s;

τ_{ij}^R ——reynolds stress tensor;

ρ ——fluid density, kg/m^3;

g_i ——the direction of axis acceleration of gravity, m^2/s;

μ ——dynamic viscosity coefficient, m^2/s;

y ——Wall distance, m;

k ——the fluid turbulence kinetic energy, m^2/s;

ε ——the ability of energy dissipation rate of turbulent flow, $m^2 \cdot s$;

$C_{\varepsilon 1} = 1.44$; $C_{\varepsilon 2} = 1.92$; $C_\mu = 0.09$; $\sigma_B = 0.9$; if $P_B > 0$, then $C_B = 1$, else $C_B = 0$.

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[14]. In the k-εmodel, 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.

The frozen crayfish were provided by Hubei Laker Aquatic Products Co., Ltd. The average weight of the crayfish is about 37 grams, and the average body length is about 13cm. The processing flow for a whole crayfish is as shown in Figure 2. As the crayfish is a multi constituent substance, which is generally composed of water, protein, fat, and carbohydrate, phase change will occur to the water during the freezing period and most water will change to ice crystals. Its physical properties will change to a certain degree[1]. Therefore, 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 10m/s, and the hydraulic diameter of every air inlet is 0.5cm. 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.

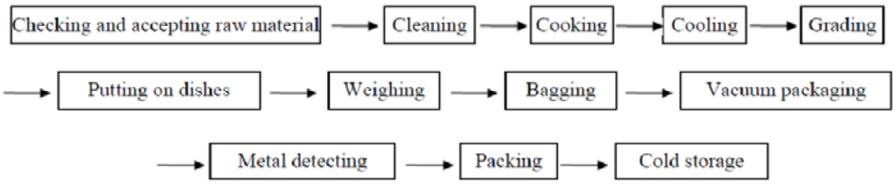


Figure 2: Schematic diagram of the processing technology for freezing cooked crayfish

Frozen goods Will be treated as 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:

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

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

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, $kJ/\left(kg\cdot°C\right)$;

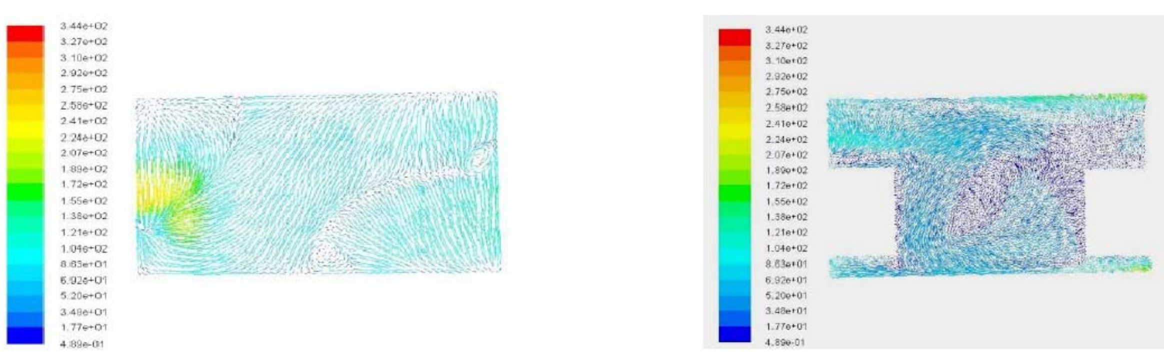
t_1, t_2 —initial temperature and cooling end temperature of frozen goods, $°C$;

V —Single frozen goods volume, m^3;

NUMERICAL SIMULATION AND EXPERIMENTAL VALIDATION

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}. When we did analog computation of the frozen products, we used unsteady analog computation and the time step was 0.5s. 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[15]. In our research, the initial temperature of the crayfish was 15□, and our calculation ended when the central temperature of the frozen crayfish body dropped to below -18□. The physical property parameters are the monomer density 1300kg/m^3, specific heat 3.5kJ/(kg·□), and the thermal conductivity 0.5W/(m·□).



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

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

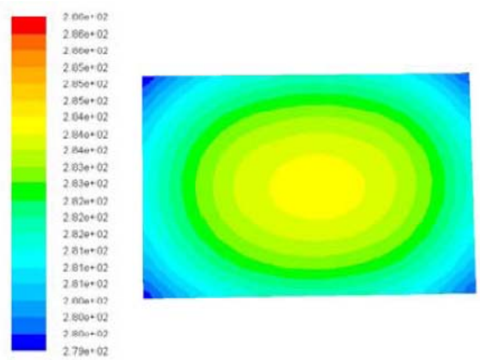
Figure 3: The velocity field distribution in the refrigerator

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 Figure 3, we can see that there are distinct rotational flow areas on both 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.

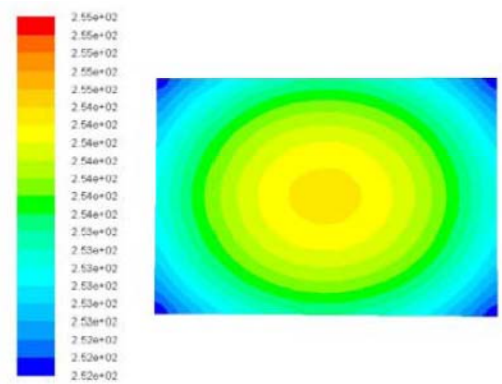
From Figure 4, we can see that as there is drastic heat exchange when the crayfish begin to be frozen, the temperature drops significantly. When the freezing goes on, it becomes steady. After the crayfish are frozen to 2000s, we can see clearly that the freezing begin to extend from all around to the center. When the crayfish are frozen to 5700s, the central temperature drops to -18□, a difference of about 2□ from the temperature all around. Thus ends the simulation of the freezing process.

Experimental validation

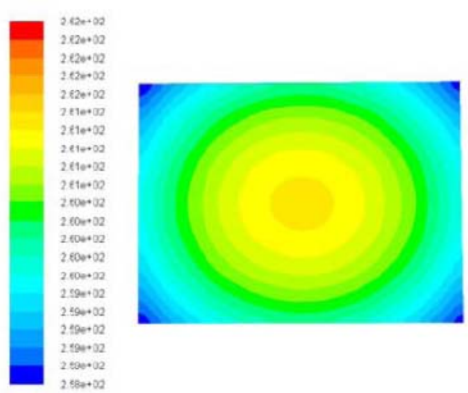
In order to decide whether the numerical simulation is correct, we have done validation experiments. We used embedded electronic display temperature detectors and anemometers, and chose five temperature measuring points, whose specific positions are shown in Figure 5. First, we measured the refrigerator in which the fans were located as Figure 1 shows and we obtained the following data: the center temperature was -19□, and it took 6400s for the center of the food to be frozen to -18□. Figure 6 is the contrast curve between the experimental value and the simulation value. The freezing time in the analog computation is 5700s. The maximum temperature difference at every stage of freezing is 4□. It proves that the simulation value and the experimental value match well.



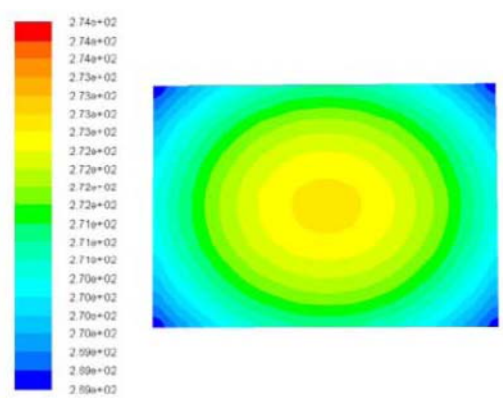
(a) Frozen to 500s



(b) Frozen to 2000s



(c) Frozen to 4000s



(d) Frozen to 5700s

Figure 4: Temperature field on the longitudinal section when crayfish are frozen to 500, 2000, and 5700s

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.

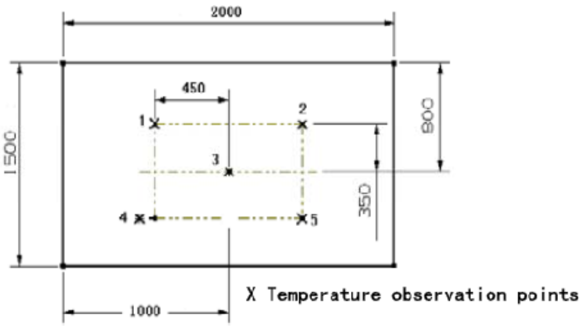


Figure 5: Positions of the temperature observation points

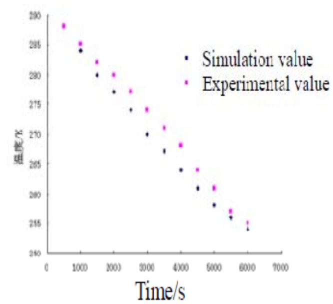


Figure 6: Comparison between exper imental data and simulation data

The influence of changing the air supply velocity on the freezing time

Based on the model as shown in Figure 1, by changing the speed of air blowing and respectively simulating temperature fields with wind velocities such as 5m/s, 7m/s and 10m/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 article[1,16], the results as shown in Figure7.

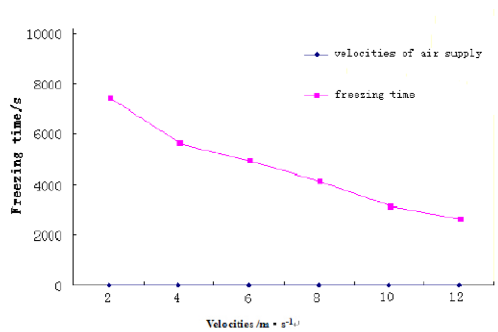
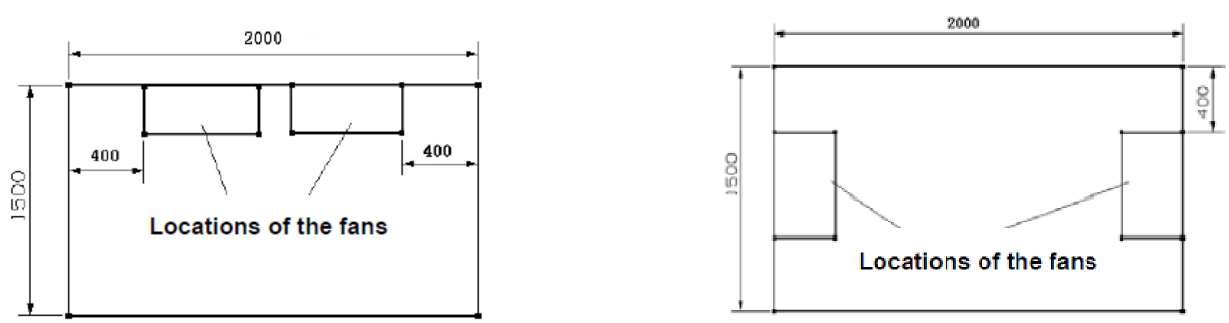


Figure 7: Freezing time under different velocities of air supply

The influence of changing the locations of the fans on the freezing time



(a) Putting the fans overhead **(b) Putting the fans in a bilateral symmetrical way**

Figure 8: Schematic diagram of changing the locations of the fans

As shown in Figure 8, the mounting positions of the fans of the same model are changed, but the other parameters such as the air supply velocity remain unchanged. We use the same method again as mentioned previously to conduct the numerical simulation and calculate the freezing time in the refrigerator and we obtain the freezing times 5980s and 5860s respectively. The results tell us that changing the locations of the fans will have a certain influence on the effect of freezing and the freezing time. The cause of the influence is the problem of homogeneous distribution of the airflow field in the refrigerator. According to the conditions of the practical object of our research, the original layout plan of the fans is proper. If we want to improve the freezing effect and reduce freezing time, we can consider optimizing airflow field.

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 in experiments and by doing analog computation on freezing time again by changing some design parameters.

(1) The results of the numerical simulation of the freezing process of crayfish with computational fluid dynamics technology matches very well with the results of our experiments, so this method can be used to calculate and predict the freezing time.

(2) Increasing air supply velocity is a main method of reducing freezing time, but to improve freezing quality, we need to consider the homogeneity of the frozen layers. Therefore, the proper air supply velocity for this refrigerator should be 8~10m/s.

(3) The fans were properly located, but some pipelines and supporting poles were arranged in disorder. We did not take these elements into consideration in our analog computation. Therefore, the air flow was actually not evenly distributed in the refrigerator. When we optimize the design, we may consider reducing supporting poles and the stocking way of leaving space in the center and both sides. In this way, we can make the temperature field in the refrigerator distributed evenly and ensure the rapid freezing of all the goods.

ACKNOWLEDGEMENT

National “twelfth five-year” science and technology support plan (Number: 2012BAD29B04-4).

REFERENCES

[1] Li Jie, Xie Jing; Numerical simulation of freezing time of shelled shrimps in an air blast freezer and experimental verification[J], Transactions of the CSAE, **25(4)**, 248-252 **(2009)**.

[2] Xie Jing, Qu Xiaohua, Xu Shiqiong; Numerical simulation and verification of airflow in cold-store[J]. Transactions of the CSAE, **21(2)**, 11-16 **(2005)**.

[3] Sun Haiting, Zhou Ke, Yang Yanqing et al.; Airflow simulation in apple cold storage using CFD model[J], Storage and Process, **14(4)**, 27-33 **(2014)**.

[4] Zhao Chunjiang, Han Jiawei, Yang Xinting et al.; Numerical simulation of temperature field distribution in refrigerated truck based on CFD, Transactions of the Chinese Society for Agricultural Machinery, **14(4)**, 27-33 **(2014)**.

[5] Guo Jiaming, Lu Enli, Lu Huazhong et al.; Numerical simulation of effects of transport enclosure structure on flow field[J], Transactions of the CSAE, **28(1)**, 74-80 **(2012)**.

[6] J.Moureh, D.Flick; Airflow pattern and temperature distribution in a typical refrigerated truck configuration loaded with pallets[J], International Joural of Refrigeration, **27(5)**, 464-474 **(2004)**.

[7] N.Zertal-Menia, J.Moureh, D.Flick; Simplified modelling of air flows in refrigerated vehicles [J], International Journal of Refrigeraion, **25(5)**, 660-672 **(2002)**.

[8] J.Rodriguez-Bermejoa, P.Barreirob, J.I.Roblaa et al.; Thermal study of a transport container[J], Journal of Food Engineering, **80(2)**, 517-527 **(2007)**.

[9] M.K.Chourasia, T.K.Goswami; Steady state CFD modeling of airflow, heat transfer and moisture loss in a commercial potato cold store [J], International Journal of Refrigeration, **30**, 672-689 **(2007)**.

[10] Hu Yaohua, Jiang Guozhen, Xiong Laiyi; CFD simulation of the flow field in the kiwi fruit cold storage[J], Journal of Agricultural Mechanization Research, **5**, 155-159 **(2012)**.

[11] Wang Yizhong, Hu Chunyuan, Chen Shaohui et al.; Numerical simulation research of Refrigerator temperature field and humidity field in cold-storage[J], Storage and Process, **58(10)**, 26-29 **(2010)**.

[12] Yu Yong, Zhang Junming, Jiang Liantian; Fluent Beginner and Advanced Course [M], Beijing: Beijing Institute of Technology Press, 9 **(2008)**.

[13] Tao Wenquan; Numerical Heat Transfer (2nd Edition) [M], Xi'an: Xi'an Jiaotong University Press, 347-360 **(2002)**.

[14] S.J.James, C.James, J.A.Evans; Modeling of food transportaion systems-a review [J], International Journal of Refrigeraion, **29(6)**, 954-957 **(2007)**.

[15] Cheng Fang, Yang Xiaomei, You Zhaohong et al; Application of numerical simulation in the research of food freezing process[J], Transactions of the Chinese Society for Agricultural Machinery, **45(7)**, 162-170 **(2014)**.

[16] Xie Jing,Miao Chen, Du Zizheng et al.; Numerical simulation and parameter optimization on performance of air curtain in cold stores[J], Transactions of the Chinese Society for Agricultural Machinery, **45(7)**, 190-195 **(2014)**.