

Simulation of the Tuna Freezing Process and Evaluation of Factors Influencing the Freezing Time of the Tuna

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Hoang Thi Nam Huong
Faculty of Mechanical Engineering
Ho Chi Minh City of Technology
Ho Chi Minh City, Viet Nam
nanxiang76@yahoo.com

Do Huu Hoang*
Faculty of Chemical Engineering
Ho Chi Minh City University of
Industry and Trade
Ho Chi Minh City, Viet Nam
hoangdh@huit.edu.vn

Vo Van Sim
Faculty of Chemical Engineering
Ho Chi Minh City University of
Industry and Trade
Ho Chi Minh City, Viet Nam
simvv@huit.edu.vn

Abstract— This paper presents the simulation of the tuna freezing process by using ANSYS software. Based on simulation results, factors affecting the freezing time including air velocity and freezing temperature were determined. Within the air velocity range $\omega = (5 \div 15) \text{ m.s}^{-1}$, an increase in the velocity by $\nabla\omega = 1 \text{ m.s}^{-1}$ led to a decrease in the freezing time by $\nabla\tau = (7.2 \div 2.3) \%$. When the freezing temperature was reduced by $\nabla t_e = 1 \text{ K}$, the freezing time was reduced by $\nabla\tau = (3.2 \div 2.5) \%$ in the freezing temperature range $t_e = (-35 \div -45) ^\circ\text{C}$.

Keywords— Ansys, finite element, heat transfer, phase transformation, simulation, temperature, tuna, velocity

I. INTRODUCTION

Tuna (also known as humpback fish) is a large fish belonging to the family Scombridae, mainly of the genus *Thunnus*, living in warm waters, about 185 km from shore. With a coastline of over 3,260 km and an exclusive economic zone of over 1 million km^2 , the marine resources of Vietnam's waters are considered to be very rich and diverse, with more than 2,000 marine species. Group of pelagic fish, mainly tuna species: frigate mackerel, bullet tuna, eastern little tuna, longtail tuna, skipjack tuna, yellowfin tuna, bigeye tuna... The estimated annual catch of yellowfin and bigeye tuna is 30.5 thousand tons; the skipjack and inshore tuna group is 313 thousand tons [1].

Tuna is a species of high economic value and dominates in the production of marine species in Vietnam. In the period (2017 - 2023), tuna has been one of Vietnam's key export seafood products. Tuna export value increased 42% from 593 million USD to 845 million USD. The proportion of tuna in Vietnam's total seafood exports has always remained at 10 - 20%. The main exported tuna species of Vietnam include yellowfin tuna, bigeye tuna, skipjack tuna... In 2023, Vietnam's tuna products were exported to 109 countries around the world. In particular, the US, Israel, Italy, Canada, Japan, Germany, Thailand, Russia, the Netherlands, and the Philippines were the 10 largest tuna import markets of Vietnam, accounting for more than 73% of the total export value [1].

The tuna quality is determined not only by the offshore fishing but also by the freezing stages which greatly affect the deliciousness, the nutritional content of meat products, and energy consumption during the freezing process. Hence, the processes of freezing tuna are very important, especially the freezing process. In Vietnam, however, there has not been in-depth research on the freezing process of tuna after offshore

fishing when most food freezing systems are designed for general applications but not for a particular product. Therefore, the energy efficiency is not high and the product quality is not stable, the product loss can be as large as nearly 20%. As mentioned above, this is an urgent practical problem that has not been addressed adequately. In this context, this study focused on the evaluation of factors influencing the tuna freezing time based on the simulation results thereby providing the basis for building a reasonable freezing process in terms of energy consumption and improvement of product quality.



Fig. 1. Tuna before freezing

II. MATERIALS AND METHODS

The freezing process is extremely complicated with several phenomena occurring at the same time, including heat transfer, mass transfer, phase change, mechanical property change, and so on. Especially at the freezing point, the thermal and physical properties of the fish (specific heat c , thermal conductivity λ , density ρ , and thermal diffusivity a) change abruptly, making the nonlinear differential equation describing the process extremely difficult to solve.

In this paper, we utilize the finite element method to solve the heat conduction problem with phase change to determine the freezing time in various modes [4]-[9]. Based on the determined freezing time, carry out a detailed assessment of the factors influencing the freezing time and construct a regression equation to establish the relationship between the freezing time and the factors.

A. Material information

Tuna samples are box-shaped and have specific dimensions, as shown in Table I and Fig. 2 [2].

TABLE I. TUNA FILLET GEOMETRICAL PARAMETERS

No.	Mass (g)	Thickness δ (mm)	Width W (mm)	Length L (mm)
1	256.5-313.5	19-21	100-110	220-230

Fonte: Data collected from factories [2]

Tuna is frozen on IQF with the following working parameters as Table II.

TABLE II. THE WORKING PARAMETER RANGE OF IQF

No.	Parameter	Working range
1	Air Temperature t_e (°C)	(-45÷-35)
2	Air velocity ω (m.s ⁻¹)	(5÷15)

Fonte: Data collected from factories [2]

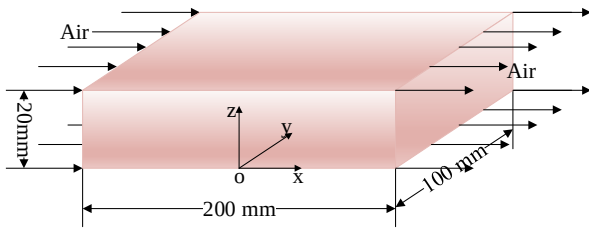


Fig. 2. Physical model of the block-typed tuna freezing process

B. The product's thermal properties

The composition of the Tuna sample (%) identified at the Service Center for experimental analysis in Ho Chi Minh City could be as follows: 0.64 % Fat; 71.9 % water; 23.9 % Protein; 1.98 % Carbohydrates; 0.0% Sugar; 1.58 % Ash.

The specific heat, thermal conductivity, and density of the Tuna (between $t = (-40\div40)$ °C) were considered dependent on temperature and composition. According to Ref. [10], the density of the product $\rho(t)$ was calculated according to Eq. (1).

$$\rho(t) = \frac{1}{\sum_{i=1}^n \frac{x_i^w}{\rho_i}} \quad (1)$$

In 1981, Levy proposed the following model expression Eq. (2) for the thermal conductivity of a two-component system [11].

$$\lambda = \frac{\lambda_2 [(2 + \Lambda) + 2(\Lambda - 1)F_1]}{(2 + \Lambda) - (\Lambda - 1)F_1} \quad (2)$$

Where Λ is the thermal conductivity ratio ($\Lambda = \lambda_1/\lambda_2$), λ_1 is the thermal conductivity of component 1, and λ_2 is the thermal conductivity of component 2. The parameter F_1 introduced by Levy is given as follows in Eq. (3).

$$F_1 = 0.5 \left\{ \left(\frac{2}{\sigma} - 1 + 2R_1 \right) - \left[\left(\frac{2}{\sigma} - 1 + 2R_1 \right)^2 - \frac{8R_1}{\sigma} \right]^{0.5} \right\} \quad (3)$$

Where:

$$\sigma = \frac{(\Lambda - 1)^2}{(\Lambda + 1)^2 + \frac{\Lambda}{2}} \quad (4)$$

and R_1 is the volume fraction of component 1, or

$$R_1 = \left[1 + \left(\frac{1}{x_1} - 1 \right) \left(\frac{\rho_1}{\rho_2} \right) \right]^{-1} \quad (5)$$

Here, x_1 is the mass fraction of component 1, ρ_1 is the density of component 1, and ρ_2 is the density of component 2.

The specific heat of the Tuna was estimated using the following Eq. (6) Schwartzberg (1976) [12]:

$$c_p = c_{pu} + (bX_s - X_{wo})\Delta c_p + EX_s \left(\frac{Rt_0^2}{18(t_0 - t)^2 - 0.8\Delta c_p} \right) \quad (6)$$

Where t is the temperature of the food product (°C); so is the freezing point of water (°C); R is the universal gas constant; Δc_p is the difference between specific heats of water and ice (J.kg⁻¹.K⁻¹); CPU is the specific heat of food above its initial freezing point; b is the amount of unfrozen water per unit weight of solids; X_s is the mass fraction of solids per unit weight of food; X_{wo} the mass fraction of water per unit weight of food above the initial freezing point; E is the molecular weight ratio of water (M_w) and food solids (M_s).

$$E = \frac{M_w}{M_s} = \frac{18}{M_s} \quad (7)$$

According to Ref. [13], the convection coefficient, α , can be approximated by either of the following Eq. (8).

$$\alpha = 25(\omega)^{0.6}, (W.m^{-2}.K^{-1}) \quad (8)$$

Where ω is the air velocity (m.s⁻¹)

Calculation results of the thermophysical properties of Tuna are shown in Fig. 3 (a,b,c).

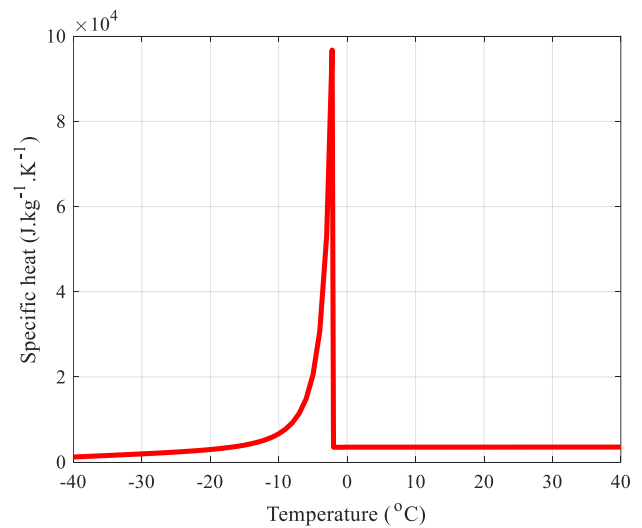
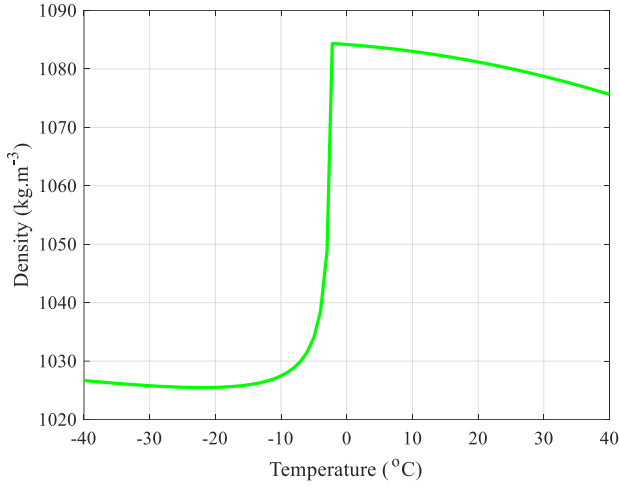
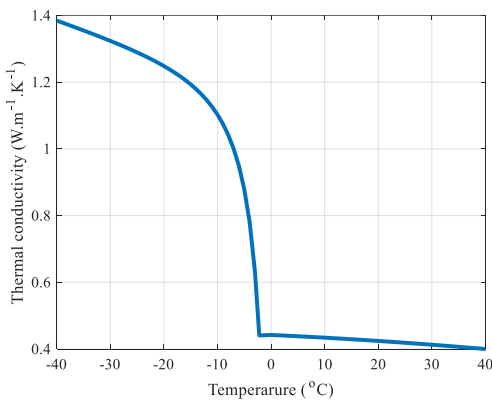
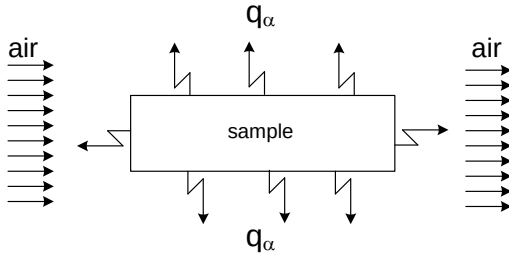


Fig. 3a. Specific heat

Fig. 3b. Density

Fig. 3c. Thermal conductivity

C. The establishment of a mathematical model for freezing processing

Based on the physical model describing the process of freezing block-typed tuna (Fig.4), the differential equation for unstable heat conduction during freezing is written in Fig. 4.


Fig. 4. The schematic of a sample heat exchange

The mathematical model for freezing processing

$$\lambda(T) \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q_v = \rho(T) C_p(T) \frac{\partial T}{\partial \tau} \quad (9)$$

Initial condition Eq. (10):

$$\tau = 0 \rightarrow T = f(x, y, z, 0) = \text{const} \quad (10)$$

Boundary conditions Eq. (11,12,13):

$$\pm \left(\frac{\partial T}{\partial x} \right)_{x=\pm \delta_x} = \pm \frac{\alpha}{\lambda(T)} (T - T_f)_{x=\pm \delta_x} \quad (11)$$

$$\pm \left(\frac{\partial T}{\partial y} \right)_{y=\pm \delta_y} = \pm \frac{\alpha}{\lambda(T)} (T - T_f)_{y=\pm \delta_y} \quad (12)$$

$$\pm \left(\frac{\partial T}{\partial z} \right)_{z=\pm \delta_z} = \pm \frac{\alpha}{\lambda(T)} (T - T_f)_{z=\pm \delta_z} \quad (13)$$

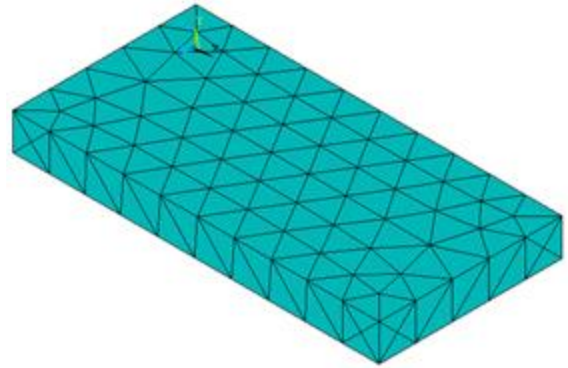
Symmetry condition Eq. (14):

$$\left(\frac{\partial T}{\partial x} \right)_{x=0} = \left(\frac{\partial T}{\partial y} \right)_{y=0} = \left(\frac{\partial T}{\partial z} \right)_{z=0} = 0 \quad (14)$$

The mathematical model for the tuna freezing problem is presented as:

$$\begin{cases} \lambda(T) \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q_v = \rho(T) C_p(T) \frac{\partial T}{\partial \tau} \\ \pm \left(\frac{\partial T}{\partial x} \right)_{x=\pm \delta_x} = \pm \frac{\alpha}{\lambda(T)} (T - T_f)_{x=\pm \delta_x} \\ \pm \left(\frac{\partial T}{\partial y} \right)_{y=\pm \delta_y} = \pm \frac{\alpha}{\lambda(T)} (T - T_f)_{y=\pm \delta_y} \\ \pm \left(\frac{\partial T}{\partial z} \right)_{z=\pm \delta_z} = \pm \frac{\alpha}{\lambda(T)} (T - T_f)_{z=\pm \delta_z} \\ \tau = 0 \rightarrow T(x, y, z, 0) = \text{const} \end{cases} \quad (15)$$

By using the finite element method, the factors will be chosen as three-dimensional, the element selected is an 8-node box shape (Fig. 5) and the grid will be divided in the same way.


Fig. 5. Tune sample after meshing

According to the Galerkin method [14], the general form of the characteristic matrix equation for the factors with no radiation is described in Eq. (16)

$$[C] \left\{ \frac{\partial T}{\partial \tau} \right\} + [K] \{T\} = \{f\} \quad (16)$$

In which

$[C] = \int_V \rho C_p [N]^T [N] dV$ is heat capacity matrix;

$[K] = \int_V [B]^T [D] [B] dV + \int_S h [N]^T [N] dS$ is heat conduction matrix;

$\{f\} = \int_S h T_K [N]^T dS$ is heat load vector.

$[N]$ is interpolation function; $[B]$ is a derivation of $[N]$; $[D]$ is matrix of heat conductivity coefficients; V is element volume, S is outer surface existing radiation and convection; T is temperature vector of nodes; $\{\partial T / \partial \tau\}$ is variation of temperature by time; T_K is environment temperature.

Eq. (16) must be discretized by time following the finite difference method (FDM) or finite element method (FEM) to

solve the temperature inside the sample. When FDM is used here, the solution is as follows:

$$\begin{aligned} \{[C] + \theta \Delta \tau [K]\} \{T\}^{p+1} = & \{[C] - (1 - \theta) \Delta \tau [K]\} \{T\}^p \\ & + \theta \Delta \tau \{f\}^{p+1} + (1 - \theta) \Delta \tau \{f\}^p \end{aligned} \quad (17)$$

Whereas θ is parameter with $0 \leq \theta \leq 1$. Therefore, the correspondent solutions are:

$$T^{p+1} = \{[C] - [K] \Delta \tau\}^{-1} * \{[C] T^p + \{f\}^p \Delta \tau\} \theta = 1 \quad (18)$$

$$T^{p+1} = [C]^{-1} * \{[C] - [K] \Delta \tau\} \{T\}^p + \{f\}^p \Delta \tau \theta = 0; \quad (19)$$

If $\theta = 1$, the Eq. (18) is implicit. $\Delta \tau$ can be selected arbitrarily while the solutions still converge, but the solution will be less accurate with a large $\Delta \tau$.

If $\theta = 0$, the Eq. (19) is explicit, and $\Delta \tau$ should be small enough to converge the solutions.

III. SIMULATION OF THE FREEZING PROCESS OF TUNA

Using Ansys software: The problem is solved using Ansys software as follows, with $\theta = 1$, selected time step $\Delta \tau = 5$ s, and automatic iteration, Eq. (19) is solved with load applied according to time step. Fig. 6 shows the iterated computation process to get convergent solutions.

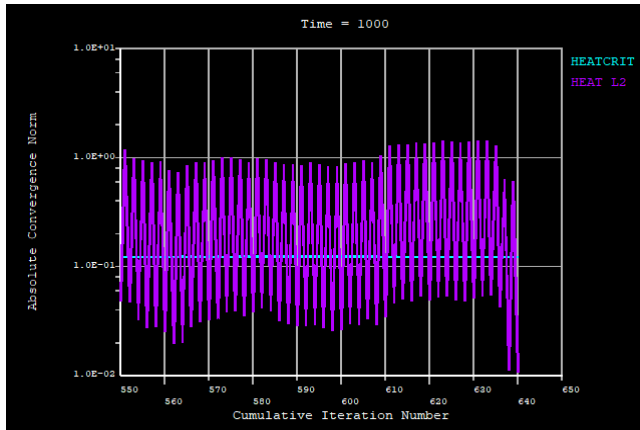


Fig. 6. Simulation results

The panorama of temperature varying by time and position in the sample is displayed in Fig. 7, The phase change in the product is displayed in Fig. 8.

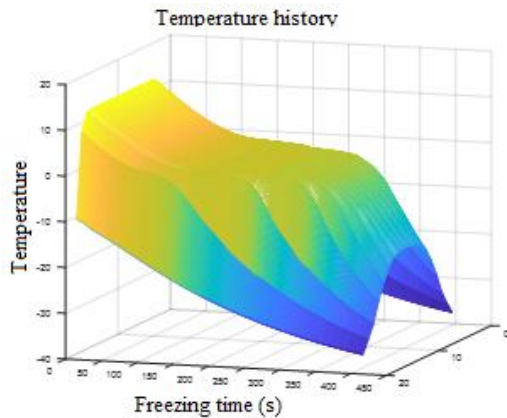


Fig. 7. Temperature history

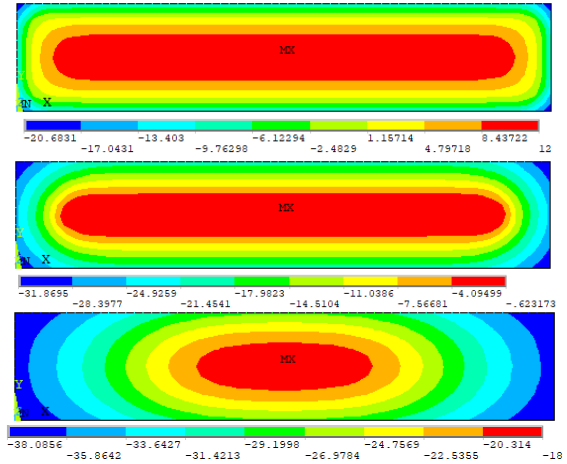


Fig. 8. The phase change in the product

According to [3], during the freezing process, the deviation between theoretically and experimentally computed temperatures is not equal. In the precooling stage, the temperature difference does not exceed 1.0 K; in the phase change stage, the temperature difference does not exceed 1.5 K; in the subcooling stage, the temperature difference does not exceed 4K.

However, considering the complexity of the process, especially the sudden variation of thermophysical properties at the freezing point, this difference is acceptable and this theoretical model can be applied with high reliability to study the freezing process of many kinds of food.

As a result, this method is completely acceptable for resolving the problem of unstable heat conduction in a variety of freezing modes. Table III and Fig. 9 (a,b,c,d,e) shows the results of the freezing time.

TABLE III. THE WORKING PARAMETER RANGE OF IQF

$t(^{\circ}\text{C})$	-35	-37.5	-40	-42.5	-45
$\omega(\text{m.s}^{-1})$					
5	1766	1626	1505	1401	1310
7.5	1444	1326	1225	1139	1063
10	1254	1150	1061	985	919
12.5	1126	1031	951	881	821
15	10323	945	870	807	751

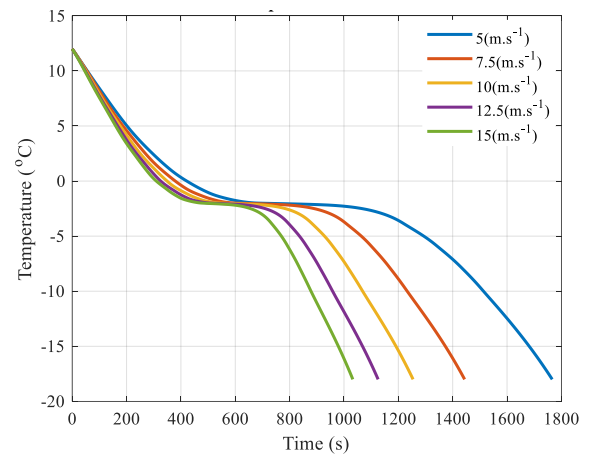
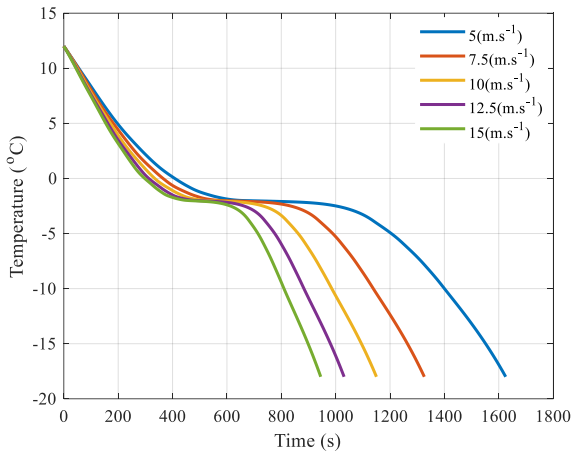
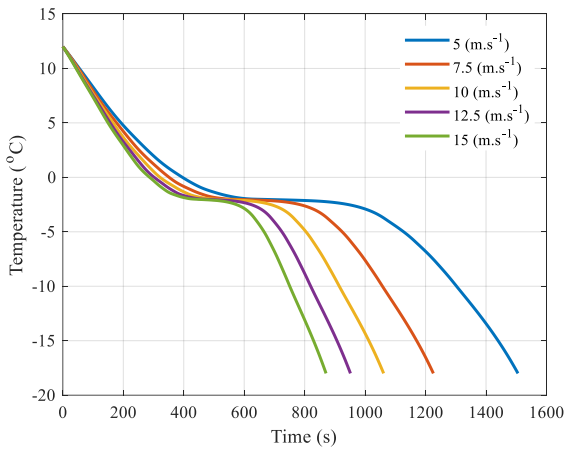
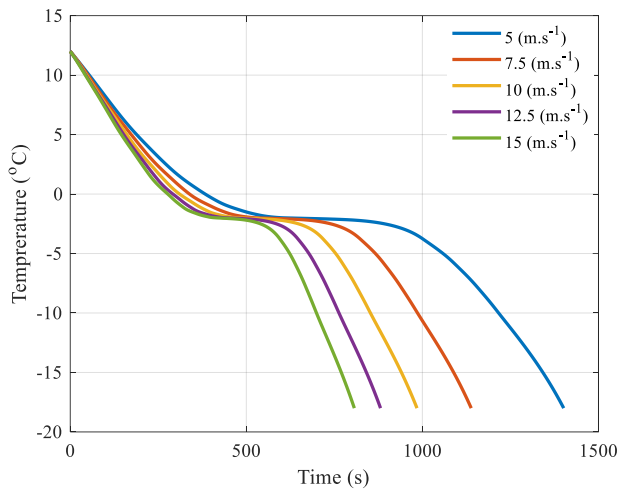
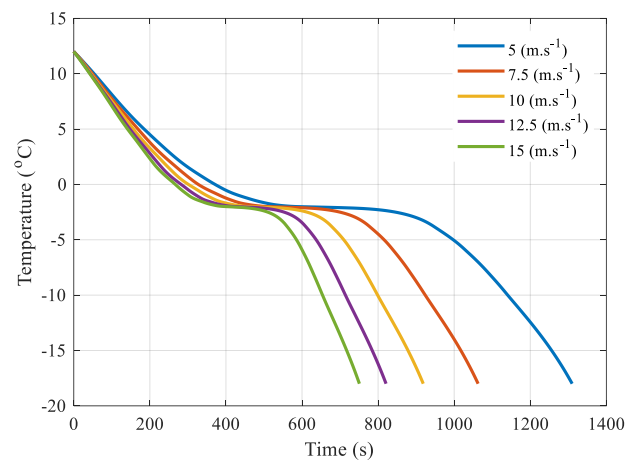


Fig. 9a. In air temperature mode $t = -35^{\circ}\text{C}$

Fig. 9b. In air temperature mode $t = -37.5^{\circ}\text{C}$ Fig. 9c. In air temperature mode $t = -40^{\circ}\text{C}$ Fig. 9d. In air temperature mode $t = -42.5^{\circ}\text{C}$ Fig. 9e. In air temperature mode $t = -45^{\circ}\text{C}$

IV. EVALUATION OF FACTORS AFFECTING FREEZING TIME

The following parameters have a direct impact on the freezing time as well as the electrical capacity of the freezing system during the process of freezing tuna: freezing air temperature and freezing air velocity.

A. The effect of air velocity on freezing time

By performed a regression equation between air velocity and freezing time in the range of ω from $5 (\text{m.s}^{-1})$ to $15 (\text{m.s}^{-1})$ at different temperature regimes from -45°C to -35°C to evaluate in detail the influence of air velocity in the freezing environment on the freezing time. The regression results are presented in Table IV and Fig.10.

TABLE IV. THE REGRESSION EQUATION SHOWING THE RELATIONSHIP OF AIR VELOCITY TO FREEZING TIME

$t (^{\circ}\text{C})$	Regression equations
-35	$\tau = 2558.27 - 190.164.\omega + 5.9368.\omega^2$
-37.5	$\tau = 2362.09 - 176.884.\omega + 5.53196.\omega^2$
-40	$\tau = 2193.54 - 165.277.\omega + 5.1753.\omega^2$
-42.5	$\tau = 2048.37 - 155.482.\omega + 4.88058.\omega^2$
-45	$\tau = 1917.67 - 146.026.\omega + 4.58028.\omega^2$

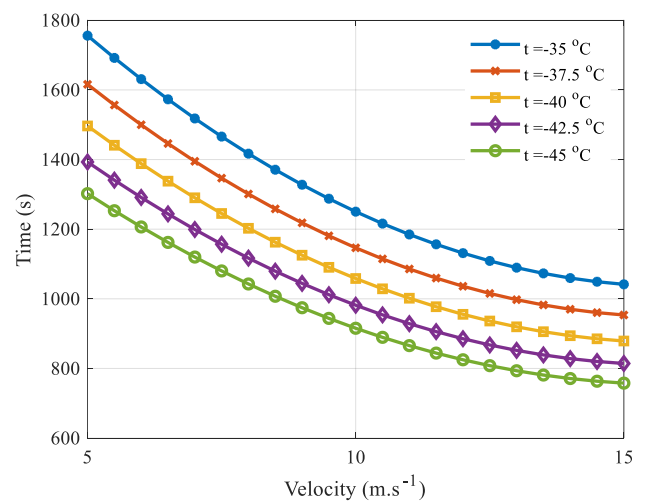


Fig. 10. Relationship between freezing time and air velocity

It has been found that increasing the air velocity speed significantly reduces the setting time. Table V shows the

reduction of freezing time corresponding to the increase per m.s^{-1} ($\nabla\omega = 1 \text{ m.s}^{-1}$).

TABLE V. FREEZING TIME REDUCTION (S) CORRESPONDING TO $\nabla\omega = 1$ (m.s^{-1}) IN DIFFERENT MODES

Temperature (°C)	Air velocity, ω (m.s^{-1})				
	5	7.5	10	12.5	15
-35	-131	-101	-71	-42	-12
-37.5	-122	-94	-66	-39	-11
-40	-114	-88	-62	-36	-10
-42.5	-107	-82	-58	-33	-9
-45	-100	-77	-54	-32	-9

Increasing the cold air velocity will significantly reduce the freezing time at all speeds in the range of ω from 5 to 15 (m.s^{-1}). However, at the same temperature with different speed modes, the freezing time reduction is not uniform, as shown below:

With the velocity of air ranging from 5 to 15 (m.s^{-1}), increasing the cold air velocity significantly reduced the freezing time. However, under the same freezing temperature conditions, the freezing time reduction was not uniform across speed modes. Specifically, when the freezing velocity increased by $\nabla\omega = 1 \text{ m.s}^{-1}$, the freezing time decreased by around 7,2 % in the velocity range of (5.0 - 7.5) m.s^{-1} , the freezing time decreased by around 6.5%, in the velocity range of (7,5 - 10) m.s^{-1} , the freezing time decreased by around 4,6 % in the velocity range of (10 - 12.5) m.s^{-1} , and the freezing time decreased by around 2,3% in the velocity range of (12.5 - 15) m.s^{-1} .

Thus, when the freezing mode is set to low speed, the freezing time decreases faster than when set to high speed.

B. The Effect of air temperature on the freezing time

Likewise, for the evaluation of the effect of air velocity on the freezing time of Tuna, we used the freezing time determination results in Table VI to construct a regression equation establishing the relationship between the freezing time and the freezing temperature. Table VI and Fig. 11 show the results of varying the freezing time with temperature.

TABLE VI. RELATIONSHIP BETWEEN FREEZING TIME AND FREEZING AMBIENT TEMPERATURE

$\omega(\text{m.s}^{-1})$	Regression equations
5	$\tau = 5414.34 + 149.99.t_e + 1.30672.t_e^2$
7.5	$\tau = 4518.76 + 126.671.t_e + 1.10858.t_e^2$
10	$\tau = 4017.98 + 114.388.t_e + 1.01168.t_e^2$
12.5	$\tau = 3588.55 + 101.511.t_e + 0.889266.t_e^2$
15	$\tau = 3336.34 + 95.2164.t_e + 0.839392.t_e^2$

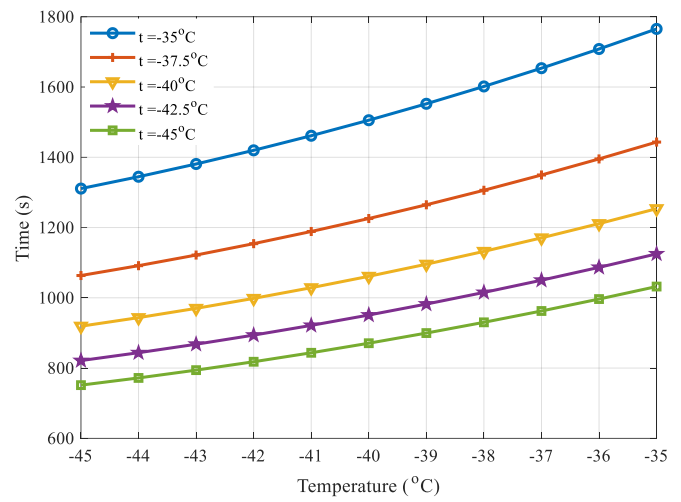


Fig. 11. Relationship between freezing time and air temperature

According to the relationship shown in Table VI, lowering the temperature will reduce the finishing time. Table VII shows the decreasing time for each temperature ($\nabla t_e = 1^\circ\text{C}$).

TABLE VII. FREEZING TIME REDUCTION (S) CORRESPONDING TO $\nabla t_e = 1^\circ\text{C}$ IN DIFFERENT MODES

ω (m.s^{-1})	-45	-42.5	-40	-37.5	-35
5	32	39	45	52	59
7.5	27	32	38	44	49
10	23	28	33	39	44
12.5	21	26	30	35	39
15	20	24	28	32	36

Reducing the cold air temperature minimized the freezing time for all freezing air temperatures in the range from -45 to -35°C, but the degree of reduction is not uniform at other temperatures. In detail, with all freezing temperatures ranging from -45°C to -35°C, lowering the cold air temperature reduced freezing time, but the degree of reduction was not uniform at other temperatures under the same freezing velocity conditions. Specifically, when the freezing temperature was reduced by $t_e = 1^\circ\text{C}$, the time reduction was on average 3.2% and 3% in the temperature ranges of t_e from -37.5°C to -35°C and from -40°C to -37.5°C, respectively. In the freezing temperature range of less than -40°C, the time reduction will continue, such as 2.85% and 2.5% reduction in the temperature range from -42.5°C to -40°C and from -45°C to -42.5°C.

V. CONCLUSION

The problem of determining the freezing time of the tuna with the phase change of heat transfer has been solved effectively by the finite element method, although it is difficult to solve by other methods. The theoretical computational results of this method are most suitable to the experimental results. This indicates that the selected study method has high reliability and the results are accepted. Factors affecting freezing time, including velocity and freezing ambient air temperature are assessed. The results of the evaluation are presented as follows:

A. The effect of air velocity on freezing time

Increasing the cold airspeed will significantly reduce the freezing time at all speeds in the range from 5m.s^{-1} to 15m.s^{-1} . However, the freezing time reduction is not uniform in the same temperature regime with different speed modes; when

increasing freezing time, the decrease in freezing time at low speed is greater than at high speed; at $\omega = 5 \text{ m.s}^{-1}$ when increasing $\Delta\omega = 1 \text{ m.s}^{-1}$, the freezing time reduction is 7.2 % ($\bar{\Delta\tau} = 114.8\text{s}$), and at $\omega = 15 \text{ m.s}^{-1}$ when increasing $\Delta\omega = 1 \text{ m.s}^{-1}$ the freezing time reduction is 2,3 % ($\bar{\Delta\tau} = 10\text{s}$).

B. The Effect of air temperature on the freezing time

With all freezing air temperatures in the range t_e from -45°C to -35°C , reducing the cold air temperature lessens freezing time, but the degree of reduction varies depending on the temperature. At high temperatures, freezing time decreases more than at low temperatures; at $t_e = -35^\circ\text{C}$ when reducing $\nabla t_e = 1^\circ\text{C}$, freezing time decreases by 3.2 % ($\bar{\Delta\tau} = 45\text{s}$), while at $t_e = -45^\circ\text{C}$ when reducing $\nabla t_e = 1^\circ\text{C}$, freezing time decreases by 2.5 % ($\bar{\Delta\tau} = 24\text{s}$).

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