Building the Method to Determine the Rate of Freezing Water in *Penaeus monodon* of the Freezing Process

Nguyen Tan Dzung, Trinh Van Dzung and Tran Duc Ba
Faculty of Chemical and Food Technology, HCMC University of Technical Education, 01-Vo Van Ngan Street, Thu Duc District, Viet Nam

**Abstract:** The method of determination the rate of freezing water in *Penaeus monodon* of freezing process was established on base the equation of energy balance in warming up process *Penaeus monodon* after freezing to determine specific heat of *Penaeus monodon*. The result obtained was built the mathematical model (19) to determine the rate of freezing water according to the freezing temperature of *Penaeus monodon*. The results indicated that when water was completely frozen (\( \omega = 1 \) or 100%), the optimal freezing temperature of *Penaeus monodon* was -22.00°C.

**Keywords:** Food freezing, the freezing process of *Penaeus monodon*, the method determining rate of freezing water

**INTRODUCTION**

The freezing technology for using in processing and preservation of foods were very important problems that has ever attracted considerable attention, it ensured food security for the world, (Heldman, 1992; Cleland, 1982). The problem posed here is how to determine the optimal freezing temperature and the optimal freezing time of food to save energy for the freezing process. Currently, there are 2 ways to determine the optimum freezing temperature and freezing time of a product, (Dzung, 2007; Clary, 1968).

- Determining the time of the freezing process in order that the center temperature of foods reach freezing point. It means that water inside the product completely crystallized, (Cleland, 1977, 1979a)
- Determining the time of the freezing process in order that the product temperature reaches the optimal freezing temperature. When water is completely frozen (\( \omega = 1 \) or 100%), (Cleland, 1979a, b; Bon, 2002)

There were many researches on mathematical modeling about the rate of freezing water of flat–shaped cattle meat (Plank, 1913), frozen velocity of water inside flat–shaped fish fillet (Lame, 1931), rate of freezing water in wet materials (Heldman, 1992). However, mathematical modeling of these authors was not suitable for determining rate of freezing water in *Penaeus monodon* in DBSCL of Vietnam because experimental results showed that error between the mathematical model and experimental data was higher than 38.45% (Cleland, 1979b; Gebhart, 1992; Holman, 1986; Heist, 1979). Because of water in food always contents dissolving compounds. Therefore, crystallization temperature, latent heat of freezing of water and other thermo physical parameters constantly change during the freezing process (Holman, 1986; Heist, 1979). These are the main causes of error between the mathematical models with experimental data. In case of large error, it will not allow the use of mathematical modeling to determine the technological mode, (Figura, 2007; Heldman, 1982). For this reason, the problem posed here was finding a new method to determine the rate of freezing water according to the freezing temperature of *Penaeus monodon* and to determine the optimal freezing temperature of *Penaeus monodon* in freezing process.

**BUILDING THE METHOD TO DETERMINE THE RATE OF FREEZING WATER**

**The basic concepts:** The freezing process of *Penaeus monodon* has 3 stages (Fig. 1), (Heldman, 1992; Cleland, 1982). In Fig. 1, if the process carried out from A to E (A → B → C → F → E), it would be called the cooling and the freezing process. Whereas, if the carried out from E to A (E → F → C → B → A), it would be called the melting and the warm up process (Heist, 1979; Heldman, 1983).
AB: cooling stage; BC: extreme cold stage; CD: crystalline water inside materials stage of theory; CF: crystalline water inside material stage of actuality; DE, FE: super freezing stage.

- **Cooling stage:** Reduce *Penaeus monodon* temperature from the initial temperature $T_p = 25^\circ$C (room temperature) to the freezing temperature of water inside the *Penaeus monodon* $T_{kt} = -1.21^\circ$C before freezing the *Penaeus monodon*, (Heist, 1979; Charm, 1962; Can, 1999).

- **Freezing stage:** Crystallize water inside the *Penaeus monodon* in environment with temperatures of $T_e = -45^\circ$C. This stage finished when the water inside the *Penaeus monodon* completely crystallized ($\omega = 1$ or 100%). At this point, the optimal freezing temperature of *Penaeus monodon* is $T_F$ ($^\circ$C), (Can, 1999; Dzung, 2012).

- **Energy balance stage:** Reducing the temperature of *Penaeus monodon* from $T_F$ ($^\circ$C) to the final temperature $T_e$ ($^\circ$C) with $T_e \leq T_F$, (Can, 1999; Dzung, 2012). It is obvious that *Penaeus monodon* is frozen to reach the freezing temperature of $T_{kF}$ ($^\circ$C), in Fig. 1, after heat supply to carry out the melting and the warm up process to determine specific heat of *Penaeus monodon*. And via the determination of specific heat of *Penaeus monodon* will build the new method to determine rate of freezing water inside *Penaeus monodon*.

**Building the method to determine rate of freezing water:** This method was built on base the energy balance equation in warming up process *Penaeus monodon* after the freezing process to determine specific heat of *Penaeus monodon* by the experiment. The results obtained could be applied to determine the optimal freezing temperature of *Penaeus monodon* of the freezing process ($T = T_F$). When temperature of *Penaeus monodon* reached the optimal freezing temperature, the rate of freezing water in *Penaeus monodon* was 100% ($\omega = 1$), (Heist, 1979; Dzung, 2012). The rate of freezing water ($\omega$) inside *Penaeus monodon* was defined as follow, (Heist, 1979):

$$\omega = \frac{G_{db}}{G_n}$$  (1)

where, $G_{db}, G_n$ – amount of crystallized water and total water inside *Penaeus monodon*, kg. The rate of freezing water $\omega$ ($0 \leq \omega \leq 1$) was determined via the determination of specific heat of the *Penaeus monodon* with equipment in Fig. 3. The *Penaeus monodon* was put into the copper box of equipment in Fig. 3. The freezing process was carried out until the temperature of *Penaeus monodon* in the copper box reached -40.5$^\circ$C after putting this box in the system of freeze DL-4 (Fig. 2) and before determining the specific heat of the *Penaeus monodon*. The heat was supplied by the electric resistance ($Q = U I \tau$, J) to determine specific heat of the *Penaeus monodon*. It was divided into 3 parts as follows:

$$Q = Q_s + Q_{cu} + Q_{dn}$$  (2)

where, $Q_s$ (J): the loss of heat pass the heat-insulated surrounding area of equipment in Fig. (3). $Q_{cu}$ (J): the heat warm up the copper box in equipment in Fig. (3):

$$Q_{cu} = G_1 C_1 (T_c - T_d), \ (J)$$  (3)
Q_{dn} (J): The heat warm up \textit{Penaeus monodon} to put into the copper box of equipment in Fig. (3):

\[ Q_{dn} = Gc (T_c - T_d), \quad (J) \]  \hfill (4)

From (2) can write as follows:

\[ Q_s = Q - (Q_{cu} + Q_{dn}) \]

From (5), the loss of heat coefficient determined \( \eta = 0.1101 \).

From (4) can write as follow:

\[ Q_{dn} = (1 - \eta) Q - Q_{cu} = (1 - \eta) UI\tau \cdot Gc (T_c - T_d), \quad (J) \]  \hfill (6)

The heat warm up \textit{Penaeus monodon} to determine specific heat. It was divided into 4 parts as follows:

\[ Q_{dn} = Gc (T_c - T_d) = Q_1 + Q_2 + Q_3 + Q_4, \quad (J) \]  \hfill (7)

where,

\[ Q_1 (J): \text{The heat warm up to thaw a part of the crystallize water inside the } \textit{Penaeus monodon}: \]

\[ Q_1 = LW_a (1 - \omega) G, \quad (J) \]  \hfill (8)

\[ Q_2 (J): \text{The heat warm up to vary temperature of the crystallize water inside the } \textit{Penaeus monodon} form \ T_d \text{ to } T_c: \]

\[ Q_2 = c_{nd}GW_a\omega (T_c - T_d), \quad (J) \]  \hfill (9)

\[ Q_3 (J): \text{The heat warm up to varies temperature of water after thawing inside the } \textit{Penaeus monodon} form \ T_d \text{ to } T_c: \]

\[ Q_3 = c_s GW_a (1 - \omega) (T_c - T_d), \quad (J) \]  \hfill (10)

\[ Q_4 (J): \text{The heat warm up to temperature of the matter inside the } \textit{Penaeus monodon} form \ T_d \text{ to } T_c: \]

\[ Q_4 = c_nGW_a (1 - W_a) ( T_c - T_d), \quad (J) \]  \hfill (11)

Substituting (8), (9), (10) and (11) into (7) found:

\[ c = c_nW_a(1-\omega)+c_{nd}W_a\omega+c_sW_a(1-W_a)+\frac{LW_a(1-\omega)}{(T_c-T_d)} \]  \hfill (12)

- When \( T > T_{kt} \), \( \omega = 0 \), \( Q_1 = 0 \), \( Q_2 = 0 \) and

\[ c = c_nW_a + c_{ck} (1 - W_a) \]  \hfill (13)

- When \( TF < T \leq T_{kt} \), \( \omega = 1 \), \( Q_1 = 0 \), \( Q_3 = 0 \) and

\[ c = c_{nd}W_a + c_{ck} (1 - W_a) \]  \hfill (15)

From Eq. (14), the rate of freezing water can be written as follow:

\[ \omega = \frac{c - (c_nW_a + c_{ck} (1 - W_a))(T_c - T_d) + LW_a}{((c_{nd} - c_n)(T_c - T_d) + L)W_a} \]  \hfill (16)

where,

\[ c = \frac{(1 - \eta) UI\tau - c_{G1}(T_c - T_d)}{G(T_c - T_d)} \]

\[ = \frac{(1 - \eta) UI\tau - c_{G1}}{G(T_c - T_d)} \cdot \frac{1}{G(J/Kg.K))} \]

From Eq. (16) and (17), the rate of freezing water was written as follow [11, 18]:

\[ \omega = \frac{(1 - \eta) UI\tau - LW_aG}{((c_{nd} - c_n)(T_c - T_d) - L)W_aG}
- \frac{[G(c_nW_a + c_{ck} (1 - W_a)) + c_{G1} (T_c - T_d)](T_c - T_d)}{((c_{nd} - c_n)(T_c - T_d) - L)W_aG} \]  \hfill (18)

where, \( T \) (°C)–average temperature of \textit{Penaeus monodon}, \( T = (T_d + T_c)/2 \).

With:

\[ \phi_1 = LW_aG \]

\[ \phi_2 = (c_nW_a + c_{ck}(1-W_a))G + c_{G1} \]

\[ \phi_3 = GW_a(c_{nd} - c_n) \]

Therefore,
\[
\omega = \frac{(1-\phi)\phi_1 - \phi_2 (T_2 - T_3)}{\phi_3 (T_3 - T_2) - \phi_1} 
\]  

Where: \(c_1, G_1\): specific heat and weight of flat-shaped copper in equipment (Fig. 3); \(G\): weight of \(P\)enaeus \(m\)onodon sample; \(T_d = T_1 = T_2 = T_3\): initial temperature of \(P\)enaeus \(m\)onodon sample. \(T_c = T_1' = T_2' = T_3'\): temperature of \(P\)enaeus \(m\)onodon sample after supplying energy. \(U\): number of voltmeter, \(I\): number of ampere meter, \(\tau\): energy supply time

The equipment (Fig. 3) was surrounded by heat-insulated material to ensure that almost energy from electric resistance transmit to \(P\)enaeus \(m\)onodon sample and a little the loss of heat to surrounding (\(\phi = 0.1110 = 11.01\%\))

MATERIALS AND METHODS

Materials: \(P\)enaeus \(m\)onodon is grown in the Flat country of Mekong River (DBSCL) of Vietnam (Can, 1999). \(P\)enaeus \(m\)onodon of approximately (40÷50) body/kg is cut off head and removed cover (Can, 1999).

Apparatus: Equipments used to determine specific heat of \(P\)enaeus \(m\)onodon are listed (Dzung, 2012):

- Determining weigh of \(P\)enaeus \(m\)onodon by Satoriusbasic Type BA310S: range scale (0÷350) g, error: ±0.1 g = ± 0.0001 kg, (Dzung, 2012)
- Determining temperature of \(P\)enaeus \(m\)onodon by Dual Digital Thermometer: range scale (-50÷70) °C, error ±0.05°C, (Dzung, 2012). DL-4 Freezing System (Fig. 2) could reduce the temperature of environment to (-50÷-45) °C. The temperature profile is measured by the automatic control system PLC, (Dzung, 2012)
- Equipment used to identify specific heat was shown in Fig. 3. The equipment includes a Voltmeter (range scale: (0÷110) V, error: ±1V), an ampere meter (range scale: (0÷2) A, error: ±10 mA) and an automatic timer (error: ±0.001s). The Voltmeter is used to measure the potential difference of Resistance (R). The Ampere meter is used to determine the current intensity which passes through 2 Resistances (R) (Fig. 3).

Methods: To determine the rate of freezing water, the experiment was carried out through 5 steps as follow, (Dzung, 2012):

Step 1: Firstly, mass of the \(P\)enaeus \(m\)onodon sample was weighed G (kg), this \(P\)enaeus \(m\)onodon sample was placed in the copper box of equipment in Fig. 3, this weighed the sample was frozen the by the system of freeze DL-4 (Fig. 2) until the average temperature of the samples reached–40.5°C, (Dzung, 2012).

Step 2: Place the copper box content \(P\)enaeus \(m\)onodon sample into the equipment in Fig. 3. The initial temperature of \(P\)enaeus \(m\)onodon (\(T_d = T_1 = T_2 = T_3, \)°C) was determined. The sample was then supplied with energy from the resistance. Parameters such as \(U\) (V), \(I\) (A) and energy supply time \(\tau\) (s) were determined. Subsequently, the system stopped supplying energy. Temperature of fillet samples

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<th>(T_c) (°C)</th>
<th>(T) (°C)</th>
<th>(\phi_1)</th>
<th>(\phi_2)</th>
<th>(\phi_3)</th>
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increased from \((T_1, T_2, T_3)\) to \((T_1', T_2', T_3')\). When energy balance occurred, \(T_c = T_1' = T_2' = T_3'\) \(^{(°C)}\), and were presented in Table 2. From results in Table 1 and 2 was determined the optimal freezing temperature of \(P.\ monodon\) in order that water inside \(P.\ monodon\) was completely crystallized. When temperature of \(P.\ monodon\) was -22.00°C \((T = T_F = -22.00°C)\). By the mathematical model (19), the rate of freezing water inside \(P.\ monodon\) was determined 100% \((\omega_E = 100\%\) or 1). Therefore, mathematical model (19) can be not only used to set up parameters for the operation of the freezing system but also to determine technological mode in freezing process of \(P.\ monodon\) which grown in the Flat country of Mekong river, Vietnam.

Currently, factories often reduce the freezing temperature of \(P.\ monodon\) to (-18\(^{+}-16\) °C for using in preservation. In such low temperature, microorganisms test showed that microorganisms could not grow, reproduce and most of the microorganisms are inactivated. However, the optimal freezing temperature of \(P.\ monodon\) has not exactly determined yet. Different with the technological freezing for using preservation only need the rate of freezing water inside \(P.\ monodon\) to reach 100%. Whereas, the technological freezing of \(P.\ monodon\) for using in the freeze drying need to have to reach 100%. Therefore, the optimal freezing temperature of \(P.\ monodon\) must be determined in order that the water in \(P.\ monodon\) was completely crystallized. The results showed that the optimal freezing temperature of \(P.\ monodon\) was -22.00°C and corresponding to \(\omega_E = 100\%\) or 1 (Table 2). These results were not only suitable to large-scale process but also a technological solution for factories to improve the freezing process, saving energy costs when the freezing system is operated, (Cleland, 1979a; Charm, 1962). In addition, results obtained were able to apply for building the mathematical model to describe about relationship the rate of freezing water inside \(P.\ monodon\) and the freezing temperature of \(P.\ monodon\), it can see this result in (Dzung, 2012).

### RESULTS AND DISCUSSION

#### Determining the optimal freezing temperature of \(P.\ monodon\)

It was obvious that mathematical model (19) was built by the energy balance equation. In there, parameters of mathematical model (19) were determined by the experiment. From results in Table 1 and 2 was determined the optimal freezing temperature of \(P.\ monodon\) and were presented in Table 2.

#### Step 3: Calculate the average temperature of the samples

\[ T = \frac{T_d + T_c}{2} \]

#### Step 4: Calculate \(\phi_1, \phi_2, \phi_3\)

#### Step 5: Finally, substituting \(\phi_1, \phi_2, \phi_3\) into the equation (19) to determine relationship between rate of freezing water inside \(P.\ monodon\) and average temperature \(T\), (Dzung, 2012).

The results obtained were presented in Table 1 and 2. From Table 1 and 2, substituting value of \(T_d, T_c, \phi_1, \phi_2, \phi_3, U, I\) and \(\tau\) into the equation (19) to determine the rate of freezing water with the temperature of \(P.\ monodon\) and were presented in Table 2.

### Table 2: The experimental value of \(T, U, I\) and \(\tau\) of \(P.\ monodon\) and the rate of freezing water with freezing temperature

<table>
<thead>
<tr>
<th>(T (°C))</th>
<th>(U (V))</th>
<th>(I (A))</th>
<th>(\tau (s))</th>
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</table>

From the experimental data in Table 1 and 2 were determined the rate of freezing water according to the freezing temperature of \(P.\ monodon\) and optimal freezing temperature of \(P.\ monodon\).

### Nomenclature:

- \(\omega \in [0,1]\): rate of freezing water:
- \(\omega_E\): rate of freezing water determined by experimental method
Wa = 0.7467 = 74.67%: initial moisture of Penaeus monodon

Cn = 4184.7 + 1.74T (J/ (kg. K): Specific heat of water

Cnd = 2090 + 7.79T (J/ (kg. K)): Specific heat of the dry matter inside Penaeus monodon

Cck = 1805.36 + 1.91T (J/ (kg. K)): Specific heat of the dry matter inside Penaeus monodon

C (J/kg/K) Specific heat of Penaeus monodon when water is crystallized

C1 = 380 (J/kg/K): Specific heat of copper

G (kg): weight of Penaeus monodon sample

G1 = 0.125 (kg): weight of copper box in equipment determines specific heat moist material

Tkt = -1.21°C: freezing temperature of water inside Penaeus monodon.

Tp = 25°C: room temperature

TF (°C): temperature of Penaeus monodon when water completely Crystallized:

Td = T1 = T2 = T3 (°C): initial temperature of Penaeus monodon sample

Tc = T1' = T2' = T3' (°C): temperature of Penaeus monodon sample after supplying energy

T = (Td + Tc)/2 (°C): average temperature of Penaeus monodon

rnc = L = -0.000021T^2 + 1.054T + 333601.5 (J/kg): Latent heat of freezing of water

U (V): number of voltmeter

I (A): number of ampere meter

τ (s): heat supply time

ϕ = 0.1101: the loss of heat coefficient

CONCLUSION

The new method was built to determine the rate of freezing water according to the freezing temperature of Penaeus monodon by the energy balance equation of determining specific heat of Penaeus monodon

From the energy balance equation has established the mathematical model (19) which was completely compatible with experiment. The results obtained also determined the optimal freezing temperature of Penaeus monodon which grows in the Flat country of Mekong River, Vietnam. It was completely compatible with large-scale process

Calculating the mathematical (19) determined technological mode for the freezing process of Penaeus monodon in DBSCL, Vietnam

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