

Study on Designing and Manufacturing the Freeze Drying System with the Process of Freezing Moist Materials inside the Freeze Drying Chamber to Preserve Valuable Products

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ABSTRACT

Freeze drying is one of the most advanced drying technologies for food processing and preserving using temperature under 0°C or under the freezing point, and pressure of drying chamber environment under 4.58mmHg to process foods. This method helps to maintain the initial quality of proteins, lipids, carbohydrates, vitamins, bioactive substances and sensory activities... In this study, the calculation and design were carried out to find suitable technology parameters to make the freeze drying system in which the freezing process occurred inside the freeze drying chamber. Heat was transferred by short wavelength thermal radiation, $\lambda = 50 \times 10^{-3}$ m. As a result, time of freeze drying had been shortened to 13.33h/batch. The system was successfully manufactured, showed the steadily working, producing the high quality products, and reduced products price. In the conditions of Vietnam, the freeze drying system replacing that of other countries is the indispensable factor to apply for processing and preserving foods.

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1. Introduction

Food drying is the process of water removal from food by evaporation to reduce food weight and transportation costs, increase sensory value, durability or prolong shelf life [1], [2]. In freeze drying technology, a process of moisture separating to dry food is carried out at the temperature and pressure lower than those of the triple point – 0.0098°C; 4.58mmHg, respectively, see Figure 1 [3].

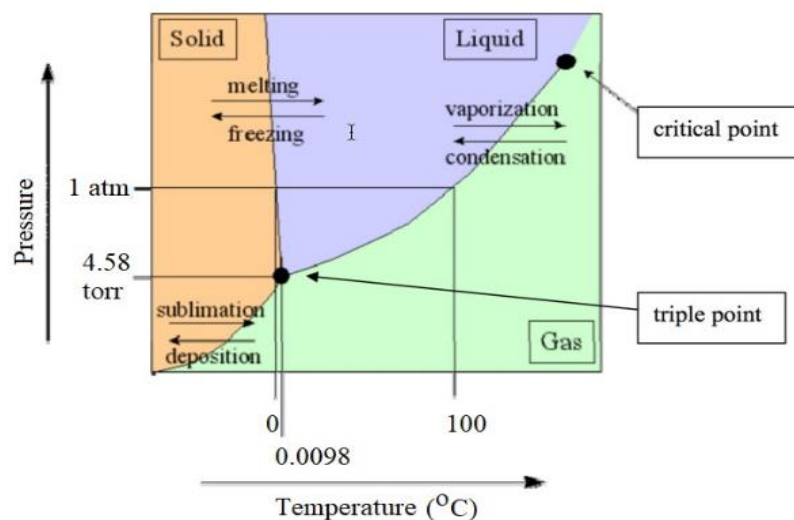


Figure 1. Diagram of phase status of water

Quality of post-freeze drying products is maintained as initial. For example, vitamins, bioactive substances and essential amino acids are not destroyed; natural pigments, odors, taste and texture are

well-maintained; lipids, carbohydrates and proteins are not oxidized, gelatinized or denatured, respectively [2], [4], [5].

However, freeze drying technology is complicated, then equipment and technology of the freeze drying are often imported from other countries, which leads to the high cost of products. Thus, the study on calculating, designing and manufacturing of the freeze drying system suitable for Vietnam's conditions needed to be carried out. The system is necessary to replace imported freeze drying equipment and technology in the food processing industry in order to preserve valuable products [3, 6].

2. Materials and Methods

2.1. Fundamentals of Freeze Drying

To calculate, design, and manufacture the freeze drying system, the initial data were needed such as equipment capacity, freezing and drying temperature, drying pressure, freezing and drying time, temperature of water crystallization in moist materials, moisture content of raw materials and products, mass of evaporating moisture during freeze drying and vacuum drying. To simplify the calculation, design and to guarantee the model generality, the initial data were collected from a certain process to freeze dry the unique product being successfully studied [3], [7], [8], [9]. Thus, in this study, the successfully studied freeze drying process of *Penaeus monodon* was used to calculate, design and manufacture the freeze-drying system DS-3 [10].

The freeze drying process of *Penaeus monodon* is through three stages.

- **Stage 1:** *Penaeus monodon* as the moist material is frozen. This stage makes water inside the shrimp change from liquid to solid state. This stage will be stopped when the temperature of the frozen moist material reaches the optimal value, and all of the water inside the shrimp has been crystallized [10], [11].

- **Stage 2:** the freeze drying stage, the frozen *Penaeus monodon* in the Stage 1 is placed inside the chamber, in which temperature and pressure are lower than those of the eutectic point O (respectively, 0.0098°C; 4.58 mmHg). It means that the temperature of the moist material and the pressure of the freeze drying chamber are lower than the crystallized temperature ($T_{\text{cry}} = 0.0098^\circ\text{C}$) and pressure (4.58mmHg). At that time, frozen water in the moist material has been changing from the solid phase to the vapor (gas) phase. This stage will end when the temperature of the moist material reaches 0°C (exactly 0.0098°C), and the free water in the moist material has been completely separated. Little of it is separated in the Stage 3 [10].

- **Stage 3:** the low temperature vacuum drying, the main purpose of this time is to separate the rest of free water in the material of the post-freeze drying stage. This time will end when the moisture content of the product reaches the 2 ÷ 6%, or the thermal equilibrium occurs, the temperature of the moist material, drying chamber and heat transfer plate are equal [10].

2.2. Methods of Calculating, Designing, and Manufacturing the Freeze Drying System

2.2.1. Requirement Initial Data for Calculating, Designing, and Manufacturing

In the freeze drying system, the freeze drying and the freezing process occurred in the only one chamber, in which moist materials were frozen and freeze dried to make valuable products. Technology parameters of the materials and the drying process had to be clearly identified from experiments. Therefore, before calculating, designing, and manufacturing, experiments were conducted to determine those technology parameters. The summary results were described in Tables 3, 4 and 5.

2.2.2. Scientific Fundamentals of Calculating, Designing, and the Freeze Drying System

a. Calculating the System to freeze the Moist Materials at the Stage 1

- **Calculating size of the freezing chamber.** The freezing chamber is also the freeze drying chamber designed in the shape of a rectangular box. Its volume was calculated by the equation (1):

$$V_{bl} = \xi \cdot \frac{G}{\beta_0 \cdot \rho} = a \cdot b \cdot h, m^3 \quad (1)$$

Where: G (kg/batch): drying capacity of the freeze drying system; ξ (kg/m³): specific mass of the moist material, β_0 : moist material filling coefficient; ρ : coefficient of space containing the moist material; a, b, h (m): width, length and height of the freeze drying chamber [10].

▪ **Calculating cooling capacity of the freezing system to freeze the moist material at Stage 1.** Cooling capacity of the chamber, in which the moist material has been frozen, was identified by the equation (2):

$$Q_0^{mn} = \left(\frac{Q_{SP} + Q_K + Q_{kk} + Q_{MT} + Q_{qn}}{\tau_1} \right) \cdot \beta_1 \quad (2)$$

Where: Q_{sp} (kJ): heat is removed to cool the moist material; Q_k (kJ): heat is removed from the moist material tray; Q_{kk} (kJ): heat is removed to cool the air inside the freezing chamber; Q_{MT} (kW): heat penetrates from the ambient environment into the freezing chamber; Q_{qn} (kW): Heat makes refrigerant from the evaporator to compressors to be the superheats; β_1 : safe coefficient; τ_1 : freezing time.

▪ **Building working cycle of Freezing System to freeze the moist material at the Stage 1.** A previous study [10] showed that the cooling cycle of freezing the moist material is the 2-stage refrigeration using R22.

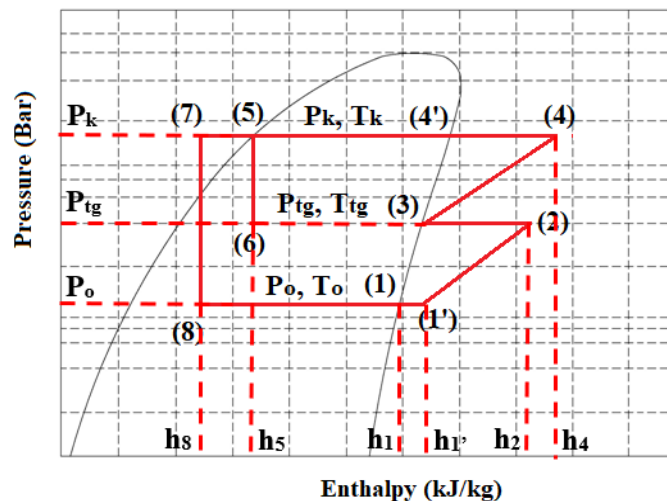


Figure 2. *P-h graph of R22*

From the P-h graph of R22, the working parameters of the cooling cycle in Figure 2 are shown in Table.

Table 1. *State Parameters of the 2-Stage Cooling Cycle*

State	h (kJ/kg)	v (m ³ /kg)	s (kJkg ⁻¹ K ⁻¹)	P (bar)	T (°C)
1	383.56	0.2452	-	0.6459	-50
1'	392.48	0.3492	1.888	0.6459	-35
2	436.44	-	1.888	3.145	39.64
3	400.20	0.0725	1.772	3.145	-13
4	446.53	-	1.772	15.315	74
4'	417.43	0.0154	-	15.315	40
5	249.99	-	-	15.315	40
6	249.99	-	-	3.145	-13
7	191.27	-	-	15.315	-8
8	191.27	-	-	0.6459	-50

▪ **Calculating to select a low pressure compressor**

- Mass flow rate (m_1 , kg/s), volume (V_{tt}^1 , m³/s) of refrigerant circulating through the elementary stage compressor (low pressure compressor):

$$m_1 = \frac{Q_0^{mn}}{h_1 - h_8}, \text{ kg/s; and } V_{tt}^1 = m_1 \times v_1, \text{ m}^3/\text{s} \quad (3)$$

- Suction capacity of low pressure compressor:

$$\lambda_{tt}^1 = \lambda_i^1 \times \lambda_w^1, \quad (4)$$

Where: Volumetric suction productivity coefficient (λ_i^1) and coefficient of suction capacity affected by temperature (λ_w^1)

$$\lambda_i^1 = \frac{P_0 - \Delta P_0}{P_0} - C \cdot \left[\left(\frac{P_{tg} + \Delta P_{tg}}{P_0} \right)^{\frac{1}{n}} - \frac{P_0 - \Delta P_0}{P_0} \right] \quad \text{and} \quad \lambda_w^1 = \frac{T_0}{T_{tg}} \quad (5)$$

In which: C = 0.03 ÷ 0.05 dead space coefficient; P_0, P_{tg} (bar) is the refrigerant evaporating pressure and the intermediate pressure, respectively: $P_{tg} = \sqrt{P_0 \cdot P_k}$, bar

- Theoretical suction volume of low pressure compressor:

$$V_{tt}^1 = V_{tt}^1 / \lambda_{TA}^1, \text{ m}^3/\text{s} \quad (6)$$

- Adiabatic compression capacity N_s^1

$$N_s^1 = m_1 \cdot (h_2 - h_1), \text{ kW} \quad (7)$$

- Indicator compressing capacity N_i^1

$$N_i^1 = N_s^1 / \eta_i^1, \text{ kW} \quad (8)$$

- Friction capacity N_{ms}^1

$$N_{ms}^1 = P_{ms} \times V_{tt}^1 / 10^3, \text{ kW} \quad (9)$$

- Useful capacity N_e^1

$$N_e^1 = N_{ms}^1 + N_i^1 \quad (10)$$

Where: η_i^1 : indicator efficiency; P_{ms} (N/m²): frictional pressure.

- Supplying electrical capacity N_{el}^1

$$N_{el}^1 = \frac{N_e^1}{\eta_{td} \cdot \eta_{el}} \quad (11)$$

Where: η_{td} : transmission efficiency; η_{el} : useful efficiency.

- Electrical motor capacity N_{dc}^1

$$N_{dc}^1 = \beta \times N_{el}^1, \text{ kW} \quad (12)$$

Where: β : safe loading coefficient for motor

■ **Calculating to select a high pressure compressor**

The calculation is similar to that of the low pressure compressor. Where m_2 was calculated as thermal balance at the inter-mediate cooling exchanger.

- Mass flow (m_2 , kg/s), volume (V_{tt}^2 , m³/s) of refrigerant circulating through a secondary compressor (high pressure compressor):

$$m_2 = m_1 \cdot \frac{h_2 - h_7}{h_3 - h_6}, \text{ kg/s} \quad \text{and} \quad V_{tt}^2 = m_2 \times v_3, \text{ m}^3/\text{s} \quad (13)$$

- Suction capacity of high pressure compressor:

$$\lambda_{tt}^2 = \lambda_i^2 \times \lambda_w^2, \quad (14)$$

Where: Volumetric suction capacity coefficient (λ_i^2) and coefficient of suction efficiency affected by temperature (λ_w^2).

$$\lambda_i^2 = \frac{P_{tg} - \Delta P_{tg}}{P_{tg}} - C \cdot \left[\left(\frac{P_k + \Delta P_k}{P_{tg}} \right)^{\frac{1}{n}} - \frac{P_{tg} - \Delta P_{tg}}{P_{tg}} \right] \quad \text{and} \quad \lambda_w^2 = \frac{T_{tg}}{T_k} \quad (15)$$

Where: C = 0.03 ÷ 0.0505 dead space coefficient; P_k (bar) condensing pressure of refrigerant.

- Theoretical suction volume of secondary compressor

$$V_{tt}^2 = V_{tt}^2 / \lambda_{tt}^2, \text{ m}^3/\text{s} \quad (16)$$

- Adiabatic compression capacity N_s^2

$$N_s^2 = m_2 \times (h_4 - h_3), \text{ kW} \quad (17)$$

- Indicator compressing capacity N_i^2

$$N_i^2 = N_s^2 / \eta_i^2, \text{ kW} \quad (18)$$

- Friction capacity N_{ms}^2

$$N_{ms}^2 = P_{ms} \times V_{tt}^2 / 10^3, \text{ kW} \quad (19)$$

- Useful capacity N_e^2

$$N_e^2 = N_{ms}^2 + N_i^2 \quad (20)$$

Where: η_i^2 : indicator efficiency; P_{ms} (N/m²): frictional pressure.

- Supplying electrical capacity N_{el}^2

$$N_{el}^2 = \frac{N_e^2}{\eta_{td} \cdot \eta_{el}} \quad (21)$$

Where: η_{td} : transmission efficiency; η_{el} : useful efficiency.

- Electrical motor capacity N_{dc}^2

$$N_{dc}^2 = \beta \times N_{el}^2, \text{ kW} \quad (22)$$

Where: β - safe loading coefficient for motor.

- Total capacity of motors

$$N_{dc} = N_{dc}^2 + N_{dc}^2, \text{ kW} \quad (23)$$

▪ **Calculating of Condenser**

$$F_{ngt} = \frac{Q_k}{q_{tr}} = \frac{m_2(h_4 - h_5) + (N_i^2 - N_s^2)}{q_{tr}} \cdot 10^3 \quad (24)$$

Where: Q_k (kW): loading heat; F_{ngt} (m²): heat exchange area; q_{tr} (W/m²): heat flow density.

▪ **Calculating the intermediate cooling exchanger**

$$F_{ig} = \frac{Q_{ig}}{q_{w.tr}} = \frac{m_1(h_5 - h_7)}{q_{w.tr}} \cdot 10^3 \quad (25)$$

Where: $q_{w.tr}$ (W/m²): heat flow density; Q_{ig} (kW): loading heat; F_{ig} (m²): heat exchange area.

b. Fundamentals of Calculating the Freeze Drying System

▪ **Calculating heat of the freeze drying chamber**

- Amount of vapor water separated from the moist material (W_a , kg/s):

$$W_a = \frac{G}{\tau} \left(\frac{W_1 - W_2}{100 - W_2} \right), \text{ kg/s} \quad (26)$$

Where: W_1 , W_2 (%): moisture content of pre and post-drying, respectively; $\tau = \tau_2 + \tau_3$ total drying time; τ_2 (s): freeze drying time; τ_3 (s): vacuum drying time.

- Exothermic heat of the freeze drying chamber (Q , kJ):

$$Q = Q_{th} + Q_{bh} - Q_{mt} \times (\tau_2 + \tau_3) = q_{th} \times \tau_2 + q_{bh} \times \tau_3 - K \times F \times \Delta t \times \tau, \text{ kJ} \quad (27)$$

Where: Q_{th} (kJ): freeze drying heat; Q_{bh} (kJ): evaporating heat; Q_{mt} (kJ): heat penetrates from the ambient into the freeze drying chamber; Q (kJ): exothermic heat of the freeze drying chamber.

$$q_{th} = r_{th} \times W_{I2}, \text{ kW} \quad \text{and} \quad q_{bh} = r_{bh} \times W_{I3}, \text{ kW} \quad \text{and} \quad W_a = W_{I2} + W_{I3}, \text{ kg/s} \quad (28)$$

- Radiative heat area of the freeze drying chamber:

$$F = \frac{q_{th}}{k \cdot C_0 \cdot \epsilon_{qd} \cdot \left\{ \left(\frac{T_{dn}}{100} \right)^4 - \left(\frac{T_{th}}{100} \right)^4 \right\}}, \text{ m}^2 \quad (29)$$

- Radiative heat wavelength:

$$\lambda = n \times N_A \times h \times c / Q, \text{ m} \quad (30)$$

Where: T_{dn} (K): temperature of radiative plate; T_{th} (K): freeze drying temperature; $n \cdot N_A$: quantity of radioactive protons; $k = 1.2$; $\epsilon_{qd} = 0.854$; $C_0 = 5.67$; [3]

▪ **Calculating condensing and freezing equipment**

$$Q_1 = W_a \times C_{ph} \times (t_h - t_n), \text{ kW} \quad \text{and} \quad Q_2 = W_a \times r_{db}, \text{ kW} \quad (31)$$

$$Q_3 = W_a \times C_{pn} \times (t_n - t_{db}), \text{ kW} \quad \text{and} \quad Q_{mt1} = K_{ngt-db} \times F_{ngt} \times \Delta t_{ngt-db}, \text{ kW} \quad (32)$$

Capacity of Condensing and freezing equipment was calculated by the equation (33):

$$Q_{[ngt-db]}^{mn} = Q_1 + Q_2 + Q_3 + Q_{mt1}, \text{ kW} \quad (33)$$

Where: Q_1 (kW): heat is removed to condense the amount of vapor water W_a ; Q_2 (kW): heat is removed to freeze the amount of post-condensation water W_a ; Q_3 (kW): heat is removed to cool amount of post-frozen water W_a ; Q_{mt1} (kW): heat penetrates from the ambient; r_{db} (kJ/kg): latent heat of freezing of water; t_h , t_n , t_{db} (°C): temperature of vapor water removed out of the freeze drying chamber, condensing temperature of vapor water, and freezing temperature of vapor water flowing from freeze drying chamber to the condensing and freezing equipment, respectively.

▪ **Heat exchange surface area of the condensing and freezing equipment**

$$F_{ngt-db} = \frac{Q_{o[ngt-db]}^{mn}}{q_{w.tr[ngt-db]}}, m^2 \quad (34)$$

Where: F_{ngt-db} (m^2): heat exchange surface area of the condensing and freezing equipment; $Q_{o[ngt-db]}^{mn}$ (kW): cooling capacity of the condensing and freezing equipment; $q_{w.tr[ngt-db]}$ (W/m^2): heat flow density of the condensing and freezing equipment.

- **Calculating of compressors and condensers to cool the condensing and freezing equipment**

$$Q_{o[ngt-db]}^{mn} \leq Q_o^{nm}, kW \quad (35)$$

Cooling capacity of the condensing and freezing equipment was determined by the equation (33). Previous study [10] showed the cooling capacity of the condensing and freezing equipment is lower than that of the moist material frozen process at Stage 1. Thus, the cooling system used to freeze the moist material at the Stage 1 was used for the condensing and freezing equipment. It saves producing cost.

- **Calculating capacity of the vacuum pumps**

$$N_b = \beta_1 \cdot \beta_2 \cdot \frac{V}{\tau_d} \cdot \ln \left[\frac{B - P_{gh}}{P_{th} - P_{gh}} \right], m^3/s \quad (36)$$

Where: V (m^3) volume of the freeze drying chamber; β_1, β_2 : safety and leaking coefficient of the freeze drying chamber; B, P_{th}, P_{gh} (N/m^2): air pressure, pressure of the freeze drying chamber, and minimum pressure of the freeze drying chamber, respectively [10].

- **Calculating of defrosting time of the condensing and freezing equipment**

$$\tau_{xb} = \frac{Q_{xb}}{K \cdot F_{ng} \cdot \Delta t_{tb}} \cdot \frac{10^3}{60}, \text{ min/batch} \quad (37)$$

Where: K ($W/(m^2K)$): heat transfer coefficient of the equipment; Δt_{tb} (K): logarithmic temperature difference; Q_{xb} (kW): defrosting heat; F_{ng} (m^2): outside surface area of the condensing and freezing equipment.

2.3. Other research methods

Carrying out research, the experimental methods were used to determine chemical compositions of the moist material and used equipment of analysis to measure temperature, pressure, time and moisture content of materials and products.

2.4. Designing and manufacturing methods

In this research, AutoCAD version 2018 (Autodesk Inc., US) was used to design the system drawing, and some mechanical processing methods are used such as: milling, planing, bending, grinding, mounding, welding and drilling... to manufacture the freeze drying system.

3. Results and Discussion

3.1. Determining the chemical compositions of the moist material

Chemical compositions of *Penaeus monodon* were determined by the chemical analysis methods and shown in Table 2 [10].

The results of Chemical compositions of the materials in Table 2 indicated that they were completely consistent with the results of Suman S., et al. [12]. Thus, these results can be used not only to identify the freeze drying process but also to calculate, design and manufacture the freeze drying system.

Table 2. Chemical compositions of the moist material of the *Penaeus monodon* in 100g material

Composition	Water	Protein	Lipid	Minerals	Vitamin A and C
Content	72.31 ÷ 77.29	19.25 ÷ 23.45	1.92 ÷ 2.28	1.65 ÷ 2.14	425.4 ÷ 467.5

3.2. Identifying kinetics of the freeze drying at the optimal conditions to find necessary parameters for designing and manufacturing freeze drying system

Previous study [10] found the optimal conditions to freeze dry *Penaeus monodon*:

- **Stage 1:** temperature of the freezing chamber and freezing time are -42.65°C and 2.57h respectively.

- **Stage 2 and 3:** temperature, pressure of the freeze drying chamber and time of freeze drying are -42.65°C , 0.008mmHg and 2.57h respectively.

After freeze drying *Penaeus monodon* at the optimum conditions, the results were shown in Table 3.

Table 3. Freeze drying *Penaeus monodon*

Stage 1 freezing			Stage 2 and 3 freeze drying and vacuum drying						
Time	"1"	"2"	Time	"2"	"3"	"4"	"5"	"6"	"7"
0.00	-42.65	25.00	0	-22	74.67	-22	760	-22	-22
0.10	-42.65	22.24	0.5	-21.65	73.87	28.87	0.008	32.91	-8.14
0.25	-42.65	9.76	1	-20.68	71.27	30.96	0.008	33	9.23
0.50	-42.65	-0.78	1.5	-20.15	67.34	31	0.008	33	18.87
1.00	-42.65	-2.01	2.5	-20.06	62.19	31	0.008	33	22.84
1.50	-42.65	-3.89	3.25	-19.98	57.11	31	0.008	33	24
1.75	-42.65	-6.78	5	-18.78	42.29	31	0.008	33	24
2.00	-42.65	-11.78	5.75	-18.65	36.13	31	0.008	33	24
2.15	-42.65	-15.63	6.25	-18.63	29.85	31	0.008	33	24
2.20	-42.65	-18.71	7	-17.99	24.97	31	0.008	33	24
2.25	-42.65	-20.67	8.25	-17.59	17.23	31	0.008	33	24
2.57	-42.65	-22.00	9.25	-16.89	13.13	31	0.008	33	24
			10	-15.88	12.21	31	0.008	33	24
			11	-14.49	9.47	31	0.008	33	24
			11.37	-1.21	6.98	31	0.008	33	24
			11.5	2.23	6.74	31	0.008	33	24
			12	7.56	6.11	31	0.008	33	24
			12.5	9.96	5.92	31	0.008	33	24
			13.75	15.69	4.86	31	0.008	33	24
			13.82	15.99	4.71	31	0.008	33	24
			15	16.77	3.23	31	0.008	33	24
			16.25	16.82	2.19	31	0.008	33	24
			17.5	17.5	2.19	31	0.008	33	24

Note: "1" Temperature of the freezing chamber; "2" Temperature of *Penaeus monodon*; "3" The residual water content of *Penaeus monodon*; "4" Temperature of the freeze drying chamber; "5" Pressure of the freeze drying chamber; "6" Temperature of the heat transfer plates; "7" Temperature of ambient of the freeze drying chamber.

From the data described in Table 3, the kinetics of the freeze drying process of *Penaeus monodon* at the optimum conditions are identified, see Figure 3.

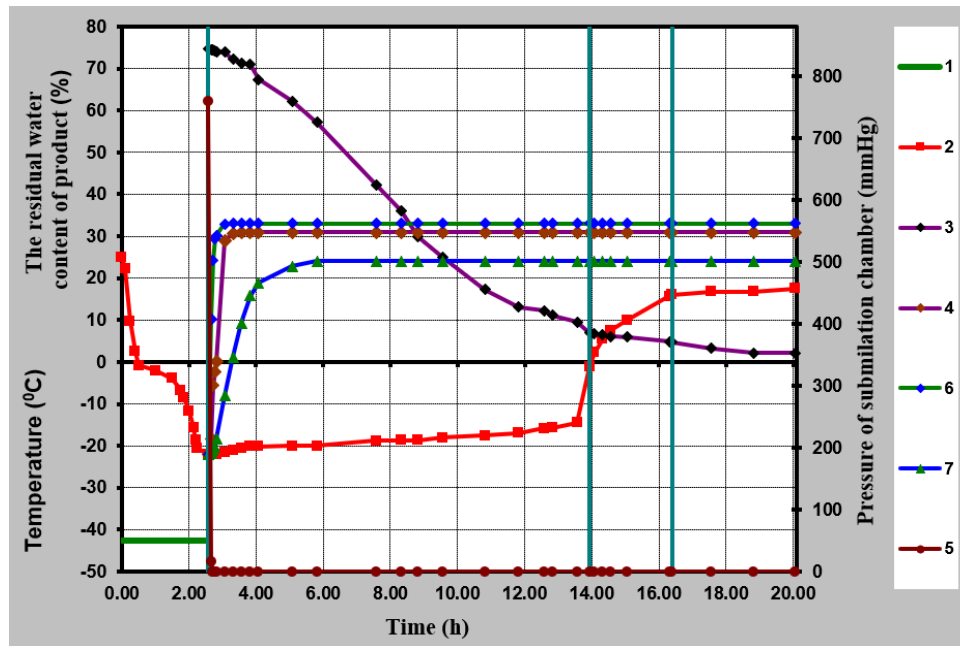


Figure 3. Kinetics of the freeze drying process of *Penaeus monodon*

Figure 3 showed that the cooling of the moist material in the Stage 1 occurred at high speed. Thus, the over cooling point was clearly identified when water was being crystallized in *Penaeus monodon*. These results are comparative to those of Sadikoglu et al., and Tsukada et al. [12], [13]. After freezing for 2.57h at -42.65°C in the freezing chamber, *Penaeus monodon* temperature reached -22°C , then residual water inside the material was crystallized. These parameters in Table 4, thus, are necessary not only for determining freeze drying technology but also for calculating, designing and manufacturing the freeze drying system.

Table 4. Necessary parameters for calculating, designing and manufacturing the freeze drying system

Parameter	Symbol	Value
Stage 1: frozen the moist material		
Moisture content of <i>Penaeus monodon</i>	W_0 (%)	74.67
Temperature of freezing chamber	T_{∞} ($^{\circ}\text{C}$)	-42.65
Freezing time	$\tau_1(\eta)$	2.57
Optimum freezing temperature of <i>Penaeus monodon</i>	T_{Fopt} ($^{\circ}\text{C}$)	-22
Ratio of frozen water of <i>Penaeus monodon</i>	$\omega(T_{\text{Fopt}})$	1
Stage 2: freeze drying		
Temperature of freeze drying chamber	T_{∞} ($^{\circ}\text{C}$)	31
Pressure of freeze drying chamber	P_{th} (mmHg)	0.008
Critical pressure of freeze drying chamber	P_{gh} (mmHg)	0.001
Crystallized temperature of water in <i>Penaeus monodon</i>	T_{cry} ($^{\circ}\text{C}$)	-1.21
Initial temperature of <i>Penaeus monodon</i> at the freeze drying process	T ($^{\circ}\text{C}$)	-22
Time of the freeze drying process	$\tau_2(\eta)$	11.37
Moisture content of <i>Penaeus monodon</i> at the end of the Stage 2	$W(\tau_2)$ (%)	6.98

Stage 3: vacuum drying at low temperature

Temperature of the vacuum chamber	T_{∞} (°C)	31
Pressure of the vacuum chamber	P_{th} (mmHg)	0.008
Temperature of <i>Penaeus monodon</i>	T (°C)	> -1.21
Time of vacuum drying	$\tau_3(\eta)$	2.45
Moisture content of the <i>Penaeus monodon</i> product	$W(\tau_3)$ (%)	4.71

On the other hand, Figure 3 showed that the temperature of *Penaeus monodon* at the Stage 2 nearly had not been changing during the freeze drying process. This result is appropriate to the result of Suling Zhai, et al. [14]. At the end of Stage 2, when the drying time reached 11.37h, moisture content of *Penaeus monodon* was 6.98%, the temperature of *Penaeus monodon* was higher than -1.21°C , the crystallized temperature of water inside *Penaeus monodon*. At that time, water inside the shrimp was not in the crystal state and changed to the liquid form, so the drying process changed to Stage 3, vacuum drying at low temperature. Temperature inside the shrimp increased rapidly and reached the temperature of the heat transfer plates and that of the drying chamber. These results are suitable with those of Tsinontides et al. [7]. Stage 3 was ended when time of drying had reached 13.82h, at that time, the moisture content and the temperature of the products, adapted to the requirements, respectively were $4.71\% < 4.8\%$ and 15.99°C .

According to the results shown in Table 3, kinetics of freeze drying of *Penaeus monodon* was established and shown in Figure 3. Besides, necessary parameters for calculating, designing and manufacturing the freeze drying system were also recognized, see Table 5.

3.3. Calculating, designing the freeze drying system

▪ **Fundamentals diagram of the freeze drying system**

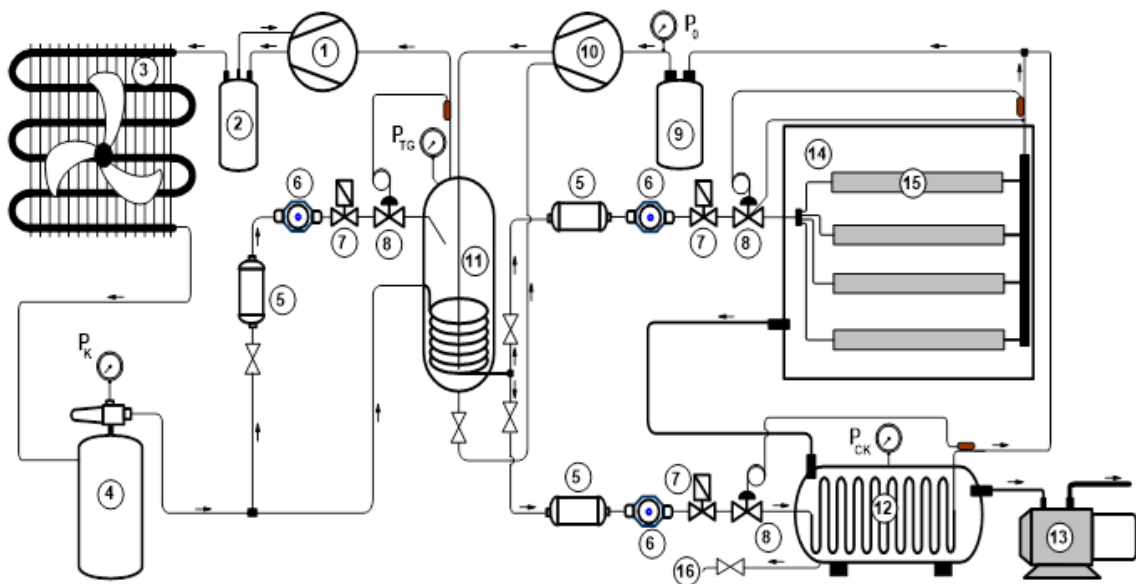


Figure 4. Fundamentals diagram of the freeze drying system.

(1)-high pressure compressor; (2)-Oil separator; (3)-Condenser; (4)-High pressure tank; (5)-Filters; (6)-Gas eyes; (7)- Solenoid valves; (8)-Expansion valves; (9)-Liquid separator; (10)-low pressure compressor; (11)-Intermediate cooling exchanger; (12)-Condensing and freezing equipment; (13)-Vacuum pump; (14)-freeze drying chamber; (15)-Heat transfer plates; (16)-Drain valve.

Due to the freezing chamber having to reach -42.65°C , the 2 Stage cooling system was used, which was described in Figure 4. This result is confirmative with that of Sadikoglu H, Ozdemir M, Seker M, and Dzung NT [1], [8].

Table 2, Table 3, and Table 4 showed the necessary initial parameters for calculating, designing and manufacturing the freeze drying system, in which the freezing process occurred inside of the freeze drying chamber. Besides, based on the calculating, and designing described in 2.2, the results of designing were presented in Table 5.

Although parameters shown in Table 5 were only designed for the freeze drying system with a capacity of 10kg (G) material/batch, the calculation method of higher or lower capacity is the same. Therefore, if the design capacity is changed, the parameters listed in Table 5 will be changed appropriately for the capacity of the freeze drying system.

Table 5. Results of calculating, designing the freeze drying system with capacity of $G = 10\text{kg/batch}$

Parameter	Equation	Result
Size of the freezing or the freeze drying chamber	1	$a = 0.5 \text{ m};$ $b = 0.8 \text{ m};$ $h = 0.6 \text{ m};$
Cooling capacity of the freezing chamber	2	$Q_o^{\text{mn}} = 1.6 \text{ kW}$
Capacity of the low pressure compressor	$3 \div 12$	$N_{dc}^1 = 1.7 \text{ kW}$
Capacity of the high pressure compressor	$13 \div 22$	$N_{dc}^2 = 1.14 \text{ kW}$
Total capacity of motors	23	$N_{dc} = 2.74 \text{ kW}$
Heat exchange area of the condenser	24	$F_{ngt} = 0.33 \text{ m}^2$
Heat exchange area of the intermediate cooling exchanger	25	$F_{ig} = 0.047 \text{ m}^2$
Exchange area of heat transfer plates in the freeze drying chamber	$26 \div 29$	$F \approx 2 \text{ m}^2$
Heat radiation wavelength	30	$\lambda = 50.10^{-3} \text{ m}$
Cooling capacity of the condensing and freezing equipment	$31 \div 33, 35$	$Q_{o[ngt-db]}^{\text{mn}} = 1.45 \text{ kW}$
Heat exchange surface area of the condensing and freezing equipment	34	$F_{ngt-db} = 0.67 \text{ m}^2$
Capacity of vacuum pumps	36	$N_b = 180 \text{ liter/h}$
Time of defrosting	37	$\tau_{xb} = (5 \div 10) \text{ min}$

3.4. Manufacturing of the freeze drying system

From the parameters in Table 5, the Auto CAD software version 2018 was used to build the technical drawing. Besides, several methods of machining and manufacturing were carried out to make the freeze drying system, in which the dried materials were frozen inside the freeze drying chamber during the Stage 1. As a result, the freeze drying system was finished and shown in Figure 5, with the following parameters:

- Equipment capacity: $10 \div 15 \text{ kg material/batch}$.
- Temperature of the freezing chamber: $(-50 \div -30)^\circ\text{C}$.
- Time of freezing: $(1.5 \div 3.5)\text{h}$ depending on kinds of moist materials.
- Temperature of freeze drying chamber: $(-50 \div 45)^\circ\text{C}$.
- Pressure of freeze drying chamber: $(0.001 \div 4.58) \text{ mmHg}$.
- Time of freeze drying: $(10 \div 72)\text{h}$ depending on kinds of moist materials.
- Temperature of condensing and freezing equipment $(-50 \div -30)^\circ\text{C}$.



Figure 5. The freeze drying system DS-6

Figure 5 showed that the freeze drying system (version DS-6), was completely designed and manufactured, in which the dried materials were frozen inside the above mentioned chamber at the Stage 1, and heat was supplied inside the vacuum chamber during freeze drying process (Stage 2) and vacuum drying at low temperature (Stage 3) by the short wavelength radiation: $\lambda = 50 \times 10^{-3} \text{ m} < 0.1 \text{ m}$.

Penaeus monodon was dried at the optimum conditions in the manufactured freeze drying system (Version DS-6): **Stage 1:** temperature of the freezing chamber -42.65°C ; freezing time 2.57h; **Stage 2 and 3:** temperature of the freeze drying chamber 31.00°C ; pressure of the freeze drying chamber 0.008mmHg; drying time 13.33h. The post-dried product was determined and the results were shown in Table 6.

Table 6. Parameters of dried products at the optimum conditions

Product Parameters	Drying Methods	Freeze Drying At the optimum conditions	Normal Drying At the optimum conditions
	Total of energy cost for 1 kg product		6.50 kWh/kg
Moisture content		4.71%	6.81%
Rehydration ratio		92.99%	15.25%
Shrinkage level		8.38%	59.25%
Lost level of total protein during drying process		2.91%	5.41%
Lost Level of amino acid lysine (lysine was denatured)		0.00%	23.51%
Lost Level of amino acid tryptophan (tryptophan was denatured)		0.00%	19.57%
Lost Level of vitamin C		3.29%	100%
Lost Level of vitamin A		0.00%	68.21%
Swelling ability to the initial status		Very good	Very poor
Protein denatured		Nearly no denatured	Completely denatured
Color		Natural orange-red	Denatured dark orange-red
Hard and porous level		Soft, porous	Hard, solid state

The freeze dried *Penaeus monodon* product was shown in Figure 6, and the normal dried one was shown in Figure 7 [15].



Figure 6. Freeze dried *Penaeus monodon*



Figure 7. Normal dried *Penaeus monodon*

Table 1, Figure 6, and Figure 7 were shown that the freeze drying system (version DS-6) with set parameters, had been steadily working and drying the *Penaeus monodon* product, which its quality is high and much better than that of the product made by normal drying. It is confirmed that the freeze drying system was successfully manufactured to preserve valuable products in Vietnam.

4. Conclusions

Results of finding the optimum freeze drying technology have already established necessary technology parameters for calculating, designing, and manufacturing the freeze drying system. Based on the input and the optimum freeze drying technology parameters of *Penaeus monodon*, the calculating, designing and manufacturing were carried out to make the freeze drying system. As a result, the freeze drying system (version DS-6) was successfully manufactured, steadily working and producing the high quality products.

Because heat transfer applied in the vacuum chamber during freeze drying was used for short wavelength thermal radiation ($\lambda < 100\text{cm} = 0.1\text{m}$), time of freeze drying has been shortened to 13.33h/batch instead of 24 h/batch when using other heat transferring methods. Thus, it reduces the drying energy and the product cost.

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REFERENCES

- [1] H. Sadikoglu, M. Ozdemir and M. Seker, "Optimal Control of the Primary Drying Stage of Freeze Drying of Solutions in Vials Using Variational Calculus," *Drying Technology*, vol. 21, no. 7, pp. 1307-1331, 2003.
- [2] T. D. Nguyen, D. M. Le and V. S. Nguyen, "Study Technological Factors Effect on the Loss of Protein, Carbohydrate and Lipid inside Royal Jelly in the Freeze Drying Process," *Current Research Journal of Biological Sciences*, vol. 7, no. 2, pp. 22-30, 2015.
- [3] T. D. Nguyen, "Study dynamics of the freeze drying process of royal jelly in Viet Nam," *Carpathian Journal of Food Science & Technology*, vol. 9, no. 3, pp. 17-29, 2017.
- [4] K. Nakagawa, A. Hottot, S. Vessot and J. Andrieu, "Modeling of freezing step during freeze-drying of drugs in vials," *AIChE Journal*, vol. 53, pp. 1369-1372, 2007.
- [5] T. D. Nguyen, "Building the Method and the Mathematical Model to Determine the Rate of Freezing Water inside Royal Jelly in the Freezing Process," *Research Journal of Applied Sciences, Engineering and Technology*, vol. 7, no. 2, pp. 403-412, 2014.
- [6] T. D. Nguyen, "Study of determining the technological mode in the freeze drying process of royal jelly in Viet Nam," *Carpathian Journal of Food Science and Technology*, vol. 8, no. 2, pp. 38-46, 2016.
- [7] S. C. Tsinontides, P. Rajniak, D. Pham, W. A. Hunke, J. Placek and S. D. Reynolds, "Freeze drying – principle and practice for successful Scale – up to manufacturing,," *International Journal Pharm*, vol. 280, pp. 1-16, 2004.
- [8] T. D. Nguyen, "Building a Mathematical Model To Determine the Relationship between Heat Emission Coefficient and Pressure of the Freeze Drying Environment of Solid Materials,," in *2018 4th International Conference on Green Technology and Sustainable Development (GTSD)*, Hochiminh city, Vietnam, 2018.
- [9] T. D. Nguyen, "Study the heat transfer model in the freezing process of basa sausage in Vietnam to determine the technological mode," *Carpathian Journal of Food Science and Technology*, vol. 10, no. 2, 5-17, p. 10, 2018.
- [10] T. D. Nguyen, "Optimization The Freeze Drying Process of Penaeus Monodon to Determine The Technological Mode," *International Journal of Chemical Engineering and Application*, vol. 3, no. 3, pp. 187-194, 2012.
- [11] T. D. Nguyen, V. D. Trinh and D. B. Tran, "Building The Method To Determine The Rate of Freezing Water of Penaeus Monodon," *Carpathian Journal of Food Science and Technology*, vol. 4, no. 2, pp. 28-35, 2012.

-
- [12] S. Suman, "Optimization the Convective Drying Process of *Penaeus monodon*," *Drying Technology: An International Journal (Thailand)*, vol. 25, no. 4, pp. 275-286, 2003.
- [13] T. Tsukada, H. Fukuyama and H. Kobatake, "Determination of Thermal Conductivity and Emissivity of Electromagnetically Levitated High-Temperature Droplet Based on the Periodic Laser-Heating Method: Theory," *International Journal of Heat and Mass Transfer*, vol. 50, pp. 3054-3061, 2007.
- [14] S. Zhai, H. Su, R. Taylor and N. K. H. Slater, "Pure ice sublimation within vials in a laboratory lyophiliser; comparison of theory with experiment," *Chemical Engineering Science*, vol. 60, pp. 1167-1176, 2005.
- [15] L. T. K. Vu, D. Q. Nguyen, D. T. A. Phan, D. T. Nguyen, "Building and solving the heat transfer models to determine suitable frying conditions for instant noodles," *Carpathian Journal of Food Science & Technology*, vol. 13, no. 4, pp. 105-115, 2021.



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