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Study on Designing and Manufacturing the DS-12 Freeze - Drying System Using Infrared Radiation Heating Process

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ABSTRACT

Freeze drying is a process of separating water inside material (food) by changing its state directly from the solid state (ice) after freezing to vapor state in a low temperature and low-pressure environment, below the triple point O (0.0098°C, 4.58mmHg). Because the drying process is conducted in an absolute vacuum and heat transfer during the drying process is mainly radiation and conduction, while convection is not possible, so the drying time is prolonged, and energy is inefficient. Therefore, this study will calculate, design, and manufacture the DS-12 freeze drying system that provides heat for the freeze-drying process by using infrared radiation. When applying the optimal technological mode for freeze-drying: drying chamber's temperature is 20.58°C; drying chamber's pressure is 0.411 mmHg; drying time is 14.785 hours, results showed that energy costs per 1 kg of product reduced to a minimum of 4.75 kWh, saving nearly 25% of total energy costs as compared to the freeze-drying process using heat from conventional thermistors. The final product has very good quality, the loss of 10-HDA (freshness) after drying is only 0.65% and moisture of product is 4.22% (less than 4.5%) which meets the technological requirements. The results of this research can be fully applied to large scale production.

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1. Introduction

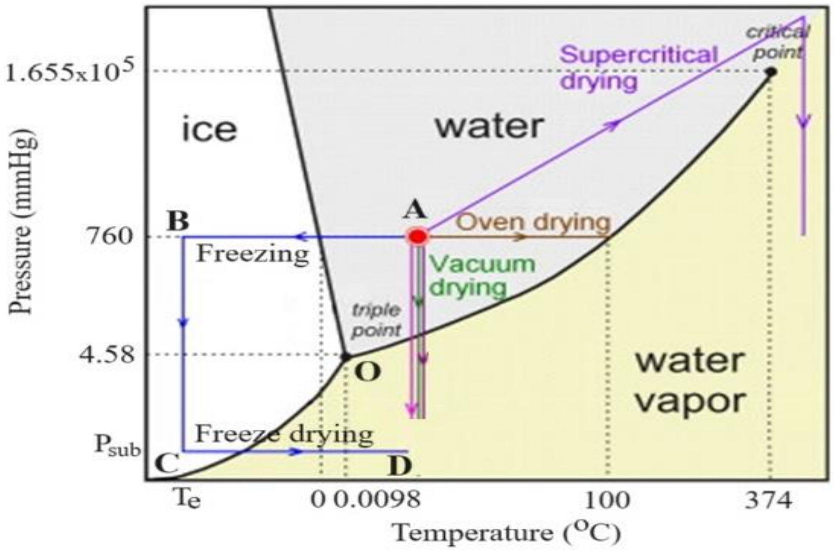

Figure 1. *Phase diagram of water inside moist material during freeze-drying [3], [7]*

Freeze-drying is the process of dehydration from moist materials under low temperature and low pressure, below the triple point O (0.0098°C; 4.58mmHg). Temperature of moist material is below the crystallization point of water (less than 0^oC), the drying pressure is less than 4.58mmHg. At that time, water from moist material transfer from solid state to vapor state directly [1]-[2].

Because the drying process is conducted in a low-pressure and low-temperature environment, products is completely qualified whereas none of previous methods could reach its quality. Protein is not hydrolysed, glucose is not gelatinized, lipids are not oxidized, vitamins, enzymes, biological active compounds are not destroyed, color and taste are almost preserved. The product has the highest porosity and reversibility as compared to other methods. In general, freeze-drying is one of the most effective ways to form products which its original quality could be maintained [1]-[3].

However, any method has its advantages and disadvantages. It can be noted that freeze-drying methods could create the best product quality. On the contrary, they consume a lot of energy than other methods and this can be explained by a complex process with various stages, as shown in figure 1:

- A→B: On the three-phase diagram at point A, the moisture of raw materials is initially in a liquid state, with a room temperature of 25^oC and a pressure of 760mmHg (atmospheric pressure). Then, the process of freezing moist materials (thanks to the refrigeration system), changing moisture from a liquid state (point A) to a solid state (point B) where moisture must be completely freezed. Therefore, the temperature at point B is the optimal temperature for moist materials due to the absolute crystallization of water inside (complete freezing) [3]-[5].

- B→C: The prerequisite for ice to sublimate is that the temperature and pressure of ice (freezing water) must be below the triple point O (0.0098^oC; 4.58mmHg), as expressed in Figure 1. Thus, after being frozen at point B, the moist material is put into a freeze-drying chamber, then the vacuum pump is operated to transform the moist material from point B to point C in which point C has $P_C = P_{Sub} <$ 4.58mmHg. Because there will be an ice sublimation pressure corresponding to different ice temperature, as illustrated in Table 1 [3]-[5], pressure P_C must also be determined at optimal conditions for the drying process to achieve the energy-efficient. Normally, point C is best located on the boundary line separating the solid phase and vapor phase. Nevertheless, due to hard conditions when operating and controlling the freeze-dryer system, it is difficult to control point C accurately on this boundary line.

Table 1. *Relationship between pressure (P_{th}) and sublimation temperature (T_{th}) of ice [3], [7]*

T_{th}, ^0C	0.0098	-1.7	-5.1	-9.8	-17.5	-26.6	-39.3	-45.4	-57.6	-66.7
P_{th}, mmHg	4.58	4.0	3.0	2.0	1.0	0.4	0.1	0.05	0.01	0.001

- C→D: This is the freeze-drying stage, moisture in the form of solid at point C (in a vacuum environment below the triple point) transfers directly to point D which is the vapor form, much energy needs to be consumed for the ice sublimation process [3]-[5].

As can be seen, it has been shown that the freeze-drying process always carried out in an absolute vacuum environment, heat transfer during the drying process is mainly radiation and conduction, while convection is not possible. On the other hand, freeze-drying systems often supply heat to the drying stage mainly by conduction, hence, the drying time is prolonged, energy costs are inefficient [5]-[7] as well as the price of final products increases, making it difficult to commercialize on market. Therefore, the research will be carried out the design and manufacture of a freeze-drying system (DS-12) which infrared radiation is used to sully heat for the process. This innovation will enhance the ability to transfer heat in a vacuum environment, combining with two other heating methods including conduction and radiation, it will shorten the drying time, maximize energy cost savings, create competitive benefits for products, and increase the potential investments for freeze-drying applications in the food production, food processing, and preservation of pharmaceutical products, etc.[5]-[7].

2. Method of calculating, designing and manufacturing the DS-12 freeze-drying system

2.1. The important initial parameters

- The drying material used in this study is royal jelly, the physical thermal parameters of the drying material and chemical compositions have been determined [4]-[5], [8]

- The optimal drying technological mode of royal jelly has been determined [2], [4]-[5], [7]. It means that when conducting the drying process, energy costs are the lowest figure, moisture content meets the technological requirements, and the product is ensured in good standards.
- Productivity of freeze-drying system G_i (kg of material/batch), [7]
- Initial moisture of material W_i (%); The required moisture content of products is W_e (%) [7].
- Drying time per batch is τ (h), [7].
- The drying process always has 3 stages: stage 1 is freezing; stage 2 is freeze-drying and stage 3 is vacuum drying (if any) [2].
- The DS-12 freeze-drying system has the ability to self-freeze, so the freezing chamber is also the drying chamber, [7].

2.2. Scientific basis for calculation and design

2.2.1. Calculate the freezing system to freeze raw materials in stage 1

- **Calculate the size of the freezing chamber** [4], [6], [8]
  - ✓ Number of trays containing raw materials in the freezing chamber:

$$N_k = \frac{G_i}{g_k} \tag{1}$$

In which: N_k – is the number of trays; g_k (kg/tray) - is the mass of the raw material. Each tray has three dimensions including width of 250mm, length of 300mm and height of 30mm.

  - ✓ Number of shelves for laying materials as well as transferring heat for the drying process in the freezing chamber:

$$N = \frac{N_k}{n_k} \tag{2}$$

With: n_k – is the number of trays in each shelf; N – is the number of shelves for laying materials as well as transferring heat for the drying process in the drying chamber; $n_k = a \times b$, a are the number of trays arranged according to width and b is the number of trays arranged according to length.

  - ✓ Determine the width of the freezing chamber:

$$R = 0.2 \times b + 2 \times \delta,\ m \tag{3}$$

  - ✓ Determine the length of the freezing chamber:

$$D = 0.4 \times a + 2 \times \delta,\ m \tag{4}$$

  - ✓ Determine the height of the freezing chamber:

$$H = (h + 1) \times N + 2 \times \delta,\ m \tag{5}$$

With δ (m) – is the distance between the top/bottom drying tray to the wall of the drying chamber ($\delta = 0.005$m); h (m) is the distance between two heat transfer shelves (usually chosen $h = 0.012 \div 0.015$ m).

  - ✓ Determine the volume of the drying chamber:

$$V = R \times D \times H,\ m \tag{6}$$

- **Calculate the cooling capacity of the refrigeration compressor** [4], [6], [8]

The cooling capacity of the refrigeration compressor for the freezing chamber is determined according to equation (7), (Dzung NT, 2012 & 2013):

$$Q_o^{Comp} = \left(\frac{Q_p + Q_{tray} + Q_{air}}{\tau} + Q_{env} + Q_{overh} \right) . k_S \text{, kW} \tag{7}$$

In which: Q_p (kJ) - refrigeration cost of the freezing process; Q_{tray} (kJ) - heat output from the tray containing materials; Q_{air} (kJ) - heat removed to cool the air in the freezing chamber; Q_{env} (kW) - heat from the environment penetrating through the wall of the freezing chamber; Q_{overh} (kW) - environmental heat entering the pipeline to superheat the steam to the compressor; τ(s) - freezing time for a batch; k_s – safe load factor.

- **Build the operating cycle of the refrigeration system in stage 1** [4], [6], [8]

The refrigeration system used to freeze moist materials in stage 1 before freeze-drying is a two-stage compression refrigeration system (see Figure 2), the refrigerant used in this system is R404A.

Table 2. *State parameters of the two-stage compression refrigeration cycle using R404A*

Status	h (kJ/kg)	v (m^3/kg)	s (kJ/(kg.K))	P (bar)	T (^{0}C)
1	338.56	-	-	0.851	-50
1’	347.50	0.249	1.700	0.851	-35
2	381.50	-	1.700	3.93	14
3	359.50	0.050	1.624	3.93	-13
4	395.52	-	1.624	18.148	52.5
4’	385.43	-	-	18.148	40
5	261.24	-	-	18.148	40
6	261.24	-	-	3.93	-13
7	215.18	-	-	18.148	-8
8	215.18	-	-	0.851	-50

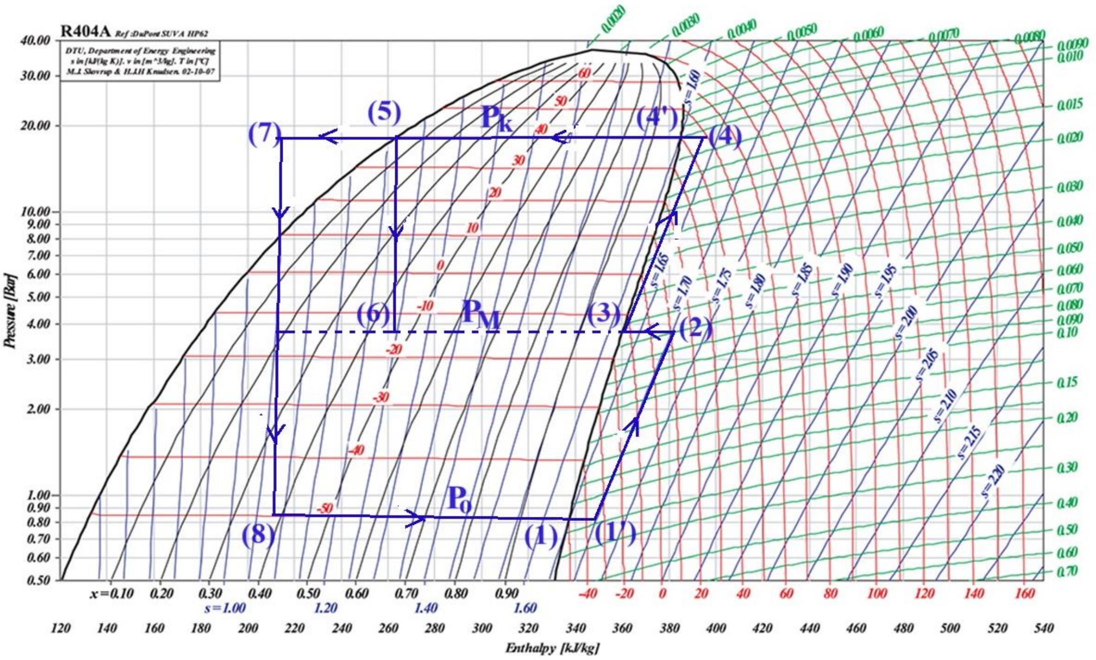

Figure 2. *P-h graph of R404A*

- **Calculate the level 1 compressor** [4], [6], [8]

- Mass flow (m_1, kg/s) and volume flow (V_{1p}, m^3/s) of refrigerant R404A circulating through the level 1 compressor:

$$m_1 = \frac{Q_o^{Comp}}{h_1 - h_8}, \text{ kg/s} \quad \text{and} \quad V_{1p} = m_1 \times v_{1'}, \ \text{m}^3\text{/s} \tag{8}$$

- Suction capacity (λ_1) of the level 1 compressor:

$$\lambda_1 = \lambda_{1w'} \times \lambda_{1i} = \left(\frac{T_o}{T_M}\right) \times \left\{ \frac{P_o - \Delta P_o}{P_o} - C\left[\left(\frac{P_M + \Delta P_M}{P_o}\right)^{\frac{1}{n}} - \frac{P_o - \Delta P_o}{P_o}\right]\right\} \tag{9}$$

In which: $P_M = \sqrt{P_o \times P_k}$, bars; C = 0.03÷0.05 dead space coefficient; Po, P_M, P_k (bar) are the refrigerant's evaporation pressure, intermediate pressure and refrigerant's condensation pressure.

- Theoretical suction volume flow of the level 1 compressor (V_{1th}, m^3/s):

$$V_{1th} = V_{1p} / \lambda_1, \ \text{m}^3\text{/s} \tag{10}$$

- Adiabatic compressor capacity (N_{1s}, kW) and indicated compressor capacity (N_{1i}, kW) of the level 1 compressor:

$$N_{1s} = m_1 \times (h_2 - h_{1'}), \text{ kW} \quad \text{and} \quad N_{1i} = N_{1s}/\eta_{1i}, \text{ kW} \tag{11}$$

- Friction capacity (N_{1ms}, kW) and effective capacity (N_{1e}, kW) of the level 1 compressor

$$N_{1ms} = P_{1ms} \times V_{1p}/10^3 \text{ , kW and } \quad N_{1e} = N_{1ms} + N_{1i}, \text{ kW} \tag{12}$$

- Electrical capacity (N_{1el}, kW) and electric motor capacity (N_{1m}, kW) of the level 1 compressor:

$$N_{1el} = \frac{N_{1e}}{\eta_{1tr} \times \eta_{1el}} \text{ , kW} \quad \text{and} \quad N_{1m} = k_1 \times N_{1el}, \text{ kW} \tag{13}$$

In which: parameters of the level 1 compressor include: η_{1i} is the performance indicator; P_{1ms} (N/m^2) is the friction pressure; η_{1tr} is the transmission efficiency; η_{1el} is the effective performance; k_1 is the safe load factor for the motor of the level 1 compressor.

- **Calculate the level 2 compressor** [4], [6], [8]

- Mass flow (m^2, kg/s) and volume flow (V_{2p}, m^3/s) of refrigerant R404A circulating through the level 2 compressor:

$$m_2 = m_1 \times \frac{h_2 - h_8}{h_3 - h_5}, \text{ kg/s} \quad \text{and} \quad V_{2p} = m_2 \times v_{3'}, \ \text{m}^3\text{/s} \tag{14}$$

- Suction capacity (λ_2) of the level 2 compressor:

$$\lambda_2 = \lambda_{2w'} \times \lambda_{2i} = \left(\frac{T_M}{T_k}\right) \times \left\{ \frac{P_M - \Delta P_M}{P_M} - C\left[\left(\frac{P_k + \Delta P_k}{P_M}\right)^{\frac{1}{n}} - \frac{P_M - \Delta P_M}{P_M}\right]\right\} \tag{15}$$

- Theoretical suction volume flow of the level 2 compressor (V_{2th}, m^3/s):

$$V_{2th} = V_{2p} / \lambda_2, \ \text{m}^3\text{/s} \tag{16}$$

- Adiabatic compressior capacity (N_{2s}, kW) and indicated compressor capacity (N_{2i}, kW) of the level 2 compressor:

$$N_{2s} = m_2 \times (h_4 - h_3), \text{ kW} \quad \text{and} \quad N_{2i} = N_{2s}/\eta_{2i}, \text{ kW} \tag{17}$$

- Friction capacity (N_{2ms}, kW) and effective capacity (N_{2e}, kW) of the level 2 compressor:

$$N_{2ms} = P_{2ms} \times V_{2p}/10^3 \text{ , kW and } N_{2e} = N_{2ms} + N_{2i}, \text{ kW} \tag{18}$$

- Electrical capacity (N_{2el}, kW) and electric motor capacity (N_{2m}, kW) of the level 2 compressor:

$$N_{2el} = \frac{N_{2e}}{\eta_{2tr} \times \eta_{2el}}, \text{kW} \quad \text{and} \quad N_{2m} = k_2 \times N_{2el}, \text{kW} \tag{19}$$

In which: parameters of the level 2 compressor include: η_{2i} is the performance indicator; P_{2ms} (N/m^2) is the friction pressure; η_{2tr} is the transmission efficiency; η_{2el} is the effective performance; k_2 is the safe load factor for the motor of the level 2 compressor.

- Total electric motor capacity (N_m, kW) of the 2 stage compressor:

$$N_m = N_{1m} + N_{2m}, \text{kW} \tag{20}$$

- **Calculate the R404A refrigerant condenser** [4], [7]

$$F_{in-cond} = \frac{Q_{condenser}}{q_{in-cond}} = \frac{m_2 \times (h_4 - h_5) + (N_{2i} - N_{2s})}{q_{in-cond}} \times 10^3, \text{m}^2 \tag{21}$$

With: $Q_{condenser}$ (kW) is the heat released by the refrigerant; $F_{in-cond}$ (m^2) is the inner wall of heat exchange area in the condenser; $q_{in-cond}$ (W/m^2) is the heat flow density of the condenser.

- **Calculate intermediate cooler** [4], [7]

$$F_{in-inter} = \frac{Q_{inter}}{q_{in-inter}} = \frac{m_1 \times (h_5 - h_7)}{q_{in-nter}} \times 10^3, \text{m}^2 \tag{22}$$

With: $q_{in-inter}$(W/m^2) is the heat flow density of the intercooler; Q_{inter} (kW) is the heat load of the intercooler; $F_{in-inter}$ (m^2): heat exchange area of the intercooler.

2.2.2. Calculate the freeze-drying system to dry materials in stage 2 and 3

- **Calculate the heat load of the sublimation chamber** [4], [7]

- The amount of water separated from the moist material during the drying process:

$$W = \frac{G_i}{\tau_{sub}} \left(\frac{W_i - W_e}{100 - W_e} \right), \text{kg/s} \tag{23}$$

In which: W_i, W_e (%) are the moisture content of raw materials and products; W (kg/s) is the amount of moisture dehydrated during the drying process; $\tau_{sub} = \tau_2 + \tau_3$ is the total time of the drying process; τ_2(s): time of stage 2 of the freeze drying; τ_3(s): time of stage 3 of the low temperature vacuum drying.

- Heat released during the drying process in stage 2 and 3:

$$Q_{chamber-sub} = Q_{sub} + Q_{vacuum} - Q_{env}, \text{kW} \tag{24}$$

With: $Q_{sub} = r_{sub} \times W_{sub}$ (kW) is the heat consumed for the second stage of freeze drying; $Q_{vacuum} = r_{vac} \times W_{vac}$ (kW) is the heat consumed for stage 3 of low-temperature vacuum drying;

$Q_{env} = K \times F_a \times \Delta t \times 10^{-3}$ (kW) is the environmental heat entering the drying chamber; $Q_{chamber-sub}$ (kW) is the freeze-drying chamber's heat; r_{sub} (kJ/kg) is the latent heat of sublimation of water; r_{vac} (kJ/kg) is the latent heat of vaporization of water; W_{sub} (kg/s) is the amount of moisture sublimated in stage 2; W_{vac} (kg/s) is the amount of moisture evaporated in stage 3; $W \times \tau = W_{sub} \times \tau_2 + W_{vac} \times \tau_3$.

- Radiant heat exchange area of the freeze-drying chamber:

$$F_{chamber-sub} = \frac{Q_{chamber-sub}}{k \times C_o \times \varepsilon_{qd} \times \left[\left(\frac{T_{shelf}}{100} \right)^4 - \left(\frac{T_{materials}}{100} \right)^4 \right]}, \text{m}^2 \tag{25}$$

With: T_{shelf} (K) is the radiation panel's temperature; $T_{materials}$ (K) is the temperature of materials during the freeze-drying process; k =1.2; ε_{qd}=0.8768 is the reference blackness; C_0 = 5.67 W/(m^2.K^4) is the radiation coefficient of an absolute black object; (Dzung NT, 2017)

- The number of infrared light bulbs for the freeze-drying chamber:

$$z = \frac{Q}{p} \tag{26}$$

With: z is the number of infrared bulbs; p (kW/bulb) – Radiant power emitted by each bulb

- **Calculate the condenser** [4], [7]

The heat load of the condenser is determined according to equation (26)

$$Q_{o[con-fre]}^{comp} = Q_1 + Q_2 + Q_3 + Q_{env1}, \text{ kW} \tag{27}$$

In which: $Q_1 = W \times C_{ph} \times (t_{ste} - t_w)$, kW is the amount of heat removed to condense steam; $Q_2 = W \times r_{cry}$ (kW) is the amount of heat removed to freeze the steam after condensation; $Q_3 = W \times (t_w - t_{ice}) \times C_{pw}$ (kW) is the amount of heat removed to lower the water's temperature after freezing;

$Q_{env1} = K_{cond\text{-}cry} \times F_{cond\text{-}cry} \times \Delta t_{cond\text{-}cry}$ (kW) is heat from the environment; r_{cry} (kJ/kg): latent heat of freezing of water; t_{ste} (^oC) is the temperature of steam releasing from the drying chamber, t_w (^oC) is the condensation temperature of steam and t_{ice} (^oC) is the freezing temperature of water from the drying chamber to the condenser.

- **Heat exchange area of the condenser** [4], [7]

$$F_{cond-cry} = \frac{Q_{o[con-fre]}^{comp}}{q_{w.tr[con-fre]}}, \text{ m}^2 \tag{28}$$

With: $F_{cond\text{-}cry}$ (m^2) is the heat exchange area of the condenser; $Q^{comp}_{o[con\text{-}fre]}$ (kW) is the load of the condenser; $q_{w.tr[con\text{-}fre]}$ (W/m^2) is the heat flow density of the condenser.

- **Calculate the refrigeration system for the condenser** [4], [7]

The cooling capacity of the refrigeration compressor running for the condenser is determined according to equation (29):

$$Q_{o[con-fre]}^{comp} \leq Q_o^{Comp}, \text{ kW} \tag{29}$$

When the conditions in equation (28) are satisfied, according to research by Dzung NT (2017), the refrigeration system used for the freezing of moist materials in stage 1 will be compatible for use in the condenser, hence it will improve the economic efficiency for DS-12 freeze-drying system's manufacture.

- **Productivity (N_p, m^3/s) of vacuum pump** [4], [7]

$$N_p = k_1 \times k_2 \times \frac{V}{\tau_d} \ln\left(\frac{B - P_{limit}}{P_{sub} - P_{limit}}\right), \text{ m}^3/\text{s} \tag{30}$$

With: V (m^3) is the volume of the freeze-drying chamber, k_1 is the safety factor and k_2 is the leakage coefficient of the freeze-drying chamber; B (N/m^2) is the atmospheric pressure; P_{sub} is the freeze-drying chamber pressure; P_{limit} is the minimum pressure of the vacuum pump; τ_d(s) is the time to lower the pressure from B to P_{sub} in the drying chamber, Dzung NT (2012).

- **Defrosting time for the condenser after a batch** [4], [7]

$$\tau_{defrost} = \frac{Q_{defrost}}{K \times F \times \Delta t_a} \times \frac{10^3}{60}, \text{ min/batch} \tag{31}$$

In which: F_e (m^2) is the outer surface area; $Q_{defrost}$ (kW) is the heat to melt frozen water; Δt_a (^oC) is the logarithmic temperature difference; K ($W/(m^2K)$) is the heat transfer coefficient of the device; $\tau_{defrost}$ (minute) is the defrosting time for one batch.

2.3. Method of designing and manufacturing the freeze-drying system

2.3.1. Designing method

Data will be obtained after calculating the mass balance and energy balance of the freeze-dryer. Thanks to this data set, design drawings will be constructed to serve the manufacturing process. In this study, Autocad 2024 software was used to design and create technical drawings, [4], [6], [7].

2.3.2. Manufacturing method

The following mechanical processing methods are used: bending, pressing, lathing, milling, or welding etc. to accurately fabricate the freeze-drying system according to the initially calculated data set, [4], [6], [7].

2.4. Method to evaluate the quality of the freeze-drying system.

Determination of chemical composition of royal jelly is presented in [3]

Experimental methods need to be conducted from raw materials to creating products in order to evaluate the operation and quality of the new freeze-drying system, the energy cost for 1 kg of product obtained from this freeze-dryer as well as the product moisture and product quality [7].

To simplify the assessment, experiments can be carried out immediately after the manufacture of the freeze-drying system, following by these parameters: the energy cost y_1 (kWh/kg), the moisture content of the product y_2 (%), recovery capacity y_3 (%) [2], [3], [5].

3. Results and discussion

3.1. Determine the initial parameters for calculation and design.

In this study, royal jelly was used as the raw material. Royal jelly was analysed for its chemical compositions at laboratory B209, Ho Chi Minh City University of Technology and Education, and the results were summarized in Table 3.

Table 3. *Chemical composition of royal jelly*

Substance	Water	Proteins	Glucids	Lipids	Minerals	10-HDA & impurities
Value (%) of material weight	59.20	14.26	15.59	4.00	1.10	5.49

Through experiments, the vital thermophysical parameters had also been determined for calculating and designing the DS-12 freeze-drying system – which integrates the self-frozen and infrared radiation heating functions. Results were presented in table 4.

Table 4. *Thermal physical parameters needed for design calculations*

Parameter	Symbol	Value	Reference
Fresh royal jelly moisture	W_0 (%)	59.20	Dzung NT (2017)
Thickness of material layer	δ(m)	12.93×10-3	Dzung NT (2017)
Thickness of glass tray	δ_0(m)	3.0×10-3	Dzung NT (2017)
Latent heat of freezing of water	$r_{freezing}$ (J/kg)	333.6×103	Dzung NT (2017)
Latent heat of sublimation of water	r_{sub} (J/kg)	3231.78×103	Dzung NT (2017)
Latent heat of vaporization of water	r_{ste} (J/kg)	2555.65×103	Dzung NT (2017)
Thermal conductivity of fresh royal jelly	ρ(kg/m^3)	1183.22	Dzung NT (2017)
Thermal conductivity of dry matter in royal jelly	ρ_1(kg/m^3)	1328.07	Dzung NT (2017)
Thermal conductivity of the glass tray	λ_0(W/(m.K))	1.0183	Dzung NT (2017)
Thermal conductivity of dry matter in royal jelly	λ_1(W/(m.K))	0.1790	Dzung NT (2017)
Specific heat of dry matter in royal jelly	c_1 (J/(kg.K))	1681.577	Dzung NT (2017)

Specific heat of water	c_w (J/(kg.K))	4186.76	Dzung NT (2017)
Specific heat of ice	c_{ice} (J/(kg.K))	2093.38	Dzung NT (2017)
Radiant heat transfer coefficient	α_r(W/(m^2.K))	4.4883	Dzung NT (2017)

In this study, the DS-11 freeze-drying system, providing heat by a resistor, was used to build a model for describing the simultaneous royal jelly freeze-drying process, along with the experimental freeze-drying of royal jelly was carried out, then the multi-objective optimization problems were established and solved. The results had established the optimal freeze-drying modes in Table 5, this means that when conducting the royal jelly drying process, the product would have the best quality, the required moisture content and energy costs would be reduced to the lowest level. Data in table 5 were considered to be the basis for calculating and designing the DS-12 freeze-drying system, which infrared radiation is use for heating purpose during the freeze-drying process.

Table 5. *Optimal freeze-drying technological parameters for royal jelly*

Stage	Parameter	Symbol	Value
Stage 1: freezing	Initial moisture content of frozen royal jelly	W_i (%)	59.20
	Crystallization temperature of moisture in royal jelly	T_{cry}, (^{0}C)	-1.06
	Freezing ambient temperature for royal jelly	$T_{env\text{-}fr}$, (^{0}C)	-40.46
	Royal jelly’s freezing time	τ_1, (h)	1,630
	Thickness of the material’s layer in the drying tray	δ(mm)	12.93
	Optimal freezing temperature of royal jelly	T_{Fopt}, (^{0}C)	-18.33
	Freezing point of water in royal jelly	$\omega(T_{Fopt})$	1.00
	Energy costs for 1 kg of frozen royal jelly	q_1 (kWh/kg)	0.28
Stage 2: freeze drying	Initial moisture of freeze-dried royal jelly	Wi (%)	59.20
	The temperature of freeze-dried royal jelly	$T_{sub} = T_{Fopt}$, (^{0}C)	-18.33
	Temperature of freeze-drying environment	$T_{shelf} = T_{env}$, (^{0}C)	20.58
	Pressure of freeze-drying environment	P_{sub}, (mmHg)	0.411
	Freeze-drying time	τ_2, (h)	18.283
	Energy costs for 1 kg of freeze-dried royal jelly product	$q_2 = y_1$ (kWh/kg)	6.32
	Moisture content of royal jelly product after freeze-drying	$y_2=W(\tau_2)=W_e$,(%)	4.19
	Loss of 10-HDA (freshness) of the product	y_3 (%)	0.78
Stage 3: low temperature vacuum drying	Drying time	τ_3, (h)	0.000
	Energy costs for 1 kg of freeze-dried royal jelly	q_3 (kWh/kg)	0.00
Total time of freeze-drying process: $\tau=\tau_1+\tau_2+\tau_3$ (h)		τ (h)	19.913

3.2. Establish the principal diagram of the DS-12 freeze-drying system.

The productivity of the drying system G_i (kg of material/batch), the drying time of each batch is τ(h) were supposed to use for calculating and designing the DS-12 freeze-dryer which has the self-frozen and infrared radiation heating modes integrated inside the system, as demonstrated in Table 5.

Due to the freezing ambient temperature $T_{env\text{-}fr}$ = -40.46^{o}C, the evaporation temperature of the refrigerant used for the refrigeration system needed to be $T_0 = T_{env\text{-}fr} - \Delta T_0$ = -50^{0}C and refrigerant condensation temperature $T_k = T_{env\text{-}air} + \Delta T_k = 33 + 7 = 40^0$C for design.

At this point, research needs to choose a refrigerant that is suitable for the evaporation temperature T_0 =-50^0C and the condensation temperature of the refrigerant is T_k = 40^0C. Therefore, the refrigerant applied for this system is R404A - a new and friendly refrigerant permitted by the world's environmental protection organisation.

Looking up the lgP – h graph of refrigerant R404A: the value of T_0 =-50^0C corresponds to P_0 =0.851 bar; the value of T_k = 40^0C corresponds to P_k =18.148 bar. Thus, the compression ratio was determined: $\beta = P_k/P_0 = 18.148/0.851 = 21.325 > 9$ (see Table 2). Because the compression ratio β is greater than 9, it is possible to use the two stage refrigeration compressor or more. In this study, a two stage refrigeration compressor was chosen with the principle diagram in Figure 3.

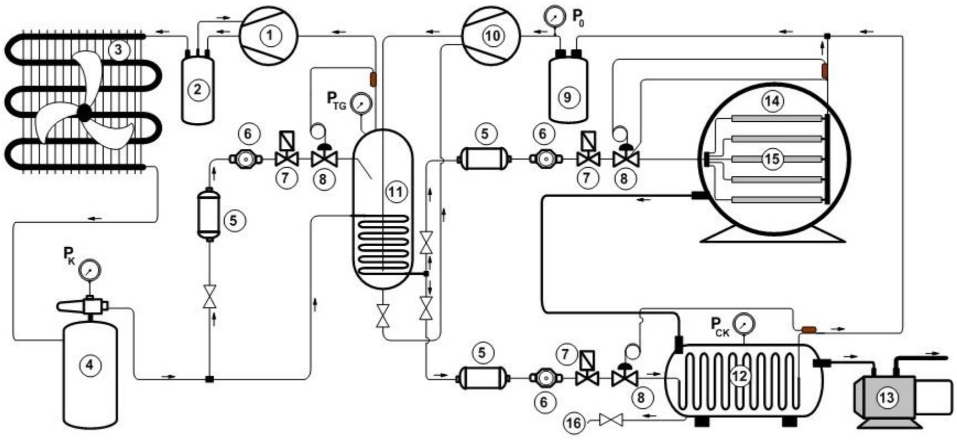

Figure 3. *Principle diagram of DS-12 self-frozen freeze-drying system*

(1)- Level 2 compressor; (2)- Oil separator; (3)- Condensing unit; (4)- High pressure storage tank; (5)- Filter; (6)- Gassonic observer; (7)- Solenoid valve; (8)- Expansion valve (Throttle valve); (9)- Liquid separator; (10)- Level 1 compressor; (12)- Condenser – freezing unit; (13)- Vacuum pump; (14)- Sublimation chamber; (15)- Heating plate (also use to place materials); (16)- Condensate drain line; P_k- High pressure manometer; P_0- Low pressure manometer; P_{TG}- Intermediate pressure manometer; P_{ck}- Vacuum manometer.

3.3. Calculation and design of the DS-12 freeze dryer system

Based on Table 3, Table 4, Table 5 and principle diagram of DS-12 self-frozen freeze-drying system was established in Figure 3, methods for calculation and design described in section 2 were applied, hence the results are shown in Table 6.

Table 6. *Results of calculation and design for the DS-12 freeze-drying system, which provides heat for the freeze-drying process by infrared radiation.*

Parameter	Symbol	Result
Equipment productivity	G_i (kg of materials/batch)	10
Size of freezing chamber as well as sublimation chamber:		
Width:	R(m)	0.6
Length:	D (m)	0.75
Height	H (m)	0.85
Cooling capacity of the refrigeration compressor for the freezing chamber in stage 1	Q_o^{Comp} (kW)	1.45
Low pressure compressor capacity	N_{1m} (kW)	1.55
High pressure compressor capacity	N_{2m} (kW)	1.15

Total engine power	N_m (kW)	2.70
Heat exchange area of the pipe's inner surface in the condenser	$F_{in\text{-}cond}$ (m^2)	0.38
Heat exchange area of the pipe's inner surface in the intercooler	$F_{in\text{-}inter}$ (m^2)	0.052
Heat exchange area of the plates in the freeze-drying chamber (also the freezing chamber)	$F_{chamber-sub}$ (m^2)	2.25
Heat consuming in the drying process of stage 2 and 3	$Q_{chamber\text{-}sub}$ (kW)	1.20
Heat capacity of each infrared light bulb	W	120
Number of infrared light bulbs	z	10
The cooling capacity of the condenser (which needs to be loaded to carry out stages 2 and 3)	$Q_{compo[con\text{-}fre]}$ (kW)	1.38
Heat exchange area of the pipe's inner surface in the condenser	$F_{cond\text{-}cry}$ (m^2)	0.72
Suction capacity of vacuum pump	N_p (m^3/h)	0.175
Defrosting time after a drying's batch	$\tau_{defrost}$(minute)	15.20

3.4. Manufacturing the DS-12 freeze-drying system

Figure 4. *The DS-12 of self-frozen freeze-drying system*

Results of calculation and design were summarized in Table 6. AutoCAD 2024 software was used to create the necessary technical drawings for manufacturing.

After being created by AutoCAD 2024 software, technical drawings were transferred to the mechanical machine systems described in section 2.3 to manufacture the freeze-dryer. The DS-12 freeze-drying system which has self-frozen function and infrared radiation heating function for the freeze-drying process were completed and shown in Figure 4. Its technical parameters are below:

- Maximum equipment productivity: 10 kg of material/batch.
- The temperature of the freezing environment in stage 1 can be adjusted: -40÷ -45°C.
- The temperature of the sublimation drying chamber in stages 2 and 3 can be adjusted: 0÷80°C.
- The temperature of the condenser is adjustable: -45÷-25°C.
- The pressure of the sublimation drying chamber in stages 2 and 3 can be adjusted: 0.005÷1.00 mmHg
- Automatic measuring equipment are controlled by a program on a computer.

3.5. Experiments to assess the stability and quality of the DS-12 freeze-drying system

By using the optimal parameters presented in Table 5 for royal jelly's freeze-drying process, experiments were conducted on the new self-frozen DS-12 freeze-drying system using heat from infrared radiation (Figure 4). After drying, royal jelly products were analysed and evaluated in terms of freeze-drying time, energy costs for 1 kg of freeze-dried royal jelly product, the moisture content of the final product and the loss of 10-HDA (freshness). Next, products would be compared to the other which was dried on the DS-11 freeze-drying system heated by a resistor. Results were expressed in Table 7.

As can be seen from Table 7, the DS-12 freeze-drying system which heat supply for the freeze drying process is infrared radiation (Figure 3), operated steadily. Freeze-dried royal jelly products were of good quality, the loss of 10-HDA (freshness) after drying was only 0.65%. As compared to products drying on the DS-11 system which provides heat for the drying process by conventional method, loss of 10-HDA (freshness) after drying was 0.78%. Thus, drying on the DS-12 freeze-drying system had resulted in better quality products.

Table 7. *Royal jelly products were dried on the DS-11 freeze-drying system heated by a resistor and the DS-12 freeze-drying system heated by infrared radiation*

Stage	Parameter	Heat supply for freeze drying by infrared radiation	Heat supply for freeze drying by resistors
Stage 1: freezing	Initial moisture content of frozen royal jelly, W_i (%)	59.20	59.20
	Crystallization temperature of moisture in royal jelly, T_{cry}, (^{0}C)	-1.06	-1.06
	Royal jelly's freezing ambient temperature, $T_{env\text{-}fr}$, (^{0}C)	-40.46	-40.46
	Royal jelly freezing time, τ_1, (h)	1,630	1,630
	The thickness of the royal jelly's layer in the drying tray, δ(mm)	12.93	12.93
	Appropriate freezing temperature of royal jelly, T_{Fopt}, (^{0}C)	-18.33	-18.33
	The freezing water ratio of royal jelly, $\omega(T_{Fopt})$	1.00	1.00
	Energy cost for 1 kg of frozen royal jelly, q_1 (kWh/kg)	0.28	0.28
Stage 2: freeze drying	Initial moisture content of freeze-dried royal jelly, W_i (%)	59.20	59.20
	Temperature of freeze-dried royal jelly, $T_{sub} = T_{Fopt}$, (^{0}C)	-18.33	-18.33
	Temperature of freeze-drying environment, $T_{shelf} = T_{env}$, (^{0}C)	20.58	20.58
	Pressure of freeze-drying environment, P_{sub}, (mmHg)	0.411	0.411
	Freeze-drying time, τ_2, (h)	14.785	18.283
	Energy cost for 1 kg of freeze-dried royal jelly, $q_2 = y_1$ (kWh/kg)	4.75	6.32
	Moisture content of royal jelly product after freeze drying, $y_2 = W(\tau_2) = W_e$, (%)	4.22	4.19
	Loss of 10-HDA (freshness) of the product, y_3 (%)	0.65	0.78
Total time of freeze drying process: $\tau = \tau_1 + \tau_2$ (h)		16.415	19.913

The moisture content of products drying on DS-11 freeze-drying system was 4.19% while this figure on the DS-12 freeze-drying system was 4.22%. Both results were less than 4.5% (standard of moisture content in freeze-dried products) so drying on the DS-11 and DS-12 freeze-drying systems meets the technological requirements. However, to achieve the required product's moisture of less than 4.5%, the drying time on the DS-12 freeze drying system took 16.415 hours, whereas the DS-11 freeze-drying system took quite a long time of 19.913h.

Due to the long drying time, drying on the DS-11 freeze-drying system consumed more energy than the other. Results in Table 7 also illustrated that if materials were dried on the DS-12 freeze drying system, the energy consumed would be 4.75 kWh/kg of product while it would be 6.32 kWh/kg of product on the DS-11 freeze-drying system.

Obviously, calculations showed that if freeze-drying process applied infrared radiation heating, energy costs would be saved from 20% to 25% as compared to the system using conventional heat. Therefore, the DS-12 freeze-drying system using infrared radiation for heating had been successfully manufactured and could be immediately put into practice to save production costs. The products also had good quality and required moisture content.

4. Conclusions

This research had successfully manufactured a DS-12 freeze-drying system which infrared radiation is apply for heating and maximum equipment capacity was 10 kg of material/batch; The temperature of the freezing environment in stage 1 can be adjusted: -45 ÷ -40°; The temperature of the freeze-drying chamber in stage 2 and 3 can be adjusted: 0÷80°C; The temperature of the condenser is adjustable: -45 ÷ -25°C; The pressure of the freeze-drying chamber in stages 2 and 3 can be adjusted: 0.005 - 1.00 mmHg; This system automatically measured and controlled by computer programming. The DS-12 freeze-drying system with the infrared radiated heating function operated with the optimal techological parameters: The temperature of the freeze-drying chamber was 20.58^{o}C; The freeze-drying chamber pressure was 0.411 mmHg; The duration of the drying process was 14.785 hours (excluding the first freezing period). Experimental results showed that products had completely qualified, the loss of 10-HDA (freshness) after drying was only 0.65%, the moisture content of products was 4.22% (less than 4.5% that meets technological requirements), energy costs were reduced to a minimum of 4.75 kWh/kg of product, saving nearly 25% as compared to the previous freeze-drying system which supplies heat for the drying process by conventional thermistors.

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Conflict of Interest

The authors declare no conflict of interest.

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