MODELING THE FREEZING PROCESS OF TURMERIC STARCH TO DETERMINE THE RATE OF FREEZING WATER

XÂY DỰNG MÔ HÌNH TOÁN QUÁ TRÌNH LẠNH ĐÔNG TINH BỘT NGHỆ ĐỂ XÁC ĐỊNH TỈ LỆ NƯỚC ĐÓNG BĂNG

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ABSTRACT

The research work is modeling the freezing process of turmeric starch to determine the rate of freezing water inside freezing turmeric starch for using in the freeze drying. The results obtained were used to determine the optimal freezing temperature of turmeric starch of -21.6^{0}C (corresponding to the rate of freezing water inside turmeric starch of 100%). This is basic parameter and very essential to set up the technological mode of the freezing process of turmeric starch for the freezing drying and determine the technological mode of the freeze drying. Corresponding to this technological mode, when operating the refrigeration system as well as the freeze drying system will save energy, at the same time, the product after the freeze drying is very good quality. Results obtained are used to calculate, design, make and control the refrigeration system as well as the freeze drying, they are applied to the actual production.

Keywords: *Turmeric, Turmeric starch; Curcumin; The rate of freezing water; The freezing process of turmeric starch; The freezing drying of turmeric starch.*

TÓM TẮT

Nghiên cứu này là xây dựng mô hình toán của quá trình lạnh đông tinh bột nghệ để xác định tỉ lệ nước đóng băng bên trong tinh bột nghệ đã lạnh đông dùng để sấy thăng hoa. Kết quả thu được dùng để xác định nhiệt độ lạnh đông thích hợp của tinh bột nghệ là -21.6^{0}C (tương ứng nước trong tinh bột nghệ kết tinh 100%). Đây là thông số cơ bản để xác định chế độ công nghệ lạnh đông tinh bột nghệ dùng cho sấy thăng hoa và xác định chế độ công nghệ sấy thăng hoa. Tương ứng với chế độ công nghệ này, khi vận hành hệ thống lạnh cũng như hệ thống sấy thăng hoa sẽ tiết kiệm được năng lượng, đồng thời sản phẩm sau khi sấy có chất lượng tốt. Kết quả đạt được được sử dụng để tính toán, thiết kế, chế tạo và điều khiển hệ thống lạnh cũng như hệ thống sấy thăng hoa, chúng được áp dụng vào thực tế sản xuất.

Từ khóa: *Nghệ; Tinh bột nghệ; Curcummin; Tỉ lệ nước đóng băng; Quá trình lạnh đông tinh bột nghệ; Sấy thăng hoa tinh bột nghệ.*

1. INTRODUCTION

Turmeric derived from the plant Curcuma longa, is a golden–colored spice commonly used in India, it is not only for health but also for food preservation and as a yellow dye in the textiles. The most important composition of turmeric is curcumin inside starch. It is a bioactive compound that is good for health human. The chemical composition of turmeric starch contains many different substances but the principal constituents of turmeric are water, protein, starch (sugars), lipids and mineral salts. Although they depend on type of turmeric but the composition remains relatively constant when comparing different regions, varieties, climate and time. The chemical composition of turmeric starch can be seen analytic data in Table 1. [1-2]

Table 1. *The chemical composition of turmeric starch*

Composition	**Value (%)**
Moisture	44.00 ± 0.15
Ash	0.32 ± 0.02
Fat	0.04 ± 0.01
Protein	0.46 ± 0.03
Starch	86.62 ± 1.15
Fiber	0.05 + 0.00
Total sugars	0.25 ± 0.01

Curcumin, which gives yellow color to turmeric, was first isolated almost 2 centuries ago, and its structure as diferuloylmethane was determined in 1910. They include the bioactive compounds as anti-inflammatory, antioxidant, anticarcinogenic, antimutagenic, anticoagulant, antifertility, antidiabetic, antibacterial, antifungal, antiprotozoal, antiviral, antifibrotic, antivenom, antiulcer, hypotensive and hypocholesteremic activities [2]. Its anticancer effect is mainly mediated through induction of apoptosis. The anti-inflammatory, the anticancer, and the antioxidant roles may be clinically exploited to control rheumatism, carcinogenesis and oxidative stress-related pathogenesis.

Turmeric starch contains traces of oleoresin and curcuminoids (yellow color). Therefore, it can be classified as a special starch with high commercial potential [2] studied the physicochemical properties of turmeric starch and their results indicated a stable viscosity, a resistant gel and easily digestible. Nonetheless, properties as swelling volume and viscosity were modified when the color was removed from starch. This emphasizes that colored turmeric starch can potentially find application in the food industry [3].

Due to these properties that curcumin inside turmeric starch have support effect cure and protect well for healthy human. It helps against and cures about stomach, duodenum, arthritis and systemic inflammation. It can increase immune system for human. Besides it against skin diseases such as: psoriasis, erythema systems, blemishes and diseases related to the nervous system such as memory loss, dementia, Parkinson disease repel, depression, the headache problems.

However, curcumin inside turmeric starch is easily denatured by temperature. Experiment is obvious that if the turmeric starch is dried by usual drying method, curcumin inside turmeric starch will be completely lost and made to decrease value of use. Therefore, the problem posed here is how to keep curcumin inside turmeric starch in preservation process. This is a question that had not any research to mention for a long time ago. To answer this problem, the freeze drying is the best method. If it applies to dry turmeric starch, curcumin inside turmeric starch of final product will be not lost or the loss is not worth considering. In the fact that the freeze drying method is complicated, it always has two stages, those are freezing stage and freeze drying stage, these two stages decide on quality final product, the loss of curcumin inside turmeric starch. As a result, research work is also divided into two stages. The first stage concentrate on study freezing stage of turmeric starch solution for using in freeze drying stage. And the aim of this study is modeling the freezing process of turmeric starch to determine the rate of freezing water, determine the optimal freezing temperature [3-4]. When freezing process is carried out reducing temperature of turmeric starch solution to reach the optimal freezing temperature, water inside turmeric starch solution will be completely crystallized (ω = 1 or ω = 100%) before carrying out freeze drying [5].

According to overview of Dzung [1-3], there are many research on mathematical modeling about the rate of freezing water of flat-shape cattle meat (Plank 1913), frozen velocity of water inside flat-shaped fish fillet (Shijov, 1931), rate of freezing water in wet materials (Raoult, 1958; Sbijov, 1967;

Golovkin, 1972, Luikov, 1974; Heldman and Daryl, 1992) [6-7]. However, mathematical model of these authors was not suitable for determining rate of freezing water in turmeric starch. Therefore, this study is building a mathematical model to determine the rate of freezing temperature of turmeric starch solution according to the freezing temperature of turmeric starch. On the foundation allow to determine the optimal freezing temperature of turmeric starch in freezing process [6-7].

2. MODELING THE FREEZING PROCESS OF TURMERIC STARCH

2.1. The freezing process

The freezing process of turmeric starch solution has three stages [1-5]:

a) Cooling stage: reduce temperature of turmeric starch solution (the initial temperature of turmeric starch solution was $T_P = T_A = 25^0C$ (room temperature)). At the end of this stage, surface temperature of turmeric starch solution was $T_s = -0.49^0C$ and center temperature of turmeric starch solution was $T_c = -2.07^0C$, average temperature of turmeric starch solution was $T_a = T_{kt} = (T_s + T_a)/2 = -1.27^0C$, and $T_s = T_0$ respectively (T_{kt}: temperature of crystallizing water inside the turmeric starch solution).

b) Freezing stage: crystallizing water inside the turmeric starch solution in freezing environment with temperatures of $T_e = -45^oC$. In this stage, water on the surface area is crystallized first. Consequently, water of successional area is crystallized. This stage finished when the water inside the turmeric starch solution completely crystallized. At this point, temperature of turmeric starch solution is the optimum freezing temperature of T_F (^oC).

c) Energy balance stage: reducing the temperature of turmeric starch solution from optimum freezing temperature to the final temperature T_e (^oC). This stage was done in a freezing storage room to maintain the temperature lower than T_e (^oC) with $T_e \le T_F$ (Holman J., 1992).

The considerable interest here was to determine the relationship between the rate of freezing water and freezing temperature of turmeric starch solution ($\omega = f(T)$). The results obtained were applied to determine the optimal freezing temperature of turmeric starch solution ($T = T_{opt}$) in order to completely crystallize water ($\omega = 1$).

2.2. Hypothesis of the building of the mathematical model

Turmeric starch solution is poured into an inox tray, turmeric starch solution will create a flat shape in tray, after that inox tray contained turmeric starch solution is frozen, it can show in Fig 1 as follows:

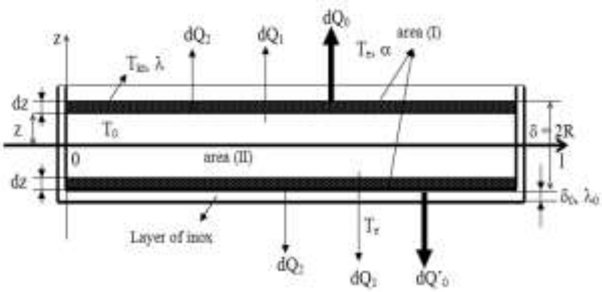

Figure 1. *Physical model of turmeric starch solution in tray*

- Turmeric starch solution in inox tray was considered approximately to the infinite flat shape with a thickness of $\delta = 2R$, a length $L >> 2R$. The isothermal surface was flat surface.
- Water was considered homogeneously distributing in turmeric starch solution. Average value of Latent heat of water was determined with temperature [2].
- Average value of thermophysical properties such as: $\rho_i, c_{pi}, a_i, \lambda_i, ...$ were determined with temperature [4-5].
- Heat transfer coefficient to the surrounding is constant: $\alpha = const$
- Equation of energy balance between area (I) and area (II) follow the rules of Leibenzon LS [1-2].

2.3. Building and solving of mathematical model of freezing process

- The rate of freezing water inside turmeric starch solution [2-3]:

$$\omega_M = \frac{dG_{nb}}{dG_n} = \frac{dG_{nb}}{d(W_0.G)}$$

$$= \frac{dG_{nb}}{d(W_0.\rho.V)} = \frac{dG_{nb}}{W_0.\rho.dV} \quad (1)$$

With: dV = F.dx (2)

Therefore: $\omega_M = \frac{dG_{nb}}{W_0.\rho.dV} = \frac{dG_{nb}}{W_0.\rho.F.dz}$

To find out: $dG_{nb} = \omega_M.W_0.\rho.F.dz$ (3)

- Building mathematical models to determine the rate of freezing water inside turmeric starch solution

From the hypothesis as on above, equation of energy balance was written as follow (Gebhart B., 1992; Dzung 2007, 2012a & b, 2014):

$dQ = \Sigma dQ_1 + \Sigma dQ_2$ (4)

Where,

ΣdQ_1 (J): the amount of heat removed to reduce the temperature of the turmeric starch solution in inox tray from T_0 to T_{kt} before freezing water in turmeric starch solution, it was determined by equation (5) as follow:

$$\Sigma dQ_1 = dQ_1 + dQ_1 = 2dQ_1$$

$$= 2.[C_{nd}.\omega_M.W_0 + C_n.(1-\omega_M).W_0 + C_{ck}(1-W_0)](T_0 - T_{kt}).\rho.F.dz$$

$$= 2.[\omega_M.W_0(C_{nd} - C_n) + C_n.W_0 + C_{ck}(1-W_0)](T_0 - T_{kt}).\rho.F.dz \quad (5)$$

ΣdQ_2 (J): the amount of heat removed to freeze water in turmeric starch solution at temperature T_{kt}, it was determined by equation (6) as follow:

$\Sigma dQ_2 = dQ_2 + dQ_2 = 2dQ_2 = 2.L.dG_{nb}$ (6)

From equation (3) and (6), we can rewrite:

$\Sigma dQ_2 = 2.L.dG_{nb} = 2.L.\omega_M.W_0.\rho.F.dz$ (7)

dQ (J): the total heat exchange between the freezing environment with product to carry out the freezing process of turmeric starch solution product. It was determined by equation (8):

$$dQ = dQ_0 + dQ'_0$$

$$= F.\frac{(T_{kt} - T_e)}{\frac{1}{\alpha} + \frac{z}{\lambda}}.d\tau + F.\frac{(T_{kt} - T_e)}{\frac{\delta_0}{\lambda_0} + \frac{z}{\lambda}}.d\tau \quad (8)$$

From equation (8), It can rewrite:

$$dQ = dQ_0 + dQ'_0$$

$$= F.(T_{kt} - T_f)\left[\frac{1}{1/\alpha + z/\lambda} + \frac{1}{\delta_0/\lambda_0 + z/\lambda}\right].d\tau \quad (9)$$

Substituting (5), (7) and (9) into (4), the results will obtain equation (10) as follow:

$$2.\left([\omega_M.W_0(C_{nd} - C_n) + C_n.W_0 + C_{ck}(1-W_0)](T_0 - T_{kt}) + L.W_0.\omega_M\right).\rho.F.dz$$

$$= F.(T_{kt} - T_e)\left[\frac{1}{1/\alpha + z/\lambda} + \frac{1}{\delta_0/\lambda_0 + z/\lambda}\right].d\tau \quad (10)$$

Where;

$\phi_1 = 2.W_0(C_{nd} - C_n)(T_0 - T_{kt})$;

$\phi_2 = 2.(C_n.W_0 + C_{ck}(1-W_0))(T_0 - T_{kt})$;

$\phi_3 = 2.L.W_0$; $r_1 = 1/\alpha$; $r_2 = \delta_0/\lambda_0$; $x = z/\lambda$.

With: $dx = dz/\lambda$ or $dz = \lambda dx$;

Substituting all into (10), the results will obtain equation (11) as follow:

$$(\omega_M.(\phi_1 + \phi_3) + \phi_2).\rho.\lambda.dx =$$

$$(T_{kt} - T_f)\left[\frac{2x + r_1 + r_2}{x^2 + (r_1 + r_2)x + r_1 r_2}\right].d\tau \quad (11)$$

Therefore;

$$d\tau = \left[\frac{\left(\omega_M.\left(\phi_1+\phi_3\right)+\phi_2\right).\rho.\lambda}{\left(T_{kt}-T_f\right)} \right]. \rightarrow$$

$$\rightarrow \left[\frac{x^2+\left(r_1+r_2\right)x+r_1r_2}{2x+r_1+r_2} \right] dx \qquad (12)$$

If $\tau = 0$, then $z = 0$ or $x = z/\lambda = 0$

If $\tau = \tau_e$ then $z = R$ hay $x = R/\lambda$

From equation (12), it can rewrite:

$$\tau_e = \int_0^{\tau_e} d\tau = \int_0^{R/\lambda} \left[\frac{\left(\omega_M.\left(\phi_1+\phi_3\right)+\phi_2\right).\rho.\lambda}{\left(T_{kt}-T_f\right)} \right]. \rightarrow$$

$$\rightarrow . \left[\frac{x^2+\left(r_1+r_2\right)x+r_1r_2}{2x+r_1+r_2} \right] dx \qquad (13)$$

From equation (13), it can rewrite:

$$\tau_e = \left[\frac{\left(\omega_M.\left(\phi_1+\phi_3\right)+\phi_2\right).\rho.\lambda}{2\left(T_{kt}-T_f\right)} \right]. \rightarrow$$

$$\rightarrow . \left[\frac{R^2}{2\lambda^2} + \left(\frac{r_1+r_2}{2}\right)\frac{R}{\lambda} + \left(r_1r_2 - \left(\frac{r_1+r_2}{2}\right)^2\right). \rightarrow \right.$$

$$\left. \rightarrow .\ln\left(\frac{2R+\lambda(r_1+r_2)}{\lambda(r_1+r_2)}\right)\right] \qquad (14)$$

Where;

$$A = \left[\frac{R^2}{2\lambda^2} + \left(\frac{r_1+r_2}{2}\right)\frac{R}{\lambda} + \left(r_1r_2 - \left(\frac{r_1+r_2}{2}\right)^2\right). \rightarrow \right.$$

$$\left. \rightarrow .\ln\left(\frac{2R+\lambda(r_1+r_2)}{\lambda(r_1+r_2)}\right)\right] \qquad (15)$$

Substituting (15) into (14), the results will obtain equation (16) as follow:

$$\omega_M = \left(\frac{2.\tau_e\left(T_{kt}-T_f\right)}{\rho.\lambda.A} - \phi_2 \right)\left(\frac{1}{\phi_1+\phi_3} \right) \qquad (16)$$

Equation (16) is mathematical model about relationship between the rate of freezing water inside turmeric starch solution and the freezing temperature of turmeric starch solution.

3. MATERIALS AND METHODS

3.1. Materials

***Figure 2**. The Refrigeration system DL-4 with the auto freezing (-45 ÷ - 40)^{0}C*

Turmeric derived from the plant Curcuma longa, is a golden–colored spice commonly used in India. In this experience is grown in the Daklak province of Viet Nam. The basic composition of turmeric is presented in table 1.

3.2. Apparatus

Equipments used to determine rate of freezing water of turmeric starch are list [1-3]:

- Three sets of temperature display Dual Digital Thermometer, made in Japan, measure temperature: range scale (-50÷-70)^{0}C, error ±0.05^{0}C.
- The Refrigeration System DL-4 (Fig 2) that were controlled automatically by computer. It could reduce the temperature of environment to (-50 ÷ -45)^{0}C. The temperature, pressure and time profile of freeze drying process are measured by computer

3.3. Methods

Determining the rate of freezing water according to mathematical model (equation (16)) carried out through 5 steps as follow [4]:

- Step 1: Mass of the turmeric starch solution sample was weighed G (kg) and put in the inox tray, it was frozen by system of freeze DL-4 until average temperature of the samples reached -21.6^{o}C, the water inside turmeric starch solution was completed crystallized. Temperature sensors will determine T_s and T_c (T_s is temperature in surface, T_c is temperature of center of turmeric starch solution sample).

- Step 2: Calculating the average temperature of the turmeric starch solution samples $T = (T_s+T_c)/2$.
- Step 3: Calculating thermophysical parameters of turmeric starch solution as follow: C_n, C_{ck}, C_{nd}, L, ϕ_1, ϕ_2, ϕ_3, A
- Step 4: Building function $\tau e = f(T)$
- Step 5: Substituting all into equation (16) will be determined the rate of freezing water inside turmeric starch solution according to the freezing temperature of turmeric starch solution.

Determining the rate of freezing water by experimental method can be reference method of Dzung (2012).

4. RESULTS AND DISCUSSIONS

4.1. Calculating thermophysical parameters of the turmeric starch solution

The thermophysical parameters of turmeric starch solution and inox tray are essential to calculate the rate of freezing water inside turmeric starch solution, they are reference to different research works, these parameters are summarized in Table 2 [1-3].

***Table 2**. The thermophysical parameters of turmeric starch solution and inox tray*

Thermophysical parameters	Unit	Value
W_0	-	0.44
T_{kt}	^0C	-1.27
δ	m	30.10^{-3}
$R = \delta/2$	m	15.10^{-3}
δ_0	m	3.10^{-3}
λ	$W.m^{-1}.K^{-1}$	0.524
λ_0	$W.m^{-1}.K^{-1}$	15.6
α	$W.m^{-2}.K^{-1}$	8.1
ρ	$Kg.m^{-3}$	1440
$r_1 = 1/\alpha$	$m^2.K.W^{-1}$	0.123457
$r_2 = \delta_0/\lambda_0$	$m^2.K.W^{-1}$	0.000128
A	-	0.000731

Experiment of the freezing process of turmeric starch solution with all data in Table 2 was carried out by freezing time in Table 3a. Results determined thermophysical parameters in Table 3a & 3b.

***Table 3a**. The thermophysical parameters of turmeric starch solution*

τ_e	T_s	T_c	T_a	L	C_n
0	-0.49	-2.05	-1.27	333600.16	4181.22
12	-4.6	-5.1	-4.85	333596.39	4171.41
17	-6.5	-7.6	-7.05	333594.07	4165.38
21	-8.2	-9.9	-9.05	333591.96	4159.90
24	-10.5	-11.3	-10.9	333590.01	4154.83
27	-12.5	-13.1	-12.8	333588.01	4149.63
30	-15.6	-16.7	-16.2	333584.48	4140.45
32	-19.4	-20.1	-19.8	333580.68	4130.59
33	-21.4	-21.8	-21.6	333578.73	4125.52
33	-22.6	-23.8	-23.2	333577.05	4121.13

***Table 3b**. The thermophysical parameters of turmeric starch*

C_{nd}	C_{ck}	ϕ_1	ϕ_2	ϕ_3
2080.11	1797.50	-10076.94	31025.06	293568.14
2052.22	1790.34	-10163.65	30934.34	293564.82
2035.08	1785.87	-10216.93	30878.13	293562.78
2019.50	1781.75	-10265.37	30826.72	293560.93
2005.09	1777.90	-10310.18	30778.91	293559.21
1990.29	1773.91	-10356.19	30729.55	293557.45
1964.19	1766.76	-10437.33	30641.89	293554.34
1936.15	1758.93	-10524.52	30546.78	293551.00
1921.74	1754.84	-10569.33	30497.54	293549.29
1909.27	1751.28	-10608.08	30454.75	293547.80

From Table 3a, it was built equation (17) that is relationship between freezing time (τ_e, min) and the freezing temperature (T_a, ^0C) during the freezing process of turmeric starch solution.

$$\tau_e = -0.066 \times T^2 - 2.966 \times T - 0.427 \quad (17)$$

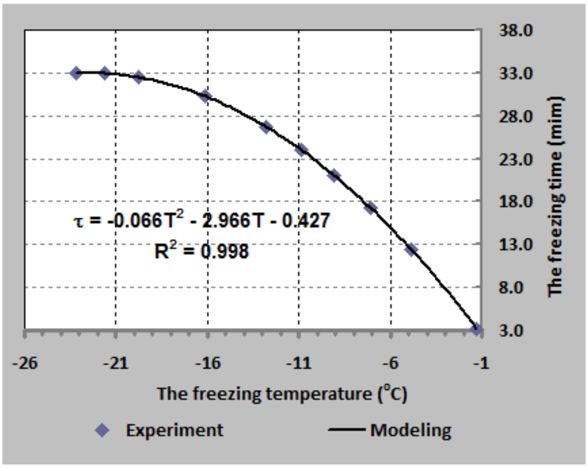

Figure 3. *Relationship between freezing time and the freezing temperature during the freezing process of turmeric starch solution.*

With $R^2 = 0.998$, it was obvious that equation (17) was completely suitable for experimental data. Therefore, it can use to calculate the rate of freezing water inside turmeric starch solution in freezing process for using in freeze drying.

Simulating experimental data and equation (17), results received were expressed in Fig 3 as follows

From Fig 3 and Table 3, they were obvious that when the freezing temperature of turmeric starch solution reduces, the freezing time increases. As a result, relationship between freezing time and the freezing temperature during the freezing process of turmeric starch solution was completely suitable for the fact in production.

4.2. Determining the rate of freezing water inside turmeric starch solution according to the freezing temperature of turmeric starch solution

Carrying out experiment with all data in Table 2, 3a, 3b and 4 of the freezing process were determined the rate of freezing water inside turmeric starch solution (ω_E) according to the freezing temperature of turmeric starch solution (T_a) by experimental method [1-2]. The results obtained were presented in Table 4.

Substituting thermophysical parameters in Table 2, 3a & 3b and equation (17) into equation (16), from equation (16) calculated the rate of freezing water inside turmeric starch solution (ω_M) according to the freezing temperature of turmeric starch solution (T_a). The results obtained were presented in Table 4.

Table 4. *The rate of freezing water inside turmeric starch solution in freezing process*

τ_e	T_a	ω_E	ω_M	Error
3.2	-1.27	0.00	0.00	0.000939
12.4	-4.85	0.31	0.34	0.032606
17.2	-7.05	0.47	0.45	0.018867
21.0	-9.05	0.60	0.56	0.037147
24.1	-10.9	0.70	0.71	0.009901
26.8	-12.8	0.79	0.74	0.050115
30.3	-16.2	0.91	0.91	1.07E-07
32.5	-19.8	0.98	0.99	0.006447
32.9	-21.6	1.00	1.00	0.000943
33.0	-23.2	1.00	1.00	0.000253

Simulating all data in Table 4, the results received were expressed in Fig 4 as follows.

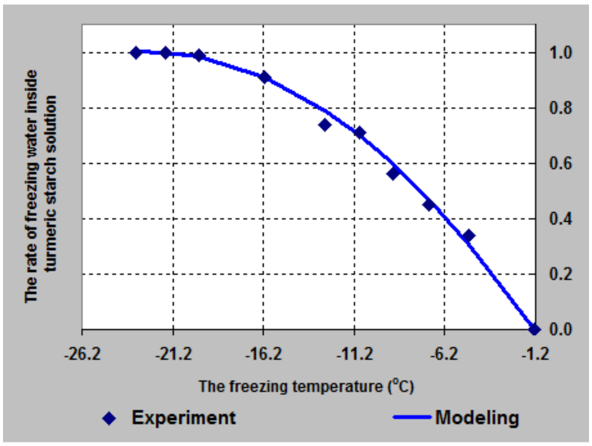

Figure 4*. Relationship between the rate of freezing water and the freezing temperature during the freezing process of turmeric starch solution.*

Test compatibility of the mathematical model (16) compared with experimental data is error of the mathematical model (16) with experimental data. It was examined by the equation (18) [2]:

$$Er = \frac{|\omega_E(T_{ai}) - \omega_M(T_{ai})|}{|\omega_E(T_{ai})|} \quad (18)$$

The maximum error of the mathematical model (16) is determined by equation (19)

$$Er_{max} = \frac{\max\left\{\left|\omega_E(T_{ai}) - \omega_M(T_{ai})\right|\right\}}{\left|\omega_E(T_{ai})\right|} \quad (19)$$

$$Er_{max} = \frac{|0.6 - 0.56|}{0.6}.100\% = 3.714\%$$

It was obvious that the mathematical model (16) was completely compatible with experimental results. Because of the maximum error of mathematical model (16) with experimental data Er_{max} = 3.714%, it was smaller than 5% [3-4]. Therefore, the mathematical model (16) can completely use of describing kinetic for the freezing process of turmeric starch solution [7].

Table 4 and Fig 4 are foundation to determine the optimal freezing temperature of turmeric starch solution. When water is completely frozen (ω = 1 or 100%), the temperature of turmeric starch solution reaches the optimal freezing temperature of -21.6^{0}C. For this reason, these research results allow to set up technology mode of freezing stage of turmeric starch solution in freeze drying process in order to make products that have good quality.

5. CONCLUSION

This study built mathematical model (equation (16)) to determine the rate of freezing water inside turmeric starch solution according to the freezing temperature of turmeric starch solution. The mathematical model (16) was completely compatible with experimental results. Because of the maximum error of mathematical model (16) with experimental data Er_{max} = 3.714% (under 5%). Therefore, it can completely use to describe kinetic as well as establish technology mode of the freezing stage of turmeric starch solution in freeze drying process. When water is completely frozen (ω = 1), the optimal freezing temperature of turmeric starch solution reaches -21.6^{0}C.

NOMENCLATURE

$\omega \in [0,1]$: Rate of freezing water

ω_E: Rate of freezing water determined by experimental method

ω_M: Rate of freezing water determined by mathematical model

W_o = 0.44 = 44% Initial moisture of turmeric starch

c_n = 4184.7 + 2.74T (J.kg^{-1}.K^{-1}) Specific heat of water

c_{nd} = 2090 + 7.79T (J.kg^{-1}.K^{-1}) Specific heat of ice

c_{ck} = 1800 + 1.9625T – 0.0593T^2 (J.kg^{-1}.K^{-1}) Specific heat of the dry matter inside turmeric starch

T_{kt} = -1.27^{0}C Freezing point of water inside turmeric starch solution

T_s (^{0}C): Surface temperature of turmeric starch solution in tray

T_c (^{0}C): Center temperature of turmeric starch solution in tray

T_0 (^{0}C): Initial temperature of turmeric starch solution in tray

$T_a = (T_d + T_c)/2$ (^{0}C): Average temperature of turmeric starch solution in tray

U (V): Number of voltmeter

I (A): Number of amperemeter

τ (s): Heat supply time

λ (W.m^{-1}.K^{-1}): Thermal conductivity coefficient of turmeric starch solution in tray

λ_0 (W.m^{-1}.K^{-1}): Thermal conductivity coefficient of inox tray

α (W/(m^2.K)): Heat emission coefficient of freezing environment

ρ (kg.m^{-3}): Density of turmeric starch solution in tray

L = 333601.5 + 1.054T – 0.000021T^2 (J.kg^{-1}): Latent heat of freezing of water

δ = 2R (m): Thickness of turmeric starch solution in tray

δ_0 (m): Thickness of inox tray

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REFERENCES

[1] Dzung N.T, et al.**,** (2012a). Building the Method to Determine the Rate of Freezing Water of Penaeus Monodon, Carpathian Journal of Food Science and Technology, 4(2), 2012, 28-35.
[2] Dzung N.T, et al.**,** (2012b). Building The Mathematical Model To Determine The Technological Mode For The Freezing Process Of Basa Fillet In ĐBSCL Of Vietnam By Experimental Method, Journal of Engineering Technology and Education, The 2012 International Conference on Green Technology and Sustainable Development (GTSD2012)
[3] Dzung N.T., (2014). 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, 7(2): 403-412.
[4] D. R. Heldman, Daryl B. Lund, (1992). Handbook of Food Engineering, Marcel Dekker New York – Basel – Hong Kong 1992, 3550 p.
[5] Gebhart B., (1992). Heat Conduction and Mass Diffusion, McGraw – Hill, New York.
[6] Figura LO, Teixeira AA (2007). Food Physics: Physical properties Measurement and Application, Germany, 554. http:// mechmath.org/books /82246
[7] Holman J., (1992). Heat Transfer, McGraw – Hill, New York.

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