CARPATHIAN JOURNAL OF FOOD SCIENCE AND TECHNOLOGY

journal homepage: **http://chimie-biologie.ubm.ro/carpathian_journal/index.html**

BUILDING AND SOLVING THE MATHEMATICAL MODEL OF TRANSIENT HEAT TRANSFER DURING THE PEANUT ROASTING PROCESS TO DETERMINE THE ROASTING PARAMETERS

Linh T.K. Vu[1], Phu Quang Pham[2], Dao Thi Anh Phan[1], Dzung Tan Nguyen[1]✉

[1]*Department of Food Technology, Faculty of Chemical and Food Technology, HCMC University of Technology and Education, No 01-Vo Van Ngan Street, Thu Duc City, Ho Chi Minh City, Viet Nam.*
[2]*Industrial University of HCMC*
✉*tandzung072@hcmute.edu.vn*

https://doi.org/10.34302/crpjfst/2022.14.4.6

Article history:
Received
14 January 2022
Accepted
29 September 2022
Published
December 2022

Keywords:
Roasting;
Roasting process;
Roasting technology;
Roasting peanuts;
Peanuts.

ABSTRACT
In this study, a mathematical model to describe the transient heat transfer of peanut roasting process was established to determine the relationship among the center and surface temperatures of peanuts, and the roasting time. The results were used to simulate the temperature gradient of peanuts over roasting time as well as to establish the technological mode for the peanut roasting process. Besides, the obtained results could be used to calculate and design a peanut roasting system. The results of the mathematical model established the suitable roasting conditions for peanuts as follows: the roasting temperature was 100°C and the roasting time was 25 minutes. At these conditions, the peanut product after roasting had bright yellow color, 100% of seed coats were peeled off with the ratio of broken grains was as low as 1.2%, and the sensory value of products was very good.

1. Introduction

Peanut (*Arachis hypogaea L.*), along with legume and Pea (*Pisum sativum L.*), is part of the legume family. It provides abundant protein in the diet and has great health benefits. Peanut is used to make many delicious dishes such as roasted with salt, dry roasted, boiled, or even eaten raw. In addition, peanut can be used to make butter, candy, ... Therefore, supplementing peanut in the diet was recommended to support good health (Smyth, et al., 1998; Smith, et al., 2014). Peanut has many benefits such as:

Improve fertility: Peanut contains high content folic acids, which are essential for women's fertility. The literature shows that women consuming a daily intake of 400 micrograms of folic acids before and during early pregnancy could reduce the baby's risk of neural tube defects after birth by 70% (Arzandeh and Jinap., 2011; Smith, et al., 2014).

Figure 1. Peanuts grown in the Southeast of Vietnam with pods removed

Support blood circulation: A quarter cup of peanuts (about 30 grams) can provide 35% of the required amount of manganese for the body. Manganese is a mineral that plays an important role in fat and carbohydrate metabolisms, calcium absorption and blood sugar regulation (Smith, et al., 2014).

Reduce the risk of cognitive impairment: according to Martins et al ., (2017), high niacin foods like peanuts reduce the risk of Alzheimer's disease by at least 70%. A quarter cup of peanuts a day can provide efficient daily amount of niacin.

Protect against cancer: A form of phytosterol called beta-sitosterol (SIT) is found abundantly in some vegetable oils, such as peanut oil. Phytosterols not only protect against cardiovascular disease by interfering with cholesterol absorption but also protect the body against cancer by inhibiting the growth of tumors (Arzandeh and Jinap., 2011).

Reduce the risk of weight gain: Peanut can also help the body lose weight. According to Martins et al,. (2017), those who ate peanut at least twice a week were less likely to gain weight than those who almost never ate peanuts.

It can be seen that peanuts are rich in nutrients that are good for human health. However, due to the high nutrient and moisture contents, fresh peanuts are susceptible to mold development if stored incorrectly (M. Gürses, 2006). Therefore, the peanuts are prone to be contaminated with aflatoxin, a mycotoxin produced naturally after being molded. Aflatoxins are known to be extremely toxic and highly carcinogenic (Dzung N.T, et al., 2021). Therefore, moldy peanuts should absolutely not to be eaten.

Currently, the food industry has used peanuts as raw materials to make several products for trade and export. Most of current processes have the peanuts roasted to remove the contaminated aflatoxins and microorganisms, to change the color and taste, and to improve the texture as well as the sensory value of the products. Therefore, there have been many studies on the peanut roasting such as those of Smyth, et al (1998), Arzandeh and Jinap (2011), M. Gürses (2006), Smith, et al (2014), Martins, et al,. (2017). These studies were mainly conducted by experiments under specific conditions to determine the appropriate roasting conditions. Nevertheless, the generalization of the peanut roasting process to apply in all conditions of production has not been concerned. Therefore, in this study, the building and solving a mathematical model of heat transfer for the peanut roasting process were conducted to determine the optimal roasting conditions. The obtained results could be used to apply in actual production to produce high quality roasted peanuts for trade and export.

2. Building and solving a mathematical model describing the roasting process

2.1. Assumptions

- *System analysis approach*

- Qualified peanuts were placed in a roasting pan with $T_e = 100^0C$ = const (equal to evaporation). During the roasting process, the peanuts must be stirred continuously so that the seeds were evenly cooked and not burned.
- Stirring time was about 30 minutes.
- After roasting, peanuts must meet the following standards: the seed were uniformly cooked and not burned, not broken, had pale yellow and delicious taste.
- 100 random peanut seeds (Figure 1) were observed to model the heat transfer problem. The results showed that seeds with cylindrical shape and spherical shape (15%) were the majority (75% and 15%, respectively), and the rest were in different shapes (10%). Because of the highest percentage of the cylindrical seeds, it was possible that the peanut was approximate to the cylindrical shape to build the heat transfer mathematical model.
- The ratio of length to diameter (*l/d*) of 100 cylindrical particles were measured, and the results are shown in Table 1.

Table 1. The ratio of the length (path of birth) to the diameter of the cylindrical peanut

l \ *d*	5	6	7
10	20%	11%	5%
12	5%	45%	2%
15	2%	2%	4%

Results in Table 1 show that peanuts with size of 6 x 12 mm were the majority (45%). Therefore, to calculate the heat transfer for the roasting process, a peanut seed model can be considered as a cylinder with radius $2R = d = 6$ mm = 6.10^{-3} m and length $l = 2h = 12$ mm = 12.10^{-3}m.

- *Modeling the roasting process of peanut by an object model*

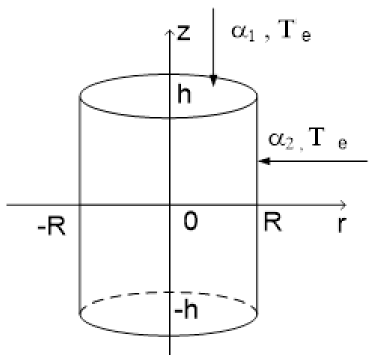

Figure 2. The object model of a peanut

- The object model was a solid cylinder with length $l = 2h = 12$ mm, diameter $d = 2R = 6$ mm, the coordinate axis was at the center of the object.

- *The thermophysical properties affecting the roasting of peanut*

- The peanut had the initial temperature evenly distributed and equal to the ambient temperature T_0= const ($\tau = 0$).

- At the beginning of the process ($\tau > 0$), the temperature of roasting medium was $T_e \neq T_0$.

- Heat emission coefficient of roasting environment on the two bottom surfaces was α_1, heat emission coefficient of the environment surrounding the cylinder was α_2. Due to the continuous roasting process, it can be inferred that $\alpha_1 = \alpha_2 = \alpha$ (Gebhart B., 1992).

- Peanuts had thermophysical properties as folows: specific heat capacity c_p (J/(kg.K)), density ρ (kg/m^3), thermal conductivity λ (W/(m.K)), thermal diffusivity a (m^2/s), the residual water content W (%), the critical residual water content W_c (%), and the oil content M (%). These parameters were determined in Table 2.

2.2. Building the mathematical model

Peanut had no internal heat source ($q_v = 0$). Based on the energy balance equation, the heat transfer model was established as follows (Luikov, 1975; Holman J., 1992):

$$\begin{cases} \dfrac{\partial T}{\partial \tau} = a\left(\dfrac{\partial^2 T}{\partial r^2} + \dfrac{1}{r}\dfrac{\partial T}{\partial r} + \dfrac{\partial^2 T}{\partial z^2}\right) \\ T = T(r, z, \tau);\ -R \le r \le R;\ -h \le z \le h \end{cases} \quad (1)$$

Initial-boundary value conditions:

- Initial conditions:

$$T(r, z, 0) = T_0 = \text{const} \quad (2)$$

- Peanut roasting temperature:

$$T_e = \text{const} \quad (3)$$

- Boundary conditions:

$$\frac{\partial T(R, z, \tau)}{\partial r} = -\frac{\alpha}{\lambda}\left[T(R, z, \tau) - T_e\right] \quad (4)$$

$$\frac{\partial T(r, h, \tau)}{\partial z} = -\frac{\alpha}{\lambda}\left[T(r, h, \tau) - T_e\right] \quad (5)$$

$$\frac{\partial T(0, z, \tau)}{\partial r} = \frac{\partial T(r, 0, \tau)}{\partial z} = 0 \quad (6)$$

2.3. Solving the mathematical model

Separation of variables (the Fourier method) were used to solve the system of equations (1) to (6), the root of a dimensionless temperature θ was found as follows:

$$\theta = \frac{T(r, z, \tau) - T_e}{T_o - T_e} =$$

$$\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} A_n A_m P_{nm} \exp\left[-\left(\mu_n^2 Fo_R + \mu_m^2 Fo_h\right)\right] \quad (7)$$

where:

$$P_{nm} = J_o\left(\mu_n \frac{r}{R}\right)\cos\left(\mu_m \frac{z}{h}\right) \quad (8)$$

$$A_n = \frac{2.J_1(\mu_n)}{\mu_n\left[J_o^2(\mu_n) + J_1^2(\mu_n)\right]} \quad (9)$$

$$A_m = \frac{2.\sin(\mu_m)}{\mu_m + \sin(\mu_m).\cos(\mu_m)} \quad (10)$$

Bi: Biot number

$$Bi_R = \frac{\alpha R}{\lambda} \quad (11)$$

$$Bi_h = \frac{\alpha h}{\lambda} \quad (12)$$

μ_n - roots of specific equation (13)

$$\frac{J_0(\mu_n)}{J_1(\mu_n)} = \frac{\mu_n}{Bi_R} \quad (13)$$

μ_m - roots of specific equation (14)

$$\cot an(\mu_m) = \frac{\mu_m}{Bi_h}$$

or $\mu_m \tan\mu_m = Bi_h$ (14)

Fo: Fourier number

$$Fo_R = \frac{a\tau}{R^2} \quad (15)$$

$$Fo_h = \frac{a\tau}{h^2} \quad (16)$$

Thermal diffusivity of the peanut:

$$a = \frac{\lambda}{c_p \rho}, \text{ m}^2/\text{s} \quad (17)$$

$J_0(\mu_n)$, $J_1(\mu_n)$: Bessel functions type 1 of the zero and first order**.**

$$J_0(x) = 1 - (\frac{1}{2}x)^2 + \frac{(\frac{1}{2}x)^4}{1^2.2^2} - \frac{(\frac{1}{2}x)^6}{1^2.2^2.3^2} + \frac{(\frac{1}{2}x)^8}{1^2.2^2.3^2.4^2} - ... \quad (18)$$

$$J_1(x) = -J_0'(x) = \frac{1}{2}x - \frac{(\frac{1}{2}x)^3}{1^2.2} + \frac{(\frac{1}{2}x)^5}{1^2.2^2.3} - \frac{(\frac{1}{2}x)^7}{1^2.2^2.3^2.4} + ... \quad (19)$$

Some equations to determine the thermophysical properties of peanuts affecting the roasting process are as follows (D.R. Heldman and Daryl B. Lund, 1992; Figura and Teixeira, 2007):

- The average critical residual water content of the peanut was $W_c = (8 \div 9)\%$, hence it should be able to choose $W_c = 8\%$.
- Peanut roasting temperature was T = 100 ^{0}C = 373.15 K
- Density of peanut:

$\rho = 1176 + 500 \times W_c$, kg.m^{-3} (20)

- Specific heat capacity of peanut was approximate according to the following equation:

$c_p = 1753.18 + 13.6 \times M$
$+ (0.95 + 0.019 \times M)(T - 291)$, J.kg^{-1}.K^{-1} (21)

Where: M is the average oil content in peanuts (M = 50%).

- Thermal conductivity of peanut was approximate according to the following equation:

$\lambda = 1.367 \times (0.007 \times W_c + 0.86) \times [0.42 \times 10^{-6} \times \rho$
$\times (273.15 + T) + 0.0254]$, W.m^{-1}.K^{-1} (22)

- Heat emission coefficient of roasting environment α (short contact when roasting) was calculated by the following equation:

$$\alpha = \frac{2}{\sqrt{\pi}} \sqrt{\frac{\lambda c_p \rho}{\tau_{tx}}} \quad (23)$$

- Maximum contact time when roasting was calculated as follows:

$$\tau_{tx}^{max} = 381.5 \frac{\delta^2}{a} \quad (24)$$

3. Materials and methods

3.1. Materials

Peanuts grown in the Southeast region of Vietnam were used in this study. The peanuts had their pod removed (Figure 1), roughly shaped like cylinders with average diameter $d = 2R = 6.10^{-3}$ m and height $l = 2h = 12.10^{-3}$ m.

3.2. Apparatus

- In this study, the roasting process was conducted by using a rotary roster equipment GD20 from Grande, manufactured in 2020 (Figure 3).
- The GD20 roasting device automatically measures and controls the technological parameters such as roasting temperature and time, the rotation speed of the drum, hence hot air could evenly contact all surfaces of the seeds, leading to a uniform temperature and shorter roasting time.

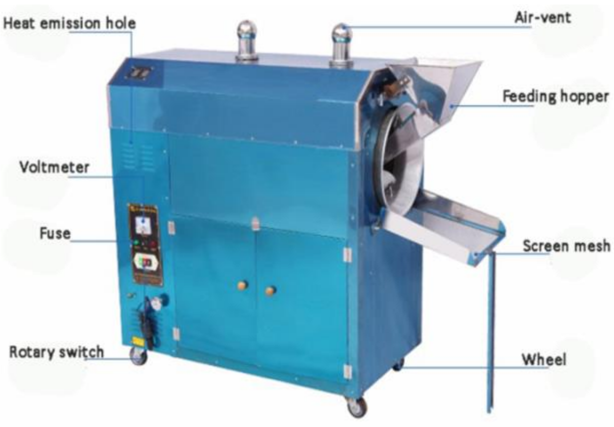

Figure 3. The peanut roaster

3.3. Methods

- In this study, the system analysis approach was used to build the mathematical model for the roasting process (Dzung et al., 2012a). In addition, modeling and optimization methods were used to build and solve the mathematical model for the peanut roasting process (Dzung et al., 2012b).

- Temperature of roasted materials were determined by two methods, experimental method and calculation method from the mathematical model.

- Mathematical tools and softwares such as Microsoft Excel 2020, Matlab 7.0 and Visual Basic 8.0 were used to build and solve the mathematical model (Dzung et al., 2012b).

4. Results and discussions

4.1. Determine the thermophysical properties

The thermophysical properties of peanuts were estimated by using equations (11), (12), (20) - (24). Results are summarized in Table 2.

Table 2. Thermophysical properties of peanuts

Parameter	Unit	Value
R	m	3×10^{-3}
h	m	6×10^{-3}
T_e	K	373.15
W_c	%	8.0
M	%	50
ρ	$kg.m^{-3}$	1216
ρ_v	$kg.m^{-3}$	854
λ	$W.m^{-1}.K^{-1}$	0.254
c_p	$J.kg^{-1}.K^{-1}$	1838.8
a	$m^2.s^{-1}$	11.36×10^{-8}
τ_{tx}^{max}	s	30224
τ_{tx}	s	1800
α	$W.m^{-2}.K^{-1}$	20.04
Bi_R	-	0.2367
Bi_h	-	0.4734

By the bisection algorithm programmed by the Visual Basic 8.0 software, roots of specific equations (13) and (14) were found. These roots (μ_m, μ_n) were then substituted into equation (7). The results showed that: series of numbers (7) converged quickly to 0 when n, m $\geq$ 2. That was:

$$\sum_{n=2}^{\infty}\sum_{m=2}^{\infty} A_n A_m P_{nm} \exp\left[-\left(\mu_n^2 Fo_R + \mu_m^2 Fo_h\right)\right] \to 0$$

Therefore, the roots of specific equation (13) and (14) were as follows: μ_n = 0.6506 (n = 1); μ_m = 0.6282 (m = 1).

4.2. Determine the peanut roasting temperature

- The roots of specific equations (13) and (14) (μ_n = 0.6506 (n = 1), μ_m = 0.6282 (m = 1)) and the thermophysical properties in Table 2 were substituted into equation (7). Visual Basic language programmed in Macro of Microsoft Excel 2020 was used to calculate the center temperature $T(0,0,\tau)_M$ and surface temperature $T(R,h,\tau)_M$ of peanut. The results are shown in Table 3 and Table 4.

- The experiments of the peanut roasting process were also carried out to determine the center temperature $T(0,0,\tau)_E$ and surface temperature $T(R,h,\tau)_E$ of the peanuts. The experimental results are also shown in Table 3 and Table 4.

Table 3. Variation of center temperature of peanuts according to roasting time

τ (minutes)	$T(0,0,\tau)_M$	$T(0,0,\tau)_E$	Er (%)
0.0	30.00	30	0.00
1.5	54.66	47.6	14.82
3.0	**75.03**	**65.2**	**15.07**
4.5	86.25	76.6	12.60
6.0	92.43	86.7	6.61
7.5	95.83	90.5	5.89
9.0	97.70	95.2	2.63
10.5	98.74	96.4	2.42
12.0	99.30	97.6	1.75
13.5	99.62	98.5	1.13
15.0	99.79	98.7	1.10
16.5	99.88	99.1	0.79
18.0	99.94	99.2	0.74
19.5	99.96	99.4	0.57
21.0	99.98	99.5	0.48
22.5	99.99	99.6	0.39
24.0	99.99	99.7	0.29
25.5	100.00	100	0.00
27.0	100.00	100	0.00
28.5	100.00	100	0.00
30.0	100.00	100	0.00

Table 4. Variation of surface temperature of peanuts according to roasting time

τ (minutes)	$T(R,h,\tau)_M$	$T(R,h,\tau)_E$	Er (%)
0.0	30.00	30	0.00
1.5	**67.44**	**58.2**	**15.87**
3.0	82.07	71.1	15.43
4.5	90.12	82.3	9.51
6.0	94.56	87.6	7.95
7.5	97.01	91.5	6.02
9.0	98.35	95.2	3.31
10.5	99.09	96.6	2.58
12.0	99.50	97.8	1.74
13.5	99.72	98.3	1.45
15.0	99.85	99.4	0.45
16.5	99.92	99.5	0.42
18.0	99.95	99.6	0.36
19.5	99.97	99.7	0.28
21.0	99.99	99.8	0.19
22.5	99.99	99.9	0.09
24.0	100.00	100	0.00
25.5	100.00	100	0.00
27.0	100.00	100	0.00
28.5	100.00	100	0.00
30.0	100.00	100	0.00

- From the data in Table 3, Matlab 8.0 software was used to simulate the variation in center temperature of peanuts according to roasting time. The results are shown in Figure 4.

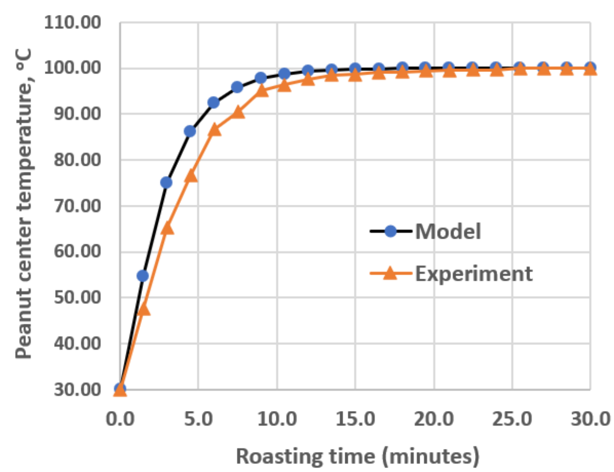

Figure 4. The relationship between center temperature of peanuts and roasting time

- From the data in Table 4, Matlab 8.0 software was used to simulate the varation in center temperature of peanuts according to roasting time. The results are shown in Figure 5.

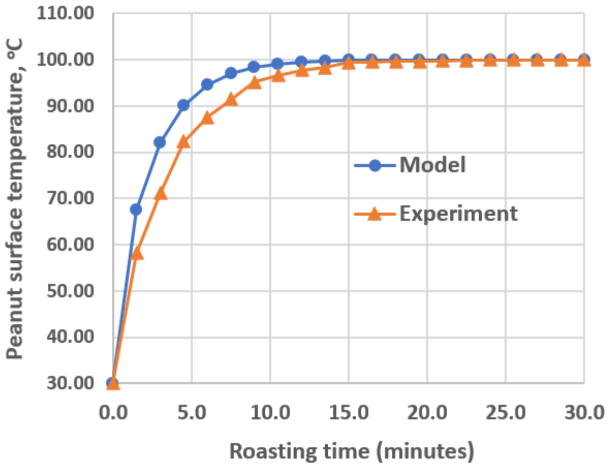

Figure 5. The relationship between surface temperature of peanuts and roasting time

- Evaluate the error of model: the term Er (%) was used to express the error between the calculated data and the experimental data. The error of the mathematical model was determined by the following expression:

$$Er = \frac{\left|T(r,z,\tau)_M - T(r,z,\tau)_E\right|}{T(r,z,\tau)_E}.100\% \quad (25)$$

- Table 3 shows that the maximum error between $T(0,0,\tau)_M$ - center temperature of peanuts calculated from the model (7), and $T(0,0,\tau)_E$ - temperature of peanuts determined by experiments was 15.07% when τ = 3.0 minutes (Figure 4). Similarly, the results in Table 4 also show that the error between $T(R,h,\tau)_M$ - surface temperature of peanuts calculated from the model (7), and $T(R,h,\tau)_E$ - surface temperature of peanuts determined by experiments was 15.87% when τ = 1.5 minutes (Figure 5). These errors could be attributed to the relatively cylindrical shape of peanuts. Besides, the thermophysical properties of peanuts were not constant but varied with roasting temperature. Moreover, instead of being a moderate unstable heat transfer, the first stage of roasting was a complicated transient heat transfer; the input energy was used to heat peanuts from the initial temperature to the roasting temperature to perform the roasting process according to the required method.

- It can be seen in Figure 4 and Figure 5 that as the roasting time increased, the errors decreased gradually. This is because the complicated transient heat transfer converted into the stable heat transfer because at this stage the thermophysical properties of peanuts had reached constant values and the moisture evaporation at the peanut surface was no longer similar to that at the initial roasting period.

- Results from Table 3, Table 4, Figure 4 and Figure 5 show that from roasting time τ = 1.5 mins to τ = 4.5 mins, the errors between the experimental data and the calculated data are relatively high. However, as analyzed above, the causes leading to the errors of the mathematical models were acceptable. Therefore, the mathematical models from (1) to (19) were suitable to describe the heat transfer of the roasting process of peanuts. These models could be used to calculate and determine the appropriate conditions for the roasting process, and be applied to the actual production.

4.3. Sensory evaluation of roasted peanuts

Raw peanuts were roasted at T_e = 100°C at three differents roasting times of 25 minutes; 27.5 minutes and 30 minutes to evaluate their color, peeling capacity of seed coats and ratio of broken of peanut seeds after roasting. The results are shown in Figures 6 and Table 5.

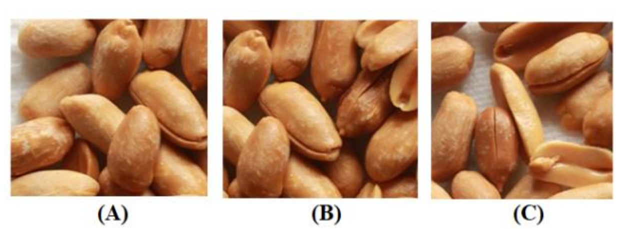

Figure 6. Roasted peanut seeds

(A)– Peanut seeds roased for 25 minutes; (B)- Peanut seeds roasted for 27.5 minutes; and (C)– Peanut seeds roasted for 30 minutes.

Results from Table 5 show that at roasting time of 25 minutes, the products had bright yellow colour with 100% of seed coats peeled off (Figure 6A) and the lowest ratio of broken seeds (only 1.2%). On the other hand, as being roasted for 27.5 minutes and 30 minutes, the products had darker color with 100% of seed coats peeled off (Figure 6B and 6C), but the ratio of broken seeds increased by 27.82% and 46.31%, respectively. This was because when the products were fully cooked, prolonging roasting time at 100 °C would cause the burning or decomposing of peanut chemical components, resulting in a significant decline in peanut quality.

Table 5. Characteristics of peanut after roasting

Roasting time, τ (minutes)	Color	Peeling capacity of seed coats, (%)	Ratio of broken seeds (%)
25.0	Bright yellow	100	1.20
27.5	Gray yellow	100	27.82
30.0	Dark yellow	100	46.31

Another roasting experiment was conducted at roasting temperatures of 105°C for 20 minutes. Results show that the peanuts and seed coats had burnt color (Table 6). In contrast, roasting peanuts at lower 95°C would lead to a longer roasting time of 35 minutes to remove the seed coats, but final products also had dark yellow color. Therefore, it was recommended to choose the roasting temperature of T_e = 100°C.

Table 6. Color of roasted peanuts at different roasting conditions

Peanut roasting temperature, °C	Roasting time, τ (minutes)	Color roasting peanut (product)
95.0	35	No bright yellow
100.0	25	Bright yellow
105.0	20	Black

4.4. Determine the roasting conditions for peanuts

From the results of building and solving the mathematical models (1) to (19) in Table 3, Table 4, Figure 4, Figure 5 as well as experimental verification in Table 5, Table 6 and Figure 6, the roasting conditions for peanuts were established as following:

- Roasting temperature was 100°C;
- Roasting time was 25 minutes.

After roasting at these conditions, the temperature of roasted peanuts calculated from the mathematical model was consistent with the experimental temperature. The roasted peanuts had good sensory quality with bright yellow color, 100% of seed coats were peeled off and the proportion of broken seeds was as low as 1.2%. Hence, these roasting conditions could be potentially applied in practice.

5. Conclusions

- Peanut roasting process was modeled in this study using mathematical models from (1) to (6). This was a model of transient heat transfer that accurately expressed the nature of the complex physical chemistry of peanut roasting process.
- Solving the mathematical models from (1) to (6) resulted in the roots of the mathematical model (7). Experimental verification showed that mathematical model (7) was completely suitable to describe the roasting process for peanuts. Therefore, model (7) could be used to calculate the roasting conditions as

well as to calculate, design and fabricate a roasting equipment.

- The roasting conditions for peanuts were also established in this study as follows: roasting time was 25 minutes; roasting temperature was 100°C. After roasting at these conditions, the seed coats were completely peeled off and the proportion of broken seeds was the lowest, only 1.2%. The roasted products had a bright yellow color, the sensory quality was dramatically improved (Fig *6 (A)*).

Nomenclature

R = 0.003 m : Radius of the peanut;
h = 0.006 m : Half height of the peanut;
T_e = 100°C : Roasting temperature;
W_c = 0.8 = 8% : The critical residual water content of the peanut;
M = 0.5 = 50% : Oil content in the peanut;
c_p = 1838.8 $J.kg^{-1}.K^{-1}$: Specific heat of the peanut;
ρ = 1216 $kg.m^{-3}$: Density of the peanut;
ρ_v = 854 $kg.m^{-3}$: Density of the peanut block;
λ = 0.254 $W.m^{-1}.K^{-1}$: Thermal conductivity coefficient of the peanut;
α = 20.04 $W.m^{-2}.K^{-1}$: Heat emission coefficient of roasting environment;
a = 11.36×10^{-8} $m^2.s^{-1}$: Thermal diffusivity of the peanut;
τ (s) roasting time;
τ_{tx} = 1800s : Short contact time when roasting;
τ_{tx}^{max} = 30224s : Maximum contact time when roasting;
Bi_R, Bi_h: Biot number of the peanut;
Fo_R, Fo_h: Fourier number of the peanut;

6. References

Arzandeh and Jinap., (2011). Effect of initial aflatoxin concentration, heating time and roasting temperature on aflatoxin reduction in contaminated peanuts and process optimization using response surface modeling. *International Journal of Food Science and Technology*. 46, 485-491.

D.R. Heldman, Daryl B. Lund, (1992). Handbook of Food Engineering, Marcel Dekker New York – Basel – Hong Kong 1992, 3550 p

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, http://chimie-biologie.ubm.ro/carpathian_journal/Vol%204(2)%202012.pdf

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)*, http://www.engh.kuas.edu.tw/004_ne.php?types=detail&year=2013&month=1; www.engh.kuas.edu.tw/files/ne/k9sxnp6t27.pdf

Dzung, N.T, et al**.**, (2021). Building and solving the heat transfer models to determine suitable frying conditions for instant noodles. *Carpathian Journal of Food Science and Technology*, 13(4), 105-115.

Figura, L.O., Teixeira, A.A. (2007). Food Physics: Physical properties Measurement and Application, Germany, 554. http:// mechmath.org/books /82246

Gebhart, B., (1992). Heat Conduction and Mass Diffusion, McGraw – Hill, New York.

Holman, J., (1992). Heat Transfer, McGraw – Hill, New York.

Luikov, A.V., (1975). Systems of differential equations of heat and mass transfer in capillary-porous bodies. International Journal of Heat and mass transfer.

Martins, et al,. (2017). Kinetics of aflatoxin degradation during peanut roasting. *Food Research International*. 97, 178-183.

M. Gürses., (2006). Mycoflora and aflatoxin content of hazelnuts, walnuts, peanuts, almonds and roasted chickpeas (LEBLEBI) sold in Turkey. *International Journal of Food Properties*. 9, 395-399.

Smyth, et al., (1998). Evaluation of analytical methods for optimizing peanut roasting for snack foods. *Peanut Science*. 25, 70-76.

Smith, et al., (2014). Oven, microwave, and combination roasting of peanuts: Comparison of inactivation of salmonella surrogate *Enterococcus faecium*, color, volatiles, flavor, and lipid oxidation. *Journal of Food Science*. 79, S1584-S1594.

Acknowledgments

The author thanks Head of Food Engineering and Technology Lab, Department of Food Technology, Faculty of Chemical and Food Technology, HCMC University of Technical Education, Viet Nam, for their support and help to carry out the experiments.