Dear Dr. Garey Fox

Editor in Chief: Transactions of the ASABE

I wish to submit a manuscript entitled “**Numerical analysis to predict the temperature distribution of passion fruit seeds during drying**” for possible consideration.

Finally I would like to confirm that the manuscript has been revised according to the suggestions of the Editors and Reviewers. I also hereby affirm that the content of this manuscript or a major portion thereof has not been published in a refereed journal, and it is not being submitted for publication elsewhere.

Thank you very much and I shall wait for your kind response.

Best regards,

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NUMERICAL ANALYSIS TO PREDICT TEMPERATURE DISTRIBUTION OF THE PASSION FRUIT SEEDS DURING DRYING

Highlights

- The temperature distribution occurs because there are differences in temperature on the surface and inside the passion fruit seeds biji
- Temperature distribution occurs simultaneously in all directions
- The deeper into the temperature distribution the lower
- The same pattern also occurs in the vertical and horizontal directions.

ABSTRACT. *The optimization of the drying process can be determined based on temperature distribution patterns using numerical modeling of the finite element method (FEM). This study has compiled a numerical equation FEM to predict the temperature distribution in passion fruit seeds during drying. The study was conducted using a circulating air tray dryer. Temperature distribution data on passion fruit seeds were measured using a data logger. The results showed that the numerical equation FEM approach can be used to simulate the temperature distribution of passion fruit seeds during drying quickly and accurately. This model has been validated by comparing the temperature distribution data measured in the drying chamber with FEM simulation results data with a relative error between 0.45 to 1.27%. The numerical model of the FEM is important as a reference for controlling temperature distribution during drying because this method is easy to implement and results in low errors.*

Keywords: *Drying, finite element methods, numerical equation, passion fruit seeds, temperature distribution*

Nomenclature:

Abbreviations

A	surface area (m^2)
c	air heat capacity (kJ/kg °C)
k	conductivity (W/m °C)
M	modulus

r the rate of heat flow towards the axis of the radius (m)

T temperature (°C)

t time (hour)

q heat energy (W)

V volume (m^3)

Subscripts

i radius index

j vertical direction index

k horizontal direction index

wt time index

Greek symbols

∂ differential

α heat diffusivity (m^2/dtk)

θ the rate of heat flow towards the vertical direction

ϕ the rate of heat flow towards the horizontal direction

Δ ingredient

INTRODUCTION

Passion fruit (*Passiflora edulis*) is one of the most consumed fruits because it is a source of vitamins and minerals that are beneficial to human health (Amaral et al., 2016; Bezerra et al., 2015; Santos, et al., 2020). It can be consumed in fresh or processed form (Do Nascimento et al., 2016; Catelam et al., 2020). Passion fruit plants can grow easily in the tropics or subtropics (Allardyce et al., 2017; Atukunda, et al., 2018). Two types of passion fruit are cultivated in Indonesia, namely yellow passion fruit (*Passiflora edulis f. Flavicarpa*) and purple passion fruit (*Passiflora edulis Sims f.*

Flavicarpa) (Ansar et al., 2020) (Figure 1).

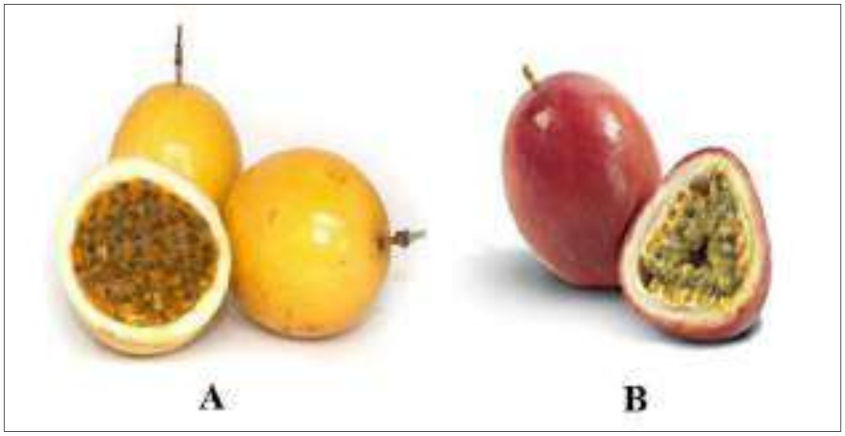

Figure 1. Yellow passion fruit (A) and purple passion fruit (B)

Nowadays, passion fruit is generally processed into syrup (Febrina et al., 2017; Ansar et al., 2019). The manufacture of the syrup has the most important economic impact on the passion fruit market because world demand continues to grow to date (Seixas et al., 2014; Figueiredo et al., 2013). Processing of passion fruit into syrup produces solid waste in the form of seeds between 4-12% of the total fruit mass (Oliveira et al., 2017; Araujo, et al., 2019). This fruit waste can be reused because it has oil and protein content, especially linoleic acid up to 70% (Malacrida & Jorge, 2012; Silva et al., 2015; Silva et al., 2019). Fatty acids from passion fruit seeds have the potential to be applied in the food, pharmaceutical, cosmetics, and energy industries (Oliveira et al., 2017; Yang et al., 2019).

Unripe passion fruit seeds generally grow sprouts, so they have a short shelf life (Vaquiro et al., 2016; Barrales et al., 2015; Bidgolya et al., 2018). To maintain the shelf life of this passion fruit, it must be dried until it reaches 14% water content so that it lasts longer before being extracted into the oil (Chen et al., 2011; Leao et al., 2014; Pereira et al., 2015). An effective drying method for grains can be carried out based on a temperature distribution mechanism to optimize the evaporation of water content (de Menezes et al., 2013; Castro et al., 2018).

Research about temperature distribution using the numerical equation of the finite element method (FEM) approach has been widely reported (Bezerra et al., 2015; Takalkar et al., 2018).

However, existing scientific publications generally still use a one-dimensional numerical equation to describe the process of drying grain (Vaquiro et al., 2016; Jinshah & Balasubramanian, 2020; Zhoua et al., 2018) have simulated temperature distribution on one dimension using FEM. While Zhou et al. (2015) have simulated a one-dimensional temperature distribution using the FEM with graph visualization. Another temperature distribution analysis has been carried out by Monjezi & Campbell (2016) at each point of the two-dimensional plate using the FEM with the system state considered a steady-state.

Temperature distribution during drying cannot be observed directly (Shinong et al., 2020), but can only be predicted and calculated using numerical modeling (Castro et al., 2018; Xiao et al., 2020). The numerical modeling that has been compiled is then simulated and displayed in a graph (Ma et al., 2019). The numerical modeling can produce valid, detailed, and comprehensive data (Essa & Mostafa, 2017; Mayer & Grof, 2020).

Research on the process of temperature distribution in seeds whose shape is not uniform during drying using a numerical equation of the FEM approach has not been found in any publication. Therefore, this research is important to describe the process of drying passion fruit seeds as a function of temperature using numerical modeling of the FEM approach. This model was used to predict the temperature distribution in passion fruit seeds during non-isothermal convective drying. Thus, the purpose of this study was to compile a numerical equation using the FEM approach to predict the temperature distribution of passion fruit seeds during drying.

MATERIALS AND METHODS

Numerical equation development

To simplify the compilation of the numerical equations of the FEM approach, then passion fruit seeds are assumed to be in the shape of a uniform ball as shown in Figure 2.

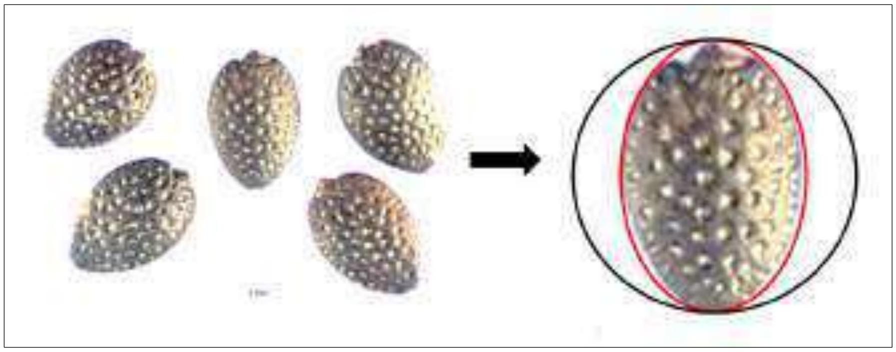

Figure 2. Purple passion fruit seeds that are assumed to have a uniform ball shape

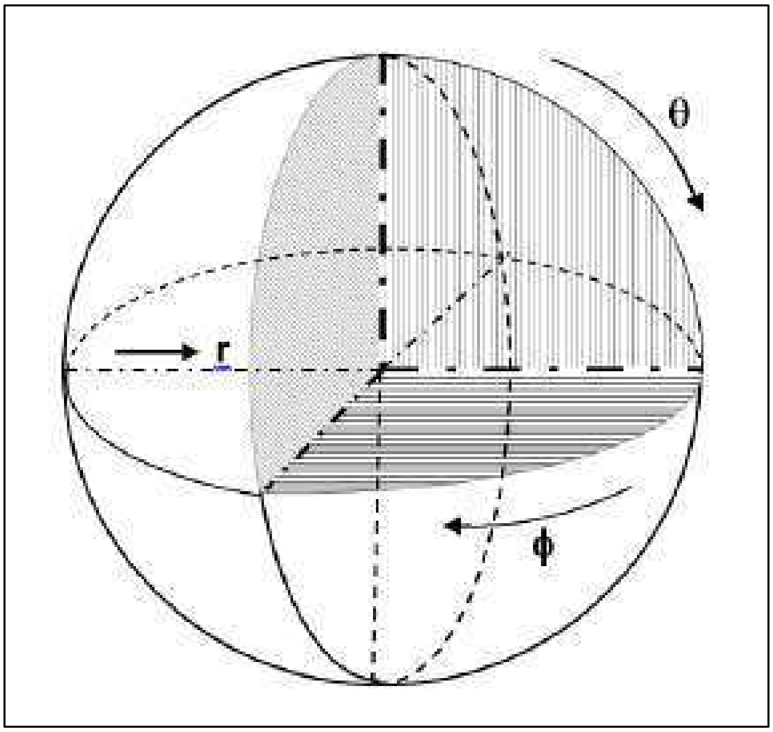

Figure 3. Modeling of three-dimensional spherical coordinate systems

By simplifying, the transformation function of the spherical coordinate system irregular (Figure 2) is simplified into a three-dimensional regular spherical coordinate system (Figure 3), so that it can be written in the form of an equation:

$$q_r A_r\big|_r + q_\theta A_\theta\big|_\theta + q_\phi A_\phi\big|_\phi - (q_r A_r\big|_{r+\Delta r} + q_\theta A_\theta\big|_{\theta+\Delta\theta} + q_\phi A_\phi\big|_{\phi+\Delta\phi}) = \Delta V \rho c_p \frac{\partial T}{\partial t} \quad (1)$$

The rate of heat flow towards the axis of the radius (r) is:

$$q_r = -k \cdot A_r \cdot \frac{\partial T}{\partial r} \quad (2)$$

The rate of heat flow towards the vertical direction (θ) is:

$$q_{\theta} = -k \cdot \frac{1}{r} \cdot A_{\theta} \cdot \frac{\partial T}{\partial \theta} \tag{3}$$

The rate of heat flow towards the horizontal direction (ϕ) is:

$$q_{\phi} = -k \cdot \frac{1}{r \sin\theta} \cdot A_{\phi} \cdot \frac{\partial T}{\partial \phi} \tag{4}$$

The results of substituting equations (2), (3), and (4) into equation (1), the equation is obtained:

$$\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta \frac{\partial T}{\partial \theta}\right) + \frac{1}{r^2 \sin^2\theta}\frac{\partial^2 T}{\partial \phi^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{5}$$

Initial condition (IC) and boundary condition (BC) equation (5) are:

IC: In all positions $T(r, \theta, \phi, t) = T_{initial} = 29{,}5\ ^{o}C$ for $t = 0$

BC: at $t > 0$ and $r = 0$; $\frac{\partial T}{\partial r} = 0$

The solution of equations (5) and BC was to use the numerical method of the FEM approach explicitly. The temperature distribution on the surface of the seeds is calculated by the equation:

$$T_{NR,j,k,wt+1} = \frac{1}{M}\left\{\left(2\Delta r - \frac{2}{(i)^2 \Delta\theta} + M\right)T_{NR,j,k} - (2\Delta r)T_{NR-1,j,k} + \left(\frac{2}{(i)^2 \Delta\theta}\right)T_{NR,j+1,k}\right\} + 2\Delta r q_{fric} \tag{6}$$

The temperature distribution in the position of the seed axis was calculated by the equation:

$$T_{i,j,k,wt+1} = \frac{1}{M}\left\{\left(1-\frac{1}{i}\right)T_{i-1,j,k} - (2-M)T_{i,j,k} + \left(1+\frac{1}{i}\right)T_{i+1,j,k} - \left(\frac{\Delta r}{(i)(\Delta\theta)}\right)T_{i,j-1,k} + \left(\frac{\Delta r}{(i)(\Delta\theta)}\right)T_{i,j+1,k}\right\} \tag{7}$$

The temperature distribution at the center position of the seeds was calculated by the equation:

$$T_{0,j,k,wt+1} = \frac{1}{M}\left\{T_{1,j,k,wt} + (M-1)T_{0,j,k,wt}\right\} \tag{8}$$

The temperature distribution of the simulation results as a function of the three-dimensional position of r, θ, and ϕ which can be calculated by the equation:

$$\bar{T}_{hit} = \frac{\rho Cp \int_0^{\pi/2}\int_0^{\pi/2}\int_0^{R} T \cdot r^2 \sin\theta \cdot dr \cdot d\theta \cdot d\phi}{\rho Cp \int_0^{V} dV} \tag{9}$$

The solution of equation (9) was to use the Trapezoidal Rule method as follows.

$$\int_0^{R} T_{i,j,k} \cdot r^2 \cdot dr = \frac{\Delta r}{2}\{(T_{0,j,k} \cdot R_0^2) + 2(T_{1,j,k} \cdot R_1^2) + 2(T_{2,j,k} \cdot R_2^2) + 2(T_{3,j,k} \cdot R_3^2) + 2(T_{4,j,k} \cdot R_4^2) +$$

$$2(T_{5,j,k} \cdot R_5^2) + 2(T_{6,j,k} \cdot R_6^2) + 2(T_{7,j,k} \cdot R_7^2) + 2(T_{8,j,k} \cdot R_8^2) + 2(T_{9,j,k} \cdot R_9^2) + (T_{10,j,k} \cdot R_{10}^2)\} = A_{j,k}$$

$$\int_0^{\pi/2} A_{j,k} \cdot \sin\theta \cdot d\theta = \frac{\Delta\theta}{2}\{(A_{0,k} \cdot \sin(0 \cdot \Delta\theta)) + 2(A_{1,k} \cdot \sin(1 \cdot \Delta\theta)) + 2(A_{2,k} \cdot \sin(2 \cdot \Delta\theta)) + 2(A_{3,k} \cdot \sin(3 \cdot \Delta\theta)) +$$

$$2(A_{4,k} \cdot \sin(4 \cdot \Delta\theta)) + 2(A_{5,k} \cdot \sin(5 \cdot \Delta\theta)) + 2(A_{6,k} \cdot \sin(6 \cdot \Delta\theta)) +$$

$$2(A_{7,k} \cdot \sin(7 \cdot \Delta\theta)) + (A_{8,k} \cdot \sin(8 \cdot \Delta\theta))\}$$

$$= B_k$$

$$\int_0^{\pi/2} B_k \cdot d\phi = \frac{\Delta\phi}{2}\{(B_0) + 2(B_1) + 2(B_2) + 2(B_3) + 2(B_4) + 2(B_5) + 2(B_6) + 2(B_7) + (B_8)\} \tag{10}$$

Sample preparation and equipment

Passion fruit seeds used in the study were obtained from purple passion fruit. The fruit is cut in half and the seeds are separated from the meat using a pulpier siever. Furthermore, passion fruit seeds are washed with water to remove the remnants of the pulp. Passion fruit seeds are drained and stored at room temperature to wait for the next process.

The equipment used is a circulated air tray type dryer with a heat source obtained from a 300 Watt electric stove (Figure 4). The main parts of the dryer include drying chamber, drying tray, electric stove, blower, and exhaust. Each component is made using industry-standard construction. The support frame is made of galvanized type iron box measuring 2.5 x 2.5 cm so that it can withstand the burden of dried material. Overall dimensions of the dryer are 100 cm long, 80 cm wide, 150 cm high, and the wheel height from the ground to the tool is 10 cm.

The inner drying chamber is insulated to reduce heat loss so that the hot air inside the drying chamber can be optimally optimized for drying. Inside the drying chamber, there are 5 shelves arranged vertically with a distance of 20 cm between the shelves to collect the dried material. The tray is made of stainless steel wire framed by wood. The electric stove is located at the bottom right side of the drying chamber. At the right end of the stove, there is a blower to encourage and circulate air in the drying chamber.

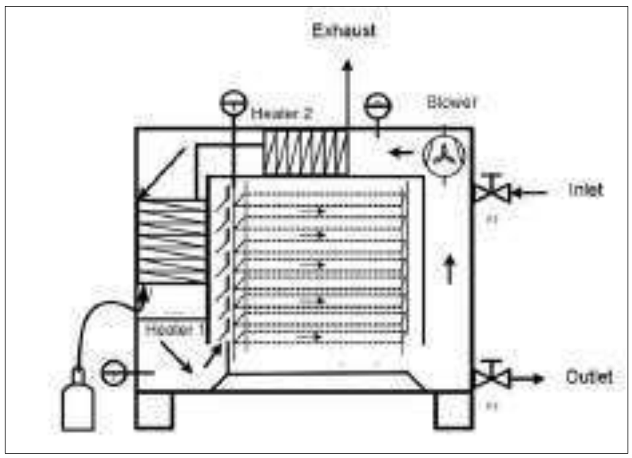

Figure 4. Sketch of a circulating air tray dryer type

Sample drying

Drying passion fruit seeds was done by placing seeds on each tray with a thickness of 1 layer. Drying is done using a temperature of 70 °C and an airflow velocity of 0.2 m/s. Hot air generated from electric stoves was used to dry the samples in a tray of 5 pieces. Some of the air was discharged through the outlet valve and some are recirculated through the heater and then returned to the drying chamber. To reduce heat loss to the environment, all parts of the drying chamber are coated with insulators. Drying was carried out for 7 hours to obtain 14% water content.

Measurement of seed temperature distribution

Seed temperature distribution data during drying is measured using a data logger. The temperature sensor is installed in one of the passion fruit seeds in each drying chamber by placing the tip of the thermocouple in the surface position and the center of the seeds. This measurement was repeated with 5 replications.

Data validation test

Data validation test used regression analysis by comparing predictive data obtained from FEM numerical model simulation results with observational data generated from measurements in the drying chamber. The closeness of the relationship between predictive data and observational data can be seen from the coefficient of determination (R^2). If the value of R^2 approaches the number one it means that there is a very close relationship (Ansar et al., 2020).

RESULTS AND DISCUSSION

Temperature distribution in the drying chamber

The measurement results of temperature distribution from time to time during the drying of passion fruit showed that the temperature distribution on each the tray had different values (Figure 5). At the beginning of drying the temperature, distribution is still uniform, but an increase occurs with increasing drying time. The biggest temperature is on the tray1, reaching 45.16°C. This is presumably because the bottom tray gets the most heat from the electric stove, so the average temperature on the bottom tray is higher than the other trays. While the average temperature on the tray no. 2, 3, 4, and 5 are 42.33; 41.45; 40.75; and 39.43 °C, respectively.

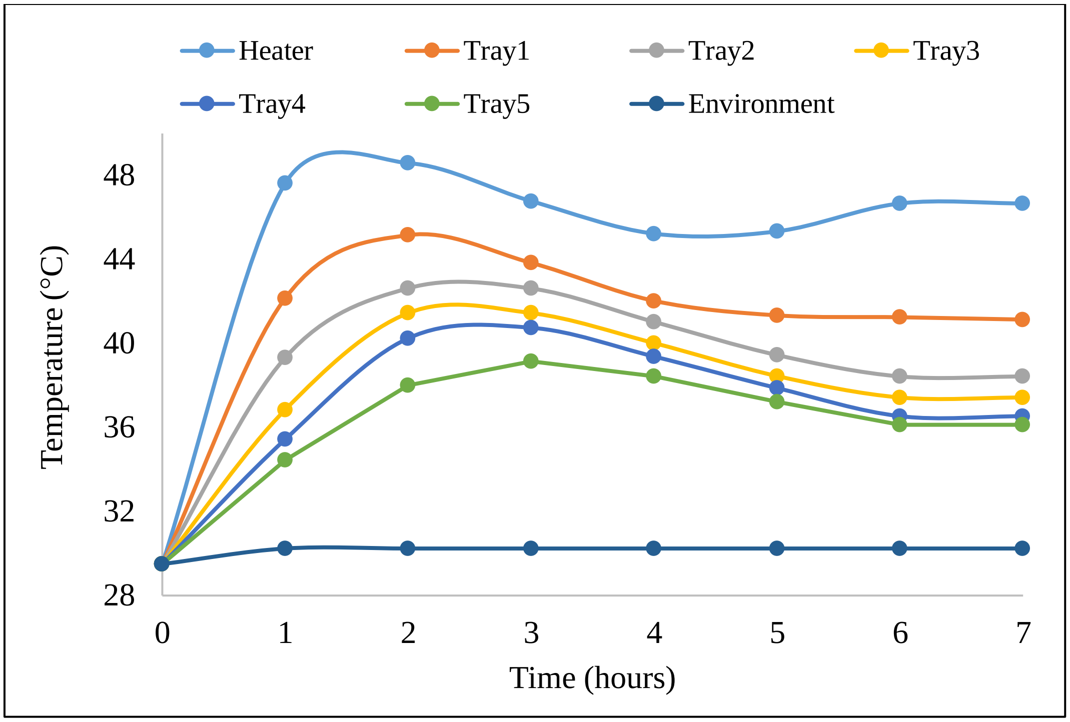

Figure 5. Temperature distribution on each tray during the drying of passion fruit seeds

In general, the drying of the tray type in this study only takes 7 hours to reduce the water content from 21% to 14.15%. This drying time is shorter when compared to the method of sun-drying which requires 10-11 hours (Shavazi et al., 2020). The same trend data has been reported by Bahadur et al. (2019) that the higher the dryer temperature, the lower the final water content produced.

Uneven airflow velocity can cause uneven temperature distribution. The higher the airflow velocity, the faster the air temperature distribution in the drying chamber. This means that the speed of airflow in the drying medium can function as a catalyst so that the temperature distribution of the seeds is also faster. The results of the study Ozakina & Kaya (2019) also reported that airflow velocity can cause a high-temperature distribution, so that the temperature distribution in the seeds is also getting bigger.

Temperature distribution in seeds

Three-dimensional temperature distribution in the passion fruit seeds during drying is shown in

Figure 6. In the figure, it appears that in the first hour there was a very rapid increase and began to fall in the second hour until towards the end of drying. Temperature distribution in the passion fruit seeds occurs because of differences in temperature and heat energy arising during drying. The same thing has been expressed by Serrano et al. (2015) that the temperature distribution of materials is strongly influenced by the coefficient of displacement of the conduction pad and the thermal diffusivity of the material.

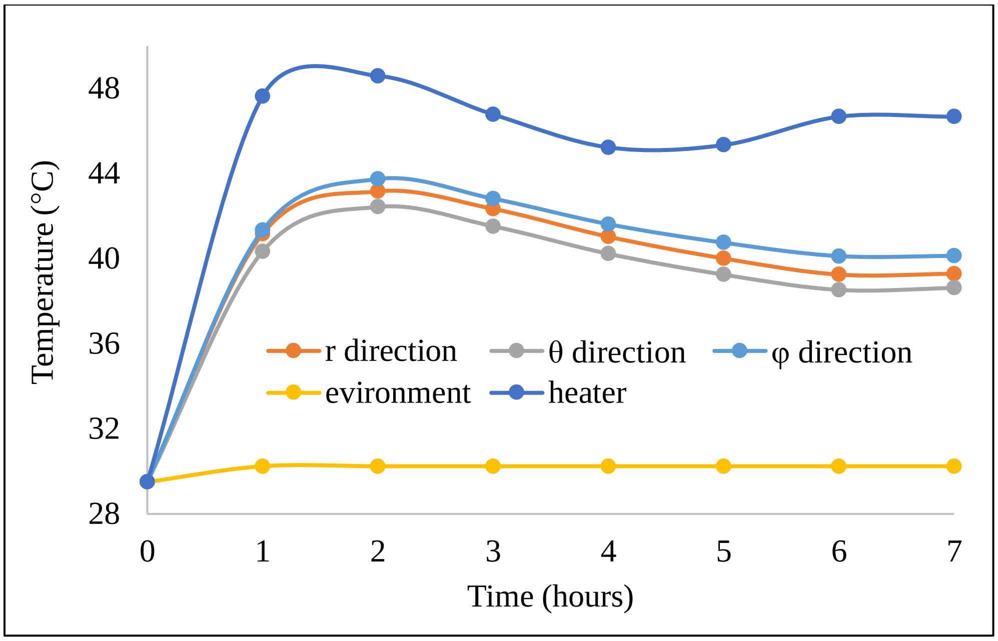

Figure 6. Three-dimensional temperature distribution in the passion fruit seeds

Three-dimensional temperature distribution of passion fruit seeds spreads from the surface of the seeds toward the center of the axis slowly until evenly distributed to all parts of the seeds. Furthermore, the temperature is distributed with an even distribution pattern in the determined boundary plane. This temperature distribution pattern follows an elliptic pattern. Numerical models for predicting 3-dimensional temperature distribution are very important when information is still limited about ideal conditions during the drying process. This developed model can accurately predict the temperature distribution in various positions of passion fruit seeds during the drying process. In the same case, Xiao et al. (2020) have explained that the modified numerical model can accurately predict the percentage of germination at various temperatures in seeds with a value of $R^2 = 0.810$.

Another phenomenon that can be revealed is that the temperature distribution occurs simultaneously in all directions of the three-dimensional axis of the seeds. The more inward (r direction), the smaller the temperature distribution, which is almost the same as the ambient temperature. Whereas the vertical direction (θ) and horizontal direction (ϕ) also have the same pattern, namely the smaller the distribution. This is following the results of the simulation program, which is for parts of the position that are closer to the sides given an initial value of T0 = 29.5 °C, then the temperature approaches the limit value. Whereas the position on the surface that receives the dryer temperature earlier has a higher temperature distribution. The same phenomenon has been reported by Fecher et al. (2014) that temperature distribution is caused by energy transfer that occurs due to temperature differences. This energy cannot be observed directly, but the direction of its displacement can be calculated using numerical modeling (Vogta et al., 2015).

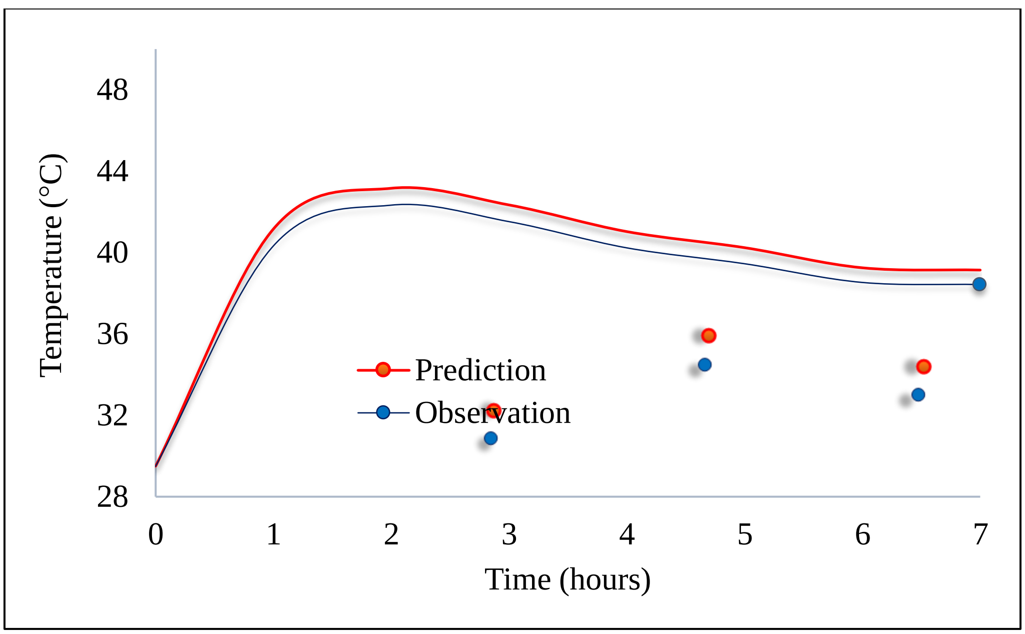

Figure 7. Prediction and observation data of temperature distribution during drying

There is a difference between the predicted temperature distribution and the observation result (Figure 7). The prediction temperature distribution is always higher than the observation temperature but has the same tendency. This difference is caused by the thermal conductivity value (k) used for simulation data slightly greater than the thermal conductivity value of passion fruit seeds. This is in line with the results of the study Reed et al. (2018) which reported that the higher the thermal conductivity value of the material, the faster the temperature propagation occurs.

Model validation

The validation of the air temperature distribution model is done by comparing the observations of the temperature distribution of the measurement results in the drying chamber with the prediction data of the FEM simulation results. The results of temperature distribution measurements in the drying chamber tend to follow the temperature distribution pattern of the simulation results with a low error. The highest error value occurred in the vertical position of 0.45%, then the horizontal position and the axis of the radius of 1.27 and 2.23% (Figure 8).

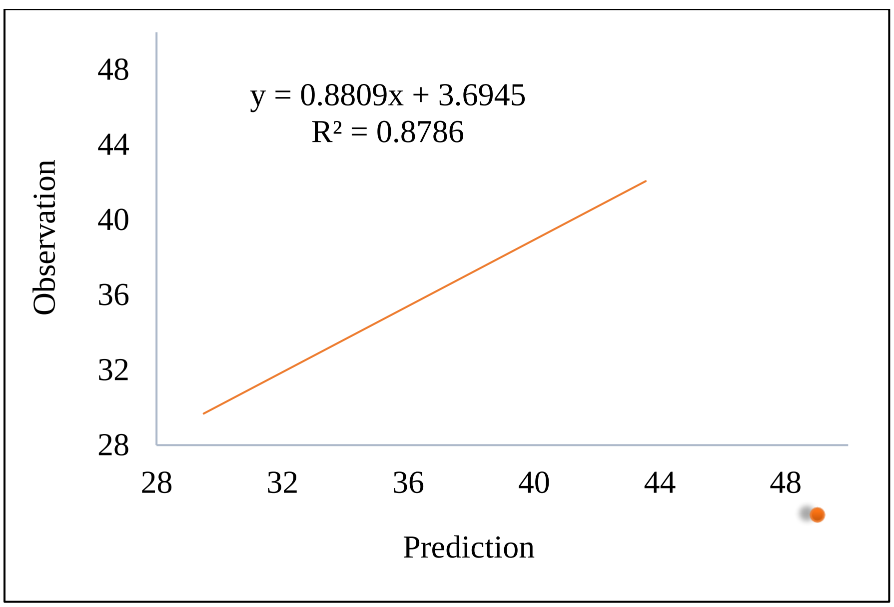

Figure 8. Validation of prediction and observation data of temperature distribution during drying.

The results of the analysis of variance showed that there were no significant differences between predicted and observational data. The temperature distribution data observations have the same pattern as the prediction data. Despite that, it is still found differences that are suspected due to the influence of the level of sensitivity of the sensor used, but the error data is still within reasonable limits. Another factor that is thought to cause differences is the effect of initial temperature variations which are not taken into account in compiling a numerical model of the FEM approach. But the difference only appears if the initial temperature is higher than the ambient temperature. Therefore, the higher the initial temperature, the higher the difference between prediction and simulation data. Similar results were also expressed by Khurana & Karwe (2009) that the simulation results differ from the predicted results when the initial temperature is higher than the ambient temperature. Thus, the results of this study can be used as a basis for further research.

The results of the analysis of variance showed that between the observations of the temperature distribution of the measurement results in the drying chamber with the FEM simulation results from data obtained R^2 value of 0.8786 (Figure 8). This data shows that there is a close relationship between observational data and predictive data. Thus, this FEM simulation model is valid and can be used as a system representation in analyzing the temperature distribution of grains during drying. In line with the results of these studies Moreno et al., (2017) also reported that the FEM method can produce accurate and valid temperature distribution prediction data and can be scientifically justified.

CONCLUSIONS

The temperature distribution in the passion fruit seeds occurs because of differences in temperature and heat energy arising during drying. This temperature distribution occurs simultaneously in all directions of the three-dimensional axis of the seeds. The deeper (direction r) the temperature distribution gets smaller. The same pattern also occurs in the vertical direction (θ) and horizontal direction (ϕ). The results of this study can be used to design dryers for grains. To improve this research, it is necessary to add blower power to provide faster air circulation.

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CONFLICT OF INTEREST

The authors declare that no conflict of interest with the founder.

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NUMERICAL EQUATION USING THE FINITE ELEMENT METHOD TO PREDICT THE TEMPERATURE DISTRIBUTION OF PASSION FRUIT SEEDS DURING DRYING

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Journal Name:	Transactions of the ASABE
Manuscript Type:	Research Article
Keywords:	drying, finite element methods, numerical equation, passion fruit seeds, temperature distribution
Abstract:	The optimization of the drying process can be determined based on temperature distribution patterns using numerical modeling of the finite element method (FEM). This study has compiled a numerical equation FEM to predict the temperature distribution in passion fruit seeds during drying. The study was conducted using a circulating air tray dryer. Temperature distribution data on passion fruit seeds were measured using a data logger. The results showed that the numerical equation FEM approach can be used to simulate the temperature distribution of passion fruit seeds during drying quickly and accurately. This model has been validated by comparing the temperature distribution data measured in the drying chamber with FEM simulation results data with a relative error between 0.45 to 1.27%. The numerical model of the FEM is important as a reference for controlling temperature distribution during drying because this method is easy to implement and results in low errors. ABSTRACT.docx

NUMERICAL EQUATION USING THE FINITE ELEMENT METHOD TO PREDICT THE TEMPERATURE DISTRIBUTION OF PASSION FRUIT SEEDS DURING DRYING

Highlights

- The design of the tray dryer type was established at the University of Mataram.
- Research data were observed for 7 hours with 5 repetitions.
- Prediction data from numerical equations has been compared with observational data.
- Model validation results have been discussed and analyzed.

ABSTRACT. *The optimization of the drying process can be determined based on temperature distribution patterns using numerical modeling of the finite element method (FEM). This study has compiled a numerical equation FEM to predict the temperature distribution in passion fruit seeds during drying. The study was conducted using a circulating air tray dryer. Temperature distribution data on passion fruit seeds were measured using a data logger. The results showed that the numerical equation FEM approach can be used to simulate the temperature distribution of passion fruit seeds during drying quickly and accurately. This model has been validated by comparing the temperature distribution data measured in the drying chamber with FEM simulation results data with a relative error between 0.45 to 1.27%. The numerical model of the FEM is important as a reference for controlling temperature distribution during drying because this method is easy to implement and results in low errors.*

Keywords: *Drying, finite element methods, numerical equation, passion fruit seeds, temperature distribution*

Nomenclature:

Abbreviations

A surface area (m^2)

c air heat capacity (kJ/kg°C)

k conductivity (W/m°C)

M modulus

r the rate of heat flow towards the axis of the radius (m)

T temperature (^{o}C)

t time (hour)

q heat energy (W)

V volume (m^3)

Subscripts

i radius index

j vertical direction index

k horizontal direction index

wt time index

Greek symbols

∂ differential

α heat diffusivity (m^2/dtk)

θ the rate of heat flow towards the vertical direction

ϕ the rate of heat flow towards the horizontal direction

Δ ingredient

INTRODUCTION

Passion fruit (*Passiflora edulis*) is one of the most consumed fruits because it has a source of vitamins and minerals that are beneficial to human health (Amaral, de Resende, Junior, & de Lima, 2016; Bezerra, Meller da Silva, Corrêa, & Rodrigues, 2015; Santos, et al., 2020). This fruit can be consumed in fresh or processed form (Do Nascimento, Mulet, Ascheri, de Carvalho, & Cárcel, 2016; Catelam, Trindade, & Romero, 2011; Ramos-González, et al., 2020). These passion fruit plants can grow easily in the tropics or subtropics (Allardyce, Fankhauser, Zakeeruddin, Grätzel, & Dyson, 2017;

Atukunda, et al., 2018). Two types of passion fruit are cultivated in Indonesia, namely yellow passion fruit (*Passiflora edulis f. Flavicarpa*) and purple passion fruit (*Passiflora edulis Sims f. Flavicarpa*) (Ansar, Nazaruddin, & Azis, 2020) (Figure 1).

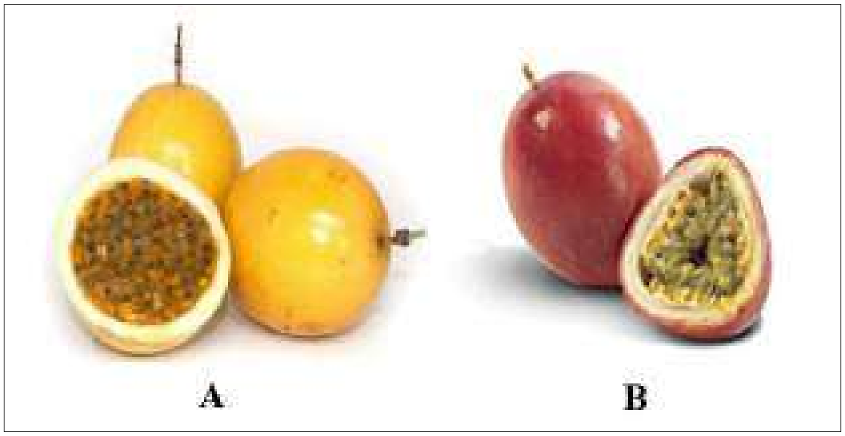

Figure 1. Yellow passion fruit (A) and purple passion fruit (B)

Nowadays, passion fruit is generally processed into syrup (Febrina, Sinulingga, & Napitupulu, 2017; Ansar, Nazaruddin, & Azis, 2019). The manufacture of the syrup has the most important economic impact on the passion fruit market because world demand continues to grow to date (Seixas, et al., 2014; Figueiredo, et al., 2013). Processing of passion fruit into syrup produces solid waste in the form of seeds between 4-12% of the total fruit mass (Oliveira, Mezzomo, Gomes, & Ferreira, 2017; Araujo, et al., 2019). This fruit waste can be reused because it has oil and protein content, especially linoleic acid up to 70% (Malacrida & Jorge, 2012; Silva, et al., 2015; Silva, et al., 2019). Fatty acids from passion fruit seeds have the potential to be applied in the food, pharmaceutical, cosmetics, and energy industries (Oliveira, Mezzomo, Gomes, & Ferreira, 2017; Oliveira, Angonese, Ferreira, & Gomes, 2017; Yang, Hu, & Long, 2019).

Unripe passion fruit seeds generally grow sprouts, so they have a short shelf life, (Váquiro, Rodríguez, Simal, Solanilla-Duque, & Telis-Romero, 2016; Barrales, Rezende, & Martínez, 2015; Bidgolya, Balouchi, Soltani, & Moradi, 2018). To maintain the shelf life of this passion fruit, it must be dried until it reaches 14% water content so that it lasts longer before being extracted into the oil

(Chen, Yang, & Liu, 2011; Leao, Sampaio, Pagani, & Da Silva, 2014; Pereira, Correa, & Oliveira, 2015). An effective drying method for grains can be carried out based on a temperature distribution mechanism to optimize the evaporation of water content (de Menezes, et al., 2013; Castro, Mayorga, & Moreno, 2018).

Research about temperature distribution using the numerical equation of the finite element method (FEM) approach has been widely reported (Bezerra, Meller da Silva, Correa, & Rodrigues, 2015; Takalkar & Bhosale, 2018). However, existing scientific publications generally still use a one-dimensional numerical equation to describe the process of drying grain (Váquiro, Rodríguez, Simal, Solanilla-Duque, & Telis-Romero, 2016; Jinshah & Balasubramanian, 2020; Zhoua, Kea, & Deng, 2018) have simulated temperature distribution on one dimension using FEM. While (Zhou, Yi, Wang, & Ye, 2015) have simulated a one-dimensional temperature distribution using the FEM with graph visualization. Another temperature distribution analysis has been carried out by Monjezi & Campbell (2016) at each point of the two-dimensional plate using the FEM with the system state considered a steady-state.

Temperature distribution during drying cannot be observed directly (Shinong, Qianlong, Jie, Yuan, & Shilin, 2020), but can only be predicted and calculated using numerical modeling (Castro, Mayorga, & Moreno, 2018; Xiao, Yang, Monaco, Song, & Rong, 2020). The numerical modeling that has been compiled is then simulated and displayed in a graph (Ma, Gu, Shen, & Li, 2019). The numerical modeling can produce valid, detailed, and comprehensive data (Essa & Mostafa, 2017; Mayer & Grof, 2020).

Research on the process of temperature distribution in seeds whose shape is not uniform during drying using a numerical equation of the FEM approach has not been found in any publication. Therefore, this research is important to describe the process of drying passion fruit seeds as a function of temperature using numerical modeling of the FEM approach. This model was used to predict the temperature distribution in passion fruit seeds during non-isothermal convective drying. Thus, the purpose of this study was to compile a numerical equation using the FEM approach to predict the temperature distribution of passion fruit seeds during drying.

MATERIALS AND METHODS

Numerical equation development

To simplify the compilation of the numerical equations of the FEM approach, then passion fruit seeds are assumed to be in the shape of a uniform ball as shown in Figure 2.

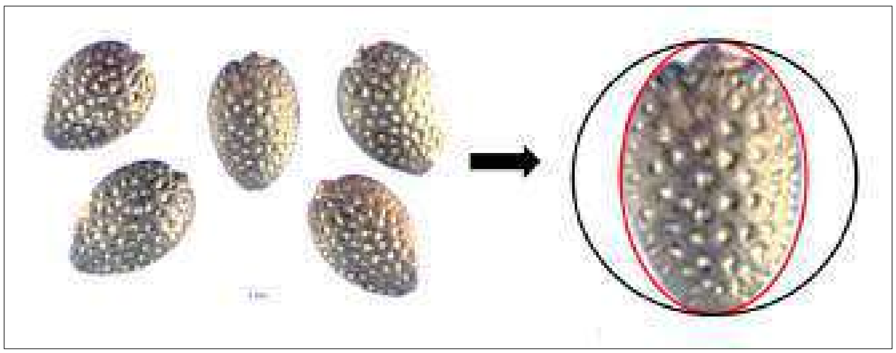

Figure 2. Purple passion fruit seeds that are assumed to have a uniform ball shape

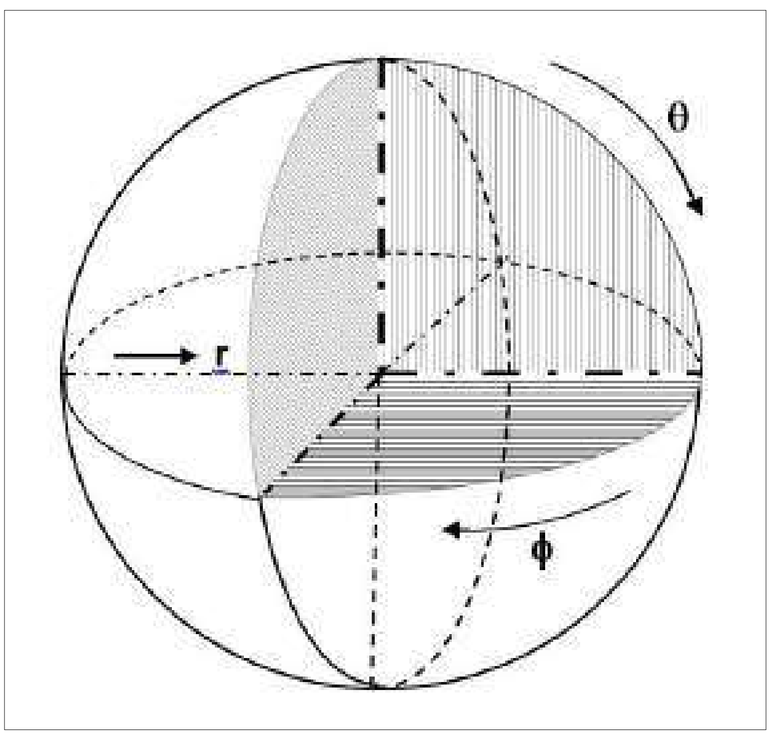

Figure 3. Modeling of three-dimensional spherical coordinate systems

By simplifying, the transformation function of the spherical coordinate system irregular (Figure 2) is simplified into a three-dimensional regular spherical coordinate system (Figure 3), so that it can be written in the form of an equation:

$$q_r A_r\big|_r + q_\theta A_\theta\big|_\theta + q_\phi A_\phi\big|_\phi - \left(q_r A_r\big|_{r+\Delta r} + q_\theta A_\theta\big|_{\theta+\Delta\theta} + q_\phi A_\phi\big|_{\phi+\Delta\phi}\right) = \Delta V \rho c_p \frac{\partial T}{\partial t} \qquad (1)$$

The rate of heat flow towards the axis of the radius (r) is:

$$q_r = -k \cdot A_r \cdot \frac{\partial T}{\partial r} \qquad (2)$$

The rate of heat flow towards the vertical direction (θ) is:

$$q_\theta = -k \cdot \frac{1}{r} \cdot A_\theta \cdot \frac{\partial T}{\partial \theta} \qquad (3)$$

The rate of heat flow towards the horizontal direction (ϕ) is:

$$q_\phi = -k \cdot \frac{1}{r\sin\theta} \cdot A_\phi \cdot \frac{\partial T}{\partial \phi} \qquad (4)$$

The results of substituting equations (2), (3), and (4) into equation (1), the equation is obtained:

$$\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta \frac{\partial T}{\partial \theta}\right) + \frac{1}{r^2 \sin^2\theta}\frac{\partial^2 T}{\partial \phi^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (5)$$

Initial condition (IC) and boundary condition (BC) equation (5) is:

In all positions T(r, θ, ϕ, t) = $T_{initial}$ = 29,5°C for t = 0

The solution of equations (5) and BC was to use the numerical method of the FEM approach explicitly. The temperature distribution on the surface of the seeds is calculated by the equation:

$$T_{NR,j,k,wt+1} = \frac{1}{M}\left\{\left(2\Delta r - \frac{2}{(i)^2 \Delta\theta} + M\right)T_{NR,j,k} - (2\Delta r)T_{NR-1,j,k} + \left(\frac{2}{(i)^2 \Delta\theta}\right)T_{NR,j+1,k}\right\} + 2\Delta r q_{fric} \qquad (6)$$

The temperature distribution in the position of the seed axis was calculated by the equation:

$$T_{i,j,k,wt+1} = \frac{1}{M}\left\{\left(1-\frac{1}{i}\right)T_{i-1,j,k} - (2-M)T_{i,j,k} + \left(1+\frac{1}{i}\right)T_{i+1,j,k} - \left(\frac{\Delta r}{(i)(\Delta\theta)}\right)T_{i,j-1,k} + \left(\frac{\Delta r}{(i)(\Delta\theta)}\right)T_{i,j+1,k}\right\} \qquad (7)$$

The temperature distribution at the center position of the seeds was calculated by the equation:

$$T_{0,j,k,wt+1} = \frac{1}{M}\left\{T_{1,j,k,wt} + (M-1)T_{0,j,k,wt}\right\} \tag{8}$$

The temperature distribution of the simulation results as a function of the three-dimensional position of r, θ, and ϕ which can be calculated by the equation:

$$\overline{T}_{hit} = \frac{\rho Cp \int_0^{\pi/2}\int_0^{\pi/2}\int_0^{R} T \cdot r^2 \sin\theta \cdot dr \cdot d\theta \cdot d\phi}{\rho Cp \int_0^{V} dV} \tag{9}$$

The solution of equation (9) was to use the Trapezoidal Rule method as follows.

$$\int_0^R T_{i,j,k} \cdot r^2 \cdot dr = \frac{\Delta r}{2}\left\{\left(T_{0,j,k} \cdot R_0^2\right) + 2\left(T_{1,j,k} \cdot R_1^2\right) + 2\left(T_{2,j,k} \cdot R_2^2\right) + 2\left(T_{3,j,k} \cdot R_3^2\right) + 2\left(T_{4,j,k} \cdot R_4^2\right) + \right.$$

$$\left. 2\left(T_{5,j,k} \cdot R_5^2\right) + 2\left(T_{6,j,k} \cdot R_6^2\right) + 2\left(T_{7,j,k} \cdot R_7^2\right) + 2\left(T_{8,j,k} \cdot R_8^2\right) + 2\left(T_{9,j,k} \cdot R_9^2\right) + \left(T_{10,j,k} \cdot R_{10}^2\right)\right\} = A_{j,k}$$

$$\int_0^{\pi/2} A_{j,k} \cdot \sin\theta \cdot d\theta = \frac{\Delta\theta}{2}\left\{\left(A_{0,k} \cdot \sin(0 \cdot \Delta\theta)\right) + 2\left(A_{1,k} \cdot \sin(1 \cdot \Delta\theta)\right) + 2\left(A_{2,k} \cdot \sin(2 \cdot \Delta\theta)\right) + 2\left(A_{3,k} \cdot \sin(3 \cdot \Delta\theta)\right) + \right.$$

$$2\left(A_{4,k} \cdot \sin(4 \cdot \Delta\theta)\right) + 2\left(A_{5,k} \cdot \sin(5 \cdot \Delta\theta)\right) + 2\left(A_{6,k} \cdot \sin(6 \cdot \Delta\theta)\right) +$$

$$\left. 2\left(A_{7,k} \cdot \sin(7 \cdot \Delta\theta)\right) + \left(A_{8,k} \cdot \sin(8 \cdot \Delta\theta)\right)\right\}$$

$$= B_k$$

$$\int_0^{\pi/2} B_k \cdot d\phi = \frac{\Delta\phi}{2}\left\{(B_0) + 2(B_1) + 2(B_2) + 2(B_3) + 2(B_4) + 2(B_5) + 2(B_6) + 2(B_7) + (B_8)\right\} \tag{10}$$

Sample preparation and equipment

Passion fruit seeds used in the study were obtained from purple passion fruit. The fruit is cut in half and the seeds are separated from the meat using a pulpier siever. Furthermore, passion fruit seeds are washed with water to remove the remnants of the pulp. Passion fruit seeds are drained and stored at room temperature to wait for the next process.

The equipment used is a circulated air tray type dryer with a heat source obtained from a 300 Watt electric stove (Figure 4). The main parts of the dryer include drying chamber, drying tray, electric stove, blower, and exhaust. Each component is made using industry-standard construction. The support frame is made of galvanized type iron box measuring 2.5 x 2.5 cm so that it can withstand the burden of dried material. Overall dimensions of the dryer are 100 cm long, 80 cm wide, 150 cm high, and the wheel height from the ground to the tool is 10 cm.

The inner drying chamber is insulated to reduce heat loss so that the hot air inside the drying chamber can be optimally optimized for drying. Inside the drying chamber, there are 5 shelves arranged vertically with a distance of 20 cm between the shelves to collect the dried material. The tray is made of stainless steel wireframed by wood. The electric stove is located at the bottom right side of the drying chamber. At the right end of the stove, there is a blower to encourage and circulate air in the drying chamber.

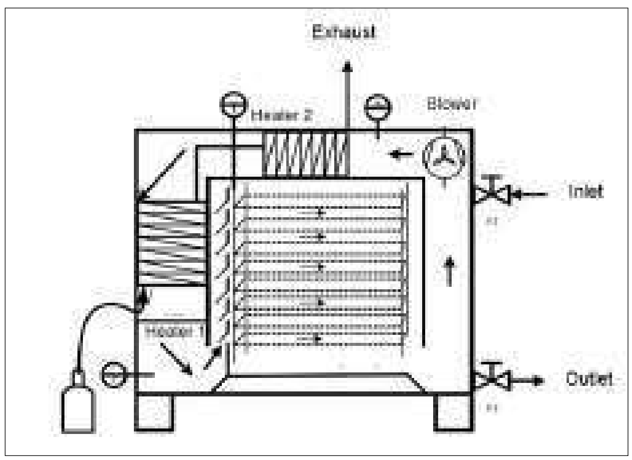

Figure 4. Sketch of a circulating air tray dryer type

Sample drying

Drying passion fruit seeds was done by placing seeds on each tray with a thickness of 1 layer. Drying is done using a temperature of 70ºC and an airflow velocity of 0.2 m/s. Hot air generated from electric stoves was used to dry the samples in a tray of 5 pieces. Some of the air was discharged through the outlet valve and some are recirculated through the heater and then returned to the drying chamber. To reduce heat loss to the environment, all parts of the drying chamber are coated with insulators. Drying was carried out for 7 hours to obtain 14% water content.

Measurement of seed temperature distribution

Seed temperature distribution data during drying is measured using a data logger. The temperature sensor is installed in one of the passion fruit seeds in each drying chamber by placing the tip of the thermocouple in the surface position and the center of the seeds. This measurement was repeated with 5 replications.

Data validation test

Data validation test used regression analysis by comparing predictive data obtained from FEM numerical model simulation results with observational data generated from measurements in the drying chamber. The closeness of the relationship between predictive data and observational data can be seen from the coefficient of determination (R^2). If the value of R2 approaches the number one it means that there is a very close relationship (Ansar, Sukmawaty, Abdullah, Nazaruddin, & Safitri, 2020).

RESULTS AND DISCUSSION

Temperature distribution in the drying chamber

The measurement results of temperature distribution from time to time during the drying of passion fruit showed that the temperature distribution on each the tray had different values (Figure 5). At the beginning of drying the temperature, distribution is still uniform, but an increase occurs with increasing drying time. The biggest temperature is on the tray1, reaching 45.16°C. This is presumably because the bottom tray gets the most heat from the electric stove, so the average temperature on the bottom tray is higher than the other trays. While the average temperature on the tray no. 2, 3, 4, and 5 are 42.33, 41.45, 40.75, and 39.43°C, respectively.

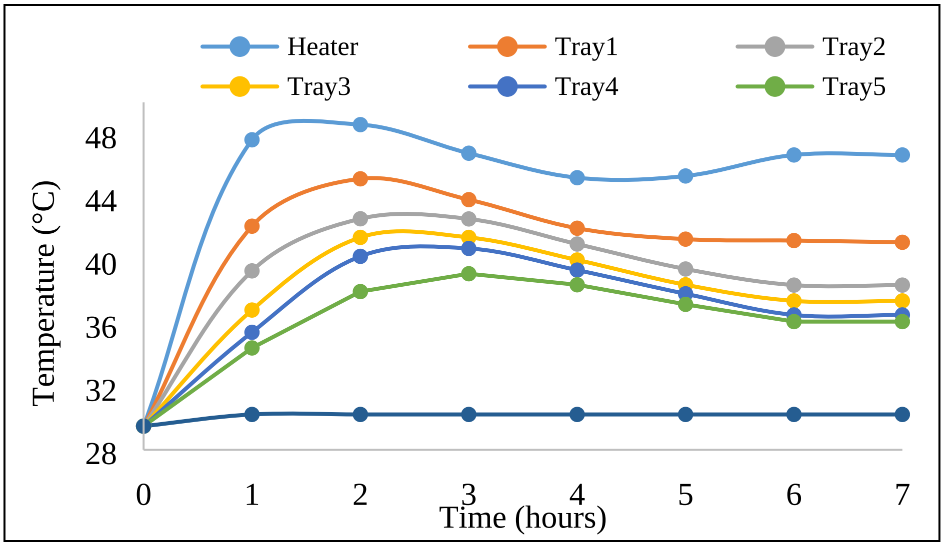

Figure 5. Temperature distribution on each tray during the drying of passion fruit seeds

In general, the drying of the tray type in this study only takes 7 hours to reduce the water content from 21% to 14.15%. This drying time is shorter when compared to the method of sun-drying which requires 10-11 hours (Shavazi, Torres, Hughes, & Pye, 2020). The same trend data has been reported by Bahadur et al. (2019) that the higher the dryer temperature, the lower the final water content produced.

Uneven airflow velocity can cause uneven temperature distribution. The higher the airflow velocity, the faster the air temperature distribution in the drying chamber. This means that the speed of airflow in the drying medium can function as a catalyst so that the temperature distribution of the seeds is also faster. The results of the study Ozakina & Kaya (2019) also reported that airflow velocity can cause a high-temperature distribution, so that the temperature distribution in the seeds is also getting bigger.

Temperature distribution in seeds

Temperature distribution in passion fruit seeds during drying is shown in Figure 6. In the figure, it appears that in the first hour there was a very rapid increase and began to fall in the second hour until towards the end of drying. Temperature distribution in passion fruit seeds occurs because of differences in temperature and heat energy arising during drying. The same thing has been expressed by Serrano-Arellano et al. (2015) that the temperature distribution of materials is strongly influenced by the coefficient of displacement of the conduction pad and the thermal diffusivity of the material.

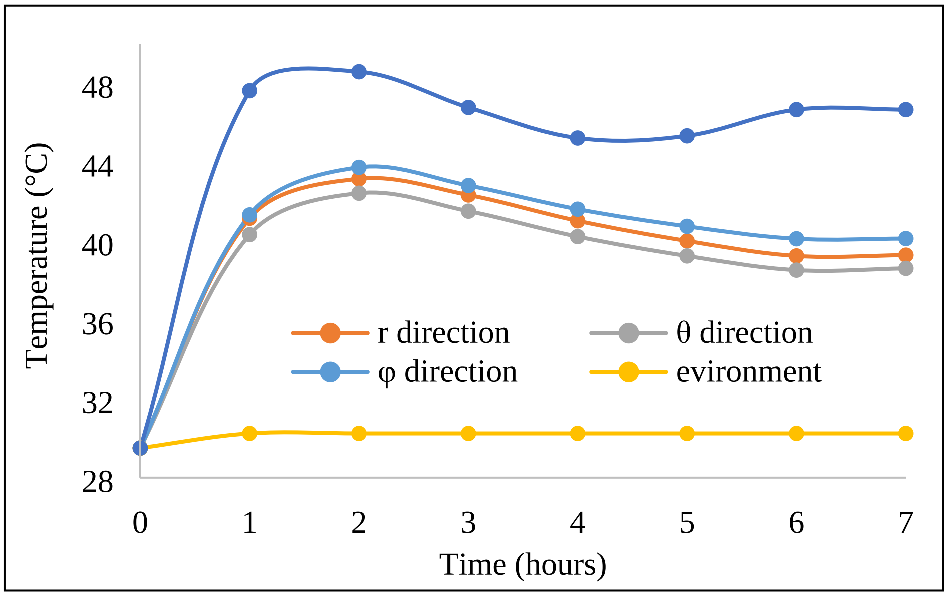

Figure 6. Three-dimensional temperature distribution in passion fruit seeds

Three-dimensional temperature distribution of passion fruit seeds spreads from the surface of the seeds toward the center of the axis slowly until evenly distributed to all parts of the seeds. Furthermore, the temperature is distributed with an even distribution pattern in the determined boundary plane. This temperature distribution pattern follows an elliptic pattern. Numerical models for predicting 3-dimensional temperature distribution are very important when information is still limited about ideal conditions during the drying process. This developed model can accurately predict the temperature distribution in various positions of passion fruit seeds during the drying process. In the same case, Xiao et al. (2020) have explained that the modified numerical model can accurately predict the percentage of germination at various temperatures in seeds with a value of $R^2 = 0.810$.

Another phenomenon that can be revealed is that the temperature distribution occurs simultaneously in all directions of the three-dimensional axis of the seeds. The more inward (r direction), the smaller the temperature distribution, which is almost the same as the ambient temperature. Whereas the vertical direction (θ) and horizontal direction (ϕ) also have the same pattern, namely the smaller the distribution. This is following the results of the simulation program, which is for parts of the position that are closer to the sides given an initial value of T0 = 29.5°C, then the temperature approaches the limit value. Whereas the position on the surface that receives the dryer temperature earlier has a higher temperature distribution. The same phenomenon has been reported by Fecher, Romero, Brabec, & Buerhop-Lutz (2014) that temperature distribution is caused by energy transfer that occurs due to temperature differences. This energy cannot be observed directly, but the direction of its displacement can be calculated using numerical modeling (Vogta, Holst, Wintera, Brendela, & Altermat, 2015).

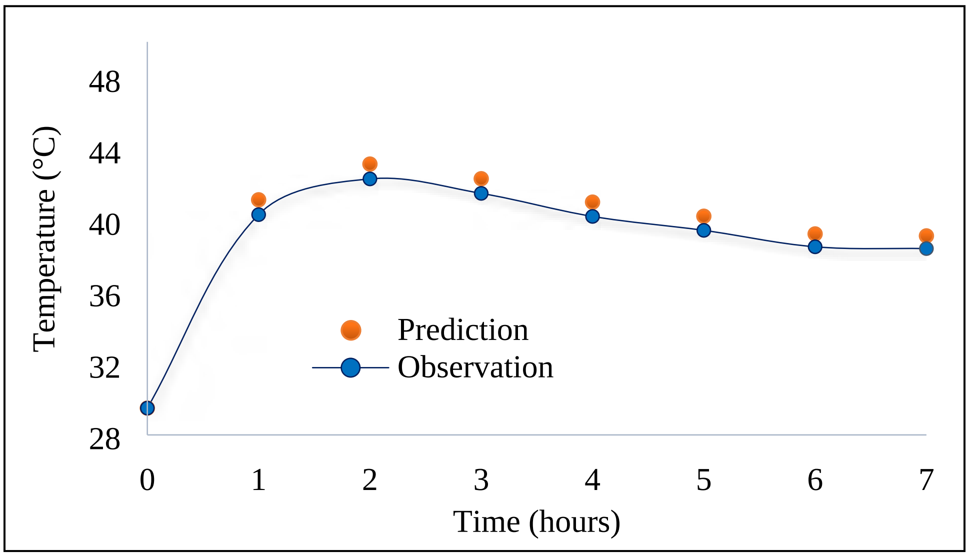

Figure 7. Prediction and observation data of temperature distribution during drying

There is a difference between the predicted temperature distribution and the observation result (Figure 7). The prediction temperature distribution is always higher than the observation temperature but has the same tendency. This difference is caused by the thermal conductivity value (k) used for simulation data slightly greater than the thermal conductivity value of passion fruit seeds. This is in line with the results of the study Reed, Sugo, & Lattice (2018) which reported that the higher the thermal conductivity value of the material, the faster the temperature propagation occurs.

Model validation

The validation of the air temperature distribution model is done by comparing the observations of the temperature distribution of the measurement results in the drying chamber with the prediction data of the FEM simulation results. The results of temperature distribution measurements in the drying chamber tend to follow the temperature distribution pattern of the simulation results with a low error. The highest error value occurred in the vertical position of 0.45%, then the horizontal position and the axis of the radius of 1.27 and 2.23% (Figure 8).

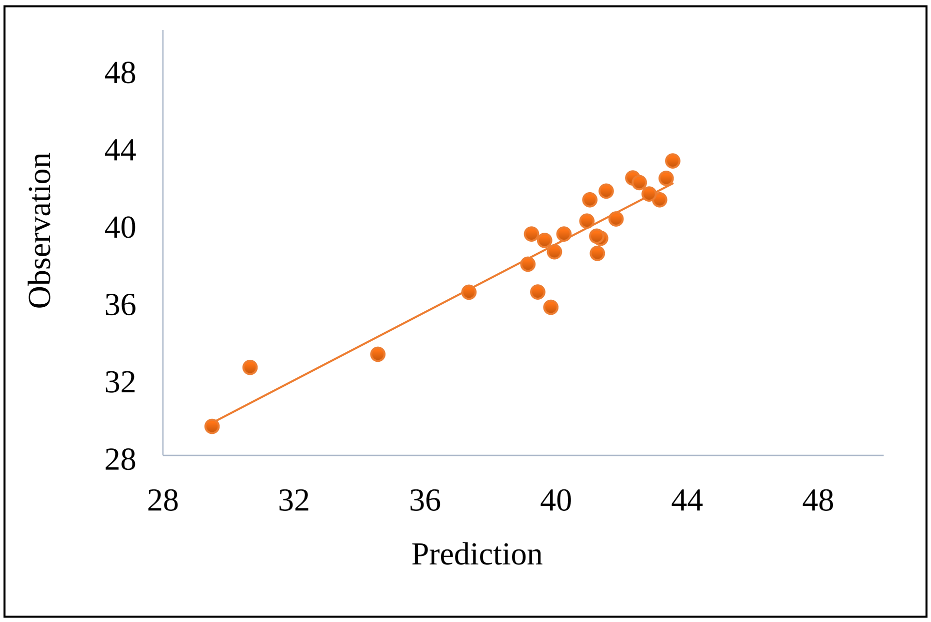

Figure 8. Validation of prediction and observation data of temperature distribution during drying.

The results of the analysis of variance showed that there were no significant differences between predicted and observational data. The temperature distribution data observations have the same pattern as the prediction data. Despite that, it is still found differences that are suspected due to the influence of the level of sensitivity of the sensor used, but the error data is still within reasonable limits. Another factor that is thought to cause differences is the effect of initial temperature variations which are not taken into account in compiling a numerical model of the FEM approach. But the difference only appears if the initial temperature is higher than the ambient temperature. Therefore, the higher the initial temperature, the higher the difference between prediction and simulation data. Similar results were also expressed by Khurana & Karwe (2009) that the simulation results differ from the predicted results when the initial temperature is higher than the ambient temperature. Thus, the results of this study can be used as a basis for further research.

The results of the analysis of variance showed that between the observations of the temperature distribution of the measurement results in the drying chamber with the FEM simulation results from data obtained R^2 value of 0.8786 (Figure 8). This data shows that there is a close relationship between observational data and predictive data. Thus, this FEM simulation model is valid and can be used as a system representation in analyzing the temperature distribution of grains during drying. In line with the results of these studies, Moreno, Fernández, & Esquivias (2017) also reported that the FEM method can produce accurate and valid temperature distribution prediction data and can be scientifically justified.

CONCLUSIONS

Temperature distribution in passion fruit seeds occurs because of differences in temperature and heat energy arising during drying. This temperature distribution occurs simultaneously in all directions of the three-dimensional axis of the seeds. The deeper (direction r) the temperature distribution gets smaller. The same pattern also occurs in the vertical direction (θ) and horizontal direction (ϕ). The speed of the drying air influences the temperature distribution. The higher the airflow velocity, the faster the air temperature distribution that occurs. The results of this study can be used to design dryers for grains. To improve this research, it is necessary to add blower power to provide faster air circulation.

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CONFLICT OF INTEREST

The authors declare that no conflict of interest with the founder.

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NUMERICAL ANALYSIS TO PREDICT TEMPERATURE DISTRIBUTION OF THE PASSION FRUIT SEEDS DURING DRYING

Highlights

- The temperature distribution occurs because there are differences in temperature on the surface and inside the passion fruit seeds
- Temperature distribution occurs simultaneously in all directions
- The deeper into the temperature distribution the lower
- The same pattern also occurs in the vertical and horizontal directions.

ABSTRACT. *The optimization of the drying process can be determined based on temperature distribution patterns using numerical analysis of the finite element method (FEM). This study has compiled a numerical analysis using FEM to predict the temperature distribution in passion fruit seeds during drying. The study was conducted using a circulating air tray dryer. Temperature distribution data on passion fruit seeds were measured using a data logger. The results showed that the numerical analysis using FEM approach can be used to simulate the temperature distribution of passion fruit seeds during drying quickly and accurately. This model has been validated by comparing the temperature distribution data measured in the drying chamber with FEM simulation results data with a relative error between 0.45 to 1.27%. The numerical analysis using FEM is important as a reference for controlling temperature distribution during drying because this method is easy to implement and results in low errors.*

Keywords: *Drying, finite element methods, numerical analysis, passion fruit seeds, temperature distribution*

Nomenclature:

Abbreviations

A surface area (m^2)

c air heat capacity (kJ/kg °C)

k conductivity (W/m °C)

M modulus

r the rate of heat flow towards the axis of the radius (m)

T temperature (°C)

t time (hour)

q heat energy (W)

V volume (m^3)

Subscripts

i radius index

j vertical direction index

k horizontal direction index

wt time index

Greek symbols

∂ differential

α heat diffusivity (m^2/dtk)

θ the rate of heat flow towards the vertical direction

ϕ the rate of heat flow towards the horizontal direction

Δ ingredient

INTRODUCTION

Passion fruit (*Passiflora edulis*) is one of the most consumed fruits because it is a source of vitamins and minerals that are beneficial to human health (Amaral et al., 2016; Bezerra et al., 2015; Santos, et al., 2020). It can be consumed in fresh or processed form (Do Nascimento et al., 2016; Catelam et al., 2020). Passion fruit plants can grow easily in the tropics or subtropics (Allardyce et al., 2017; Atukunda, et al., 2018). Two types of passion fruit are cultivated in Indonesia, namely yellow passion fruit (*Passiflora edulis f. Flavicarpa*) and purple passion fruit (*Passiflora edulis Sims f.*

Flavicarpa) (Ansar et al., 2020) (Figure 1).

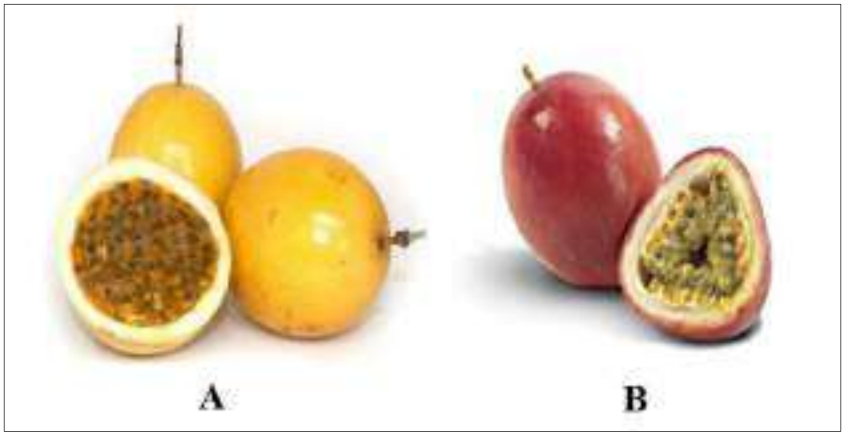

Figure 1. Yellow passion fruit (A) and purple passion fruit (B)

Nowadays, passion fruit is generally processed into syrup (Febrina et al., 2017; Ansar et al., 2019). The demand for passion fruit syrup products continues to increase until now (Seixas et al., 2014; Figueiredo et al., 2013). Processing of passion fruit into syrup produces solid waste in the form of seeds between 4-12% of the total fruit mass (Oliveira et al., 2017; Araujo et al., 2019). This fruit waste can be reused because it has oil and protein content, especially linoleic acid up to 70% (Malacrida & Jorge, 2012; Silva et al., 2015; Silva et al., 2019). Fatty acids from passion fruit seeds have the potential to be applied in the food, pharmaceutical, cosmetics, and energy industries (Oliveira et al., 2017; Yang et al., 2019).

Unripe passion fruit seeds generally grow sprouts, so they have a short shelf life (Vaquiro et al., 2016; Barrales et al., 2015; Bidgolya et al., 2018). To maintain the shelf life of this passion fruit seeds, it must be dried until it reaches 14% wet basis water content so that it lasts longer before being extracted into the oil (Chen et al., 2011; Leao et al., 2014; Pereira et al., 2015). An effective drying method for grains can be carried out based on a temperature distribution mechanism to optimize the evaporation of water content (de Menezes et al., 2013; Castro et al., 2018).

Research on temperature distribution using numerical analysis of the finite element method (FEM) has been widely reported (Bezerra et al., 2015; Takalkar et al., 2018). This numerical analysis can be used to explain the temperature distribution process during drying (Vaquiro et al., 2016; Jinshah & Balasubramanian, 2020; Zhoua et al., 2018). While Zhou et al. (2015) have simulated a one-dimensional temperature distribution using the FEM with graph visualization. Another temperature distribution analysis has been carried out by Monjezi & Campbell (2016) at each point of the two-dimensional plate using the FEM with the system state considered a steady-state.

Temperature distribution during drying cannot be observed directly (Shinong et al., 2020), but can only be predicted and calculated using numerical analysis (Castro et al., 2018; Xiao et al., 2020). The numerical modeling that has been compiled is then simulated and displayed in a graph (Ma et al., 2019). The numerical analysis can produce valid, detailed, and comprehensive data (Essa & Mostafa, 2017; Mayer & Grof, 2020).

Research on the process of temperature distribution in seeds whose shape is not uniform during drying using a numerical analysis using FEM approach has not been found in any publication. Therefore, this research is important to describe the process of drying passion fruit seeds as a function of temperature using numerical analysis using FEM approach. This model was used to predict the temperature distribution in passion fruit seeds during non-isothermal convective drying. Thus, the purpose of this study was to compile a numerical analysis using FEM approach to predict the temperature distribution of passion fruit seeds during drying.

MATERIALS AND METHODS

Numerical analysis development

To simplify the compilation of the numerical analysis of the FEM approach, then passion fruit seeds are assumed to be in the shape of a uniform ball as shown in Figure 2.

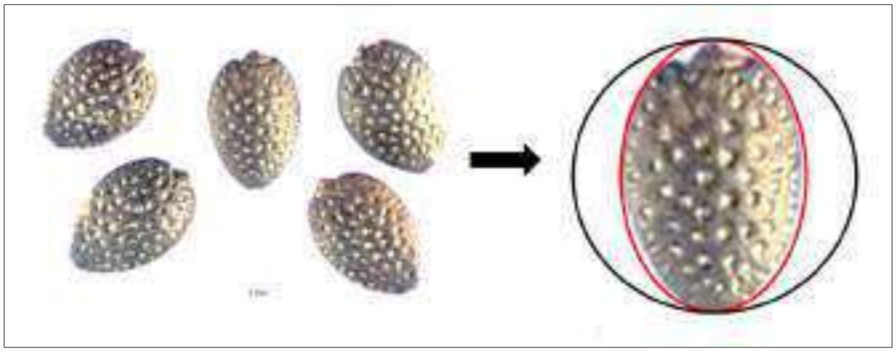

Figure 2. Purple passion fruit seeds that are assumed to have a uniform ball shape

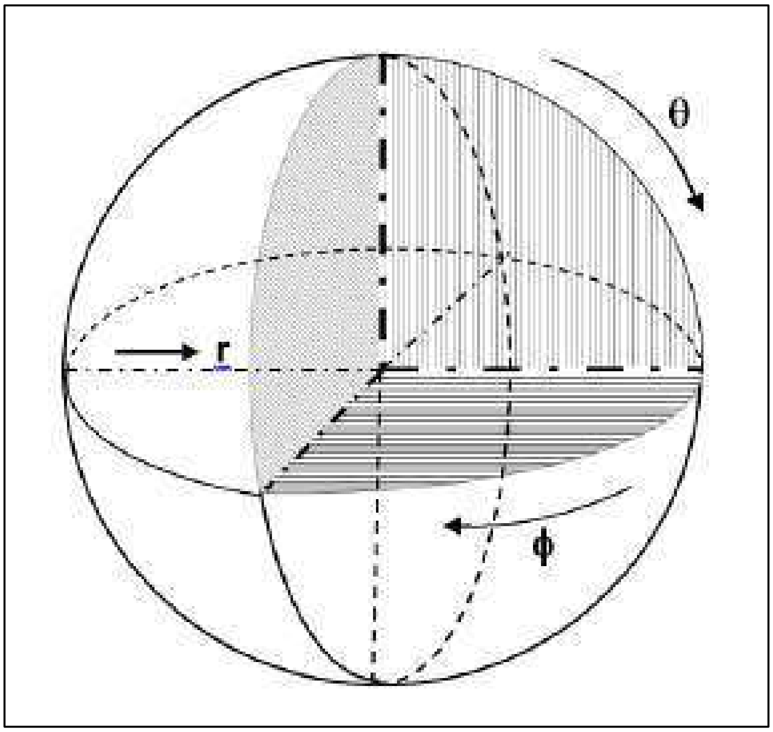

Figure 3. Modeling of three-dimensional spherical coordinate systems

By simplifying, the transformation function of the irregular spherical coordinate system (Figure 2) is simplified into a three-dimensional regular spherical coordinate system (Figure 3), so that it can be written in the form of an equation:

$$q_r A_r\big|_r + q_\theta A_\theta\big|_\theta + q_\phi A_\phi\big|_\phi - \left(q_r A_r\big|_{r+\Delta r} + q_\theta A_\theta\big|_{\theta+\Delta\theta} + q_\phi A_\phi\big|_{\phi+\Delta\phi}\right) = \Delta V \rho c_p \frac{\partial T}{\partial t} \qquad (1)$$

The rate of heat flow towards the axis of the radius (r) is:

$$q_r = -k \cdot A_r \cdot \frac{\partial T}{\partial r} \qquad (2)$$

The rate of heat flow towards the vertical direction (θ) is:

$$q_\theta = -k \cdot \frac{1}{r} \cdot A_\theta \cdot \frac{\partial T}{\partial \theta} \tag{3}$$

The rate of heat flow towards the horizontal direction (ϕ) is:

$$q_\phi = -k \cdot \frac{1}{r \sin\theta} \cdot A_\phi \cdot \frac{\partial T}{\partial \phi} \tag{4}$$

The results of substituting equations (2), (3), and (4) into equation (1), the equation is obtained:

$$\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta \frac{\partial T}{\partial \theta}\right) + \frac{1}{r^2 \sin^2\theta}\frac{\partial^2 T}{\partial \phi^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{5}$$

Initial condition (IC) and boundary condition (BC) equation (5) are:

IC: In all positions $T(r, \theta, \phi, t) = T_{initial} = 29{,}5$ °C for $t = 0$

BC: at $t > 0$ and $r = 0$; $\frac{\partial T}{\partial r} = 0$

The solution of equations (5) and BC was to use the numerical analysis using FEM approach explicitly. The temperature distribution on the surface of the seeds is calculated by the equation:

$$T_{NR,j,k,wt+1} = \frac{1}{M}\left\{\left(2\Delta r - \frac{2}{(i)^2 \Delta\theta} + M\right)T_{NR,j,k} - (2\Delta r)T_{NR-1,j,k} + \left(\frac{2}{(i)^2 \Delta\theta}\right)T_{NR,j+1,k}\right\} + 2\Delta r q_{fric} \tag{6}$$

The temperature distribution in the position of the seed axis was calculated by the equation:

$$T_{i,j,k,wt+1} = \frac{1}{M}\left\{\left(1 - \frac{1}{i}\right)T_{i-1,j,k} - (2 - M)T_{i,j,k} + \left(1 + \frac{1}{i}\right)T_{i+1,j,k} - \left(\frac{\Delta r}{(i)(\Delta\theta)}\right)T_{i,j-1,k} + \left(\frac{\Delta r}{(i)(\Delta\theta)}\right)T_{i,j+1,k}\right\} \tag{7}$$

The temperature distribution at the center position of the seeds was calculated by the equation:

$$T_{0,j,k,wt+1} = \frac{1}{M}\left\{T_{1,j,k,wt} + (M - 1)T_{0,j,k,wt}\right\} \tag{8}$$

The temperature distribution of the simulation results as a function of the three-dimensional position of r, θ, and ϕ which can be calculated by the equation:

$$\overline{T}_{hit} = \frac{\rho Cp \int_0^{\pi/2}\int_0^{\pi/2}\int_0^{R} T \cdot r^2 \sin\theta \cdot dr \cdot d\theta \cdot d\phi}{\rho Cp \int_0^{V} dV} \tag{9}$$

The solution of equation (9) was to use the Trapezoidal Rule method as follows.

$$\int_0^R T_{i,j,k} \cdot r^2 \cdot dr = \frac{\Delta r}{2}\{(T_{0,j,k} \cdot R_0^2) + 2(T_{1,j,k} \cdot R_1^2) + 2(T_{2,j,k} \cdot R_2^2) + 2(T_{3,j,k} \cdot R_3^2) + 2(T_{4,j,k} \cdot R_4^2) +$$

$$2(T_{5,j,k} \cdot R_5^2) + 2(T_{6,j,k} \cdot R_6^2) + 2(T_{7,j,k} \cdot R_7^2) + 2(T_{8,j,k} \cdot R_8^2) + 2(T_{9,j,k} \cdot R_9^2) + (T_{10,j,k} \cdot R_{10}^2)\} = A_{j,k}$$

$$\int_0^{\pi/2} A_{j,k} \cdot \sin\theta \cdot d\theta = \frac{\Delta\theta}{2}\{(A_{0,k} \cdot \sin(0 \cdot \Delta\theta)) + 2(A_{1,k} \cdot \sin(1 \cdot \Delta\theta)) + 2(A_{2,k} \cdot \sin(2 \cdot \Delta\theta)) + 2(A_{3,k} \cdot \sin(3 \cdot \Delta\theta)) +$$

$$2(A_{4,k} \cdot \sin(4 \cdot \Delta\theta)) + 2(A_{5,k} \cdot \sin(5 \cdot \Delta\theta)) + 2(A_{6,k} \cdot \sin(6 \cdot \Delta\theta)) +$$

$$2(A_{7,k} \cdot \sin(7 \cdot \Delta\theta)) + (A_{8,k} \cdot \sin(8 \cdot \Delta\theta))\}$$

$$= B_k$$

$$\int_0^{\pi/2} B_k \cdot d\phi = \frac{\Delta\phi}{2}\{(B_0) + 2(B_1) + 2(B_2) + 2(B_3) + 2(B_4) + 2(B_5) + 2(B_6) + 2(B_7) + (B_8) \tag{10}$$

Sample preparation and equipment

Passion fruit seeds used in the study was obtained from the purple passion fruit. The fruit is cut in half and the seeds are separated from the meat using a pulpier siever. Furthermore, passion fruit seeds are washed with water to remove the remnants of the pulp. Passion fruit seeds are drained and stored at room temperature to wait for the next process.

The equipment used is a circulated air tray type dryer with a heat source obtained from a 300 Watt electric stove (Figure 4). The main parts of the dryer include drying chamber, drying tray, electric stove, blower, and exhaust. Each component is made using industry-standard construction. The support frame is made of galvanized type iron box measuring 2.5 x 2.5 cm so that it can withstand the burden of dried material. Overall dimensions of the dryer are 100 cm long, 80 cm wide, 150 cm high, and the wheel height from the ground to the tool is 10 cm.

The inner drying chamber is insulated to reduce heat loss so that the hot air inside the drying chamber can be optimally optimized for drying. Inside the drying chamber, there are 5 shelves arranged vertically with a distance of 20 cm between the shelves to collect the dried material. The tray is made of stainless steel wire framed by wood. The electric stove is located at the bottom right side of the drying chamber. At the right end of the stove, there is a blower to encourage and circulate air in the drying chamber.

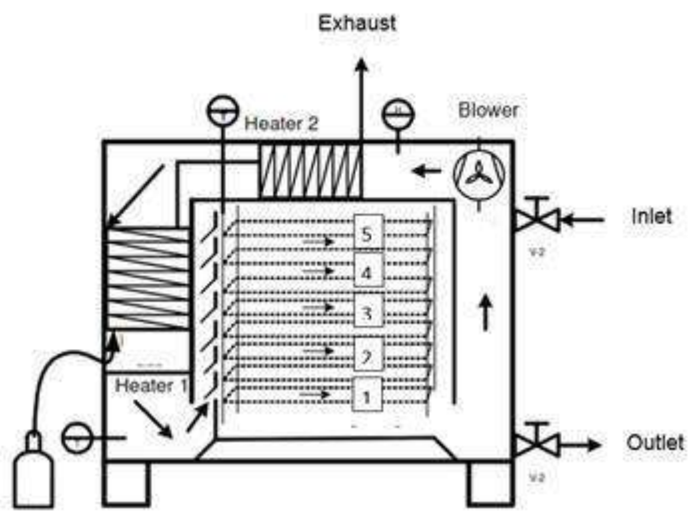

Figure 4. Sketch of a circulating air tray dryer type

Sample drying

Drying passion fruit seeds was done by placing the seeds on a tray. The drying process used a temperature of 70 °C and an air flow velocity of 0.2 m/s. Hot air from the electric stove was used to dry the samples in trays. Some of the air was expelled through the exhaust valve and some was recirculated through the heater and then returned to the drying chamber. To reduce heat loss to the environment, all parts of the drying chamber are insulated. The drying duration was calculated when the temperature in the drying chamber reaches 70 °C up to 7 hours.

Measurement of seed temperature distribution

Seed temperature distribution data during drying is measured using a data logger. The temperature sensor is installed in one of the passion fruit seeds in each drying chamber by placing the tip of the thermocouple in the surface position and the center of the seeds. This measurement was repeated with 5 replications.

Data validation test

Data validation test used regression analysis by comparing predictive data obtained from numerical analysis using FEM results with observation data generated from measurements in the drying chamber. The closeness of the relationship between predictive data and observational data can be seen from the coefficient of determination (R^2). If the value of R^2 approaches the number one it means that there was a close relationship (Ansar et al., 2020).

RESULTS AND DISCUSSION

Temperature distribution in the drying chamber

The measurement results of temperature distribution from time to time during the drying of passion fruit showed that the temperature distribution on each tray had different values (Figure 5). As the drying time increases, the material temperature also increases. The highest temperature for the seeds on tray 1 reached 45.16 °C achieved for 6 hours. This is presumably because the bottom tray gets the most heat from the electric stove, so the average temperature on the bottom tray is higher than the other trays. While the average temperature on the tray no. 2, 3, 4, and 5 are 42.33; 41.45; 40.75; and 39.43 °C, respectively.

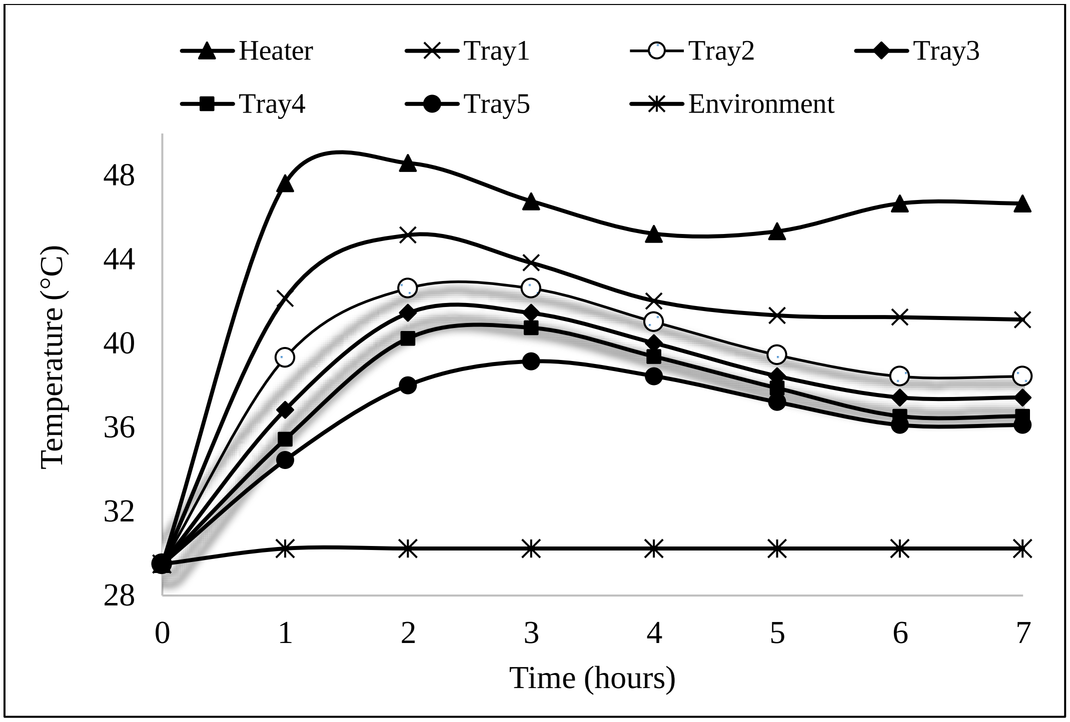

Figure 5. Temperature distribution on each tray during the drying of passion fruit seeds

In general, the drying of the tray type in this study only takes 7 hours to reduce the water content from 21% to 14.15%. This drying time is shorter when compared to the method of sun-drying which requires 10-11 hours (Shavazi et al., 2020). These results were in agreement with these reported by Bahadur et al. (2019) that direct drying in the sun was slower than artificial drying.

Uneven airflow velocity can cause uneven temperature distribution. The higher the airflow velocity, more even temperature distribution in the drying chamber. This means that the speed of airflow in the drying medium can function as a catalyst so that the temperature distribution of the seeds is also faster. The results of study by Ozakina & Kaya (2019) also reported that airflow velocity can cause a high-temperature distribution, so that the temperature distribution in the seeds was also getting bigger.

Temperature distribution in seeds

Three-dimensional temperature distribution in the passion fruit seeds during drying is shown in Figure 6. In the figure, it appears that in the first hour there was a very rapid increase and began to fall in the second hour until towards the end of drying. Temperature distribution in the passion fruit seeds occurs because of differences in temperature and heat energy arising during drying. The same thing has been expressed by Serrano et al. (2015) that the temperature distribution of materials is strongly influenced by the coefficient of displacement of the conduction pad and the thermal diffusivity of the material.

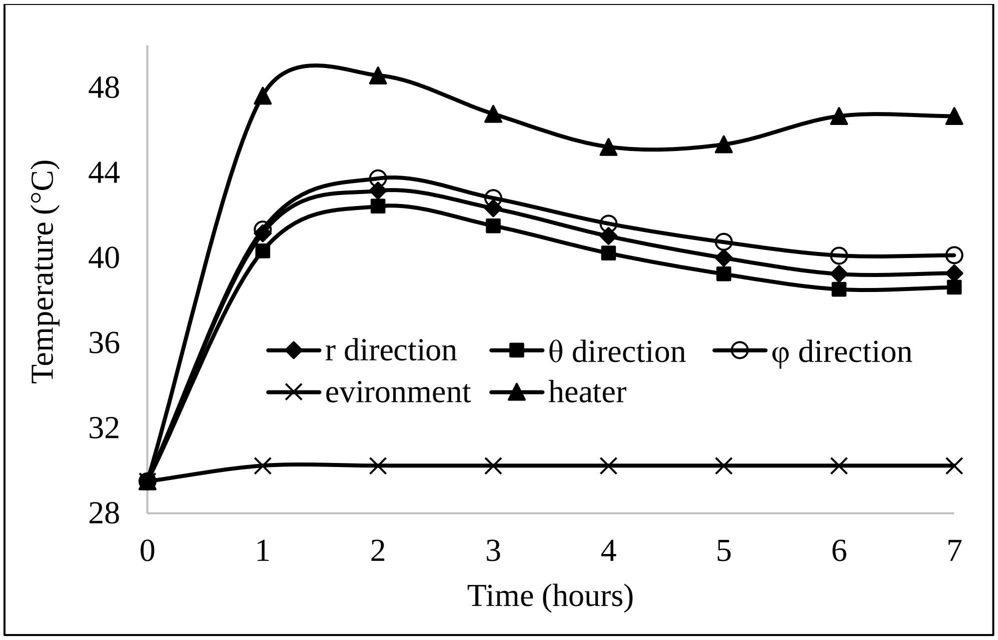

Figure 6. Three-dimensional temperature distribution in the passion fruit seeds

Three-dimensional temperature distribution of passion fruit seeds spreads from the surface of the seeds toward the center of the axis slowly until evenly distributed to all parts of the seeds. Furthermore, the temperature is distributed with an even distribution pattern in the determined boundary plane. This temperature distribution pattern follows an elliptic pattern. Numerical analysis for predicting 3-dimensional temperature distribution are very important when information is still limited about ideal conditions during the drying process. This developed model can accurately predict the temperature distribution in various positions of passion fruit seeds during the drying process. In the same case, Xiao et al. (2020) have explained that the modified numerical analysis can accurately predict the percentage of germination at various temperatures in seeds with a value of $R^2 = 0.810$.

Another phenomenon that can be revealed is that the temperature distribution occurs simultaneously in all directions of the three-dimensional axis of the seeds. The more inward (r direction), the smaller the temperature distribution, which is almost the same as the ambient temperature. Whereas the vertical direction (θ) and horizontal direction (ϕ) also have the same pattern, namely the smaller the distribution. This is following the results of the simulation program, which is for parts of the position that are closer to the sides given an initial value of T0 = 29.5 °C, then the temperature approaches the limit value. Whereas the position on the surface that receives the dryer temperature earlier has a higher temperature distribution. The same phenomenon has been reported by Fecher et al. (2014) that temperature distribution is caused by energy transfer that occurs due to temperature differences. This energy cannot be observed directly, but the direction of its displacement can be calculated using numerical analysis (Vogta et al., 2015).

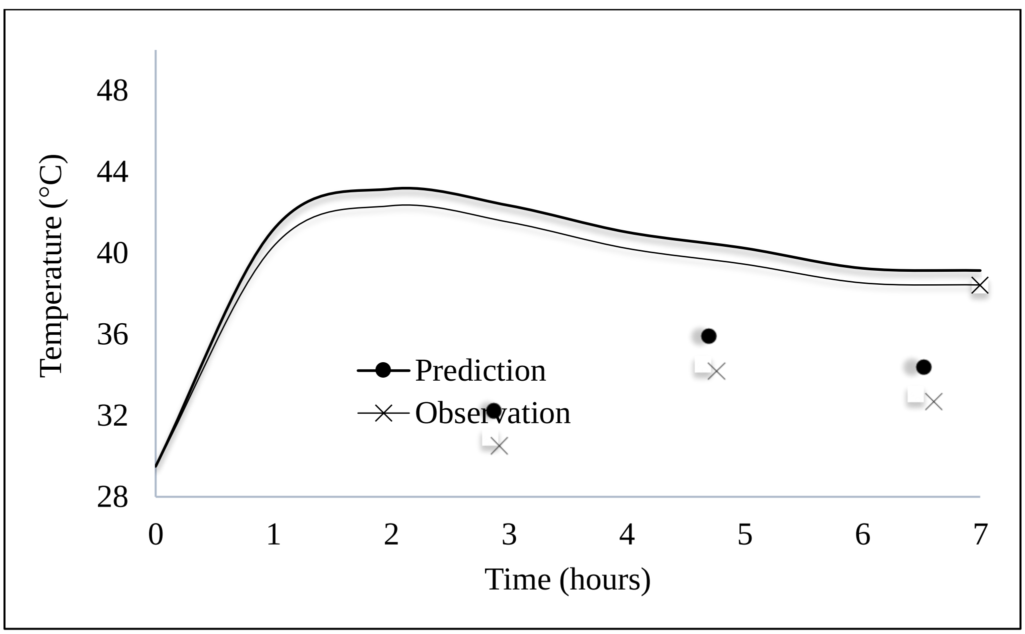

Figure 7. Prediction and observation data of temperature distribution during drying

There is a difference between the predicted temperature distribution and the observation result (Figure 7). The prediction temperature distribution is always higher than the observation temperature but has the same tendency. This difference is caused by the thermal conductivity value (k) used for simulation data slightly greater than the thermal conductivity value of passion fruit seeds. This is in line with the results of the study Reed et al. (2018) which reported that the higher the thermal conductivity value of the material, the faster the temperature propagation occurs.

Model validation

The validation of the air temperature distribution model was done by comparing the observation of the temperature distribution of the measurement results in the drying chamber with the prediction data of the FEM simulation results. The results of temperature distribution measurements in the drying chamber tend to follow the temperature distribution pattern of the simulation results with a low error. The highest error value occurred in the vertical position of 0.45%, then the horizontal position and the axis of the radius of 1.27 and 2.23%, respectively (Figure 8).

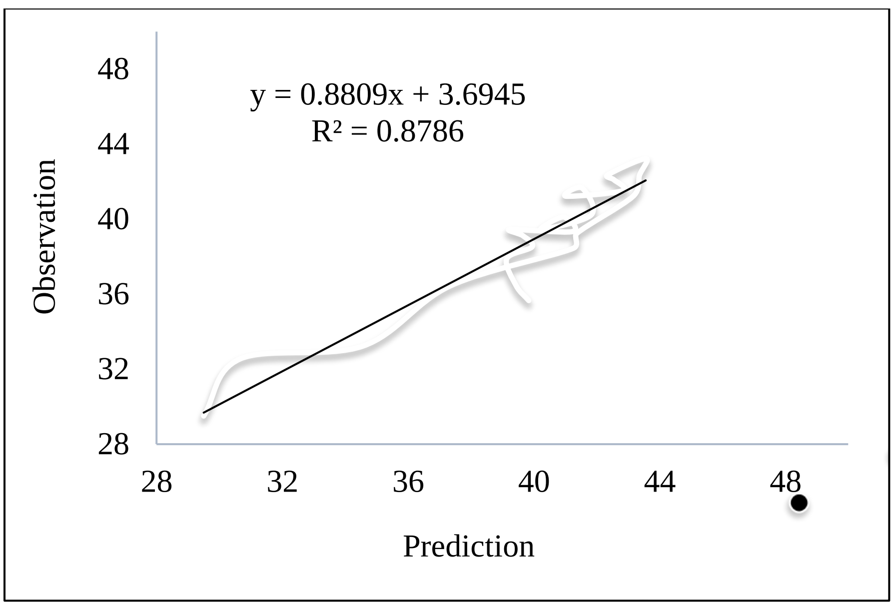

Figure 8. Validation of prediction and observation data of temperature distribution during drying.

The results of the analysis of variance showed that there were no significant differences between predicted and observation data. The temperature distribution data observations have the same pattern as the prediction data. Despite that, it is still found differences that are suspected due to the influence of the level of sensitivity of the sensor used, but the error data was still within reasonable limits. Another factor that is thought to cause differences is the effect of initial temperature variations which are not taken into account in compiling a numerical analysis using FEM approach. But the difference only appears if the initial temperature was higher than the ambient temperature. Therefore, the higher the initial temperature, the higher the difference between prediction and simulation data. Similar results were also expressed by Khurana & Karwe (2009) that the simulation results differ from the predicted results when the initial temperature is higher than the ambient temperature. Thus, the results of this study can be used as a basis for further research.

The results of the analysis of variance show that there was a close relationship between the observed temperature distribution data and the predicted data from the numerical analysis simulation results indicated by the termination coefficient value (R^2) which is 0.8786 (Figure 8). Thus, this numerical analysis using FEM was valid and can be used as a system representation in analyzing the temperature distribution of grains during drying. In line with the results of these studies Moreno et al., (2017) also reported that numerical analysis using FEM can produce accurate and valid temperature distribution prediction data and can be scientifically justified.

CONCLUSIONS

The temperature distribution in the passion fruit seeds occurs because of differences in temperature and heat energy arising during drying. This temperature distribution occurs simultaneously in all directions of the three-dimensional axis of the seeds. The deeper (direction r) the temperature distribution gets smaller. The same pattern also occurs in the vertical direction (θ) and horizontal direction (ϕ). The results of this study can be used to design dryers for grains. To improve this research, it is necessary to add blower power to provide faster air circulation.

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CONFLICT OF INTEREST

The authors declare that no conflict of interest with the founder.

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06-Jul-2021
Dear Dr. Ansar Ansar:

Your manuscript PRS-14664-2021 NUMERICAL EQUATION USING THE FINITE ELEMENT METHOD TO PREDICT THE TEMPERATURE DISTRIBUTION OF PASSION FRUIT SEEDS DURING DRYING" has gone through an initial review for publication in
Transactions of the ASABE.
The reviewers have recommended substantial revisions.

I am forwarding you constructive suggestions from the reviewers and/or Associate Editor to improve your manuscript. The comments are at the end of this letter and/or in attached files.

Please work directly with the Associate Editor, Dr. Sammy Sadaka (ssadaka@uaex.edu, samysadaka@gmail.com), as you make your revisions. Include with your resubmission an itemized response to each reviewer comment. Your revised manuscript and your responses to the reviewers' comments will be sent to the Associate Editor when you submit them via your Author Center.

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Review evaluations of your manuscript entitled "NUMERICAL EQUATION USING THE FINITE ELEMENT METHOD TO PREDICT THE TEMPERATURE DISTRIBUTION OF PASSION FRUIT SEEDS DURING DRYING (PRS-14664-2021)" are attached. Based upon the reviewer's comments and my review of your manuscript, major revision is needed to improve your manuscript.

Consider the reviewer's comments and make an appropriate revision to your manuscript. Please provide a list of summaries of how you addressed the reviewer's questions and suggestions or why a suggestion was not considered. Please indicate your corrections and changes with line numbers in your response to the reviewers and the editor.

- The manuscript title may be revised to highlight the manuscript relevance and minimize redundancy
- The manuscript needs extensive English editing.
- You need to indicate the boundary conditions. It is not clear. See line 122.
- Figure 5 shows 7 curves with only 6 legends. Please check. Use different marks.
- Figure 6 needs to be checked, similar to Figure 5. Why using markers in your figures if the results were obtained from finite element simulation?
- Figure 7: temperature needs the line to connect the markers. Once again, why markers if it is the results of a simulation?
- Line 280: The speed of the drying air…. The speed of air is not a part of the research. How can you explain including this terminology in the conclusion?

Reviewers' comments, if any, to the author (also look for attached files):
Reviewer: 1

Comments for the Author
I recommend certain changes. Good effort in compiling the manuscript.
1. Change all 4 highlights. Put the outcome of your research, not the methods used.
2. Line 47: Change “has a source” to “is a source”
3. Line 49: Change “This fruit” to “It”
4. Line 51: Remove “These”
5. Check all citations, do the last name of first author et al. in 3 and above authors papers.
6. Line 60-62: Rephrase sentence to a simpler one.
7. Line 71: passion fruit seed not passion fruit?
8. Line 72: water content is on dry basis or wet basis, please mention it in the manuscript.
9. Line 80-83: Please use proper citations, sentences do not make sense.
10. Line 109: Change from “spherical coordinate system irregular” to “irregular spherical coordinate system”
11. Line 143-146: Use past tense.
12. Line 162-167: Please be consistent with past tense. Check results and Discussion also.
13. Line 162-167: Mention how 5 pieces of fruit were placed on the tray and when exactly the drying duration of 7 hours begins?
14. Line 179: Make “R2” to “R2”
15. Line 180: Remove “very”
16. Figure 5, 6, 7 and 8: Replace color legends with black and white legends
17. Line 196-198: Rephrase.
18. Line 202-204: Rephrase.
19. Figure 8: Mention units and R2

Reviewer: 2

Comments for the Author
The authors claimed they developed a 3 D FEM model to predict the temperature distribution inside passion fruit seeds. This manuscript was poorly drafted, and lot of important information was not provided. The main issues are:
1) The authors claimed they developed a 3D model, but the passion fruit was assumed as a perfect ball. Using 3D to predict the temperature distribution of this perfect ball will have the same results as that using 2D. For this situation, 3D model is not needed, and the 3D model cannot be validated.
2) The authors only measured the surface temperature of the fruit, which cannot be used to validate the 3D model.
3) The authors did not provide any information on how the 3D model was solved, and how the parameters were selected.
4) All the predicted results can be done by a 1D or 2D model. The predicted results were also 1d or 2D results because the authors’ assumptions.

Reviewer: 3

Comments for the Author
Recommendation: Major Revision

The current study explores temperature distribution during the drying of passion fruit seeds using the finite element method. Here are some questions and comments that can strengthen the manuscript if they are addressed.

Q1. Using the term "numerical equation FEM approach" is not common. However, you may use "FEM approach," "Numerical Analysis Using FEM," or just "Numerical Analysis."

Q2. One of the advantages of using FEM, is to tackle complex geometries. Why are you assuming a spherical shape rather than a shape closer to a passion fruit?

Q3. Should we assume symmetric heat dissipation from a passion fruit? How this simplification affects your results?

Line 155: vertically or horizontally?
Line 185: on each tray
Line 186: what increases with increasing drying time? The statement needs revision.
Line 187: is the highest temperature for the seeds on tray 1?
Line 187: please mention after how long the temperature reached 45.16°C?
Figure 4: please number the trays in the picture. So, it would be easier to follow the results (lines 187-190).
Results:
- By mentioning tray temperature, do you mean the surface temperature of seeds on each tray?
Lines 196-198: the discussion is not much related to the previous result.
Lines 200, 201: faster temperature distribution? More even temperature distribution?
Line 202: study by
Line 253: , respectively
Lines 269-271: The statement is hard to follow or understand. Please revise it.

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This is a confirmation that a revision of your manuscript "NUMERICAL ANALYSIS TO PREDICT TEMPERATURE DISTRIBUTION OF THE PASSION FRUIT SEEDS DURING DRYING" has been successfully submitted to the appropriate Associate Editor via the ASABE ScholarOne Manuscripts site. The revision has the updated manuscript number PRS-14664-2021.R1.

Journal: Transactions of the ASABE

Co-authors, in order: Ansar, Ansar; Nazaruddin, Nazaruddin; Azis, Atri Dewi

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12-Oct-2021
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Ansar, Ansar; Nazaruddin, Nazaruddin; Azis, Atri Dewi,
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Numerical Analysis to Predict Temperature Distribution of the Passion Fruit Seeds during Drying

Ansar[1,], Nazaruddin[2], A. D. Azis[3]*

Published in *Transactions of the ASABE* (in press): - (doi: 10.13031/trans.14664).

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Submitted for review on 07 May 2021 as manuscript number PRS 14664 ; approved for publication as a Research Article by the Processing Systems Community of ASABE on 12 October 2021.

Highlights

- *The temperature distribution occurs because there are differences in temperature on the surface and inside the passion fruit seeds*
- *Temperature distribution occurs simultaneously in all directions*
- *The deeper into the temperature distribution the lower*
- *The same pattern also occurs in the vertical and horizontal directions.*

ABSTRACT*. The optimization of the drying process can be determined based on temperature distribution patterns using numerical analysis of the finite element method (FEM). This study has compiled a numerical analysis using FEM to predict the temperature distribution in passion fruit seeds during drying. The study was conducted using a circulating air tray dryer. Temperature distribution data on passion fruit seeds were measured using a data logger. The results showed that the numerical analysis using FEM approach can be used to simulate the temperature distribution of passion fruit seeds during drying quickly and accurately. This model has been validated by comparing the temperature distribution data measured in the drying chamber with FEM simulation results data with a relative error between 0.45 to 1.27%. The numerical analysis using FEM is important as a reference for controlling temperature distribution during drying because this method is easy to implement and results in low errors.*

Keywords. Drying, finite element methods, numerical analysis, passion fruit seeds, temperature distribution

Nomenclature:

Abbreviations

A surface area (m^2)

c air heat capacity (kJ/kg °C)

k conductivity (W/m °C)

M modulus

r the rate of heat flow towards the axis of the radius (m)

T temperature (°C)

t time (hour)

q heat energy (W)

V volume (m^3)

Subscripts

i radius index

j vertical direction index

k horizontal direction index

wt time index

Greek symbols

∂ differential

? the rate of heat flow towards the vertical direction

INTRODUCTION

Passion fruit (*Passiflora edulis*) is one of the most consumed fruits because it is a source of vitamins and minerals that are beneficial to human health (Amaral et al., 2016; Bezerra et al., 2015; Santos, et al., 2020). It can be consumed in fresh or processed form (Do Nascimento et al., 2016; Catelam et al., 2020). Passion fruit plants can grow easily in the tropics or subtropics (Allardyce et al., 2017; Atukunda, et al., 2018). Two types of passion fruit are cultivated in Indonesia, namely yellow passion fruit (*Passiflora edulis f. Flavicarpa*) and purple passion fruit (*Passiflora edulis Sims f. Flavicarpa*) (Ansar et al., 2020) (Figure 1).

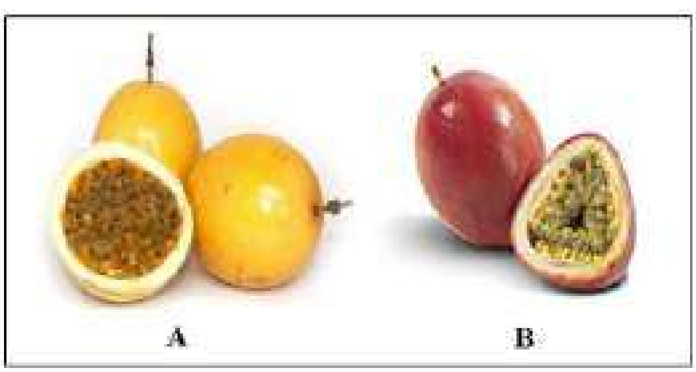

Figure 1. Yellow passion fruit (A) and purple passion fruit (B).

Nowadays, passion fruit is generally processed into syrup (Febrina et al., 2017; Ansar et al., 2019). The demand for passion fruit syrup products continues to increase until now (Seixas et al., 2014; Figueiredo et al., 2013). Processing of passion fruit into syrup produces solid waste in the form of seeds between 4-12% of the total fruit mass (Oliveira et al., 2017; Araujo et al., 2019). This fruit waste can be reused because it has oil and protein content, especially linoleic acid up to 70% (Malacrida

& Jorge, 2012; Silva et al., 2015; Silva et al., 2019). Fatty acids from passion fruit seeds have the potential to be applied in the food, pharmaceutical, cosmetics, and energy industries (Oliveira et al., 2017; Yang et al., 2019).

Unripe passion fruit seeds can germinate easily, so they have a short shelf life (Vaquiro et al., 2016; Barrales et al., 2015; Bidgolya et al., 2018). To maintain the shelf life of this passion fruit seeds, it must be dried until reaches the water content of 14% (wet basis) so that it lasts longer before being extracted into the oil (Chen et al., 2011; Leao et al., 2014; Pereira et al., 2015). An effective drying method for grains can be carried out based on a temperature distribution mechanism to optimize the evaporation of water content (de Menezes et al., 2013; Castro et al., 2018).

Research on temperature distribution using numerical analysis of the finite element method (FEM) has been widely reported (Bezerra et al., 2015; Takalkar et al., 2018). This numerical analysis can be used to explain the temperature distribution process during drying (Vaquiro et al., 2016; Jinshah & Balasubramanian, 2020; Zhoua et al., 2018). While Zhou et al. (2015) have simulated a one-dimensional temperature distribution using the FEM with graph visualization. Another temperature distribution analysis has been carried out by Monjezi & Campbell (2016) at each point of the two-dimensional plate using the FEM with the system state considered a steady-state.

Temperature distribution during drying cannot be observed directly (Shinong et al., 2020), but can only be predicted and calculated using numerical analysis (Castro et al., 2018; Xiao et al., 2020). The numerical modeling that has been compiled is then simulated and displayed in a graph (Ma et al., 2019). The numerical analysis can produce valid, detailed, and comprehensive data (Essa & Mostafa, 2017; Mayer & Grof, 2020).

Research on the process of temperature distribution in seeds whose shape is not uniform during drying using the numerical analysis FEM approach has not been found in any publication. Therefore, this research is important to describe the process of drying passion fruit seeds as a function of temperature using the numerical analysis FEM approach. This model was used to predict the temperature distribution in passion fruit seeds during non-isothermal convective drying. Thus, the purpose of this study was to compile the numerical analysis FEM approach to predict the temperature distribution of passion fruit seeds during drying.

MATERIALS AND METHODS

Numerical analysis development

To simplify the compilation of the numerical analysis FEM approach, then passion fruit seeds were assumed to be in the shape of a uniform ball as shown in Figure 2.

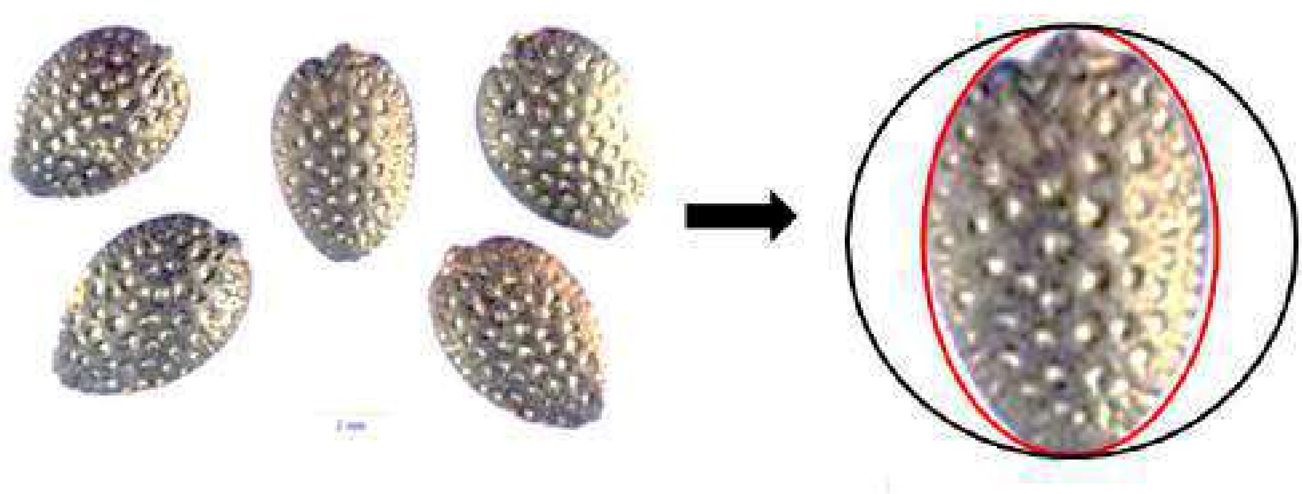

Figure 2.Purple passion fruit seeds that were assumed to have a uniform ball shape.

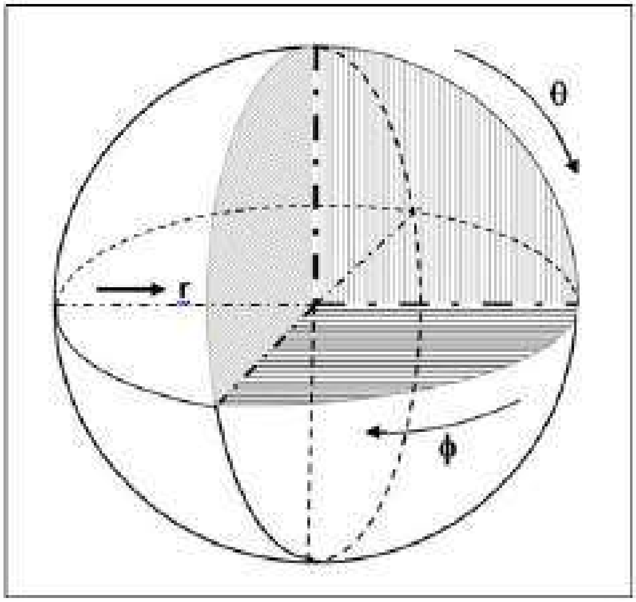

Figure 3. Modeling of three-dimensional spherical coordinate systems.

By simplifying, the transformation function of the irregular spherical coordinate system (Figure 2) was simplified into a three-dimensional regular spherical coordinate system (Figure 3), so that it can be written in the form of an equation:

$$q_r A_r\big|_r + q_\theta A_\theta\big|_\theta + q_\phi A_\phi\big|_\phi - \left(q_r A_r\big|_{r+\Delta r} + q_\theta A_\theta\big|_{\theta+\Delta\theta} + q_\phi A_\phi\big|_{\phi+\Delta\phi}\right) = \Delta V \rho c_p \frac{\partial T}{\partial t} \quad (1)$$

The rate of heat flow towards the axis of the radius (r) was:

$$q_r = -k \cdot A_r \cdot \frac{\partial T}{\partial r} \quad (2)$$

The rate of heat flow towards the vertical direction (?) was:

$$q_\theta = -k \cdot \frac{1}{r} \cdot A_\theta \cdot \frac{\partial T}{\partial \theta} \quad (3)$$

The rate of heat flow towards the horizontal direction (?) was:

$$q_\phi = -k \cdot \frac{1}{r\sin\theta} \cdot A_\phi \cdot \frac{\partial T}{\partial \phi} \qquad (4)$$

The results of substituting equations (2), (3), and (4) into equation (1), the equation was obtained:

$$\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial T}{\partial\theta}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial^2 T}{\partial\phi^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (5)$$

Initial condition (IC) and boundary condition (BC) equation (5) were:

IC: In all positions T(r, ?, ?, t) = $T_{initial}$ = 29,5 °C for t = 0

$$\frac{\partial T}{\partial r} = 0$$

BC: at t > 0 and r = 0;

The solution of equations (5) and BC was to use the numerical analysis using FEM approach explicitly. The temperature distribution on the surface of the seeds was calculated by the equation:

$$T_{NR,j,k,m+1} = \frac{1}{M}\left\{\left(2\Delta r - \frac{2}{(i)^2\Delta\theta} + M\right)T_{NR,j,k} - (2\Delta r)T_{NR-1,j,k} + \left(\frac{2}{(i)^2\Delta\theta}\right)T_{NR,j+1,k}\right\} + 2\Delta r q_{\theta x} \qquad (6)$$

The temperature distribution in the position of the seed axis was calculated by the equation:

$$T_{i,j,k,m+1} = \frac{1}{M}\left\{\left(1-\frac{1}{i}\right)T_{i-1,j,k} - (2-M)T_{i,j,k} + \left(1+\frac{1}{i}\right)T_{i+1,j,k} - \left(\frac{\Delta r}{(i)(\Delta\theta)}\right)T_{i,j-1,k} + \left(\frac{\Delta r}{(i)(\Delta\theta)}\right)T_{i,j+1,k}\right\} \qquad (7)$$

The temperature distribution at the center position of the seeds was calculated by the equation:

$$T_{0,j,k,wt+1} = \frac{1}{M}\left\{T_{1,j,k,wt} + (M-1)T_{0,j,k,wt}\right\} \tag{8}$$

The temperature distribution of the simulation results as a function of the three-dimensional position of r, ?, and ? which can be calculated by the equation:

The solution of equation (9) was to use the Trapezoidal Rule method as follows.

$$\int_0^R T_{i,j,k} \cdot r^2 \cdot dr = \frac{\Delta r}{2}\{(T_{0,j,k} \cdot R_0^2) + 2(T_{1,j,k} \cdot R_1^2) + 2(T_{2,j,k} \cdot R_2^2) + 2(T_{3,j,k} \cdot R_3^2) + 2(T_{4,j,k} \cdot R_4^2) + 2(T_{5,j,k} \cdot R_5^2) + 2(T_{6,j,k} \cdot R_6^2) + 2(T_{7,j,k} \cdot R_7^2) + 2(T_{8,j,k} \cdot R_8^2) + 2(T_{9,j,k} \cdot R_9^2) + (T_{10,j,k} \cdot R_{10}^2)\}$$

$$= A_{j,k}$$

$$\int_0^{\pi/2} B_k \cdot d\phi = \frac{\Delta\phi}{2}\{(B_0) + 2(B_1) + 2(B_2) + 2(B_3) + 2(B_4) + 2(B_5) + 2(B_6) + 2(B_7) + (B_8) \tag{10}$$

Sample preparation and equipment

Passion fruit seeds used in the study was obtained from the purple passion fruit. The fruit was cut in half and the seeds are separated from the meat using a pulpier siever. Furthermore, passion fruit seeds were washed with water to remove the remnants of the pulp. Passion fruit seeds are drained and stored at room temperature to wait for the next process.

The equipment used was a circulated air tray type dryer with a heat source obtained from a 300 Watt electric stove (Figure 4). The main parts of the dryer include drying chamber, drying tray, electric stove, blower, and exhaust. Each component is made using industry-standard construction. The support frame is made of galvanized type iron box measuring 2.5 x 2.5 cm so that it can withstand the burden of dried material. Overall dimensions of the dryer were 100 cm long, 80 cm wide, 150 cm high, and the wheel height from the ground to the tool was 10 cm.

The inner drying chamber was insulated to reduce heat loss so that the hot air inside the drying chamber can be optimally optimized for drying. Inside the drying chamber, there were 5 shelves arranged vertically with a distance of 20 cm between the shelves to collect the dried material. The tray was made of stainless steel wire framed by wood. The electric stove is located at the bottom right side of the drying chamber. At the right end of the stove, there was a blower to encourage and circulate air in the drying chamber.

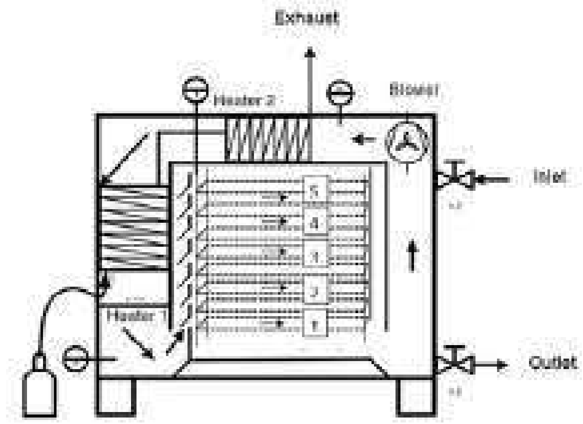

Figure 4. Sketch of a circulating air tray dryer type.

Sample drying

Drying passion fruit seeds was done by placing the seeds on a tray. The drying process used a temperature of 70 °C and an air flow velocity of 0.2 m/s. The hot air from the electric stove was used to dry the samples in trays. Some of the air was expelled through the exhaust valve and some was recirculated through the heater and then returned to the drying chamber. To reduce heat loss to the environment, all parts of the drying chamber are insulated. The drying duration was calculated when the temperature in the drying chamber reaches 70 °C for up to 7 hours. The temperature in the drying chamber and the environment were measured by a thermocouple.

Measurement of seed temperature distribution

Seed temperature distribution data during drying is measured using a data logger. The temperature sensor was installed in one of the passion fruit seeds in each drying chamber by placing the tip of the thermocouple in the surface position and the center of the seeds. This measurement was repeated with 5 replications.

Data validation test

Data validation test used regression analysis by comparing predictive data obtained from the numerical analysis using FEM results with observation data generated from measurements in the drying chamber. The relationship between predictive data and observational data can be seen from the coefficient of determination (R^2). If the value of R^2 approaches the number one it means that there was a close relationship (Ansar et al., 2020).

RESULTS AND DISCUSSION

Temperature distribution in the drying chamber

The measurement results of temperature distribution from time to time during the drying of passion fruit showed that the temperature distribution on each tray had different values (Figure 5). As the drying time increases, the material temperature also increases. The highest temperature for the seeds on tray 1 reached 45.16 °C achieved for 6 hours. This is presumably because the bottom tray gets the most heat from the electric stove, so the average temperature on the bottom tray is higher than the other trays. While the average temperature on the tray no. 2, 3, 4, and 5 were 42.33, 41.45, 40.75, and 39.43 °C, respectively.

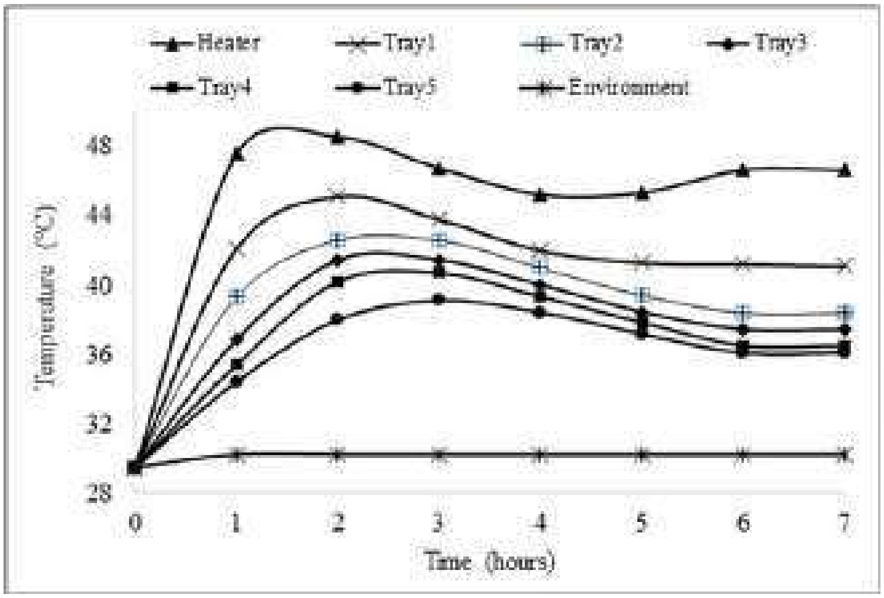

Figure 5. Temperature distribution on each tray during the drying of passion fruit seeds.

In general, the drying of the tray type in this study only takes 7 hours to reduce the water content from 21% to 14.15%. This drying time is shorter when compared to the method of sun-drying which requires 10-11 hours (Shavazi et al., 2020). These results were in agreement with these reported by Bahadur et al. (2019) that direct drying in the sun was slower than artificial drying.

Uneven airflow velocity can cause uneven temperature distribution. The higher the airflow velocity, more even temperature distribution in the drying chamber. This means that the speed of airflow in the drying medium can function as a catalyst so that the temperature distribution of the seeds is also faster. The results of study by Ozakina & Kaya (2019) also reported that airflow velocity can cause a high-temperature distribution, so that the temperature distribution in the seeds was also getting bigger.

Temperature distribution in seeds

Three-dimensional temperature distributionin the passion fruit seeds during drying is shown in Figure 6. In the figure, it appears that in the first hour there was a very rapid increase and began to fall in the second hour until towards the end of drying. Temperature distribution in the passion fruit seeds occurs because of differences in temperature and heat energy arising during drying. The same thing has been expressed by Serrano et al. (2015) that the temperature distribution of materials is strongly influenced by the coefficient of displacement of the conduction pad and the thermal diffusivity of the material.

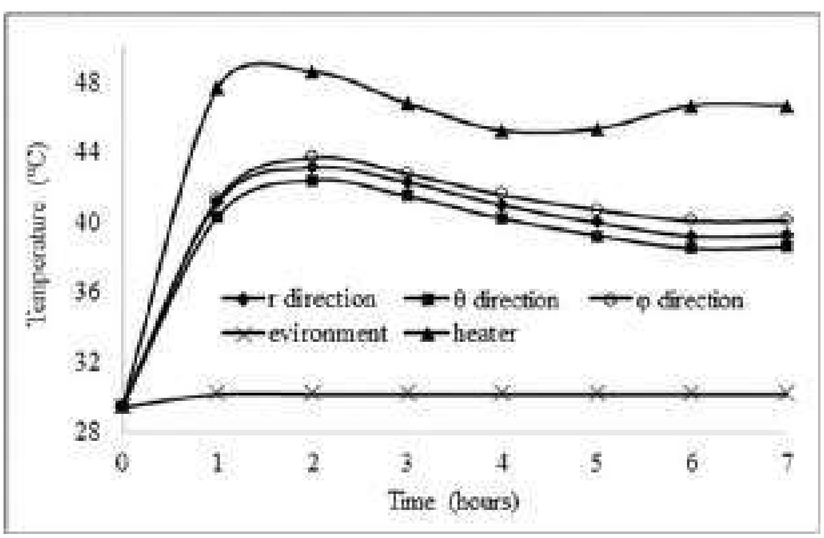

Figure 6. Three-dimensional temperature distribution in the passion fruit seeds.

Three-dimensional temperature distribution of passion fruit seeds spreads from the surface of the seeds toward the center of the axis slowly until evenly distributed to all parts of the seeds. Furthermore, the temperature is distributed with an even distribution pattern in the determined boundary plane. This temperature distribution pattern follows an elliptic pattern.

Numerical analysis for predicting 3-dimensional temperature distribution are very important when information is still limited about ideal conditions during the drying process. This developed model can accurately predict the temperature distribution in various positions of passion fruit seeds during the drying process. In the same case, Xiao et al. (2020) have explained that the modified numerical analysis can accurately predict the percentage of germination at various temperatures in seeds with a value of $R^2 = 0.810$.

Another phenomenon that can be revealed is that the temperature distribution occurs simultaneously in all directions of the three-dimensional axis of the seeds. The more inward (r direction), the smaller the temperature distribution, which is almost the same as the ambient temperature. Whereas the vertical direction (?) and horizontal direction (?) also have the same pattern, namely the smaller the distribution. This is following the results of the simulation program, which is for parts of the position that are closer to the sides given an initial value of T0 = 29.5 °C, then the temperature approaches the limit value. Whereas the position on the surface that receives the dryer temperature earlier has a higher temperature distribution. The same phenomenon has been reported by Fecher et al. (2014) that temperature distribution is caused by energy transfer that occurs due to temperature differences. This energy cannot be observed directly, but the direction of its displacement can be calculated using numerical analysis (Vogta et al., 2015).

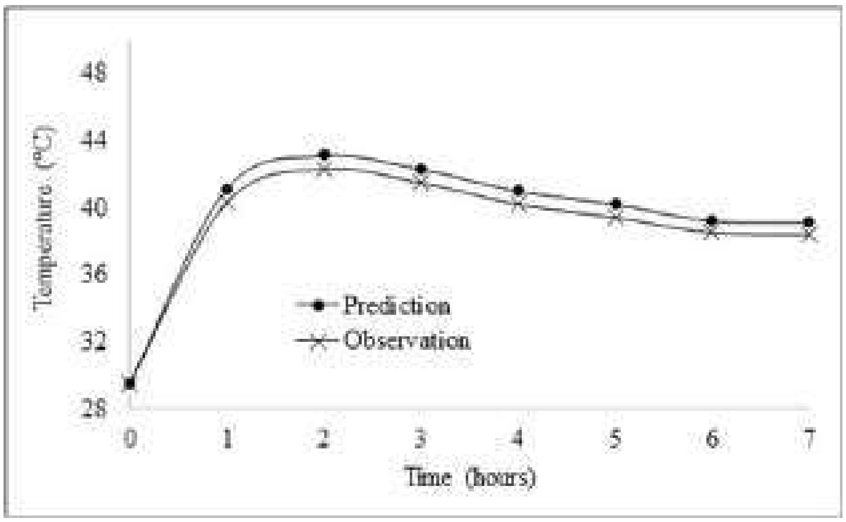

Figure 7. Prediction and observation data of temperature distribution during drying.

There is a difference between the predicted temperature distribution and the observation result (Figure 7). The prediction temperature distribution is always higher than the observation temperature but has the same tendency. This difference is caused by the thermal conductivity value (k) used for simulation data slightly greater than the thermal conductivity value of passion fruit seeds. This is in line with the results of the study Reed et al. (2018) which reported that the higher the thermal conductivity value of the material, the faster the temperature propagation occurs.

Model validation

The validation of the air temperature distribution model was done by comparing the observation of the temperature distribution of the measurement results in the drying chamber with the prediction data of the FEM simulation results. The results of temperature distribution measurements in the drying chamber tend to follow the temperature distribution pattern of the simulation results with a low error. The highest error value occurred in the vertical position of 0.45%, then the horizontal position and the axis of the radius of 1.27 and 2.23%, respectively (Figure 8).

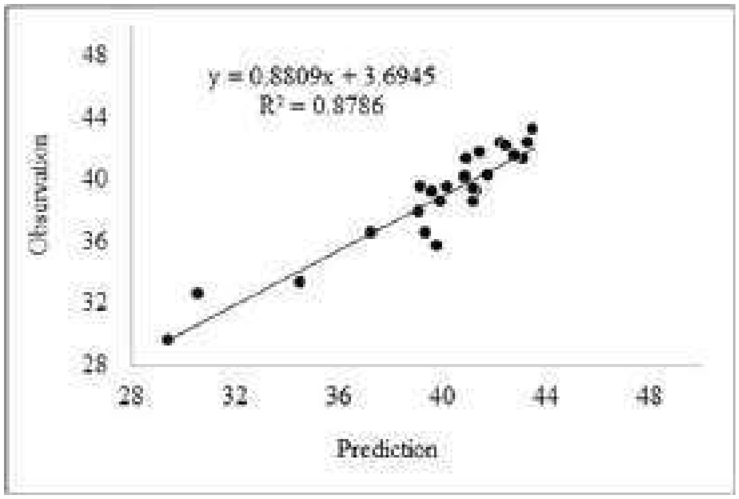

Figure 8. Validation of prediction and observation data of temperature distribution during drying.

The results of the analysis of variance showed that there were no significant differences between predicted and observation data. The temperature distribution data observations have the same pattern as the prediction data. Despite that, it is still found differences that are suspected due to the influence of the level of sensitivity of the sensor used, but the error data was still within reasonable limits. Another factor that is thought to cause differences is the effect of initial temperature variations which are not taken into account in compiling a numerical analysis using FEM approach. But the difference only appears if the initial temperature was higher than the ambient temperature. Therefore, the higher the initial temperature, the higher the difference between prediction and simulation data. Similar results were also expressed by Khurana & Karwe (2009) that the simulation results differ from the predicted results when the initial temperature is higher than the ambient temperature. Thus, the results of this study can be used as a basis for further research.

The results of the analysis of variance show that there was a close relationship between the observed temperature distribution data and the predicted data from the numerical analysis simulation results indicated by the termination coefficient value (R^2) which is 0.8786 (Figure 8). Thus, this numerical analysis using FEM was valid and can be used as a system representation in analyzing the temperature distribution of grains during drying. In line with the results of these studies Moreno et al., (2017) also reported that numerical analysis using FEM can produce accurate and valid temperature distribution prediction data and can be scientifically justified.

CONCLUSIONS

The temperature distribution in the passion fruit seeds occurs because of differences in temperature and heat energy arising during drying. This temperature distribution occurs simultaneously in all directions of the three-dimensional axis of the seeds. The deeper (direction r) the temperature distribution gets smaller. The same pattern also occurs in the vertical direction (?) and horizontal direction (?). The results of this study can be used to design dryers for grains. To improve this research, it is necessary to add blower power to provide faster air circulation.

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CONFLICT OF INTEREST

The authors declare that no conflict of interest with the founder.

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