

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 ($\text{kJ/kg } ^\circ\text{C}$)

k conductivity ($\text{W/m } ^\circ\text{C}$)

M modulus

- 29 r the rate of heat flow towards the axis of the radius (m)
30 T temperature ($^{\circ}\text{C}$)
31 t time (hour)
32 q heat energy (W)
33 V volume (m^3)

34 *Subscripts*

- 35 i radius index
36 j vertical direction index
37 k horizontal direction index
38 wt time index

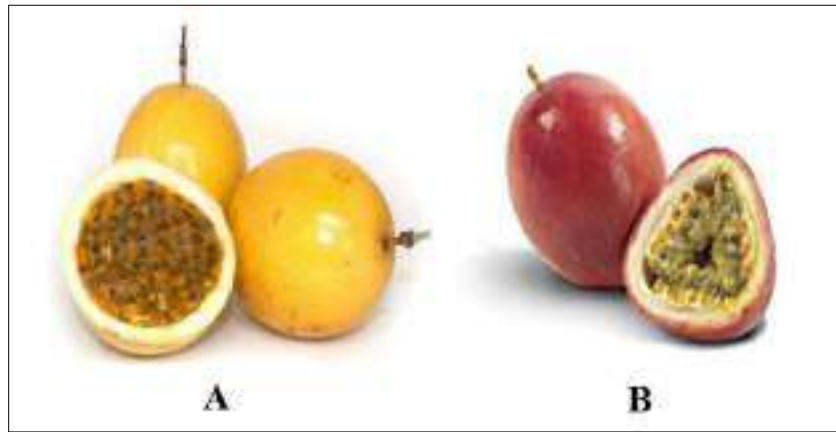
39 *Greek symbols*

- 40 ∂ differential
41 α heat diffusivity (m^2/dtk)
42 θ the rate of heat flow towards the vertical direction
43 ϕ the rate of heat flow towards the horizontal direction
44 Δ ingredient

45

46 **INTRODUCTION**

47 Passion fruit (*Passiflora edulis*) is one of the most consumed fruits because it is a source of
48 vitamins and minerals that are beneficial to human health (Amaral et al., 2016; Bezerra et al., 2015;
49 Santos, et al., 2020). It can be consumed in fresh or processed form (Do Nascimento et al., 2016;
50 Catelam et al., 2020). Passion fruit plants can grow easily in the tropics or subtropics (Allardyce et al.,
51 2017; Atukunda, et al., 2018). Two types of passion fruit are cultivated in Indonesia, namely yellow
52 passion fruit (*Passiflora edulis f. Flavicarpa*) and purple passion fruit (*Passiflora edulis Sims f.*



54
55 **Figure 1. Yellow passion fruit (A) and purple passion fruit (B)**

56
57 Nowadays, passion fruit is generally processed into syrup (Febrina et al., 2017; Ansar et al., 2019).
58 The manufacture of the syrup has the most important economic impact on the passion fruit market
59 because world demand continues to grow to date (Seixas et al., 2014; Figueiredo et al., 2013).
60 Processing of passion fruit into syrup produces solid waste in the form of seeds between 4-12% of the
61 total fruit mass (Oliveira et al., 2017; Araujo, et al., 2019). This fruit waste can be reused because it has
62 oil and protein content, especially linoleic acid up to 70% (Malacrida & Jorge, 2012; Silva et al., 2015;
63 Silva et al., 2019). Fatty acids from passion fruit seeds have the potential to be applied in the food,
64 pharmaceutical, cosmetics, and energy industries (Oliveira et al., 2017; Yang et al., 2019).

65 Unripe passion fruit seeds generally grow sprouts, so they have a short shelf life (Vaquiro et al.,
66 2016; Barrales et al., 2015; Bidgolya et al., 2018). To maintain the shelf life of this passion fruit, it must
67 be dried until it reaches 14% water content so that it lasts longer before being extracted into the oil
68 (Chen et al., 2011; Leao et al., 2014; Pereira et al., 2015). An effective drying method for grains can be
69 carried out based on a temperature distribution mechanism to optimize the evaporation of water content
70 (de Menezes et al., 2013; Castro et al., 2018).

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

73 However, existing scientific publications generally still use a one-dimensional numerical equation to
74 describe the process of drying grain (Vaquiro et al., 2016; Jinshah & Balasubramanian, 2020; Zhou et
75 al., 2018) have simulated temperature distribution on one dimension using FEM. While Zhou et al.
76 (2015) have simulated a one-dimensional temperature distribution using the FEM with graph
77 visualization. Another temperature distribution analysis has been carried out by Monjezi & Campbell
78 (2016) at each point of the two-dimensional plate using the FEM with the system state considered a
79 steady-state.

80 Temperature distribution during drying cannot be observed directly (Shinong et al., 2020), but
81 can only be predicted and calculated using numerical modeling (Castro et al., 2018; Xiao et al., 2020).
82 The numerical modeling that has been compiled is then simulated and displayed in a graph (Ma et al.,
83 2019). The numerical modeling can produce valid, detailed, and comprehensive data (Essa & Mostafa,
84 2017; Mayer & Grof, 2020).

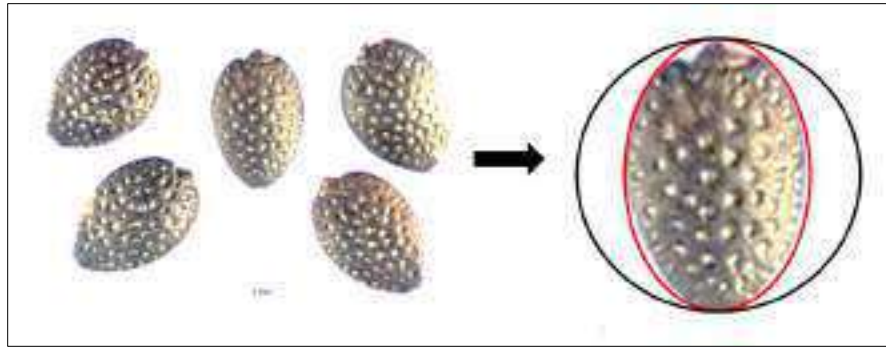
85 Research on the process of temperature distribution in seeds whose shape is not uniform during
86 drying using a numerical equation of the FEM approach has not been found in any publication.
87 Therefore, this research is important to describe the process of drying passion fruit seeds as a function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

92

93 **MATERIALS AND METHODS**

94 *Numerical equation development*

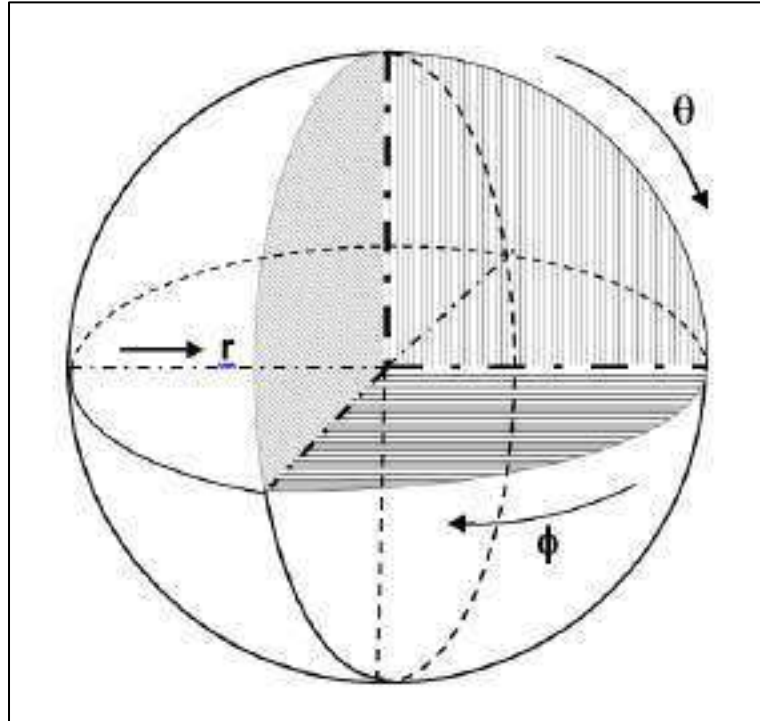
95 To simplify the compilation of the numerical equations of the FEM approach, then passion fruit
96 seeds are assumed to be in the shape of a uniform ball as shown in Figure 2.



97

98

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



99

100

Figure 3. Modeling of three-dimensional spherical coordinate systems

101

102

103

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:

104

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

105

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

106

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

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

$$108 \quad q_{\theta} = -k \cdot \frac{1}{r} \cdot A_{\theta} \cdot \frac{\partial T}{\partial \theta} \quad (3)$$

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

$$110 \quad q_{\phi} = -k \cdot \frac{1}{r \sin \theta} \cdot A_{\phi} \cdot \frac{\partial T}{\partial \phi} \quad (4)$$

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

$$112 \quad \frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial T}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 T}{\partial \phi^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (5)$$

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

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

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

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

$$118 \quad T_{NR,j,k,wt+1} = \frac{1}{M} \left\{ \left(2\Delta r - \frac{2}{(i)^2 \Delta \theta} + M \right) T_{NR,j,k} - (2\Delta r) T_{NR-1,j,k} + \left(\frac{2}{(i)^2 \Delta \theta} \right) T_{NR,j+1,k} \right\} + 2\Delta r q_{fric} \quad (6)$$

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

$$120 \quad T_{i,j,k,wt+1} = \frac{1}{M} \left\{ \left(1 - \frac{1}{i} \right) T_{i-1,j,k} - (2-M) T_{i,j,k} + \left(1 + \frac{1}{i} \right) T_{i+1,j,k} - \left(\frac{\Delta r}{(i)(\Delta \theta)} \right) T_{i,j-1,k} + \left(\frac{\Delta r}{(i)(\Delta \theta)} \right) T_{i,j+1,k} \right\} \quad (7)$$

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

$$122 \quad T_{0,j,k,wt+1} = \frac{1}{M} \left\{ T_{1,j,k,wt} + (M-1) T_{0,j,k,wt} \right\} \quad (8)$$

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

$$\bar{T}_{hit} = \frac{\rho C p \int_0^R \int_0^{\pi/2} \int_0^{\pi/2} T \cdot r^2 \sin \theta \cdot dr \cdot d\theta \cdot d\phi}{\rho C p \int_0^V dV} \quad (9)$$

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

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

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

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

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

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

$$= B_k$$

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

134

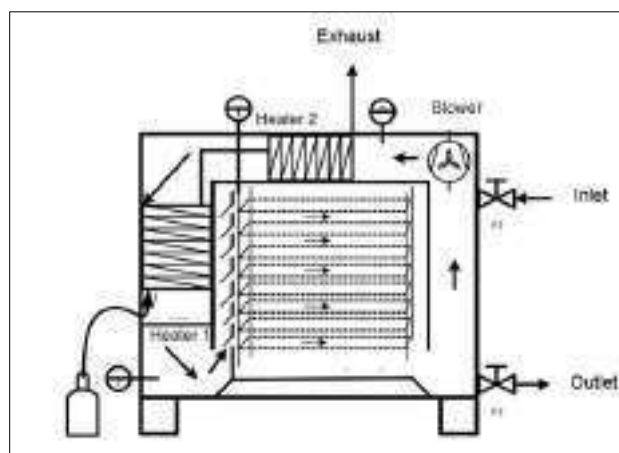
135 ***Sample preparation and equipment***

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

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

145 height from the ground to the tool is 10 cm.

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



152

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

154 ***Sample drying***

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

161

162 ***Measurement of seed temperature distribution***

163 Seed temperature distribution data during drying is measured using a data logger. The temperature

164 sensor is installed in one of the passion fruit seeds in each drying chamber by placing the tip of the
165 thermocouple in the surface position and the center of the seeds. This measurement was repeated with
166 5 replications.

167

168 *Data validation test*

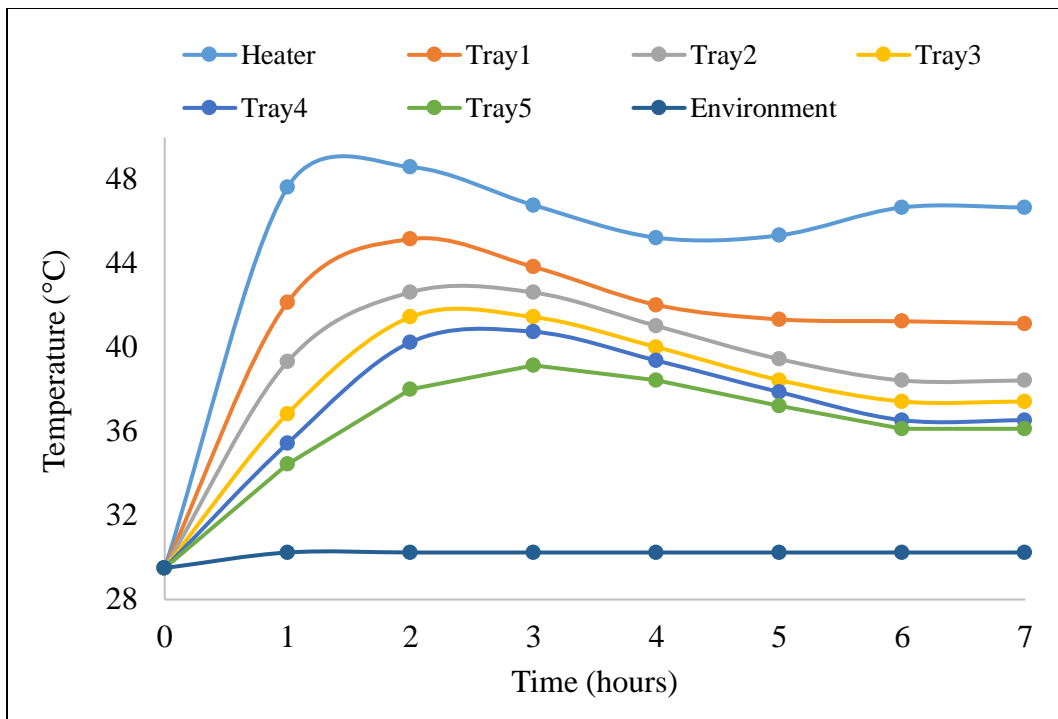
169 Data validation test used regression analysis by comparing predictive data obtained from FEM
170 numerical model simulation results with observational data generated from measurements in the drying
171 chamber. The closeness of the relationship between predictive data and observational data can be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

174

175 **RESULTS AND DISCUSSION**

176 *Temperature distribution in the drying chamber*

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



184
185 **Figure 5. Temperature distribution on each tray during the drying of passion fruit seeds**

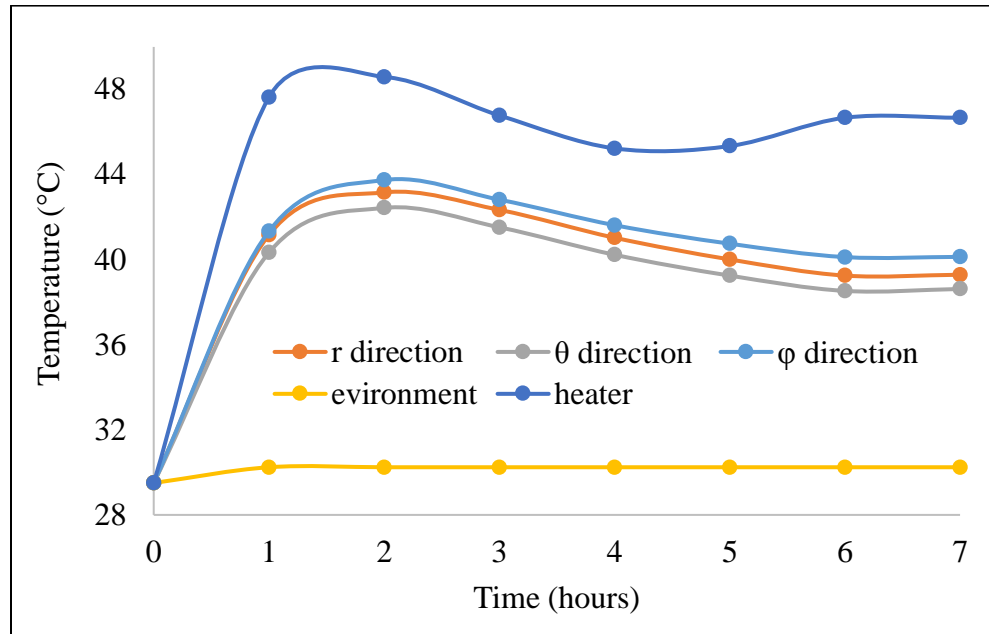
186
187 In general, the drying of the tray type in this study only takes 7 hours to reduce the water content
188 from 21% to 14.15%. This drying time is shorter when compared to the method of sun-drying which
189 requires 10-11 hours (Shavazi et al., 2020). The same trend data has been reported by Bahadur et al.
190 (2019) that the higher the dryer temperature, the lower the final water content produced.

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

197
198 ***Temperature distribution in seeds***

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

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

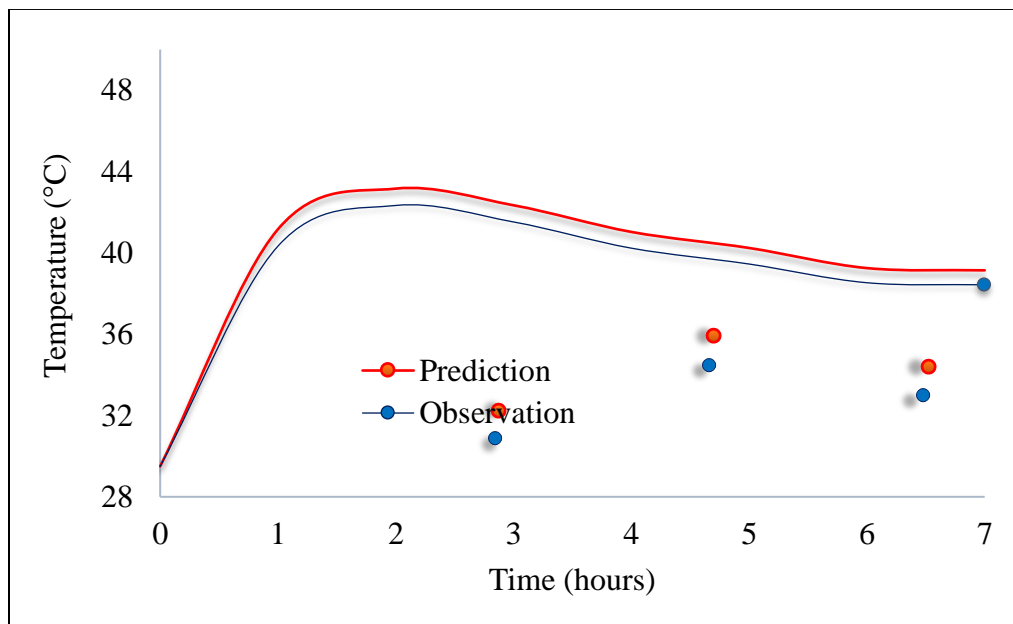


206
207 **Figure 6. Three-dimensional temperature distribution in the passion fruit seeds**

208
209 Three-dimensional temperature distribution of passion fruit seeds spreads from the surface of the
210 seeds toward the center of the axis slowly until evenly distributed to all parts of the seeds. Furthermore,
211 the temperature is distributed with an even distribution pattern in the determined boundary plane. This
212 temperature distribution pattern follows an elliptic pattern. Numerical models for predicting 3-
213 dimensional temperature distribution are very important when information is still limited about ideal
214 conditions during the drying process. This developed model can accurately predict the temperature
215 distribution in various positions of passion fruit seeds during the drying process. In the same case, Xiao
216 et al. (2020) have explained that the modified numerical model can accurately predict the percentage of

217 germination at various temperatures in seeds with a value of $R^2 = 0.810$.

218 Another phenomenon that can be revealed is that the temperature distribution occurs
219 simultaneously in all directions of the three-dimensional axis of the seeds. The more inward (r
220 direction), the smaller the temperature distribution, which is almost the same as the ambient
221 temperature. Whereas the vertical direction (θ) and horizontal direction (ϕ) also have the same pattern,
222 namely the smaller the distribution. This is following the results of the simulation program, which is
223 for parts of the position that are closer to the sides given an initial value of $T_0 = 29.5$ °C, then the
224 temperature approaches the limit value. Whereas the position on the surface that receives the dryer
225 temperature earlier has a higher temperature distribution. The same phenomenon has been reported by
226 Fecher et al. (2014) that temperature distribution is caused by energy transfer that occurs due to
227 temperature differences. This energy cannot be observed directly, but the direction of its displacement
228 can be calculated using numerical modeling (Vogta et al., 2015).



229
230 **Figure 7. Prediction and observation data of temperature distribution during drying**

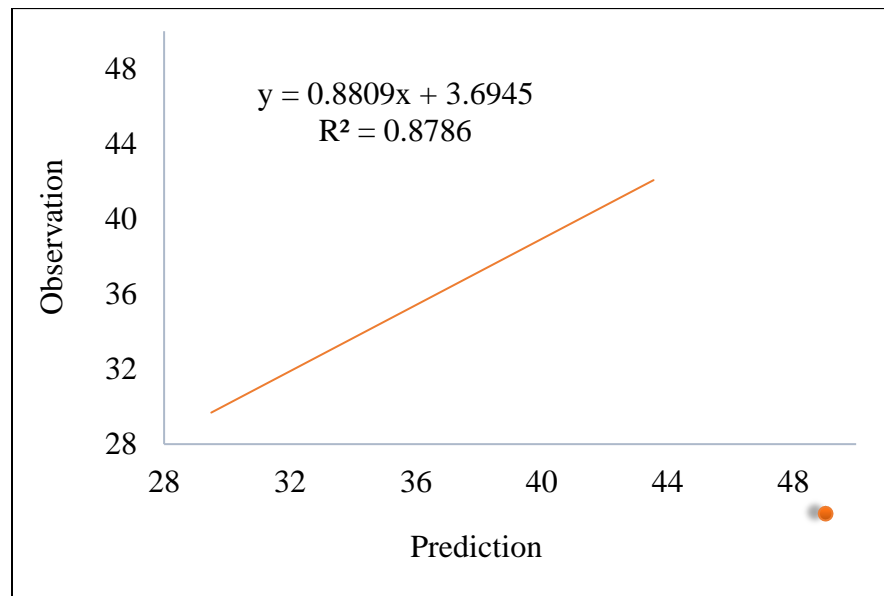
231
232 There is a difference between the predicted temperature distribution and the observation result
233 (Figure 7). The prediction temperature distribution is always higher than the observation temperature

234 but has the same tendency. This difference is caused by the thermal conductivity value (k) used for
235 simulation data slightly greater than the thermal conductivity value of passion fruit seeds. This is in line
236 with the results of the study Reed et al. (2018) which reported that the higher the thermal conductivity
237 value of the material, the faster the temperature propagation occurs.

238

239 ***Model validation***

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



246

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

249

250 The results of the analysis of variance showed that there were no significant differences between
251 predicted and observational data. The temperature distribution data observations have the same pattern

252 as the prediction data. Despite that, it is still found differences that are suspected due to the influence
253 of the level of sensitivity of the sensor used, but the error data is still within reasonable limits. Another
254 factor that is thought to cause differences is the effect of initial temperature variations which are not
255 taken into account in compiling a numerical model of the FEM approach. But the difference only
256 appears if the initial temperature is higher than the ambient temperature. Therefore, the higher the initial
257 temperature, the higher the difference between prediction and simulation data. Similar results were also
258 expressed by Khurana & Karwe (2009) that the simulation results differ from the predicted results when
259 the initial temperature is higher than the ambient temperature. Thus, the results of this study can be used
260 as a basis for further research.

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

268

269 **CONCLUSIONS**

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

276

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281 this research can be carried out well.

282

283 **CONFLICT OF INTEREST**

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

285

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Date Submitted

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

Journal:	<i>American Society of Agricultural and Biological Engineers</i>
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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:	<p>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.</p> <p>ABSTRACT.docx</p>

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1 **NUMERICAL EQUATION USING THE FINITE ELEMENT METHOD** 2 **TO PREDICT THE TEMPERATURE DISTRIBUTION OF PASSION** 3 **FRUIT SEEDS DURING DRYING**

4 **Highlights**

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

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

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

23 **Nomenclature:**

24 *Abbreviations*

- 25 A surface area (m²)
26 c air heat capacity (kJ/kg°C)
27 k conductivity (W/m°C)
28 M modulus

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

30 T temperature ($^{\circ}\text{C}$)

31 t time (hour)

32 q heat energy (W)

33 V volume (m^3)

34 *Subscripts*

35 i radius index

36 j vertical direction index

37 k horizontal direction index

38 wt time index

39 *Greek symbols*

40 ∂ differential

41 α heat diffusivity (m^2/dtk)

42 θ the rate of heat flow towards the vertical direction

43 ϕ the rate of heat flow towards the horizontal direction

44 Δ ingredient

45

46 **INTRODUCTION**

47 Passion fruit (*Passiflora edulis*) is one of the most consumed fruits because it has a source of
48 vitamins and minerals that are beneficial to human health (Amaral, de Resende, Junior, & de Lima,
49 2016; Bezerra, Meller da Silva, Corrêa, & Rodrigues, 2015; Santos, et al., 2020). This fruit can be
50 consumed in fresh or processed form (Do Nascimento, Mulet, Ascheri, de Carvalho, & Cárcel, 2016;
51 Catelam, Trindade, & Romero, 2011; Ramos-González, et al., 2020). These passion fruit plants can
52 grow easily in the tropics or subtropics (Allardyce, Fankhauser, Zakeeruddin, Grätzel, & Dyson, 2017;

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



56
57 **Figure 1. Yellow passion fruit (A) and purple passion fruit (B)**

58
59 Nowadays, passion fruit is generally processed into syrup (Febrina, Sinulingga, & Napitupulu,
60 2017; Ansar, Nazaruddin, & Azis, 2019). The manufacture of the syrup has the most important
61 economic impact on the passion fruit market because world demand continues to grow to date (Seixas,
62 et al., 2014; Figueiredo, et al., 2013). Processing of passion fruit into syrup produces solid waste in the
63 form of seeds between 4-12% of the total fruit mass (Oliveira, Mezzomo, Gomes, & Ferreira, 2017;
64 Araujo, et al., 2019). This fruit waste can be reused because it has oil and protein content, especially
65 linoleic acid up to 70% (Malacrida & Jorge, 2012; Silva, et al., 2015; Silva, et al., 2019). Fatty acids
66 from passion fruit seeds have the potential to be applied in the food, pharmaceutical, cosmetics, and
67 energy industries (Oliveira, Mezzomo, Gomes, & Ferreira, 2017; Oliveira, Angonese, Ferreira, &
68 Gomes, 2017; Yang, Hu, & Long, 2019).

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

73 (Chen, Yang, & Liu, 2011; Leao, Sampaio, Pagani, & Da Silva, 2014; Pereira, Correa, & Oliveira,
74 2015). An effective drying method for grains can be carried out based on a temperature distribution
75 mechanism to optimize the evaporation of water content (de Menezes, et al., 2013; Castro, Mayorga, &
76 Moreno, 2018).

77 Research about temperature distribution using the numerical equation of the finite element
78 method (FEM) approach has been widely reported (Bezerra, Meller da Silva, Correa, & Rodrigues,
79 2015; Takalkar & Bhosale, 2018). However, existing scientific publications generally still use a one-
80 dimensional numerical equation to describe the process of drying grain (Váquiro, Rodríguez, Simal,
81 Solanilla-Duque, & Telis-Romero, 2016; Jinshah & Balasubramanian, 2020; Zhoua, Kea, & Deng,
82 2018) have simulated temperature distribution on one dimension using FEM. While (Zhou, Yi, Wang,
83 & Ye, 2015) have simulated a one-dimensional temperature distribution using the FEM with graph
84 visualization. Another temperature distribution analysis has been carried out by Monjezi & Campbell
85 (2016) at each point of the two-dimensional plate using the FEM with the system state considered a
86 steady-state.

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

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

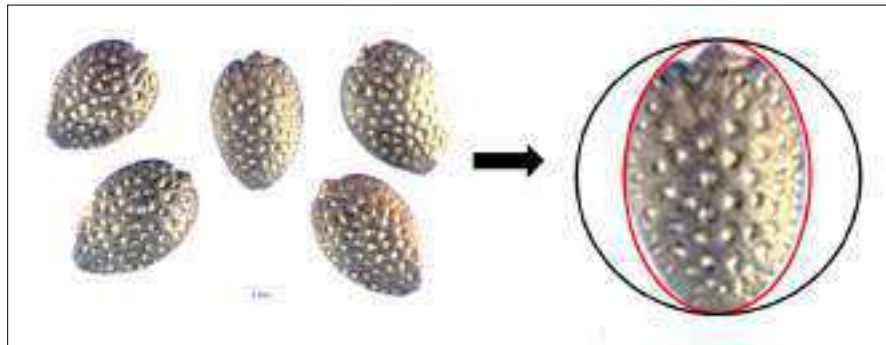
98 purpose of this study was to compile a numerical equation using the FEM approach to predict the
99 temperature distribution of passion fruit seeds during drying.

100

101 MATERIALS AND METHODS

102 *Numerical equation development*

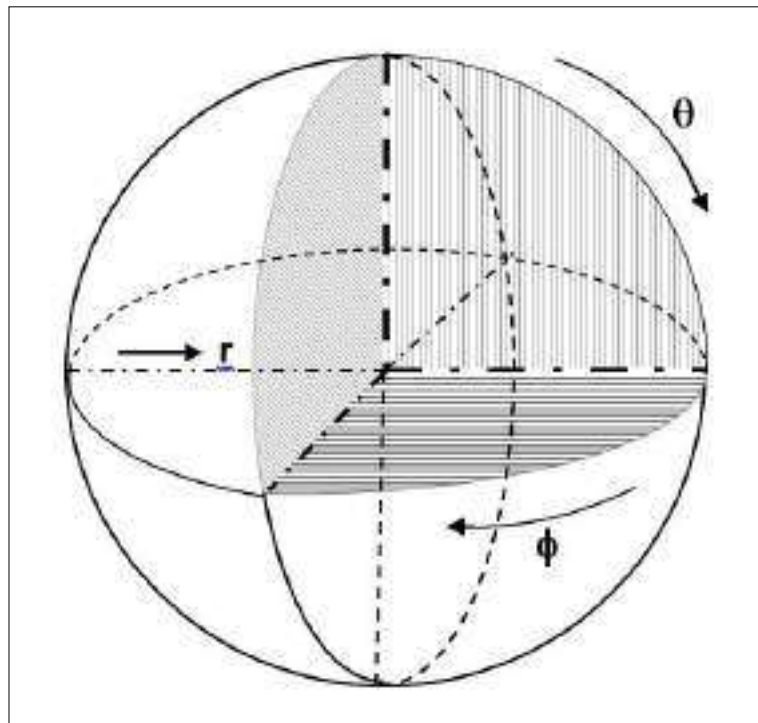
103 To simplify the compilation of the numerical equations of the FEM approach, then passion fruit
104 seeds are assumed to be in the shape of a uniform ball as shown in Figure 2.



105

106

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



107

108

Figure 3. Modeling of three-dimensional spherical coordinate systems

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

$$112 \quad q_r A_r \Big|_r + q_\theta A_\theta \Big|_\theta + q_\phi A_\phi \Big|_\phi - (q_r A_r \Big|_{r+\Delta r} + q_\theta A_\theta \Big|_{\theta+\Delta\theta} + q_\phi A_\phi \Big|_{\phi+\Delta\phi}) = \Delta V \rho c_p \frac{\partial T}{\partial t} \quad (1)$$

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

$$114 \quad q_r = -k \cdot A_r \cdot \frac{\partial T}{\partial r} \quad (2)$$

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

$$116 \quad q_\theta = -k \cdot \frac{1}{r} \cdot A_\theta \cdot \frac{\partial T}{\partial \theta} \quad (3)$$

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

$$118 \quad q_\phi = -k \cdot \frac{1}{r \sin \theta} \cdot A_\phi \cdot \frac{\partial T}{\partial \phi} \quad (4)$$

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

$$120 \quad \frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial T}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 T}{\partial \phi^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (5)$$

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

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

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

$$125 \quad T_{NR,j,k,w+1} = \frac{1}{M} \left\{ \left(2\Delta r - \frac{2}{(i)^2 \Delta \theta} + M \right) T_{NR,j,k} - (2\Delta r) T_{NR-1,j,k} + \left(\frac{2}{(i)^2 \Delta \theta} \right) T_{NR,j+1,k} \right\} + 2\Delta r q_{fric} \quad (6)$$

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

$$127 \quad T_{i,j,k,w+1} = \frac{1}{M} \left\{ \left(1 - \frac{1}{i} \right) T_{i-1,j,k} - (2-M) T_{i,j,k} + \left(1 + \frac{1}{i} \right) T_{i+1,j,k} - \left(\frac{\Delta r}{(i)(\Delta \theta)} \right) T_{i,j-1,k} + \left(\frac{\Delta r}{(i)(\Delta \theta)} \right) T_{i,j+1,k} \right\} \quad (7)$$

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

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

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:

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

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

$$\begin{aligned} \int_0^R T_{i,j,k} \cdot r^2 \cdot dr &= \frac{\Delta r}{2} \{ (T_{0,j,k} \cdot R_0^2) + 2(T_{1,j,k} \cdot R_1^2) + 2(T_{2,j,k} \cdot R_2^2) + 2(T_{3,j,k} \cdot R_3^2) + 2(T_{4,j,k} \cdot R_4^2) + \\ & 2(T_{5,j,k} \cdot R_5^2) + 2(T_{6,j,k} \cdot R_6^2) + 2(T_{7,j,k} \cdot R_7^2) + 2(T_{8,j,k} \cdot R_8^2) + 2(T_{9,j,k} \cdot R_9^2) + (T_{10,j,k} \cdot R_{10}^2) \} = A_{j,k} \\ \int_0^{\pi/2} A_{j,k} \cdot \sin \theta \cdot d\theta &= \frac{\Delta \theta}{2} \{ (A_{0,k} \cdot \sin(0 \cdot \Delta \theta)) + 2(A_{1,k} \cdot \sin(1 \cdot \Delta \theta)) + 2(A_{2,k} \cdot \sin(2 \cdot \Delta \theta)) + 2(A_{3,k} \cdot \sin(3 \cdot \Delta \theta)) + \\ & 2(A_{4,k} \cdot \sin(4 \cdot \Delta \theta)) + 2(A_{5,k} \cdot \sin(5 \cdot \Delta \theta)) + 2(A_{6,k} \cdot \sin(6 \cdot \Delta \theta)) + \\ & 2(A_{7,k} \cdot \sin(7 \cdot \Delta \theta)) + (A_{8,k} \cdot \sin(8 \cdot \Delta \theta)) \} \\ &= B_k \\ \int_0^{\pi/2} B_k \cdot d\phi &= \frac{\Delta \phi}{2} \{ (B_0) + 2(B_1) + 2(B_2) + 2(B_3) + 2(B_4) + 2(B_5) + 2(B_6) + 2(B_7) + (B_8) \} \end{aligned} \quad (10)$$

141

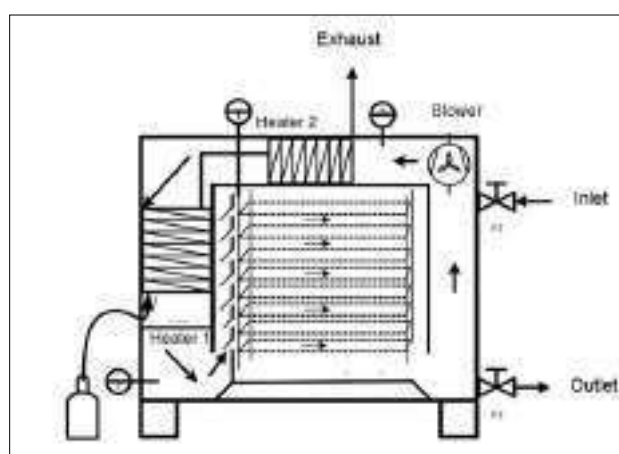
142 ***Sample preparation and equipment***

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

147 The equipment used is a circulated air tray type dryer with a heat source obtained from a 300 Watt
148 electric stove (Figure 4). The main parts of the dryer include drying chamber, drying tray, electric stove,
149 blower, and exhaust. Each component is made using industry-standard construction. The support frame

150 is made of galvanized type iron box measuring 2.5 x 2.5 cm so that it can withstand the burden of dried
 151 material. Overall dimensions of the dryer are 100 cm long, 80 cm wide, 150 cm high, and the wheel
 152 height from the ground to the tool is 10 cm.

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



159
 160 **Figure 4. Sketch of a circulating air tray dryer type**

161 *Sample drying*

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

168

169 *Measurement of seed temperature distribution*

170 Seed temperature distribution data during drying is measured using a data logger. The temperature
171 sensor is installed in one of the passion fruit seeds in each drying chamber by placing the tip of the
172 thermocouple in the surface position and the center of the seeds. This measurement was repeated with
173 5 replications.

174

175 *Data validation test*

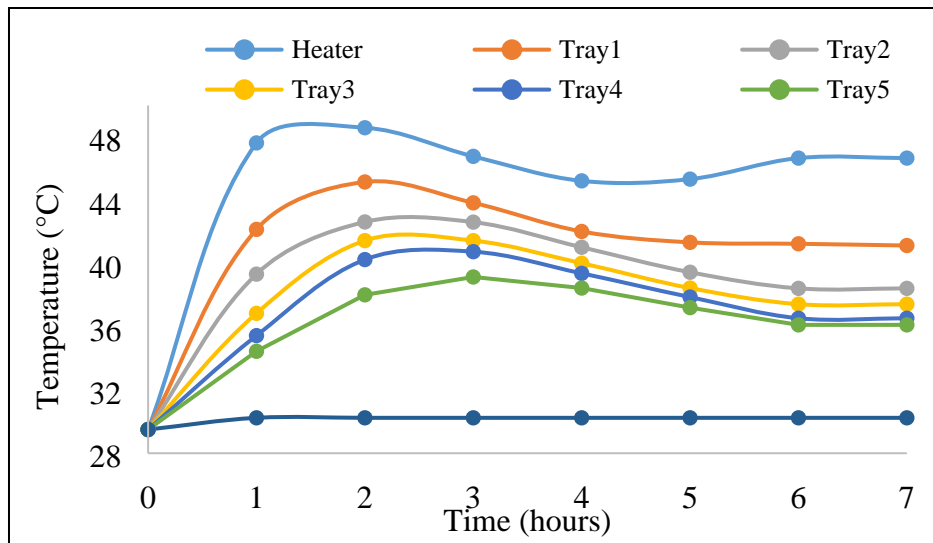
176 Data validation test used regression analysis by comparing predictive data obtained from FEM
177 numerical model simulation results with observational data generated from measurements in the drying
178 chamber. The closeness of the relationship between predictive data and observational data can be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

181

182 **RESULTS AND DISCUSSION**

183 *Temperature distribution in the drying chamber*

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



191
192 **Figure 5. Temperature distribution on each tray during the drying of passion fruit seeds**

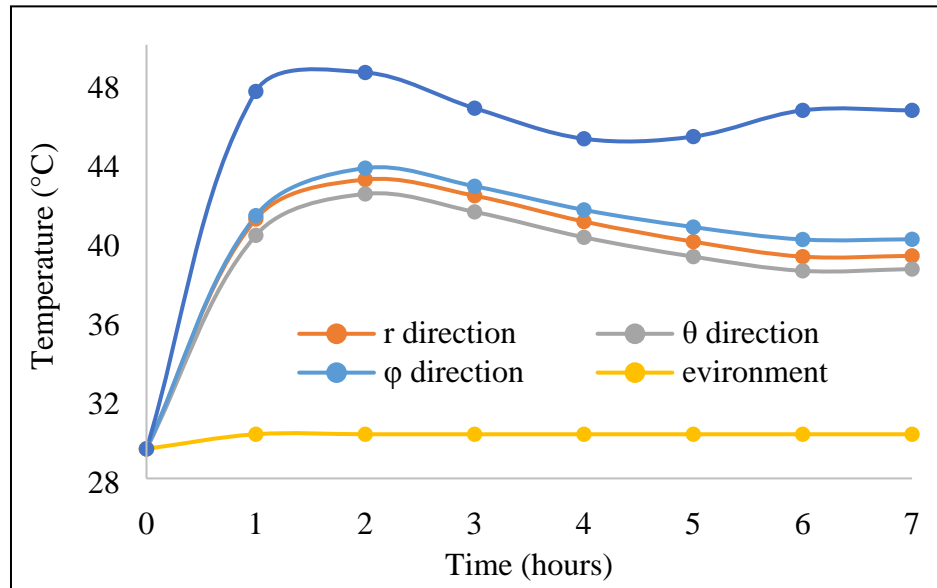
193
194 In general, the drying of the tray type in this study only takes 7 hours to reduce the water content
195 from 21% to 14.15%. This drying time is shorter when compared to the method of sun-drying which
196 requires 10-11 hours (Shavazi, Torres, Hughes, & Pye, 2020). The same trend data has been reported
197 by Bahadur et al. (2019) that the higher the dryer temperature, the lower the final water content
198 produced.

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

205 206 *Temperature distribution in seeds*

207 Temperature distribution in passion fruit seeds during drying is shown in Figure 6. In the figure,
208 it appears that in the first hour there was a very rapid increase and began to fall in the second hour until

209 towards the end of drying. Temperature distribution in passion fruit seeds occurs because of differences
 210 in temperature and heat energy arising during drying. The same thing has been expressed by Serrano-
 211 Arellano et al. (2015) that the temperature distribution of materials is strongly influenced by the
 212 coefficient of displacement of the conduction pad and the thermal diffusivity of the material.

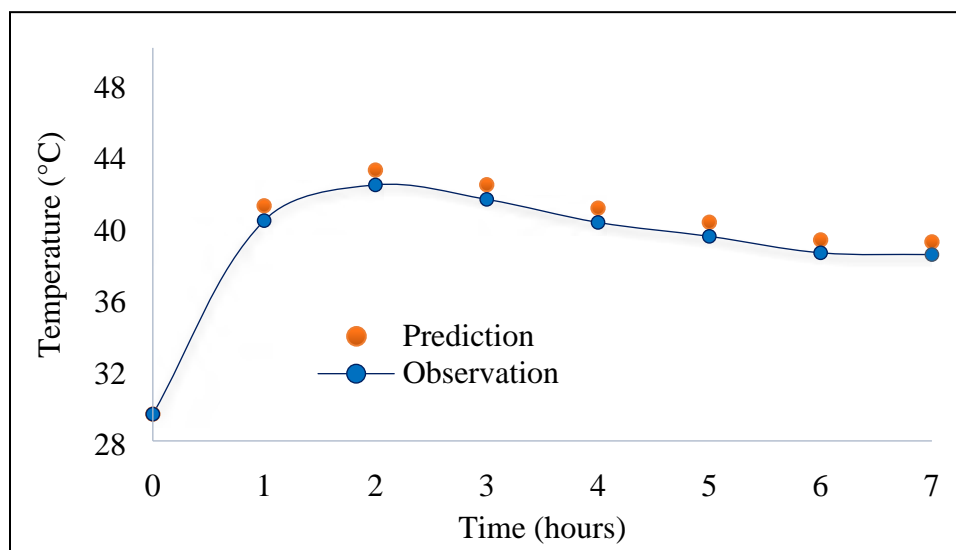


213
 214 **Figure 6. Three-dimensional temperature distribution in passion fruit seeds**

215
 216 Three-dimensional temperature distribution of passion fruit seeds spreads from the surface of the
 217 seeds toward the center of the axis slowly until evenly distributed to all parts of the seeds. Furthermore,
 218 the temperature is distributed with an even distribution pattern in the determined boundary plane. This
 219 temperature distribution pattern follows an elliptic pattern. Numerical models for predicting 3-
 220 dimensional temperature distribution are very important when information is still limited about ideal
 221 conditions during the drying process. This developed model can accurately predict the temperature
 222 distribution in various positions of passion fruit seeds during the drying process. In the same case, Xiao
 223 et al. (2020) have explained that the modified numerical model can accurately predict the percentage of
 224 germination at various temperatures in seeds with a value of $R^2 = 0.810$.

225 Another phenomenon that can be revealed is that the temperature distribution occurs
 226 simultaneously in all directions of the three-dimensional axis of the seeds. The more inward (r direction),

227 the smaller the temperature distribution, which is almost the same as the ambient temperature. Whereas
 228 the vertical direction (θ) and horizontal direction (ϕ) also have the same pattern, namely the smaller the
 229 distribution. This is following the results of the simulation program, which is for parts of the position
 230 that are closer to the sides given an initial value of $T_0 = 29.5^\circ\text{C}$, then the temperature approaches the
 231 limit value. Whereas the position on the surface that receives the dryer temperature earlier has a higher
 232 temperature distribution. The same phenomenon has been reported by Fecher, Romero, Brabec, &
 233 Buerhop-Lutz (2014) that temperature distribution is caused by energy transfer that occurs due to
 234 temperature differences. This energy cannot be observed directly, but the direction of its displacement
 235 can be calculated using numerical modeling (Vogta, Holst, Wintera, Brendela, & Altermat, 2015).



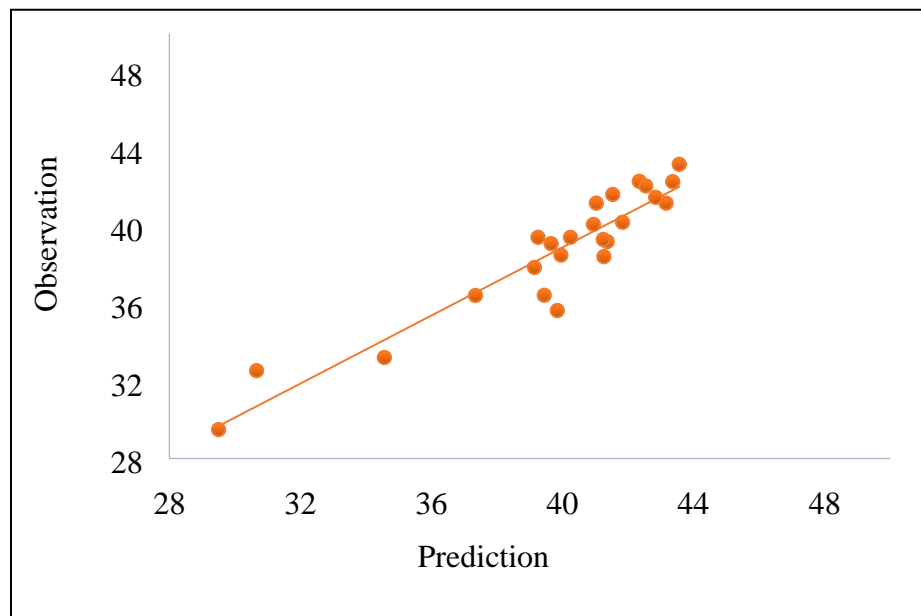
236
 237 **Figure 7. Prediction and observation data of temperature distribution during drying**

238
 239 There is a difference between the predicted temperature distribution and the observation result
 240 (Figure 7). The prediction temperature distribution is always higher than the observation temperature
 241 but has the same tendency. This difference is caused by the thermal conductivity value (k) used for
 242 simulation data slightly greater than the thermal conductivity value of passion fruit seeds. This is in line
 243 with the results of the study Reed, Sugo, & Lattice (2018) which reported that the higher the thermal
 244 conductivity value of the material, the faster the temperature propagation occurs.

245

246 ***Model validation***

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



253

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

256

257 The results of the analysis of variance showed that there were no significant differences between
258 predicted and observational data. The temperature distribution data observations have the same pattern
259 as the prediction data. Despite that, it is still found differences that are suspected due to the influence
260 of the level of sensitivity of the sensor used, but the error data is still within reasonable limits. Another
261 factor that is thought to cause differences is the effect of initial temperature variations which are not

262 taken into account in compiling a numerical model of the FEM approach. But the difference only
263 appears if the initial temperature is higher than the ambient temperature. Therefore, the higher the initial
264 temperature, the higher the difference between prediction and simulation data. Similar results were also
265 expressed by Khurana & Karwe (2009) that the simulation results differ from the predicted results when
266 the initial temperature is higher than the ambient temperature. Thus, the results of this study can be used
267 as a basis for further research.

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

275

276 **CONCLUSIONS**

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

284

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289 be carried out well.

290

291 CONFLICT OF INTEREST

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

293

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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 ($\text{kJ/kg } ^\circ\text{C}$)

k conductivity ($\text{W/m } ^\circ\text{C}$)

M modulus

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

30 T temperature ($^{\circ}\text{C}$)

31 t time (hour)

32 q heat energy (W)

33 V volume (m^3)

34 *Subscripts*

35 i radius index

36 j vertical direction index

37 k horizontal direction index

38 wt time index

39 *Greek symbols*

40 ∂ differential

41 α heat diffusivity (m^2/dtk)

42 θ the rate of heat flow towards the vertical direction

43 ϕ the rate of heat flow towards the horizontal direction

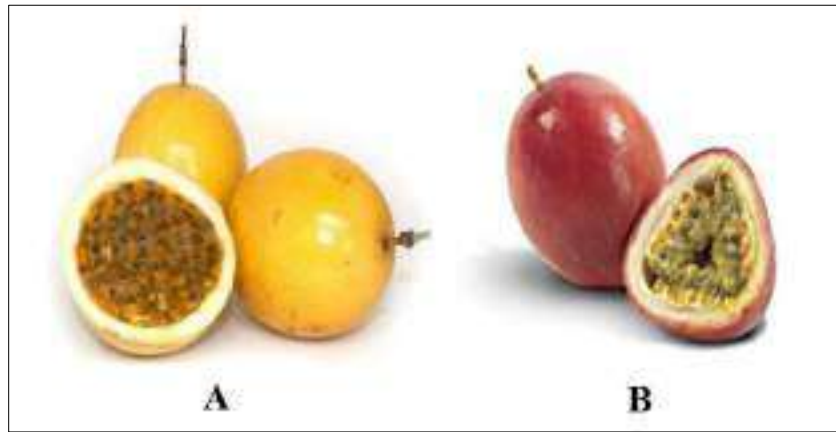
44 Δ ingredient

45

46 **INTRODUCTION**

47 Passion fruit (*Passiflora edulis*) is one of the most consumed fruits because it is a source of
48 vitamins and minerals that are beneficial to human health (Amaral et al., 2016; Bezerra et al., 2015;
49 Santos, et al., 2020). It can be consumed in fresh or processed form (Do Nascimento et al., 2016;
50 Catelam et al., 2020). Passion fruit plants can grow easily in the tropics or subtropics (Allardyce et al.,
51 2017; Atukunda, et al., 2018). Two types of passion fruit are cultivated in Indonesia, namely yellow
52 passion fruit (*Passiflora edulis f. Flavicarpa*) and purple passion fruit (*Passiflora edulis Sims f.*

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



54
55 **Figure 1. Yellow passion fruit (A) and purple passion fruit (B)**

56
57 Nowadays, passion fruit is generally processed into syrup (Febrina et al., 2017; Ansar et al., 2019).
58 The demand for passion fruit syrup products continues to increase until now (Seixas et al., 2014;
59 Figueiredo et al., 2013). Processing of passion fruit into syrup produces solid waste in the form of seeds
60 between 4-12% of the total fruit mass (Oliveira et al., 2017; Araujo et al., 2019). This fruit waste can
61 be reused because it has oil and protein content, especially linoleic acid up to 70% (Malacrida & Jorge,
62 2012; Silva et al., 2015; Silva et al., 2019). Fatty acids from passion fruit seeds have the potential to be
63 applied in the food, pharmaceutical, cosmetics, and energy industries (Oliveira et al., 2017; Yang et al.,
64 2019).

65 Unripe passion fruit seeds generally grow sprouts, so they have a short shelf life (Vaquiro et al.,
66 2016; Barrales et al., 2015; Bidgolya et al., 2018). To maintain the shelf life of this passion fruit seeds,
67 it must be dried until it reaches 14% wet basis water content so that it lasts longer before being extracted
68 into the oil (Chen et al., 2011; Leao et al., 2014; Pereira et al., 2015). An effective drying method for
69 grains can be carried out based on a temperature distribution mechanism to optimize the evaporation of
70 water content (de Menezes et al., 2013; Castro et al., 2018).

71 Research on temperature distribution using numerical analysis of the finite element method
72 (FEM) has been widely reported (Bezerra et al., 2015; Takalkar et al., 2018). This numerical analysis

73 can be used to explain the temperature distribution process during drying (Vaquiro et al., 2016; Jinshah
74 & Balasubramanian, 2020; Zhou et al., 2018). While Zhou et al. (2015) have simulated a one-
75 dimensional temperature distribution using the FEM with graph visualization. Another temperature
76 distribution analysis has been carried out by Monjezi & Campbell (2016) at each point of the two-
77 dimensional plate using the FEM with the system state considered a steady-state.

78 Temperature distribution during drying cannot be observed directly (Shinong et al., 2020), but
79 can only be predicted and calculated using numerical analysis (Castro et al., 2018; Xiao et al., 2020).
80 The numerical modeling that has been compiled is then simulated and displayed in a graph (Ma et al.,
81 2019). The numerical analysis can produce valid, detailed, and comprehensive data (Essa & Mostafa,
82 2017; Mayer & Grof, 2020).

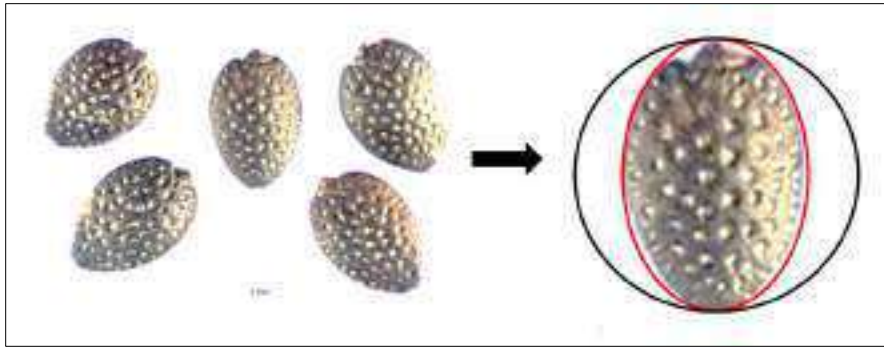
83 Research on the process of temperature distribution in seeds whose shape is not uniform during
84 drying using a numerical analysis using FEM approach has not been found in any publication.
85 Therefore, this research is important to describe the process of drying passion fruit seeds as a function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

90

91 **MATERIALS AND METHODS**

92 ***Numerical analysis development***

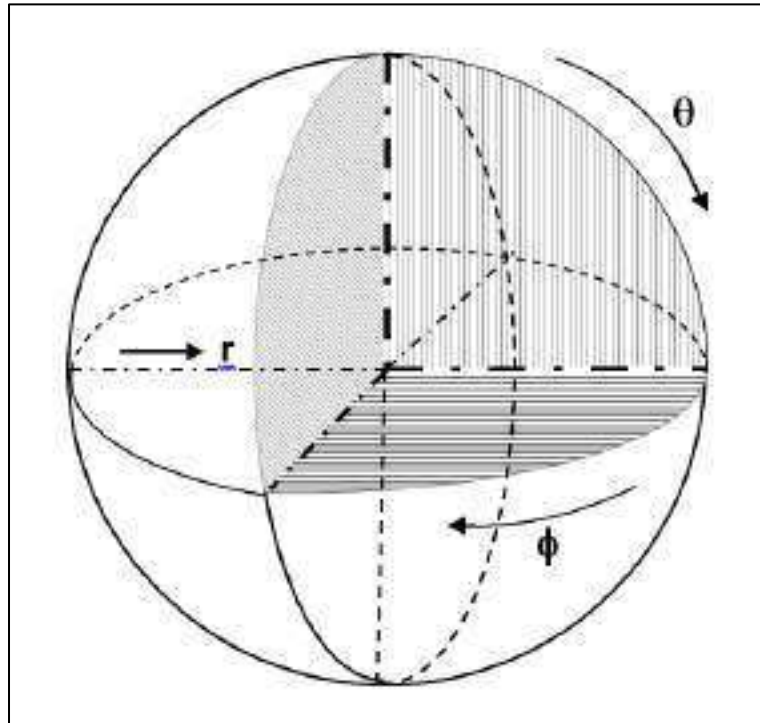
93 To simplify the compilation of the numerical analysis of the FEM approach, then passion fruit
94 seeds are assumed to be in the shape of a uniform ball as shown in Figure 2.



95

96

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



97

98

Figure 3. Modeling of three-dimensional spherical coordinate systems

99

By simplifying, the transformation function of the **irregular spherical coordinate system** (Figure 100 2) is simplified into a three-dimensional regular spherical coordinate system (Figure 3), so that it can 101 be written in the form of an equation:

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

103

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

104

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

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

106
$$q_{\theta} = -k \cdot \frac{1}{r} \cdot A_{\theta} \cdot \frac{\partial T}{\partial \theta} \quad (3)$$

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

108
$$q_{\phi} = -k \cdot \frac{1}{r \sin \theta} \cdot A_{\phi} \cdot \frac{\partial T}{\partial \phi} \quad (4)$$

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

110
$$\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial T}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 T}{\partial \phi^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (5)$$

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

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

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

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

116
$$T_{NR,j,k,wt+1} = \frac{1}{M} \left\{ \left(2\Delta r - \frac{2}{(i)^2 \Delta \theta} + M \right) T_{NR,j,k} - (2\Delta r) T_{NR-1,j,k} + \left(\frac{2}{(i)^2 \Delta \theta} \right) T_{NR,j+1,k} \right\} + 2\Delta r q_{fric} \quad (6)$$

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

118
$$T_{i,j,k,wt+1} = \frac{1}{M} \left\{ \left(1 - \frac{1}{i} \right) T_{i-1,j,k} - (2-M) T_{i,j,k} + \left(1 + \frac{1}{i} \right) T_{i+1,j,k} - \left(\frac{\Delta r}{(i)(\Delta \theta)} \right) T_{i,j-1,k} + \left(\frac{\Delta r}{(i)(\Delta \theta)} \right) T_{i,j+1,k} \right\} \quad (7)$$

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

120
$$T_{0,j,k,wt+1} = \frac{1}{M} \left\{ T_{1,j,k,wt} + (M-1) T_{0,j,k,wt} \right\} \quad (8)$$

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

123

$$\bar{T}_{hit} = \frac{\rho C p \int_0^{\pi/2} \int_0^{\pi/2} \int_0^R T \cdot r^2 \sin \theta \cdot dr \cdot d\theta \cdot d\phi}{\rho C p \int_0^V dV} \quad (9)$$

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

125
$$\int_0^R T_{i,j,k} \cdot r^2 \cdot dr = \frac{\Delta r}{2} \left\{ (T_{0,j,k} \cdot R_0^2) + 2(T_{1,j,k} \cdot R_1^2) + 2(T_{2,j,k} \cdot R_2^2) + 2(T_{3,j,k} \cdot R_3^2) + 2(T_{4,j,k} \cdot R_4^2) + \right.$$

126
$$\left. 2(T_{5,j,k} \cdot R_5^2) + 2(T_{6,j,k} \cdot R_6^2) + 2(T_{7,j,k} \cdot R_7^2) + 2(T_{8,j,k} \cdot R_8^2) + 2(T_{9,j,k} \cdot R_9^2) + (T_{10,j,k} \cdot R_{10}^2) \right\} = A_{j,k}$$

127
$$\int_0^{\pi/2} A_{j,k} \cdot \sin \theta \cdot d\theta = \frac{\Delta \theta}{2} \left\{ (A_{0,k} \cdot \sin(0 \cdot \Delta \theta)) + 2(A_{1,k} \cdot \sin(1 \cdot \Delta \theta)) + 2(A_{2,k} \cdot \sin(2 \cdot \Delta \theta)) + 2(A_{3,k} \cdot \sin(3 \cdot \Delta \theta)) + \right.$$

128
$$\left. 2(A_{4,k} \cdot \sin(4 \cdot \Delta \theta)) + 2(A_{5,k} \cdot \sin(5 \cdot \Delta \theta)) + 2(A_{6,k} \cdot \sin(6 \cdot \Delta \theta)) + \right.$$

129
$$\left. 2(A_{7,k} \cdot \sin(7 \cdot \Delta \theta)) + (A_{8,k} \cdot \sin(8 \cdot \Delta \theta)) \right\}$$

130
$$= B_k$$

131
$$\int_0^{\pi/2} B_k \cdot d\phi = \frac{\Delta \phi}{2} \left\{ (B_0) + 2(B_1) + 2(B_2) + 2(B_3) + 2(B_4) + 2(B_5) + 2(B_6) + 2(B_7) + (B_8) \right\} \quad (10)$$

132

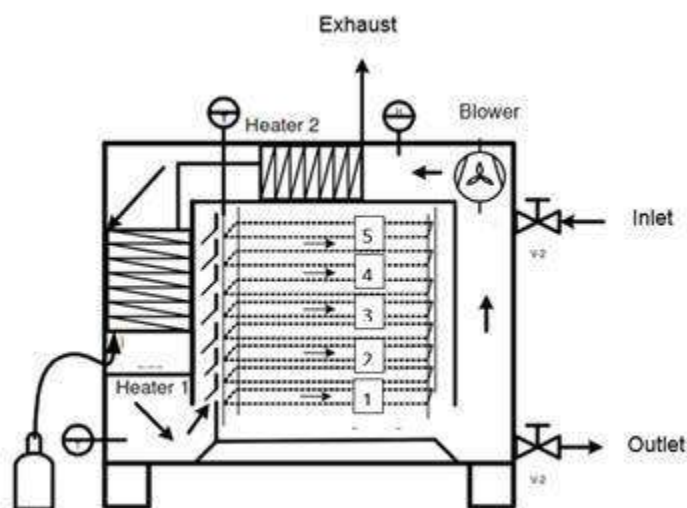
133 ***Sample preparation and equipment***

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

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

143 height from the ground to the tool is 10 cm.

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



150

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

152 *Sample drying*

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

159

160 *Measurement of seed temperature distribution*

161 Seed temperature distribution data during drying is measured using a data logger. The temperature
162 sensor is installed in one of the passion fruit seeds in each drying chamber by placing the tip of the
163 thermocouple in the surface position and the center of the seeds. This measurement was repeated with
164 5 replications.

165

166 *Data validation test*

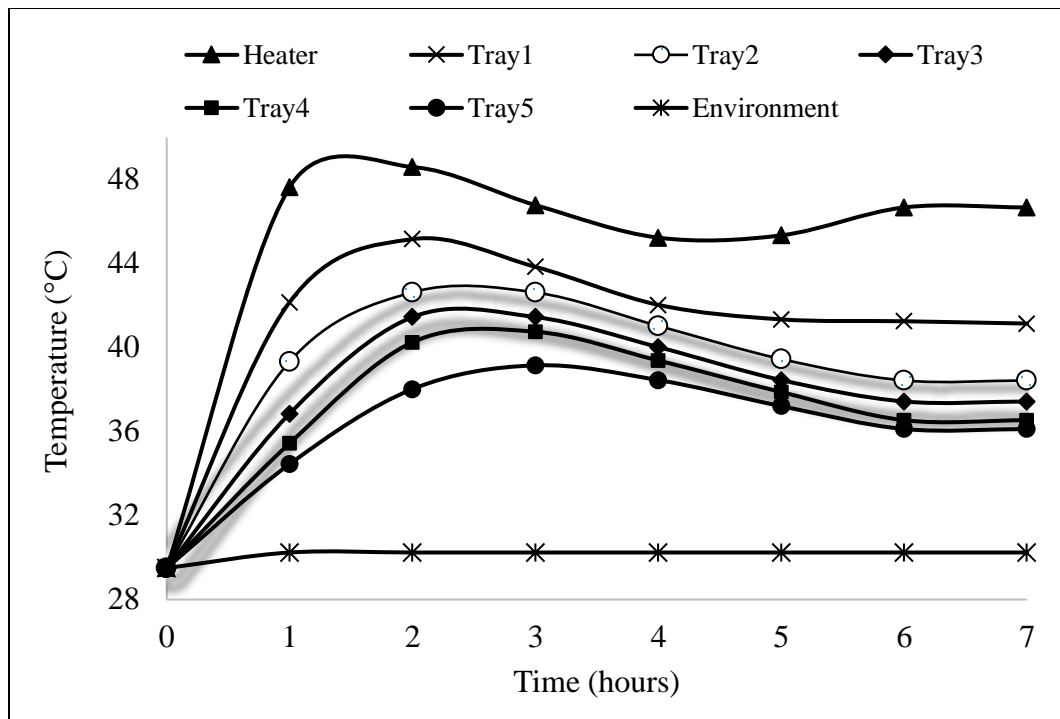
167 Data validation test used regression analysis by comparing predictive data obtained from
168 numerical analysis using FEM results with observation data generated from measurements in the drying
169 chamber. The closeness of the relationship between predictive data and observational data can be seen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

172

173 **RESULTS AND DISCUSSION**

174 *Temperature distribution in the drying chamber*

175 The measurement results of temperature distribution from time to time during the drying of
176 passion fruit showed that the temperature distribution on each tray had different values (Figure 5). As
177 the drying time increases, the material temperature also increases. The highest temperature for the seeds
178 on tray 1 reached 45.16 °C achieved for 6 hours. This is presumably because the bottom tray gets the
179 most heat from the electric stove, so the average temperature on the bottom tray is higher than the other
180 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,
181 respectively.



182
183 **Figure 5. Temperature distribution on each tray during the drying of passion fruit seeds**

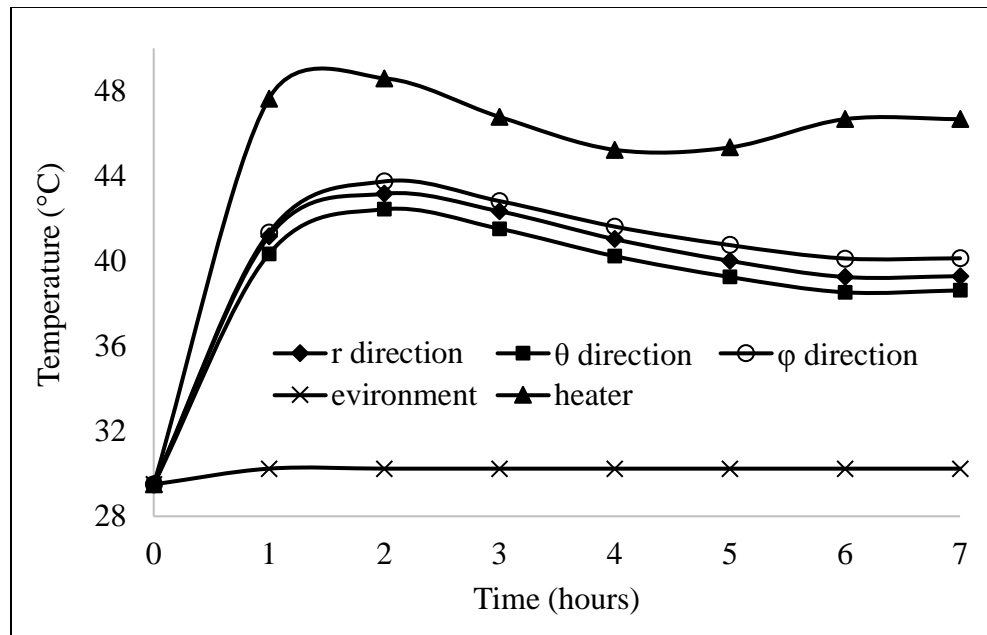
184
185 In general, the drying of the tray type in this study only takes 7 hours to reduce the water content
186 from 21% to 14.15%. This drying time is shorter when compared to the method of sun-drying which
187 requires 10-11 hours (Shavazi et al., 2020). These results were in agreement with these reported by
188 Bahadur et al. (2019) that direct drying in the sun was slower than artificial drying.

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

194
195 **Temperature distribution in seeds**

196 Three-dimensional temperature distribution in the passion fruit seeds during drying is shown in
197 Figure 6. In the figure, it appears that in the first hour there was a very rapid increase and began to fall

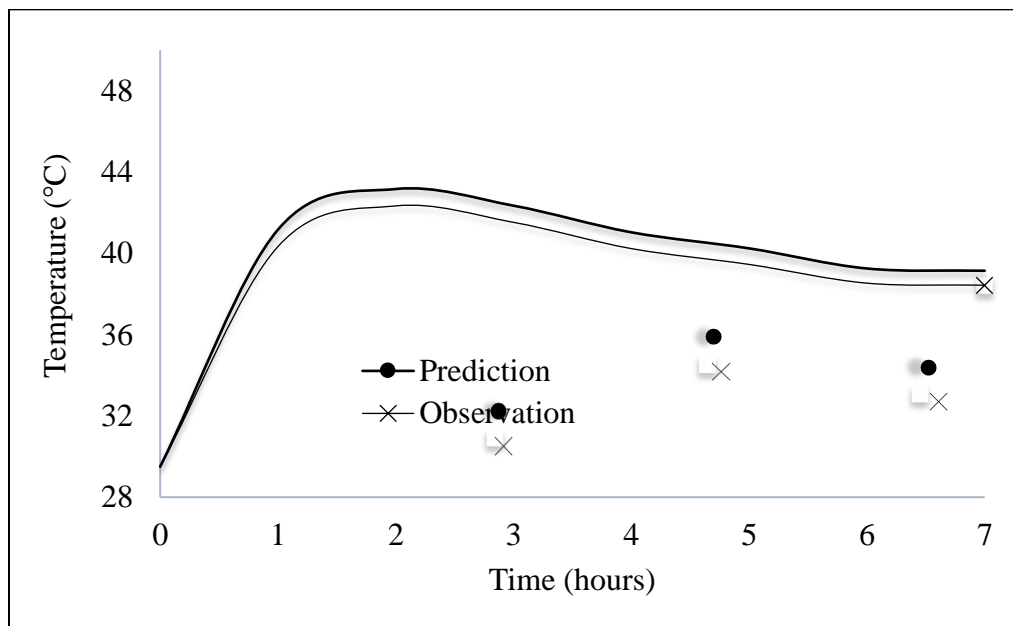
198 in the second hour until towards the end of drying. Temperature distribution in the passion fruit seeds
199 occurs because of differences in temperature and heat energy arising during drying. The same thing has
200 been expressed by Serrano et al. (2015) that the temperature distribution of materials is strongly
201 influenced by the coefficient of displacement of the conduction pad and the thermal diffusivity of the
202 material.



203
204 **Figure 6. Three-dimensional temperature distribution in the passion fruit seeds**

205
206 Three-dimensional temperature distribution of passion fruit seeds spreads from the surface of the
207 seeds toward the center of the axis slowly until evenly distributed to all parts of the seeds. Furthermore,
208 the temperature is distributed with an even distribution pattern in the determined boundary plane. This
209 temperature distribution pattern follows an elliptic pattern. Numerical analysis for predicting 3-
210 dimensional temperature distribution are very important when information is still limited about ideal
211 conditions during the drying process. This developed model can accurately predict the temperature
212 distribution in various positions of passion fruit seeds during the drying process. In the same case, Xiao
213 et al. (2020) have explained that the modified numerical analysis can accurately predict the percentage
214 of germination at various temperatures in seeds with a value of $R^2 = 0.810$.

215 Another phenomenon that can be revealed is that the temperature distribution occurs
216 simultaneously in all directions of the three-dimensional axis of the seeds. The more inward (r
217 direction), the smaller the temperature distribution, which is almost the same as the ambient
218 temperature. Whereas the vertical direction (θ) and horizontal direction (ϕ) also have the same pattern,
219 namely the smaller the distribution. This is following the results of the simulation program, which is
220 for parts of the position that are closer to the sides given an initial value of $T_0 = 29.5$ °C, then the
221 temperature approaches the limit value. Whereas the position on the surface that receives the dryer
222 temperature earlier has a higher temperature distribution. The same phenomenon has been reported by
223 Fecher et al. (2014) that temperature distribution is caused by energy transfer that occurs due to
224 temperature differences. This energy cannot be observed directly, but the direction of its displacement
225 can be calculated using numerical analysis (Vogta et al., 2015).



226
227 **Figure 7. Prediction and observation data of temperature distribution during drying**

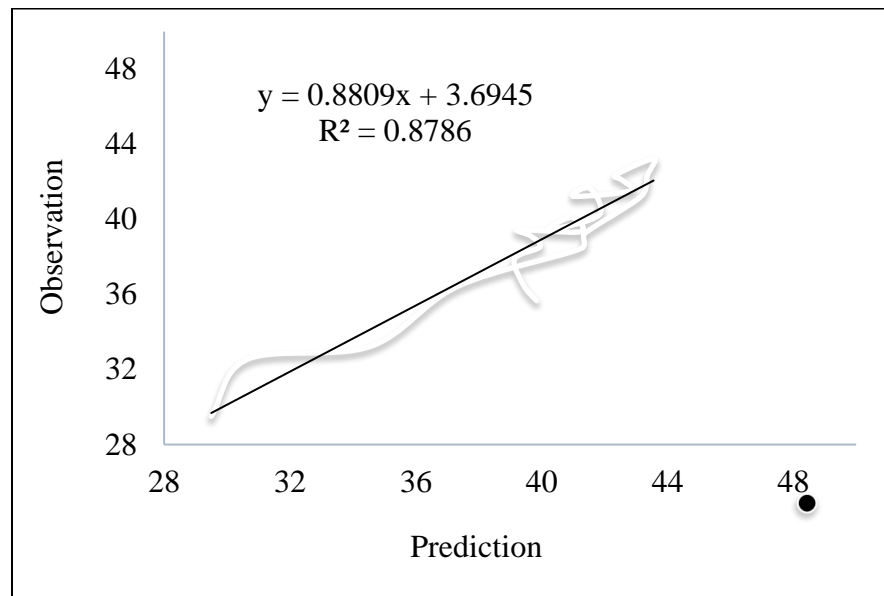
228
229 There is a difference between the predicted temperature distribution and the observation result
230 (Figure 7). The prediction temperature distribution is always higher than the observation temperature
231 but has the same tendency. This difference is caused by the thermal conductivity value (k) used for

232 simulation data slightly greater than the thermal conductivity value of passion fruit seeds. This is in line
233 with the results of the study Reed et al. (2018) which reported that the higher the thermal conductivity
234 value of the material, the faster the temperature propagation occurs.

235

236 ***Model validation***

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



243

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

246

247 The results of the analysis of variance showed that there were no significant differences between
248 predicted and observation data. The temperature distribution data observations have the same pattern
249 as the prediction data. Despite that, it is still found differences that are suspected due to the influence

250 of the level of sensitivity of the sensor used, but the error data was still within reasonable limits. Another
251 factor that is thought to cause differences is the effect of initial temperature variations which are not
252 taken into account in compiling a numerical analysis using FEM approach. But the difference only
253 appears if the initial temperature was higher than the ambient temperature. Therefore, the higher the
254 initial temperature, the higher the difference between prediction and simulation data. Similar results
255 were also expressed by Khurana & Karwe (2009) that the simulation results differ from the predicted
256 results when the initial temperature is higher than the ambient temperature. Thus, the results of this
257 study can be used as a basis for further research.

258 The results of the analysis of variance show that there was a close relationship between the
259 observed temperature distribution data and the predicted data from the numerical analysis simulation
260 results indicated by the termination coefficient value (R^2) which is 0.8786 (Figure 8). Thus, this
261 numerical analysis using FEM was valid and can be used as a system representation in analyzing the
262 temperature distribution of grains during drying. In line with the results of these studies Moreno et al.,
263 (2017) also reported that numerical analysis using FEM can produce accurate and valid temperature
264 distribution prediction data and can be scientifically justified.

265

266 CONCLUSIONS

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

273

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276 the Director of the Research and Community Service for the financial support that has been provided
277 through the 2017 National Strategic Research Scheme with contract no. 271.DB/UN18/LPPM/2017, so
278 this research can be carried out well.

279

280 CONFLICT OF INTEREST

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

282

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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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Associate Editor

Associate Editor Comments for Authors:

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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9 Juli 2021 19.06

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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

No action is required by you at this point. The Associate Editor will review your revisions and consult with outside reviewers if needed. The Community Editor will contact you after that.

If you have questions, please contact:
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12-Oct-2021

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Numerical Analysis to Predict Temperature Distribution of the Passion Fruit Seeds during Drying

Ansar^{1,}, Nazaruddin², A. D. Azis³*

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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 (m²)

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 (m³)*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).

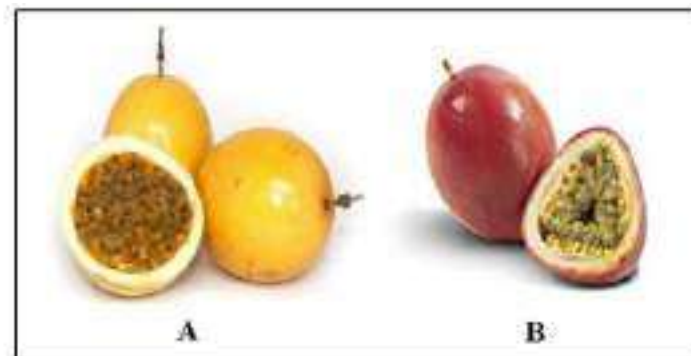


Figure 1. Yellow passion fruit (A) and purple passion fruit (B).

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; Zhou 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.

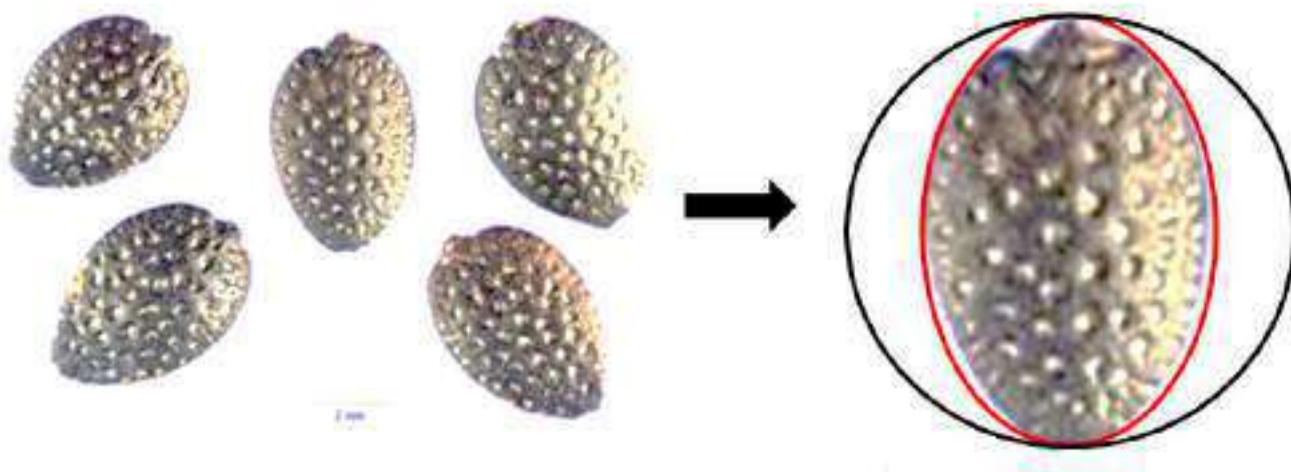


Figure 2. Purple passion fruit seeds that were assumed to have a uniform ball shape.

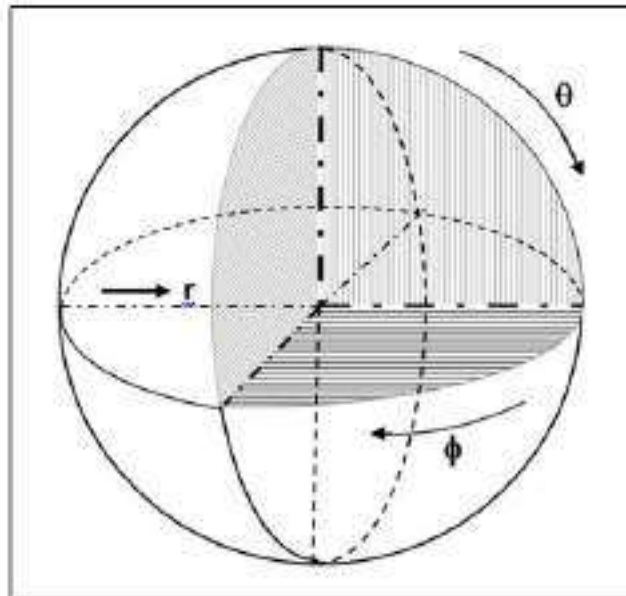


Figure 3. Modeling of three-dimensional spherical coordinate systems.

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:

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

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

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

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

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

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

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

$$T_{NR,j,\theta,t+1} = \frac{1}{M} \left[\left(2\Delta r - \frac{2}{(i)^2 \Delta \theta} + M \right) T_{NR,j,\theta} - (2\Delta r) T_{NR-1,j,\theta} + \left(\frac{2}{(i)^2 \Delta \theta} \right) T_{NR,j+1,\theta} \right] + 2\Delta r q_{\theta,t} \quad (6)$$

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

$$T_{i,j,\theta,t+1} = \frac{1}{M} \left[\left(1 - \frac{1}{i} \right) T_{i-1,j,\theta} - (2-M) T_{i,j,\theta} + \left(1 + \frac{1}{i} \right) T_{i+1,j,\theta} - \left(\frac{\Delta r}{(i)(\Delta \theta)} \right) T_{i,j-1,\theta} + \left(\frac{\Delta r}{(i)(\Delta \theta)} \right) T_{i,j+1,\theta} \right] \quad (7)$$

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, φ, and θ which can be calculated by the equation:

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

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

$$= A_{j,k}$$

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

Sample preparation and equipment

Passion fruit seeds used in the study was obtained from the purple passion fruit. The fruit was cut in half and the seeds are separated from the meat using a pulpier sieve. 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.

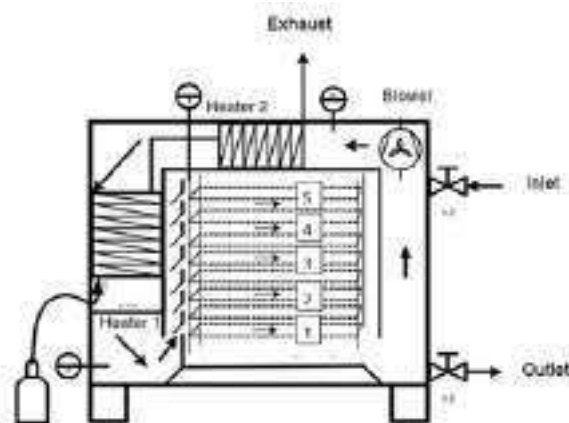


Figure 4. Sketch of a circulating air tray dryer type.

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.

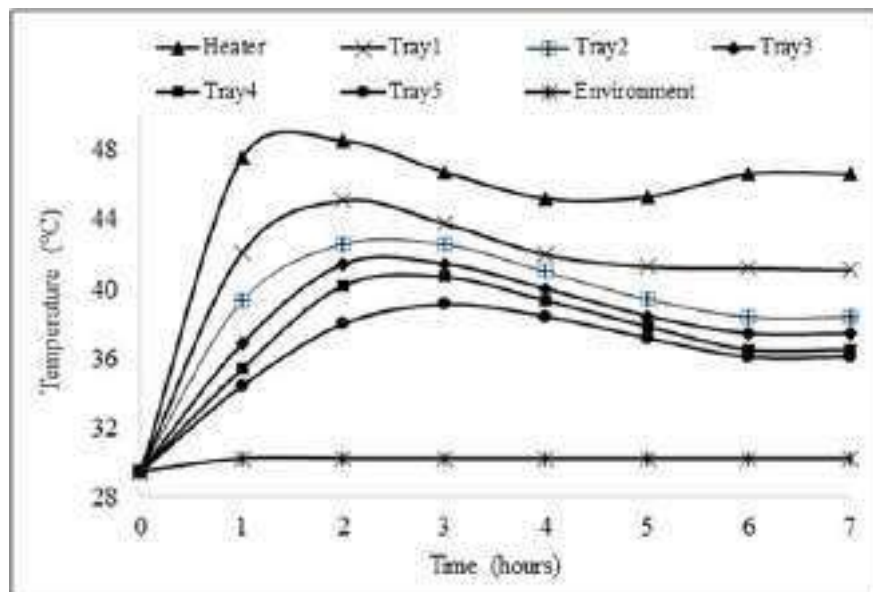


Figure 5. Temperature distribution on each tray during the drying of passion fruit seeds.

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 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.

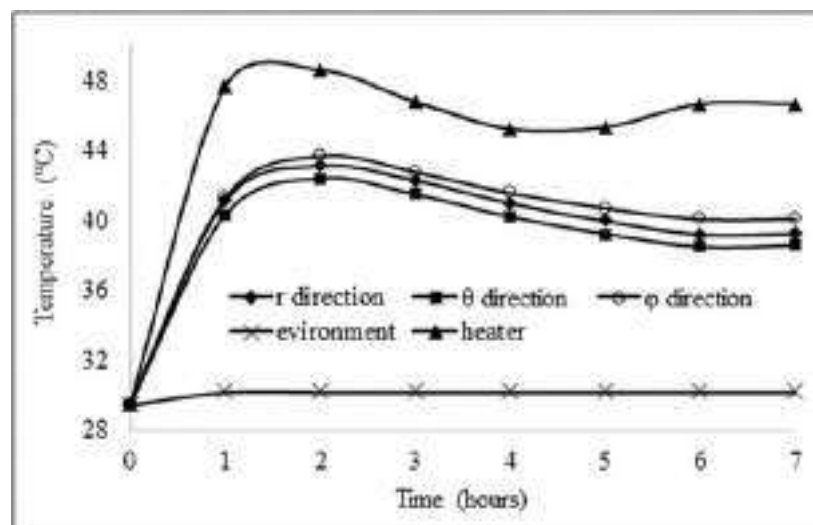


Figure 6. Three-dimensional temperature distribution in the passion fruit seeds.

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 (?) 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 $T_0 = 29.5\text{ }^\circ\text{C}$, 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).

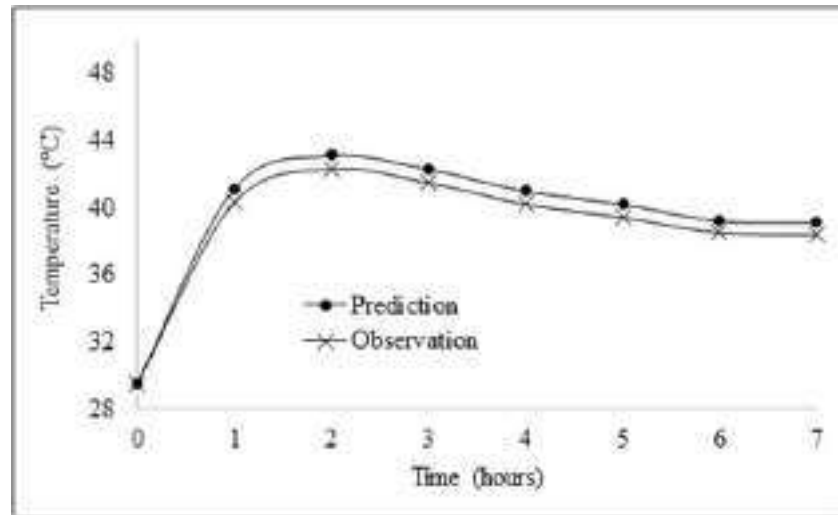


Figure 7. Prediction and observation data of temperature distribution during drying.

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).

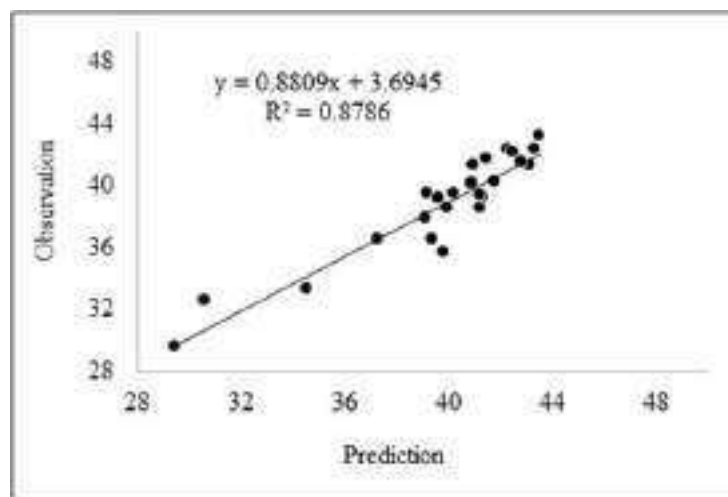


Figure 8. Validation of prediction and observation data of temperature distribution during drying.

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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