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Influence of Shrinkage during Drying on Curcuma Effective Diffusivity with 2D Image Analysis

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***Abstract*—**The effects of drying conditions on shrinkage of curcuma were studied. A thin-layer dryer with machine vision 2D system and image analysis software was used. Curcuma slices were dried at temperatures of 50, 60 and 70 ºC and the falling drying rate data were used to calculate the effective diffusion coefficients from the Fick's equation. Changes in area of the slice were measured every 5 minute during drying. Shrinkage showed almost linear relation with moisture content. It was found that air temperature had no significant effect on shrinkage. Shrinkage of volume and surface area of curcuma slices at the studied air drying temperatures ranges from 0.6719 to 0.9183 and 0.0575 to 0.2190 respectively. The linear equation model is fit-able to represent the shrinkage of sliced curcuma with high coefficient of determination. Effective diffusivity values by considering the shrinkage were estimated in the range of 4.93×10^{-9} m^2/s to 7.18×10^{-9} m^2/s, while without considering the shrinkage were in the range of 10.4×10^{-9} m^2/s to 14.4×10^{-9} m^2/s.

***Keywords*—**Drying, shrinkage, moisture, diffusivity, image analysis, curcuma.

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NOMENCLATURE

a	Parameter for shrinkage model (dimensionless)
A	Surface area of product (m^2)
b	Parameter for shrinkage model (dimensionless)
D	Diffusivity of moisture (m^2/s)
L	Product thickness (m)
M	Moisture content (kg water/kg dry solids)
MR	Moisture ratio (dimensionless)
n	Power constant (dimensionless)
R	Gas constant (8.314 kJ/molK)
R^2	Coefficient of determination (dimensionless)
RH	Relative humidity (dimensionless)
S	Shrinkage (dimensionless)
SE	Deviation (dimensionless)
t	Drying time (s)
T	Temperature (ºC, K)
V	Volume (m^3)
Y	Data/predicted value

Subscripts:

0	At the beginning of the drying process
abs	Absolute
e	At equilibrium
eff	Effective
exp	Experimental
pre	Predicted

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I. INTRODUCTION

DEHYDRATION of foods is one of the most common processes used to improve food stability, since it decreases considerably the water activity of the material, reduces microbiological activity and minimizes physical and chemical changes during its storage. One of the most important physical changes that the food suffers during drying is the reduction of its external volume. Loss of water and heating cause stresses in the cellular structure of the food leading to change in shape and decrease in dimension. Shrinkage of food materials has a negative consequence on the quality of the dehydrated product and should be taken into consideration when predicting moisture and temperature profiles in the dried material. Changes in shape, loss of volume and increased hardness cause in most cases a negative impression to the consumer [1].

Curcuma or java turmeric or *temulawak* (*Curcuma xanthorrhiza* Roxb.) is one of the important medicinal plants in Indonesia. Its rhizome is used for food suplement material and traditional herbal medicine called *jamu*. Many small traditional medicine companies need curcuma in dried-slices also called *simplicia*. As one of the herbs producing countries in the world, Indonesia produced 518 million tons of herbs in 2011, of which 41.4 million tons were exported equaling US$ 211.4 million. Recently, there has been an increasing demand for organic and natural vegetables due to human health benefits [2].

Shrinkage has been studied by direct measurements with a caliper or micrometer or by changes in related parameters such as porosity and density. Recently, there have been many studies to describe the shrinkage behavior of various fruits and vegetables in terms of prediction models. Lozano *et al*. found a general correlation for prediction of fruit and vegetable shrinkage with changing in moisture content [3]. Shrinkage has been correlated linearly to moisture content [4,5]. Hatamipour and Mowla reported a linear correlation for volume change and empirical relation for axial contraction of carrots during drying in a fluidized bed dryer with inert particles [6], while potato shrinkage has been reported as non-isotropic or irregular [7].

Shape is one of the most common object measurements for food quality evaluation. Image processing technique can be easily applied to measure the shape of food. Some authors used image analysis to measure the dimensional change of zedoary herb [8], pineapple, mango and banana during drying [9]. Changes of parameters such as area, perimeter, equilibrium diameter, and shape factor were measured by image analysis and correlated with change in moisture content by second order polynomial trends. Non-isotropic shrinkage of potato slabs during convective drying with two digital cameras for top and side view was measured by Mendiola *et al*. [10]. Cellular surface area of potato cells was recorded and related to moisture content by means of an empirical equation. Computer vision was used to analyze the effect of drying on shrinkage, color and image texture of apple discs [11]. Yadollahinia *et al*. used machine vision system and image processing to measure changes in area, perimeter, major and minor diameters, diameters parallel and perpendicular to airflow, roundness and elongation of the potato slices during drying [12].

The present demand of high-quality products in the herbs market requires the content of the active compounds and organoleptical properties in the dehydrated medical plants to be maintained at a very high level, as possible as in the initial fresh product. A thorough understanding of the factors responsible for the decrease in the quality of the product during the dehydration process is thus of major relevance. It is obvious that drying changes physical properties of the product. Also, the change in physical dimension of product is specific and varies according to drying conditions. Moisture content of curcuma when harvested is about 80% to 90%, while the final moisture content after drying is less than 10%, thus changes in the volume of dried slices of curcuma is quite large and cannot be ignored. Meanwhile, the drying of *temuputih* herb takes place in the falling rate period where diffusion is the dominant physical mechanism governing moisture movement in the product [13]. For the materials undergoing shrinkage, variations in volume must be considered in the effective diffusivity. Drying characteristics of herbs was investigated by many researchers but there are a few papers about in-dryer measuring of dimensional shrinkage of them.

The aim of this work was to determine shrinkage of curcuma slices during drying using machine vision and image analysis and to study the effect of shrinkage on drying characteristics of curcuma slices during drying.

II. Materials and Methods

A. Samples Preparation

Fresh curcuma rhizome was obtained from test field of Centre for Medicinal and Aromatical Plant in Bogor, Indonesia. Moisture content was determined by drying the samples at 70 ºC in a vacuum oven (Memmert, Germany) for 24h. Prior to starting of each experiment, zedoaries were washed and sliced into 3 mm thick chips with a knife and then dipped into boiling water for 5 minutes.

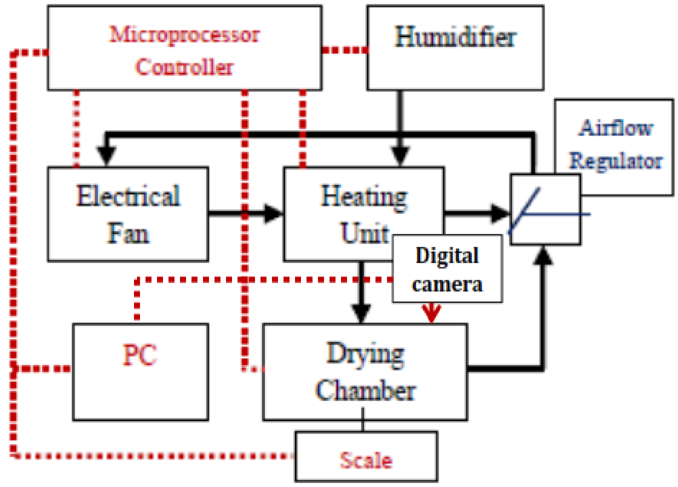

Figure 1 Schematic of the experimental dryer coupled to the digital image system

B. Experimental Dryer

A thin-layer dryer was designed and made based on computer vision for measuring the effects of drying on surface shrinkage and relation between surface shrinkage and moisture content of fruit slices. The drying experiments were carried out using the laboratory dryer in the Department of Mechanical and Biosystem Engineering, Bogor Agricultural University of Indonesia. The experiment could be regulated to any desired drying air temperature between 30 ºC and 80 ºC and relative humidity between 20% and 90%. The air temperature and the relative humidity are controlled by AVR Atmel microprocessor controller with temperature accuracy of ±1 ºC and relative humidity accuracy of ±2%. The unit is equipped with a 2000W steam injection humidifier, a 2000W heating and heating control unit, an electrical fan, temperature and humidity measurement sensor by SHT15 Sensirion, digital camera, and a drying chamber (**Figure 1**). The desired drying air temperature and relative humidity are maintained by PID control system. The air from the heating unit at the desired temperature entered the drying chamber. The lever manual-controller regulates the velocity of the drying air flowing through the drying chamber and it was measured by a hot wire digital Kanomax anemometer with the accuracy of ±0.1 m/s [13].

An image acquisition system consisting of a digital web camera, illumination chamber, computer hardware and software was developed to capture and process the images. All parameters related to shape (area, perimeter, major and minor diameters) determined by the image processing software for all of the captured images. In each experiment one of the slices was placed on the top shelf of samples in the illumination drying chamber to record the surface shrinkage by capturing images. The other slices were placed on the bottom shelf, which was used to evaluate weight loss and moisture of samples during drying. Weighing of samples inside the drying chamber was done automatically at desired time interval using a digital balance (GF-3000 A&D with an accuracy of 0.01g). The digital camera and digital balance were interfaced to a PC via USB and RS-232 port, respectively [8].

During drying sample was monitored continuously and images of the slice were captured by machine vision system. After drying had finished, parameter value related to shape (surface area) was determined by the image processing software for all images.

C. *Drying Experiments*

The experiments were conducted in triplicate at three levels drying air temperatures at 40% RH (50 ºC, 60 ºC and 70 ºC) and at three levels drying air humidity at 50 ºC (20%, 30% and 40%) while air velocity kept constant at 0.8-0.9 m/s. Drying experiments were continued until a constant mass was obtained. The moisture loss from the samples and surface shrinkage during drying were determined respectively by weighing the sample with the digital balance and capturing image from slice every 5 minutes.

D. *Shrinkage Modeling*

Shrinkage defined as the reduction of size of volume, area (surface area) or the thickness of the material. Volume shrinkage of dried material is formulated as follows [8],

$$S = \frac{V}{V_0} \tag{1}$$

In this study, the material of shrinkage is assumed uniform (isotropic) so that the thickness shrinkage is proportional to the reduction in surface dimensions. For the slab-shaped material, relation between surface area and thickness and volume shrinkage ratio is

$$\frac{L}{L_0} = \left(\frac{A}{A_0}\right)^{1/2} \tag{2}$$

$$\frac{V}{V_0} = \left(\frac{A}{A_0}\right)^{3/2} \tag{3}$$

Reduced volume of the dried material is proportional to the volume of water so that the volume shrinkage model uses linear equations as follows,

$$\frac{V}{V_0} = a\frac{M}{M_0} + b \tag{4}$$

Combining Equations (2), (3) and (4), we get Equation (5); this was applied to calculate the length of a shrinking curcuma slab's edge.

$$L(M) = L_0\left(a\frac{M}{M_0} + b\right) \tag{5}$$

E. *Mathematical Modeling*

Dehydration characteristics of many food products are often described using empirical thin layer equations. However, their parameters have no physical sense. In most situations, Fick's second law of diffusion has been used to describe moisture diffusion processes. The solution of Fick's equation can be applied for different solid geometry, e.g. slab, cylinder and sphere [14]. For slab-shaped solids, with the assumptions of moisture migration by diffusion, uniform initial moisture distribution, negligible external resistance to heat and mass transfer, constant temperature, and constant effective diffusion coefficient, then the solution of Fick's law for a slab can be written by a series type equation:

$$MR = \frac{M-M_e}{M_0-M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}exp\left(\frac{-(2n+1)^2\pi^2 D\cdot t}{4L^2}\right) \tag{6}$$

For long dehydration periods (MR<0.6), a limiting form is obtained for slab-shaped equation by considering only the first term in its series expansion. Then, Equation (6) can be written as follows,

$$M = \frac{8}{\pi^2}exp\left(-\frac{\pi^2 D_{eff}\cdot t}{4L^2}\right) \tag{7}$$

The coefficient of determination (R^2) and standard error (SE) were used as the primary criteria for selecting the best equation to account for the validation of a curve when non-linear regression techniques are used [15][16]. The SE gives the deviation between the predicted and experimental values and it is required to reach zero. These statistical values can be calculated as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(Y_{exp,i}-Y_{pre,i})^2}{\sum_{i=1}^{N}(Y_{exp,i}-\bar{Y}_{exp})^2} \tag{8}$$

$$SE = \frac{\sqrt{\sum_{i=1}^{N}(Y_{exp,i}-Y_{pre,i})^2}}{N-n} \tag{9}$$

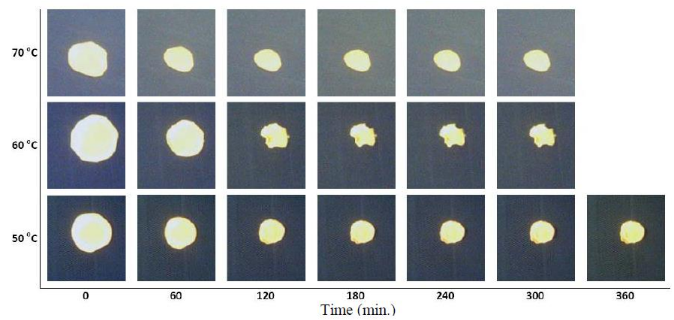

Figure 2 Gallery of 2D-images of a curcuma slice as a function of drying time at temperatures of 50, 60 and 70 ºC

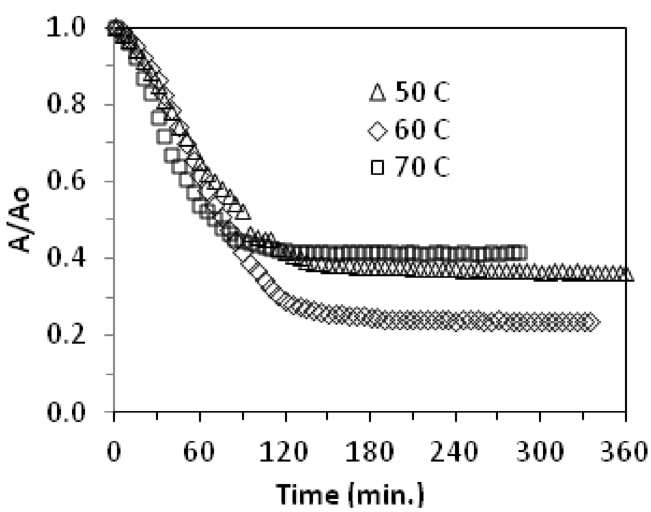

Figure 3 Area changes with drying time at the different temperatures

III. Results and Discussion

A. Shrinkage Behavior during Drying

Figure 2 shows a gallery of images of a curcuma slice during drying at different temperatures. Obvious visual changes can be seen in the size of the slice (shrinkage). The plot of dimensionless area changes (A/A_0) versus drying time for the samples dried at the different air temperatures is shown in **Figure 3**. These images show that surface area of samples decreased rapidly from the beginning to a half-drying time and then more slowly afterwards to the end of drying.

Area shrinkage of curcuma slice versus its dimensionless moisture content at studied air temperatures are shown in **Figure 4**. Both figures show area shrinkage decreased at longer time and at lower moisture content. The ANOVAs test results indicate that air temperature had no significant effect on the shrinkage (*P-values* < 0.03). Similar results were obtained by several authors with potato [17] and with wheat and canola kernels [18]. Other authors [19] [20] also reported independence of shrinkage characteristics on both the temperature and humidity of drying air.

The extent of area shrinkage, volume shrinkage and the amount of moisture evaporated during drying at the studied temperatures are given in **Table 1**. It presents that the percentage reduction in moisture content of the material is greater than the shrinkage volume of materials at all levels of drying temperature. Shrinkage of volume and surface area of curcuma slices at the studied temperatures ranges from 73.3% to 88.5% and 58.6% to 74.4% respectively with an average 79.9% (±7.8%) and 66.2% (±9.2%) respectively, whereas removal moisture content varied 98.7% to 99.2% with an average 98.9% (±0.3%).

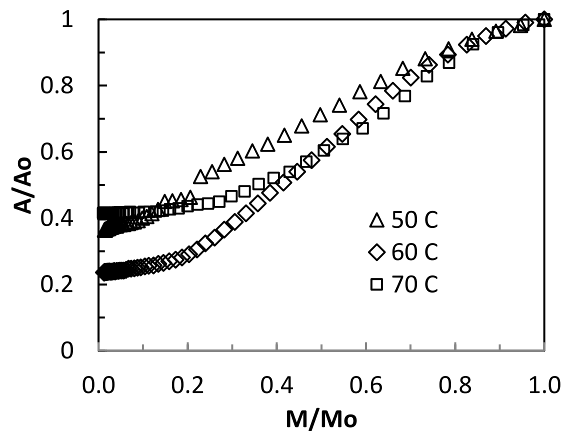

Figure 4 Dimensionless area changes (A/A0) versus moisture content (M/M0) at the different temperatures

Table I Curcuma shrinkage at different studied temperatures

Temp. (°C)	RH (%)	Area (mm^2)		A_{shrink} (%)	Volume (mm^3)		V_{shrink} (%)	Moisture loss (%)
		A_0	A_{end}		V_0	V_{end}		
70	40	276	115	58.6	829	221	73.3	98.9
60	40	438	104	76.4	1314	151	88.5	99.2
50	40	307	112	63.5	920	203	78.0	98.7

B. Shrinkage Model of Curcuma

Total volume shrinkage of curcuma slice versus its dimensionless moisture content is shown in **Figure 5**. It presents that the curves are almost linear. The value of constants *a* and *b* in Equation (4) at each drying temperatures varied within the ranges of 0.6719 to 0.9183 and 0.0575 to 0.2190, respectively, as shown in **Table II**. The model of linear equations that describes the shrinkage of curcuma obtained using all the drying data as presented in Equation (10) where the value of a, b, R^2 and SE are 0.7977, 0.1596, 0.900 and 0.0757, respectively.

$$\frac{V}{V_0} = 0.7977\frac{M}{M_0} + 0.1596 \quad (10)$$

Table II Constants a and b of shrinkage model (Eq. 4)

Temp.	*a*	*B*	R^2	*SE*
70 °C	0.6719	0.2190	0.9081	0.0617
60 °C	0.9183	0.0575	0.9606	0.0533
50 °C	0.8238	0.1979	0.9944	0.0163

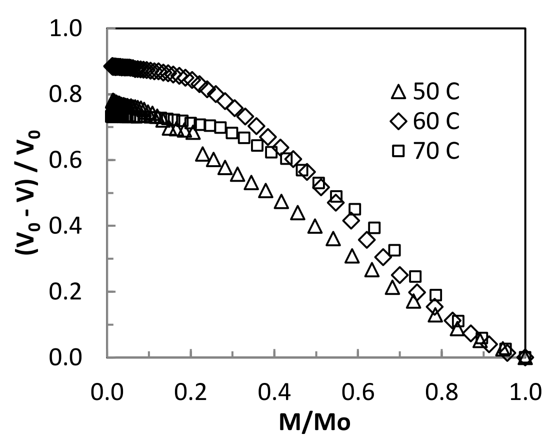

Figure 5 Total volume shrinkage ((V0-V)/V0) versus moisture content (M/M0)

Several authors also described the shrinkage behavior as a function of moisture content during convective drying with a linear model [6,21]. Plot of Equation (10) is given in **Figure 6**.

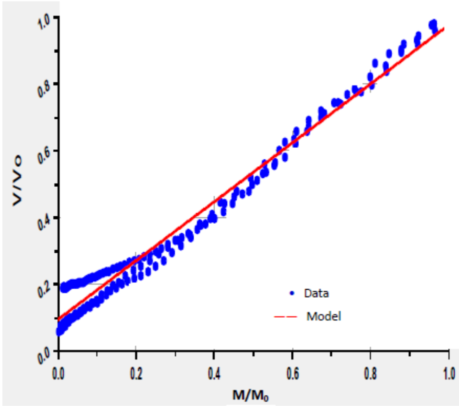

Figure 6 Linear model of curcuma shrinkage during drying

C. *Effective Diffusivity of Curcuma*

By using Equations (5) and (7), the value of the effective diffusivity by considering shrinkage (Sh) and without shrinkage (No-Sh) at each drying conditions can be determined (see **TABLE III**). Effective diffusivity value by considering the shrinkage in the range of 4.93×10^{-9} m^2/s to 7.18×10^{-9} m^2/s is smaller than that without shrinkage in the range of 10.4×10^{-9} m^2/s to 14.4×10^{-9} m^2/s. The same results was reported for other rhizome slices which are between 4.74×10^{-9} m^2/s and 6.19×10^{-9} m^2/s, and between 9.51×10^{-9} m^2/s and 11.57×10^{-9} m^2/s, respectively for zedoary shrinkage and without shrinkage [8], and between 0.26×10^{-9} m^2/s and 1.72×10^{-9} m^2/s, and between 1.25×10^{-9} m^2/s and 2.04×10^{-9} m^2/s, respectively for carrot shrinkage and without shrinkage [21].

The average values of determination coefficient of the model by considering shrinkage and without shrinkage are 99.1% and 99.6% while the average values of standard error by considering shrinkage and without shrinkage are 0.028 and 0016, respectively. These results indicate that shrinkage did not occur proportionally, thus it is possible that curcuma shrinkage is not isotropic or not uniform.

TABLE III EFFECTIVE DIFFUSIVITY OF CURCUMA

Temp.	Model	*D-eff* (m^2/s)	R^2	*SE*
70 ºC	Sh	7.18E-09	0.9957	0.0198
	No-Sh	1.44E-08	0.9954	0.0179
60 ºC	Sh	4.95E-09	0.9841	0.0409
	No-Sh	1.18E-08	0.9961	0.0165
50 ºC	Sh	4.93E-09	0.9941	0.0236
	No-Sh	1.04E-08	0.9969	0.0146

The correlation between the drying temperatures and the effective diffusivity by considering shrinkage thus can be obtained in the Arrhenius type equation [15] as follows,

$$D = 2.77 \times 10^{-6} exp\left(-\frac{15.041}{R{\cdot}T_{abs}}\right) \quad (11)$$

where the value of Arrhenius pre-exponential factor (D_0) and activation energy for moisture diffusion (*Ea*) are 2.77 x10^{-6} m^2/s and 15.041 kJ/mol, respectively, while the value of R^2 is 0.982.

IV. CONCLUSIONS

A dryer with 2D-digital image processing system was used for measuring shrinkage of curcuma slice during drying. The result shows that shrinkage of sliced curcuma is influenced by its moisture content, whereas the drying air temperatures does not significantly affect to curcuma shrinkage. Shrinkage of volume and surface area of curcuma slices at the studied air drying temperatures ranges from 0.6719 to 0.9183 and 0.0575 to 0.2190 respectively. The linear equation model can be used to represent the shrinkage of sliced curcuma with high coefficient of determination. Shrinkage is affected by curcuma drying diffusivity. Effective diffusivity values by considering the shrinkage (in the range of 4.93×10^{-9} m^2/s to 7.18×10^{-9} m^2/s) are smaller than without considering the shrinkage (in the range of 10.4×10^{-9} m^2/s to 14.4×10^{-9} m^2/s).

It is possible that curcuma shrinkage was not isotropic or not uniform, therefore, in the future study, the machine vision and image analysis should be performed in 3D.

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