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Research Article

A NUMERICAL ANALYSIS HEAT AND MASS TRANSFER ON DRYING PROCESS OF AGRICULTURAL PRODUCT USING FINITE ELEMENT METHOD: INHOMOGENEOUS MOISTURE CASE

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ABSTRACT

A 2D modeling of heat and mass transfer on drying process phenomena has been simulated very well. The model based on Luikov couple equation on axisymmetric coordinate and the rule of finite element method. There were assumption in this research, such as; (1) the temperature and moisture content of agricultural product was not uniform at initial condition, (2) there was not heat generation inside the product, (3) all boundaries were contact with the surrounding hot air, (4) water diffusion (moisture diffusion) outward toward the surface of product, and (5) the physical properties of products were function of temperature and moisture. This research have some objectives and divided on two sections, first, setup of computation domain on two sub-domains, and second, investigation of heat and mass transfer on agricultural product. The result of this study show that increasing of temperature in the surface is very fast than in the center of cocoa bean. Future work, we will investigate drying process phenomena by combining air velocity variation and temperature.

INTRODUCTION

Cocoa is one of agricultural products that become the main commodity and as a foreign exchange earner in Indonesia. Currently, Indonesia is one of the largest cocoa producers in the world after Cote d'Ivoire and Ghana, this is due to an increase in the area of cocoa farming every year (Anonim, 2015). Domestically, the cocoa bean area is dominated by Sulawesi with 996,241 Ha total agriculture area and 484,387 Ton total production (Anonim, 2015). Statistically, this value was very good but actually the value of cocoa beans was very low in international market, one of the contributing factors was the poor post-harvest process.

Drying process is one of post-harvest processes and is complex stage. On this stage, thoroughness is required because the slightest mistake can damage the cocoa beans, so needed a technique to keep the quality of coffee beans. There are many ways to obtain the proper drying method, such as; experimental (Ndukwu *et al*., 2014; Zamrun *et al*., 2016) and simulation or mathematical modeling (Manoj *et al*., 2013; Hii *et al*., 2008), and mathematical method is very easily and low cost (Alfat *et al*., 2017). One of mathematical modeling to simulate drying process is finite element method (Alfat *et al*., 2017; Somboon *et al*., 2015). This method is most powerful to show or figure out mechanism of heat and mass transfer on material. Besides that, the method can be used to simulation a phenomenon in complex domain.

Based on the condition above, we will simulate heat and mass simulation on agricultural product which objective of the study was divided on two parts namely main and specific objective. The main objective of this paper is to design a numerical method for heat and mass transfer as a part of coffee drying. For specific objective, we want to setup of computation domain

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on two sub-domains, and investigation of heat and mass transfer on drying phenomena.

The paper is lied out as follows. In Section 2, we illustrate the computational domain and assumptions of the study as a part of drying simation of agricultural product. In Section 3, we introduce the mathematical model of heat and mass transfer that simplified through the main heat and mass transfer equation by Luikov. In addition, the non-dimensional formulation and the used physical properties will be shown. Meanwhile, numerical method and numerical scheme are discussed in Section 4. Section 5, illustrates the results of several numerical simulations. The conclusions and future work are drawn in Section 6.

Computational Domain and Assumptions

In the study of drying simulation on the agricultural product (cocoa bean) can be illustrated as combination wet (testa) and dried (kernel) domain (see **Figure 1**) and these domains have different physical properties. Some assumptions were made to develop the model as follows:

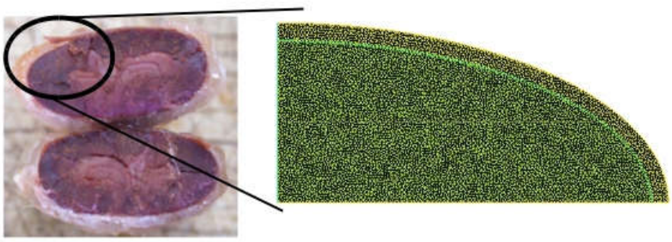


Figure 1 Cocoa bean profile and computational illustration domain

1. The coordinate system was axisymmetric systems and also unsteady heat and mass equations.
2. The temperature and moisture content of agricultural product was not uniform at initial condition.
3. Agricultural product (cocoa bean) was an isotropic and inhomogeneous material
4. There was not heat generation inside the product.
5. All boundaries were contact with the surrounding hot air.
6. Water diffusion (moisture diffusion) outward toward the surface of product
7. The physical properties of products were function of temperature and moisture.

Development Model

Governing Equation

Heat and mass transfer phenomena has been explained by Luikov's equation and then simplified by Husein (Husein *et al.*, 1973). In this model, axisymmetric system has considered to simulate this phenomenon. As for the heat and mass equation as follows:

$$\frac{\partial M}{\partial t} = D\frac{\partial^2 M}{\partial r^2} + \frac{D}{r}\frac{\partial M}{\partial r} + D\frac{\partial^2 M}{\partial z^2} \quad (1)$$

$$\rho_p c_p \frac{\partial T}{\partial t} = \kappa_p \frac{\partial^2 T}{\partial r^2} + \frac{\kappa_p}{r}\frac{\partial T}{\partial r} + \kappa_p \frac{\partial^2 T}{\partial z^2} + L\rho\frac{\partial M}{\partial t} \quad (2)$$

where M and T are parameters of moisture (kg/kg) and temperature (K), r and z are radial and vertical coordinate on axisymmetric system, Meanwhile, t, D, κ_p, c_p, ρ_p and L are time (s), moisture diffusivity (m^2/s), thermal conduction (W·K/m), specific heat (J·K/kg), density (kg·m^{-3}), latent heat of vaporization of water (J/kg), respectively.

Boundary and Initial Condition

Based on assumptions that considered in section Computational Domain and Assumptions, the boundary condition satisfied as follows:

$$D\frac{\partial M}{\partial n} + h_m\left(M - M_\infty\right) = 0 \qquad \text{on } \Gamma_N \quad (3)$$

$$\kappa_p \frac{\partial T}{\partial n} + h_t\left(T - T_\infty\right) = 0 \qquad \text{on } \Gamma_N \quad (4)$$

where n is the normal of the surface; T_∞ and M_∞ are the temperature (K) and moisture of the air (kg/kg), respectively; h_t and h_m are the convection heat transfer coefficients (W/(m^2K)) and the surface mass transfer coefficient (kg/(m^2s)), respectively; and Γ_N and Γ_D are Neumann boundary and Dirichlet boundary.

Meanwhile, for initial condition (t=0) that used in computation model were uniform and according on physical properties of cocoa bean. As for temperature (T_0) and moisture content (M_0) of agriculture product as follow:

$$T(r,z,0) = T_0(r,z) \qquad (r,z) \in \Omega \quad (5)$$

$$M(r,z,0) = M_0(r,z) \qquad (r,z) \in \Omega \quad (6)$$

Non-dimensional Formulation

In the simulation, we introduce some non-dimensional numbers, this is very important to get the better result. There are non-dimensional numbers in this simulation, these is used as determiner of heat and mass transfer coefficients. The numbers as follows:

$$\mathrm{Re} = \frac{\rho_a u_a D_p}{\mu_a} \quad (7)$$

$$\mathrm{Pr} = \frac{c_a \mu_a}{\kappa_a} \quad (8)$$

$$Le = \frac{\alpha}{D} \quad (9)$$

Re	=	Reynolds number
Pr	=	Prandtl number
Le	=	Lewis number
ρ_a	=	Air density, kg/m^3
u_a	=	Air velocity, m/s
μ_a	=	Air viscosity, m^2/s
c_a	=	Specific heat, kJ/(kg·K)
κ_a	=	Thermal conductivity, W/(m·K)
D_p	=	Diameter of product, m
α	=	Thermal diffusivity
D	=	Diffusion coefficient of air

Meanwhile, Nusselt number is obtained by the Chilton-Colburn analogy (Nadi *et al*., 2012):

$$Nu = 0.248\,\mathrm{Re}^{0.612}\,\mathrm{Pr}^{\frac{1}{3}} \qquad (10)$$

Based on equation (7) – (10), the heat and mass transfer coefficient satisfied:

$$h_t = \frac{Nu\kappa_a}{D_p} \qquad (11)$$

$$h_m = \frac{h_c}{\rho_a c_a Le^{\frac{2}{3}}} \qquad (12)$$

Physical Properties

In this section, we introduce some physical properties of agricultural product and air. Here, the agricultural product is cocoa bean and drying temperature (T_a) is 40 °C. Based on that, physical properties of cocoa and air as follows:

Table 1 Physical properties of cocoa bean

Parameter	Value
Temperature of testa	25
Temperature of kernel	15
Moisture of testa	1
Moisture of kernel	0.65
Density (ρ_p) (Somboon et al. 2015)	78.845M + 1723
Thermal conductivity (κ_p) (Somboon et al. 2015)	0.0116M + 0.062
Specific heat (c_p) (Somboon et al. 2015)	1110+44.8M

Table 2 Physical properties of air (Somboon et al. 2015).

Parameter	Value
Density	1.127
Velocity	12.0
Viscosity	1.91252 x 10-5
Specific heat	1.005
Thermal conductivity	0.0271
Thermal diffusivity	$2.0 \times 10^{-5} + 2.0 \times 10^{-7} T_a$
Diffusion coefficient	$2.0 \times 10^{-6} + 2.0 \times 10^{-5} T_a$
Moisture	0.1

Numerical Method

Simulation of drying process on cocoa bean using heat and mass equation was based by finite element method with P1-elements. To solve the equations 1 - 2, we introduce the backward implicit Euler scheme quadrature. So, the PDE in equation 1 -2 has semi-discrete form as follows:

$$\rho_p^k c_p^k \left(\frac{T^k - T^{k-1}}{\tau_1}\right) = \nabla \cdot \left(\kappa_p^k \nabla T^k\right) + L\rho^k \left(\frac{M^k - M^{k-1}}{\tau_1}\right) \quad r, y \in \Omega \qquad (13)$$

$$\left(\frac{M^k - M^{k-1}}{\tau_2}\right) = \nabla \cdot \left(D^k \nabla M^k\right)_{r,\, y \in \Omega} \qquad (14)$$

$$\kappa_p^k \frac{\partial T^k}{\partial n} = h_t\left(T_\infty - T^k\right) \text{ on } \Gamma_N \qquad (15)$$

$$D^k \frac{\partial M^k}{\partial n} = h_m\left(M_\infty - M^k\right) \text{ on } \Gamma_N \qquad (16)$$

Where k is time increment (k = 1, 2, 3, ..., 10000) and is set as positif number, we put $\tau_1 = \tau_2 = \tau = 0.5$ and represent time interval. To solve semi-discrete form in equation (13) – (16), we use special finite element software; FreeFEM++ (Hecht. 2012). This is open source software that competible in all operating systems (OS).

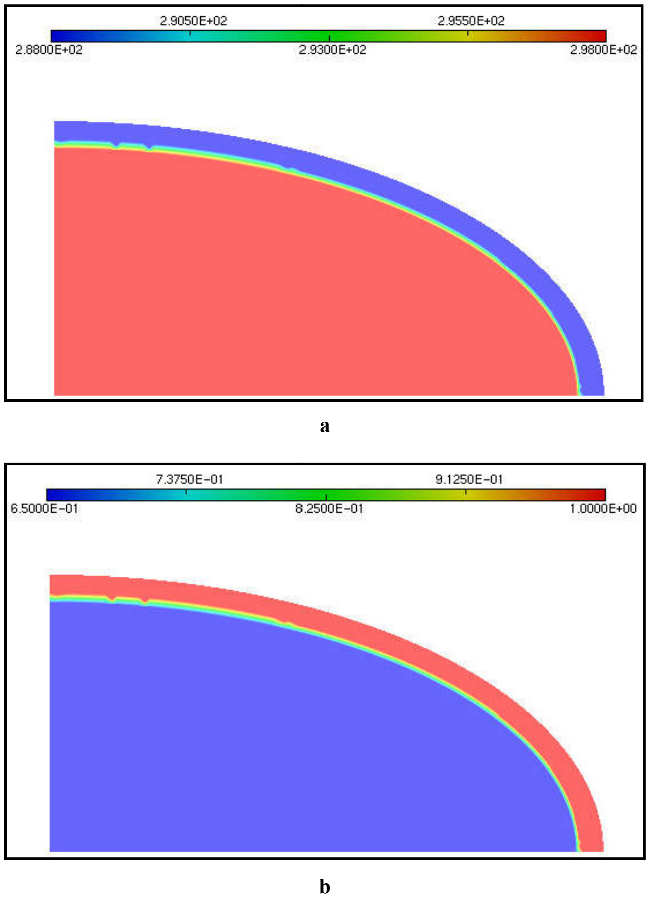
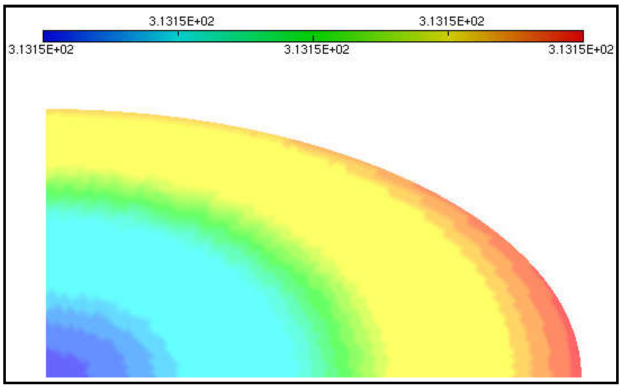


Figure 2 Profile of (a) initial temperature (T_0) and (b) initial moisture (M_0)

RESULTS AND DISCUSSION

The simulation of drying process phenomena has been simulated by the couple system equations (13) – (14). Here, $T^k(x)$ and $M^k(x)$ are approximated as solution of temperature (T) and moisture (M), respectively, at $t = k\tau$. This simulation used two sub domains which represent wet area (testa) and dried area (kernel) of cocoa bean, the domains illustrated were shown by Figure 2. Meanwhile, the results of drying process at t = 5000 were illustrated in Figure 3. Based on Figure 3 show that heat transfer was very fast and inversely proportional to the mass flow which moves very slowly. Based on Figure 3 show that heat transfer was very fast and inversely proportional to the mass flow which moves very slowly.



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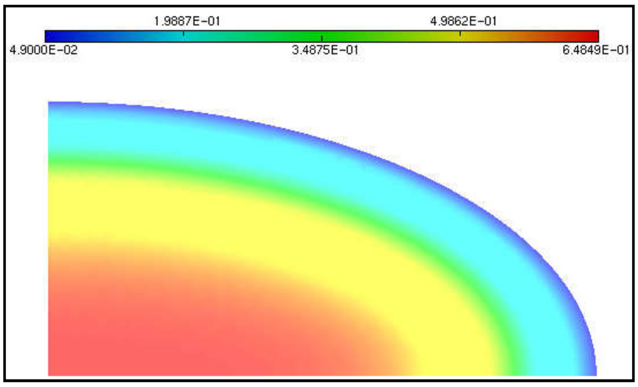
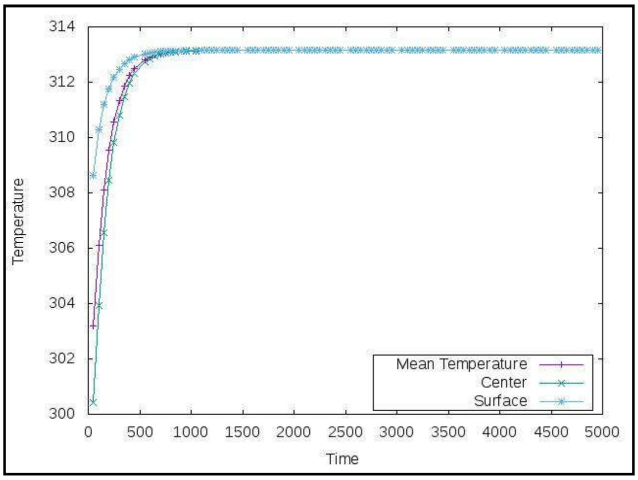


b

Figure 3 Profile of (a) temperature (T) and (b) moisture (M) at $t = 5000$

Physically, during drying process phenomena accompanied by heat transfer on cocoa bean during time t. From **Figure 4**, Heat flows very quickly on surface and center of product, cocoa bean temperature has reached maximum at $t = 1000$. In contrast to heat transfer, the mass flow on cocoa beans is very slow, but qualitatively decreases the water content (moisture) of cocoa bean. Basically, if time increment (k) in the study is set more bigger that 10000, its result show that moisture will be equilibrium point or the average moisture of cocoa bean become 0.1 kg/kg. Meanwhile in the other hand, maximum temperature of cocoa reach at 313 K. Experimentally, uniformity of moisture content in cocoa is very difficult to achieve. If the condition occurs, the part of cocoa bean (surface area) will be shrinkage.



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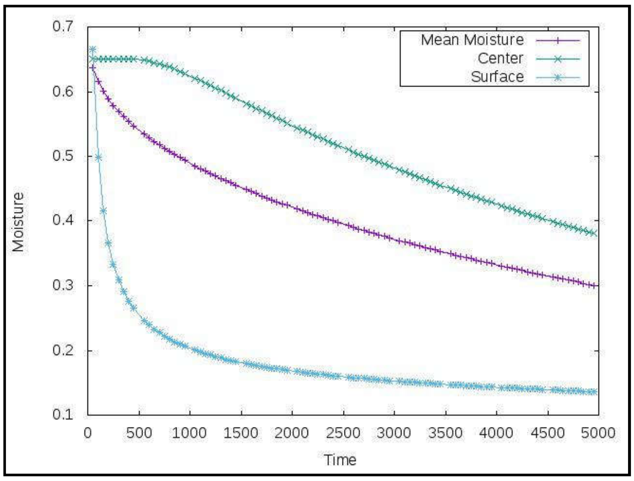

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Figure 4 (a) Predicted heat transfer among average temperature, surface, and center of cocoa bean, (b) Predicted moisture transfer among average moisture, surface, and center of cocoa bean

CONCLUSION AND FUTURE WORK

The finite element method (FEM) has been implemented to simulate drying process phenomena in cocoa bean and this simulation already successful to simulate drying phenomena. From this result, we have information that increase of temperature in the surface is very fast than in the center of cocoa. Meanwhile, rate of drying is very fast in the surface and its processing was slow in the center of cocoa bean.

Generally, there are many factors to accelerate a drying process, such as; temperature (T), air velocity (v) and pressure (P). In the future work, we will combine air velocity variation and temperature. Beside that, the results of this study can be developed for studies relating to the process of drying food, such as; how to design a good oven system computationally.

Acknowledgment

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