Numerically Simulations the Germinated Parboiled Thunya-sirin Glutinous Rice under a Combined Far infrared Radiation and Air Convection Drying

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Abstract. The objective of this study was to describe the development of a three-dimensional (3-D) mathematical model, which was used to during drying of germinated parboiled Thunya-sirin glutinous rice product under dryer. The three-dimensional mathematical models were solved numerically using the finite element method; additionally the mathematical model was validated by comparing the simulated results with the experimental. In this study, the following drying parameters were set for investigation: Far infrared intensities at 3 to 5 kW/m² were combined with a 40°C temperature and 1 m/s air velocity. The results showed that the mathematical model can be satisfied to predict the evolutions of germinated parboiled Thunya-sirin glutinous rice product. An increase of the applied intensity from 3 kW/m² to 5 kW/m² resulted in the shorter drying time and the reduced energy consumption by 200 minutes and 5.29 kWh/kg water removed, respectively. The average effective moisture diffusivities of the germinated parboiled rice were in the ranges $1.25 \times 10^{-10}$ – $3.48 \times 10^{-10}$ m²/s.

1. Introduction
Germinated parboiled Thunya-sirin glutinous rice (Oryza sativa var. glutinosa) has very low amylose content resulting in a sticky and dense quality when cooked. It is paddy which undergoing the processes of soaking, steaming, drying and de-husking to obtain the edible form for consumption. In addition, germinated parboiled Thunya-sirin glutinous rice is a material for the One Tambon One Product (OTOP) project in Maha Sarakham province in North-eastern Thailand, an entrepreneurship stimulus project organized by the Thai government to promote local products. Germinated parboiled Thunya-sirin glutinous rice is an excellent source of protein, dietary fibre, fat, minerals and vitamins [1]. Because of the importance of rice for human consumption, and the drying of rice is an important part of the food production. In recent years, combined far infrared radiation and air convection drying has been widely applied for foodstuffs including pineapple rings [2], soybean grain [3], whole longans [4]...
and longan puree \[^5\]. Nevertheless, the germinated parboiled Thunya-sirin glutinous rice grain is harvested usually at high moisture levels. The moisture content level of rice grains at the time of harvest may be as high as 35% dry basis and this must be reduced to about 14% dry basis for the safety of storage. Therefore, the drying process is necessary to prevent quality deterioration. Since a material is heated intensely, the temperature gradient in the material reduces within the short period this phenomenon is in agreement with those reported by Ponkham et al. \[^2\] and Dondee et al. \[^3\]. Noting the advantages of combined far infrared radiation and air convection drying, the objective of this study was to describe the development of a three-dimensional (3-D) mathematical model, which was used to during drying of germinated parboiled Thunya-sirin glutinous rice product under dryer. The 3-dimensional mathematical models were solved numerically using the finite element method; additionally the mathematical model was validated by comparing the simulated results with the experimental.

2. Materials and Methods

Paddy rice was harvested at SAN-DEE farm, Maha Sarakham province in northeastern Thailand. It was washed thoroughly in water to remove dust particles and soaked in water at ambient temperature (approximately 30°C) for 48 hr. with water being changed every 4-6 hr. The mass ratio paddy rice: water was 1:2. After soaking, a small bud appeared at the rice. For the cooking process, the samples were cooked in a steam cabinet under atmospheric pressure, for 30 min. After cooking, the freshly cooked rice was washed with cold water (4°C) for 30 s to prevent agglomeration of the cooked rice kernels \[^6\].In this study, the following drying parameters were set for investigation: Far infrared intensities at 3 to 5 kW/m\(^2\) were combined with a 40°C temperature and 1 m/s air velocity. For each experiment, 1,000 g of freshly cooked rice was spread on a stainless steel wire mesh tray (300 mm×300 mm×50 mm) and the sample tray was placed in the drying chamber under the far infrared radiator. Moisture contents after washing was in the ranges of 350-380% (dry basis, d.b.). Each experiment was replicated three times and the final product with moisture content of 14% for the safety of storage.

The moisture content of germinated parboiled grains was determined in a hot-air oven (Memmert: Model 100-800) at 103°C, 72 hr.\[^7\] The drying air temperature was measured by K-type thermocouples which were connected to a data logger (YOKOGAWA DX220-1-2), with an accuracy of reading ±1°C.

2.1 Numerically Simulations

This research describes the development of 3-D mathematical model, which was used to simulate the heat and mass transfer during drying of germinated parboiled Thunya-sirin glutinous rice. Finite element method (FEM) was employed in this study to solve the equations. In order to simplify the rice drying process the following assumptions were made:
- Germinated parboiled Thunya-sirin glutinous rice was assumed to be isotropic and homogeneous
- Mass transfer within rice was controlled by liquid diffusion only
- The effect of shrinkage was negligible
- Heat and mass transfer occurred in x, y and z directions only

Governing equations for heat and mass transfer

Heat transfer within germinated parboiled rice was assumed to be driven by conduction as temperature gradients developed in all directions. The conduction equation to describe energy transfer, which is defined as: Eq. (1)

\[
\rho_s C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z}\right)
\]
where \( t \) is the time (s), \( x \) is the distance in x direction (m), \( y \) is the distance in y direction (m), \( z \) is the distance in z direction (m), \( T \) is the temperature of germinated parboiled rice (K), \( \rho_s \) is Density of germinated parboiled rice (kg m\(^{-3}\)), \( C_P \) is the isobaric specific heat capacities (J kg\(^{-1}\) K\(^{-1}\)), \( k \) is the thermal conductivity of germinated parboiled rice (W m\(^{-1}\) K\(^{-1}\)). Diffusion term is significantly less than the evaporation term under intensive thin layer drying process.

The moisture transfer within germinated parboiled rice was assumed to be driven by liquid diffusion. Exhibits the mass conservation of liquid water the conduction equation to describe the mass transfer to derive the governing equation can be described by Eq.2

\[
\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left( D_{\text{eff}} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_{\text{eff}} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( D_{\text{eff}} \frac{\partial T}{\partial z} \right)
\]  

(2)

The following initial conditions were considered: The onset of the drying process in the temperature and moisture content of take the following form: Eq.(3)

\[
t = 0, \quad 0 \leq x \leq r_x, \quad 0 \leq y \leq r_y, \quad 0 \leq z \leq r_z, \quad M = M_0
\]

\[
t > 0, \quad x = 0, \quad y = 0, \quad z = 0, \quad \frac{dM}{dt} = 0
\]

\[
t > 0, \quad x = r, \quad y = r, \quad z = r, \quad M = M_e
\]

(3)

where \( x, y, \) and \( z \) are distance in x y and z direction (m), boundary conditions for the surface are given by Eq.4

\[-kV T = h_i \left( T_h - T_s \right) - \rho \lambda h_{\text{mass}} \left( M_s - M_e \right)
\]

(4)

\[
\frac{\partial T}{\partial n} = 0 \quad \text{at} \quad x, y \quad \text{and} \quad z = 0
\]

The mechanism of far infrared irradiation combined hot air could be directly penetrates into the grain surface. Energy is completely absorbed from the grain surface into the depth of 1 mm the grain \(^8\). Three-dimensional heat transfer of germinated parboiled rice boundary condition at the surface as follows from: Eq. 5

\[-kV T = \sigma \left( T_e^4 - T_s^4 \right) - \rho \lambda h_{\text{mass}} \left( M_s - M_e \right)
\]

(5)

where \( \sigma \) is the Stefan–Boltzman constant \((5.669 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4})\)

2.2 Effective moisture diffusivity : To determine effective moisture diffusivity, germinated parboiled Thunya-sirin glutinous rice grains were assumed to be spherical. An analytical solution of Fick’s second law for a spherical shape can be expressed by Eq. (6)

\[
MR = \frac{6}{\pi} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left( -n^2 \pi^2 \frac{D_{\text{eff}}}{r^2} \right)
\]

(6)
2.3 Specific energy consumption: Energy consumption for different drying conditions was measured by a clamp-on power meter (YOKOGAWA; model MX 100, JAPAN). Total energy consumption was the sum of energy consumed by the far infrared radiation source (\(E_{\text{FIR}}\)), blower (\(E_{\text{blower}}\)) and an electrical heater (\(E_{\text{heater}}\)). Specific energy consumption (SEC) (kWh/kg water evaporated) were calculated as follows as Eq. (7)

\[
SEC = \frac{E_{\text{FIR}} + E_{\text{blower}} + E_{\text{heater}}}{M_f m_s - M_i m_s} \quad (7)
\]

where \(M_f\) is the final moisture contents of germinated parboiled Thunya-sirin glutinous rice (kg water/kg dry matter) and \(m_s\) is mass of dry solid (kg).

3. Results and discussion

The changes of moisture content and surface temperature of germinated parboiled Thunya-sirin glutinous rice versus drying time were experimentally investigated under combined far infrared radiation and air convection drying. The decrease in the drying rate is also due to the reduction of moisture content leading to the lower concentration difference as the driving force of the mass transfer. Clearly, good agreements between the predicted and experimental drying curves are the average values of the entire sample layer. According to the mechanism of infrared radiation drying, heat is generated deep inside the grain and tends to be selectively absorbed in the regions with high moisture content \(^9\). As shown in Figure 1. During the early period, far infrared radiation was absorbed by the water molecules in the penetrating layer, resulting in rapid water evaporation from the surface of rice.

![](image)

**Figure 1.** Measured moisture ratio of germinated parboiled Thunya-sirin glutinous rice for various far infrared intensities

The average effective moisture diffusivities of the germinated parboiled rice were in the ranges 1.25 \(\times 10^{-10}\) – 3.48\(\times 10^{-10}\) m\(^2\)/s. The effective moisture diffusivities of the samples under different applied far infrared intensities were calculated and presented in Table 1. An increase of the
applied intensities from 3 kW/m$^2$ to 5 kW/m$^2$ resulted in the shorter drying time and the reduced energy consumption by 200 minutes and 5.29 kWh/kg water removed.

Table 1. Effective moisture diffusivity of germinated parboiled Thunya-sirin glutinous rice

| Intensity | Effective moisture diffusivities | $R^2$  |
|-----------|----------------------------------|--------|
| 3 kW/m$^2$| 1.25 x10$^{-10}$                | 0.936  |
| 4 kW/m$^2$| 2.09 x10$^{-10}$                | 0.957  |
| 5 kW/m$^2$| 3.48x10$^{-10}$                 | 0.994  |

4. Conclusions

The present study has demonstrated that the drying curves of germinated parboiled Thunya-sirin glutinous rice under far infrared intensities at 3 to 5 kW/m$^2$ were combined with a 40°C temperature and 1 m/s air velocity. The mathematical model was satisfied to predict the evolutions of experimental. The average effective moisture diffusivities of the germinated parboiled rice were in the ranges $1.25 \times 10^{-10}$ – $3.48 \times 10^{-10}$ m$^2$/s. This technique is believed that the combined drying method should be considered as an appropriate drying method for germinated parboiled Thunya-sirin glutinous rice.

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