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Estimation of convective heat transfer coefficient in agricultural products under solar drying conditions

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Abstract. This research estimated convective heat transfer coefficients of agricultural products (banana, taro and chili) under solar (open sun) drying conditions using the $Nu = h_c(X/K_v) = C(Ra)^n$ equation. Values of constants C and n were obtained by linear regression analysis. Results showed that natural convective heat transfer coefficients of agricultural products were in the range 0.720-3.559 W/m^2·°C. The C value of agricultural products was 1.0000-1.0011, while n was in the range 0.071-0.274, Pr = 0.697-0.705 and 2.931×10^5-1.803×10^8 < Gr < 6.139×10^8-2.230×10^9.

1. Introduction

Most people living in developing countries are dependent on agriculture. After harvest, agricultural products are dried (moisture removal process) to increase storage life, minimise packaging requirement and reduce transportation weight [1]. Drying of agricultural products is an important post-harvest process to reduce loss. Traditionally, agricultural products i.e. banana, taro and chili are sundried outdoors. Solar drying has long been practiced throughout the world.

Solar drying of agricultural products has been intensively researched. Tiwari et al. [2] determined the convective mass transfer coefficients (h_c) of jaggery under natural and forced convection greenhouse drying modes as 0.55-1.43 W/m^2·°C and 0.33-1.80 W/m^2·°C respectively, while Jain and Tiwari [3] studied convective heat transfer coefficients of cabbage and peas under open sun, natural and forced convection greenhouse drying modes and reported values as 25.00-10.00 W/m^2·°C, 17.00-8.00 W/m^2·°C and 38.00-15.00 W/m^2·°C respectively. Kumar and Tiwari [4] found that convective mass transfer coefficients for onions under open sun, natural and forced convection greenhouse drying modes varied as 1.19-2.75 W/m^2·°C, 1.28-2.28 W/m^2·°C and 1.09-3.08 W/m^2·°C respectively.

Sethi and Arora [5] improved the efficiency of a conventional greenhouse by using inclined north wall reflection for faster drying of bitter gourd slices under natural and forced convection modes. Air temperature inside the improved greenhouse increased from 1 °C to 6.7 °C and 1 °C to 4 °C under natural and forced convection modes respectively, while Shahi et al. [6] studied the drying of agricultural products such as tomato, capsicum, cabbage, leafy vegetables, carrot and apple in a polyhouse type solar dryer in Kashmir. The concrete floor was painted black for better absorption of solar radiation and the north wall of the polyhouse was covered with a black body to reduce heat losses. Payback time of the dryer was reported to be 1.5 years.

The convective heat transfer coefficient is an important prerequisite when designing a system to dry food materials and agricultural products using solar energy. Therefore, here, experiments were conducted to calculate convective heat transfer coefficients of banana, taro and chili as preliminary data to design a drying system with laminar or turbulent airflow suitable for communities and entrepreneurs.

2. Theoretical Background

Heat and mass transfer analyses for food and agricultural product drying systems have been intensively investigated for both natural and forced convection modes. Heat transfer coefficients under natural and forced convection can be evaluated by equation (1) and equation (2) [2, 7] expressed as follows

$$N_{\mathrm{u}} = \frac{h_{\mathrm{c}} X}{K_{\mathrm{v}}} = C(Gr\,\mathrm{Pr})^n \qquad \text{(for open sun drying using natural convection)} \qquad (1)$$

$$N_{\mathrm{u}} = \frac{h_{\mathrm{c}} X}{K_{\mathrm{v}}} = C(\mathrm{Re}\,\mathrm{Pr})^n \qquad \text{(for open sun drying with forced convection)} \qquad (2)$$

Rate of heat utilised to evaporate moisture [8] can be expressed as

$$\dot{Q}_{\mathrm{c}} = 0.016 \cdot h_c \cdot [P(T_p) - \gamma P(T_c)] \qquad (3)$$

When substituting h_{c} from equation (1), equation (3) becomes

$$\dot{Q}_{\mathrm{c}} = 0.016 \cdot \frac{K_v}{X} \cdot C(Gr\,\mathrm{Pr})^n \cdot [P(T_p) - \gamma P(T_c)] \qquad (4)$$

Evaporated moisture can be determined by dividing equation (4) by the latent heat of vaporization (λ) and multiplying by the area of agricultural product drying trays (A_{t}) and the time interval (t) as

$$\dot{m}_{\mathrm{mv}} = \frac{\dot{Q}_c}{\lambda} \cdot A_t t = 0.016 \cdot \frac{K_v}{X\lambda} \cdot C(Gr\,\mathrm{Pr})^n \cdot [P(T_p) - \gamma P(T_c)] \cdot A_t t \qquad (5)$$

Let $$0.016 \cdot \frac{K_v}{X\lambda} \cdot [P(T_p) - \gamma P(T_c)] \cdot A_t t = Z \qquad (6)$$

Thus $$\frac{\dot{m}_{cv}}{Z} = C(Gr\,\mathrm{Pr})^n \qquad (7)$$

The logarithm on both sides of equation (7) can be written as

$$\ln\left[\frac{\dot{m}_{cv}}{Z}\right] = \ln C + n \ln(Gr\,\mathrm{Pr}) \qquad (8)$$

This is in the form of a linear equation

$$y = mx + c \qquad (9)$$

where $y = \ln\left[\frac{\dot{m}_{cv}}{Z}\right]$, $m = n$, $x = \ln[\text{Re Pr}]$ and $c = \ln C$. Thus, $C = e^c$ with similarly in the case of forced convection mode, $y = \ln\left[\frac{\dot{m}_{cv}}{Z}\right]$, $m = n$, $x = \ln[\text{Re Pr}]$ and $c = \ln C$, Thus, $C = e^c$.

Values of y and x can be evaluated for different time intervals and the constants C and n can then be obtained from the above equations. Constants C and n can be further used to evaluate the convective heat transfer coefficient under natural convection drying computed by equation (1) and also to evaluate the convective mass transfer coefficient under natural and forced convection. Knowing the convective heat transfer coefficient (h_c), the evaporative mass transfer coefficients (h_m) can then be evaluated from equation (10) as follows

$$h_m = 16.273\times10^{-3}\cdot h_c\cdot\left(\frac{P(T_p)-\lambda P(T_c)}{T_p-T_c}\right) \tag{10}$$

The physical properties of humid air consist of thermal conductivity, density, dynamic viscosity, partial vapour pressure at temperature, specific heat, coefficient of volume expansion and latent heat of vaporisation following Jain and Tiwari [9] and Jain [10]. The natural convection coefficient of the agricultural products banana, taro and chili can then be calculated.

3. Methods

Agricultural products as banana, taro and chili of different shapes and mass were sourced from the local Taladmai Market in Yala Province and dried under open sun conditions with free convection. The banana was split into two halves while the taro was cut into slices 0.05 m × 0.47 m × 0.78 m. The experimental setup consisted of wire mesh trays with dimensions 0.35 m × 0.35 m to accommodate 465.5, 428.3 and 232.6 g samples of banana, taro and chili respectively as single layer drying shown in **Figure 1**. Using a similar method, Tiwari et al. [2] and Jain and Tiwari [3] determined convective heat transfer coefficients for open sun drying of jaggery, cabbage and peas.

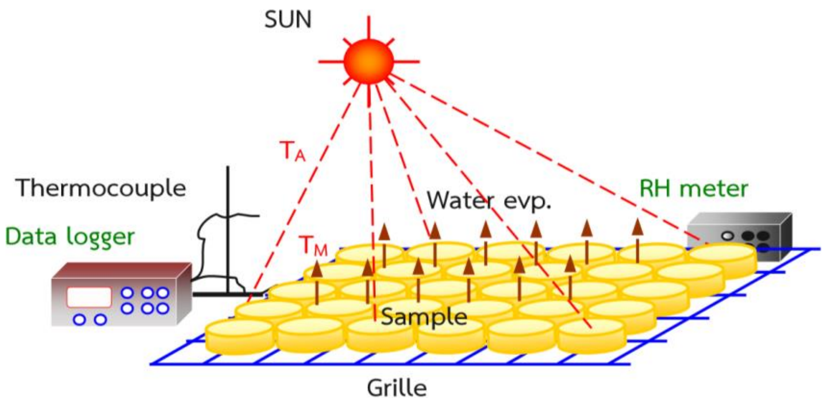

Figure 1. Agricultural products dried under open sun conditions.

A four-channel digital temperature indicator (Digital Multimeter, Unaohm 9400 Model) with minimum temperature measurement of 0.1°C (accuracy ±0.1%) and K-type thermocouples was used to measure air temperature on the surface, under and at the centre of the agricultural product material. A dial type hygrometer (FlashLink Data Logger, DeltaTrak Model) with a minimum measurement of 0.1 was used to measure relative humidity above the agricultural products. An electronic balance ((Mettler Toledo, BP 1502 Model) of 2 kg capacity with minimum of 0.1 g was used to measure mass at hourly intervals. The banana, taro and chili remained on the electronic balance during drying with time intervals of 10 min and the experiment was completed after approximately 2 h.

4. Results and Discussion

Experimental data obtained for banana, taro and chili drying under natural convection mode (not shown) were used to determine the values of the constant *C* and exponent *n* in the Nusselt number (*N*u) expression by simple linear regression analysis. Values of constant *C* and exponent *n* were then considered further to determine the convective heat transfer coefficients using equation (1). Values of the constants (*C* and *n*) and convective heat transfer coefficients for banana, taro and chili during natural convection drying mode are presented in **Table 1**.

Table 1. Values of constants (*C* and *n*), Grashof number (*G*r), Prandtl number (*P*r) and convective heat transfer coefficients of banana, taro and chili during open sun drying.

Agricultural product	*C* and *n* values	*P*r	*G*r	h_c (W/m^2·°C)
Banana	1.0000 and 0.2530	0.697	$1.803\times10^8 < Gr < 2.230\times10^9$	3.463
Taro	1.0000 and 0.2740	0.697	$6.227\times10^7 < Gr < 6.139\times10^8$	3.559
Chili	1.0011 and 0.0705	0.705	$2.931\times10^5 < Gr < 6.372\times10^8$	0.720

Values of the constant *C* were 1.0000, 1.0000 and 1.0011, while exponent (*n*) was 0.2530, 0.2740 and 0.0705 for banana, taro and chili dried under open sun conditions respectively. The Grashof (*G*r) and Prandtl (*P*r) numbers ranged 2.931×10^5-$1.803\times10^8 < Gr < 6.139\times10^8$-$2.230\times10^9$ and 0.697-0.705 respectively. The product of Grashof and Prandtl numbers indicated that entire drying of banana, taro and chili in natural mode falls within a laminar flow because $GrPr \leq 10^7$ [11].

The convective heat transfer coefficients of agricultural products varied from 1.08 W/m^2·°C to 1.40 W/m^2·°C (3.463 W/m^2·°C for banana, 3.559 W/m^2·°C for taro and 0.720 W/m^2·°C for chili). Different values of the convective heat transfer coefficient were obtained for chili compared to banana and taro because chili has a thin and hollow peel compared to banana and taro which have a thick peel texture than can hold water well. Therefore, banana and taro can transfer more heat than chili.

5. Conclusion

The natural convective heat transfer coefficient of taro was higher than banana and chili with results ranging from 0.720 to 3.559 W/m^2·°C. The *C* values of the three agricultural products ranged between 1.0000 and1.0011 with *n* in the range 0.071 to 0.274, Pr = 0.697-0.705 and 2.931×10^5-$1.803\times10^8 < Gr < 6.139\times10^8$-$2.230\times10^9$.

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