Experimental Study of Greenhouse Prawn Drying under Natural Convection

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ABSTRACT

In this present study, greenhouse drying (natural convection) of prawn, *Macrobrachium lamarrei* (H.Milne Edwards) has been studied during July, 2006 for the composite climate of New Delhi. The hourly parameters such as moisture evaporation, prawn temperature and relative humidity inside greenhouse have been recorded during the process of complete drying of prawn. These parameters were used for determination of the convective heat transfer coefficient. Convective heat transfer coefficients are mainly dependent on the rate of moisture transfer under the drying process. Among different curve fitting, a quadratic curve exhibited best relation between convective heat transfer coefficient and drying time as it gave the maximum coefficient of determination (R^2 = 99.04%).

Key words: Greenhouse, drying of prawn, convective heat transfer coefficient and convective mass transfer coefficient

1. INTRODUCTION

Prawn is a very important foodstuff in most of the countries, due to its high protein content and nutritional value. However, it is a great perishable product, especially in hot climates and tropical areas where cold preservations techniques are often missing (Zakhia, 2000). Prawn salting/brining, open sun drying or smoking, are traditional techniques for improving preservation and storage. Open sun drying is still the most common method to preserve food products in tropical and subtropical countries. Considerable losses can occur during open sun drying due to various reasons such as contamination by insects and microorganisms. Also the quality of the prawn is lowered significantly, over drying, insufficient drying, contamination by foreign materials, insects and microorganisms as well as discoloring by UV-radiation are characteristic for open sun drying. In general, open sun dried prawn products do not fulfill the nutritional quality standards.

Drying is simply the process of moisture removal from a product. It can be performed by various methods for a variety of different substances from solids to gases and even liquids (Hall, 1980). Drying is a process of simultaneous heat and mass transfers. Where, the heat energy applied to the prawn is utilized to increase the temperature of prawn and to vaporize the moisture present in the prawn through provision of latent heat of vaporization. The removal of moisture from the interior of the prawn takes place due to induced vapor pressure difference between the prawn and surrounding medium. The desired difference of vapor pressure may be obtained either by increasing the vapor pressure of the prawn surface or by decreasing the vapor pressure of the surrounding or by both.

The modeling of heat and mass transfer mechanisms for solar drying of prawn is complex phenomenon. The convective heat transfer coefficient is an important parameter in drying rate simulation. Since, the temperature difference between the air and prawn varies with this coefficient. Anwar and Tiwari (2001b), Jain and Tiwari (2003), Kumar and Tiwari (2006) evaluated the convective heat transfer coefficient for some crops (green chilies, green peas, white gram, onions, potatoes, and cauliflower) under solar drying and developed a mathematical model for predicting the drying parameters. Jain and Tiwari (2004) further studied the dependence of convective heat transfer coefficient on the drying time during complete solar drying process of green peas and cabbage. The convective heat transfer coefficient of jaggery under solar drying has been evaluated by Tiwari et al. (2004). Their model for convective heat transfer coefficient has been adopted from Kumar and Tiwari (1996).

In comparison, to open sun drying the use of appropriate greenhouse dryers lead to reduction of the drying time up to 50%, and to a significant improvement of the product quality in terms of color, texture and taste (Esper and Muhlbauer, 1998). Wiset et al. (2001) reported effects of high temperature drying on rice quality and shows significant advantages in terms of energy saving and quality deterioration, especially fungal infestation. Furthermore, the contamination by insects, microorganisms and bacteria can be prevented. The storage losses can be reduced to a minimum while the shelf life of the products can be increased significantly.

Therefore, the present studies were undertaken to determine the convective heat and mass transfer coefficients at different time kinetics of drying prawn under the natural convection of greenhouse.

2. THEORY

2.1 Convective heat transfer coefficient

The Nusselt number *Nu* under natural convection is a function of Grashof *Gr* and Prandtl *Pr* numbers.

$$Nu = \frac{h_c X}{K_V} = C(Gr\,\mathrm{Pr})^n \qquad (1)$$

where, Gr and Pr can be evaluated at mean vapor temperature by using the expression given in the nomenclature, h_c is the convective heat transfer coefficient in W/m^2 ^{o}C; X is the characteristics length in m; K_v is the thermal conductivity of the humid air in W/m ^{o}C and C and n are the constants of Eq. (1).

Therefore, the convective heat transfer coefficient can be determined by using the expression given in Eq. (1) for the Nusselt number as

$$h_c = \frac{K_V}{X} C(Gr\,\mathrm{Pr})^n \qquad (2)$$

The rate of heat utilized to evaporate moisture is given as (Malik et al., 1982)

$$\dot{Q}_e = 0.016\ h_c \left[P(T_p) - \gamma\ P(T_g)\right] \qquad (3)$$

where, $\dot{Q}_e$ is the rate of heat utilized in J/m^{2}s; $P(T_p)$ and $P(T_g)$ are the partial vapor pressures of air at the temperatures in ^{o}C of the prawn surface (T_p) and inside greenhouse (T_g) at relative humidity (γ), respectively.

Substituting h_c from Eq. (2), then Eq. (3) becomes surrounding humid

$$Q_e = 0.016 \frac{K_V}{X} C\,(Gr\ \mathrm{Pr})^n \left[P(T_p) - \gamma\ P(T_g)\right] \tag{4}$$

The moisture evaporated (m_{ev}) in kg is determined by dividing Eq. (4) by the latent heat of vaporization (λ) and multiplying by the area of the container (A_t) and time interval (t) in s.

$$\mathrm{m_{ev}} = \frac{\mathrm{Q_e}}{\lambda} \mathrm{A_c\, t} = 0.016 \frac{K_V}{X\lambda} C\,(Gr\ \ \mathrm{Pr})^n \left[P(T_p) - \gamma\ P(T_g)\right] A_C\, t \tag{5}$$

Rearranging the terms and Equation (5) becomes

$$\frac{m_{ev}}{Z} = C\left(Gr\,,\ \mathrm{Pr}\right)^n \tag{6}$$

where, Z= $0.016\ \frac{K_V}{X\lambda} \left[P\ (T_p) - \gamma\ P\ (T_g)\right] A_C\, t$

Taking logarithm of both sides of Eq. (6),

$$\ln \left[\frac{\mathrm{m_{ev}}}{\mathrm{Z}}\right] = \mathrm{n\ ln\ (Gr,Pr\ ) + ln\ C} \tag{7}$$

Equation (7) is the analogy of a straight line equation,

$$Y = b_1\ X + b_o$$

where, b_1 and b_o are the independent and dependent variables. Y =ln $\left[\frac{\mathrm{m_{ev}}}{\mathrm{Z}}\right]$, b_1 = n,

X= ln (Gr Pr) and b_o = ln C

Thus,

$$C = e^{bo} \tag{8}$$

Once the numerical values of the constants C and n are known, the convective heat transfer coefficient is computed by Eq. (2) and using measured values obtained from (Table 1) of the ambient air, inside greenhouse air, surface temperature of prawn and relative humidity in greenhouse condition during a given time period.

2.2 Convective mass transfer coefficient

The convective mass transfer coefficient can be determined using the relation

$$h_e = \frac{\dot{Q}_e}{T_g - T_p} \tag{9}$$

where, h_e is the convective mass transfer coefficient in W/m^2 ^{o}C, $\dot{Q}_e$ is the rate of heat utilized in W/m^2, greenhouse air temperature (T_g) and, T_p is the average temperature just above the prawn surface.

2.3 Physical properties of humid air

The following expressions were used for calculating values of the physical properties of humid air, i.e. specific heat (C_v) in J/kg^{o}C, thermal conductivity (K_v) in W/m^2 ^{o}C, density (ρ_v) in kg/ m^3, dynamic viscosity μ_v in kg/m and the partial vapor pressure P in N/m^2. For obtaining the physical properties of humid air, T_i is taken as the average temperature (T_p) just above the prawn surface (T_p) and greenhouse air temperature (T_g).

$$C_v = 999.2 + 0.1434\, T_i + 1.101 \times 10^{-4}\, T_i^2 - 6.7581 \times 10^{-8}\, T_i \quad \text{(Kyokai, 1978)} \tag{10}$$

$$K_v = 0.0244 + 0.6773 \times 10^{-4} \quad \text{(Kyokai, 1978)} \tag{11}$$

$$\rho_V = \frac{353.44}{T_i + 273.15} \quad \text{(Toyama et al., 1987)} \tag{12}$$

$$\mu_v = 1.718 \times 10^{-5} + 4.620 \times 10^{-8} \quad \text{(Kyokai, 1978)} \tag{13}$$

$$P(T) = \exp 25.317 - \frac{5144}{T_i + 273} \quad \text{(Fernandez and Chargoy, 1990)} \tag{14}$$

$$T_i = \frac{T_p + T_g}{2} \ \text{or}\ T_i = \frac{T_p + T_e}{2} \tag{15}$$

2.4 Computation technique

The average surface temperature of prawn $\overline{T}_p$ and inside greenhouse temperature above the prawn surface $\overline{T}_g$ were calculated at hourly intervals for corresponding moisture evaporated. The physical properties of humid air were evaluated for the mean temperatures of $\overline{T}_p$ and $\overline{T}_g$ using Eqs. (10-15). These physical properties were utilized for calculating the values for the Grashof *Gr* and (*Pr*) Prandtl numbers. The values of *C* and *n* in Eqn (2) were obtained by linear regression analysis expressed in Eq. (8) at the increment of every hour of observation and thus the mean values of h_c were computed at the corresponding hour of drying. The computer program was prepared in the Excell.

3. MATERIAL AND METHODS

3.1 Experimental greenhouse

The experimental set-up of the greenhouse drying of prawn under natural convection is shown in Fig.1. The plastic covered greenhouse traps the solar energy in the form of thermal energy within the cover and reduces the convective heat loss. The fraction of trapped energy received partly by the prawn, floor, exposed tray area and remaining solar radiation will heat the enclosed air inside the greenhouse. A roof type even span greenhouse of 120 ×0.78 m^2 effective floor area was used for experimental purposes, which is covered with transparent UV-stabilized low density polyethylene film (LDPE) of 250 micron. The orientation of the greenhouse was from east-west direction. The inclinations of south and north roof were 25.90^o and 25.90^o. The central height and walls were maintained as 0.60 and 0.40 m, respectively. There were provisions of two vents, each of 0.2 × 0.1m ^{2} on the south and north roof for natural ventilation purposes during over heating inside the greenhouse, if any.

Figure 1. Experimental set-up for prawn drying inside greenhouse

3.2 Instrumentation

A non-contact thermometer (Raytek-AG 42) having least count of 0·1 °C was used for measurement the temperature of prawn surface. A digital hygro-thermometer (model: Lutron HT-3003) was used to measure the relative humidity in the greenhouse. It had a least count of 0.1% relative humidity with accuracy of ±3% on the full scale ranges of 5-99.9% of relative humidity. An electronic balance of 1 kg weighing capacity with least count of 0·1 g was used to weigh the sample during the drying. The difference in weight gave the moisture evaporated during that observed time interval. The solar intensity was measured with a solarimeter. It measures the solar radiation in mW/cm^2 having a least count of 2 mW/cm^2 with $\pm$ 2% accuracy over the full-scale range of 0-120 mW/cm^2. Ambient air temperature (T_a) and surface temperature just above the prawn inside greenhouse (T_g) were measured by calibrated alcohol-filled, glass-bulb thermometers (least count was 1^{o}C).

3.3. Experimental observation

Prawn, *Macrobrachium lamarrei* (H. Milne Edwards) was considered for drying in greenhouse. The fresh prawn procured from local market, washed with fresh water. Surface water was removed by blotting with absorbent paper. A steel wire mesh tray of 0.25 × 0.20m was used during drying of the prawn. The prawns were arranged in a single layer in the drying tray. The tray was kept on the measuring balance. Experiments were conducted in July 2006 between 10:00 and 17:00 h for two consecutive days under the composite climate of New Delhi, India (Latitude-28°35′ Longitude – 77 ° 12′ E and altitude– 216 m above msl). The solar radiation ranged during these hours between 150 and 620 W /m^2 °C.

4. RESULTS AND DISCUSSION

The computed values of convective heat transfer coefficients for prawn during greenhouse drying are summarized in Table 1. It took 12 h (two sunny days) to dry the prawn. The moisture evaporation rate was higher in the initial few hours (3–4 h) of drying. The Grashof number (*Gr*) ranged from ($1{\cdot}17\times10^6$ to $0{\cdot}008\times10^6$) and Prandtl number (*Pr*) remained steady as 0.71 throughout the drying process. The product of Grashof and Prandtl number indicates that the entire drying falls within a laminar flow regime, since $GrPr \leq 10^7$ (Holman, 1992). Changes in coefficients C and n are observed as the number of observations and drying time increase. The values of C and n are 1.47, 1.00 and 0.26, 0.22 for 1st and 2nd days observations, respectively. Accordingly, the values of Nusselt number also changed with the changes in coefficients (C and n) with increase of drying time.

Table 1: Observation on greenhouse prawn drying under natural convection (initial total weight=162.9 g; number of prawn =250; month-July, 2006).

Day	*Drying time (h)*	*I(t) W/m^2 °C*	*T_a °C*	*Greenhouse drying*			
1st				*T_p*	*T_g*	*γ (%)*	*m_{ev} (g)*
	0	620	36	38	51	32.80	-
	1	540	37	46	53	31.20	49.4
	2	300	38	48	54	35.50	33.9
	3	560	39	49	54	33.10	19.6
	4	460	39	49	54	32.60	13.6
	5	400	38	49	52	31.10	8.3
	6	280	38	49	50	30.90	7.4
	7	160	36	41	44	28.00	3.6
2nd	8	420	32	43	40	39.20	2.1
	9	320	34	47	44	31.90	1.2
	10	200	33	49	43	34.00	0.5
	11	400	34	50	45	23.00	0.1
	12	600	35	51	47	24.60	0.1

The convective heat transfer coefficient (h_c) for prawn drying ranged from 9.2-1.23 W/ m^2 °C. The convective heat transfer coefficient declined with a decrease in moisture content of prawn as expected. Furthermore, the convective mass transfer coefficient (h_e) can be evaluated using Eq. (9). Experimental convective heat transfer coefficients have been fitted by various mathematical relations as a function of drying time in hours viz., Linear, Y= a + b×T, Log-Linear, Y= a×T^b, Exponential, Y= a×$e^{b\times T}$ and Quadratic, Y= a + b×T+ c×T^2. A Quadratic curve exhibited best relation between convective heat transfer coefficient and drying time as evident by the maximum coefficient of determination (R^2 = 99.04%) with the following relation.

$$Y = 10.402 - 1.1709 \times T + 0.0354 \times T^2;\ R^2 = 99.04\% \quad (16)$$

Where, Y = convective heat transfer coefficient in W/m^2 ^{o}C

T = drying time (h)

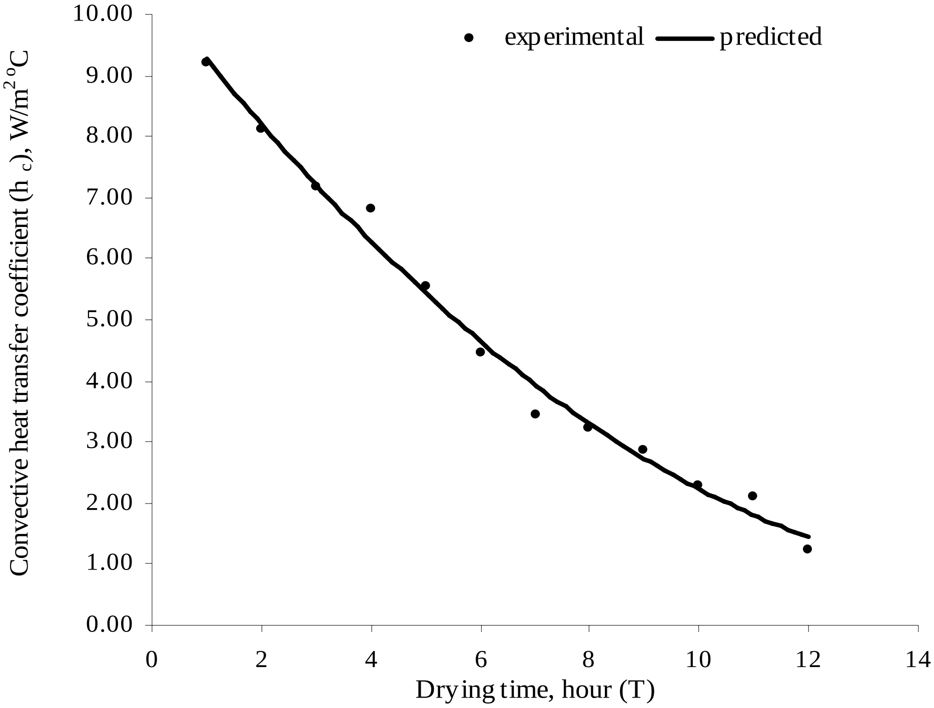

Figure 2. Variation of convective heat transfer coefficient with drying time for prawn under natural convection in greenhouse (July, 2006)

5. CONCLUSION

The convective heat transfer coefficients of prawn have been determined under greenhouse drying condition at different drying times. Convective heat transfer coefficient was a function of moisture removal, physical properties of moist air, operating temperature and surface area. The values of convective heat transfer coefficient varied significantly with the type and size of substances. This was mainly because of size and initial moisture content of the prawn. The developed mathematical models successfully predict the convective heat transfer coefficients as the function of moisture content of prawn.

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NOMENCLATURE

A_t	*area of tray, m^2*
C	*constant*
C_v	*specific heat of humid air, J/ kg °C*
C_f	*specific heat of prawn, J/ kg °C*
c	*coefficient*
Gr	*Grashof number ($=\beta g X^3 \rho_v^2\ \Delta T^1/\mu^2$)*
g	*acceleration of gravity, m/s^2*
h_c	*convective heat transfer coefficient of prawn, W/m^2 °C*
$h_{c,pre}$	*predicted convective heat transfer coefficient of prawn, W/m^2 °C*
K_v	*thermal conductivity of humid air, W/ m °C*
X	*characteristic dimension, m*
m_{ev}	*moisture evaporated, kg*
Nu	*Nusselt number ($=h_c L/K_v$)*
n	*coefficient*
Pr	*Prandtl number ($=\mu_v C_v/K_v$)*
$P(T)$	*partial vapor pressure at temperature T, Pa^2*
$\dot{Q}_e$	*rate of heat utilized to evaporate moisture, W/m^2s*
R^2	*coefficient of determination*

T_p	*surface temperature of prawn, °C*
T_e	*temperature of humid air above the prawn surface, °C*
T_i	*average of prawn and humid air temperature, °C*
ΔT	*effective temperature difference, °C*
t	*time, s*
β	*coefficient of volumetric expansion,*
γ	*relative humidity (dec.)*
λ	*latent heat of vaporization, J/ kg ^oC*
μ_v	*dynamic viscosity of humid air, kg/ ms*
ρ_v	*density of humid air, kg/ m^3*