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***Research Paper :***

# Thermal modeling and its experimental validation for drying of Prawn (*Macrobrachium lamarrei*) (H.Milne Edwards) in a greenhouse under natural convection

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## ABSTRACT

An experimental study was carried out to develop a thermal model to predict the prawn (*Macrobrachium lamarrei)* (H.Milne Edwards) temperature, the greenhouse air temperature and the amount of moisture evaporated (prawn mass during drying) under natural convection mode. The prawn having initial weight 162.9g (250 numbers) was dried in a roof-type even span greenhouse with floor area of 1.20×0.78 m$^2$. Experiment was carried out during July 3–4, 2006 at IIT Delhi (Latitude 28$^0$35'N and Longitude 72$^0$12' E) between 10 am to 5 pm for two consecutive days. A computer program was developed in MATLAB 7.0 software to calculate the prawn temperature, the greenhouse air temperature, the amount of moisture evaporated and also used to predict the thermal performance of the greenhouse on the basis of solar intensity and ambient air temperature. The model developed was validated with the experimental data and exhibited fair agreement.

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**Key words :** Thermal modeling, Drying of prawn, Greenhouse, Natural convection

In many rural areas of developing and under developed countries, the availability of electricity and other non-renewable sources of energy are not only irregular and unreliable for many fish farmers but also expensive. Thus, in such locations, electrical heating for fish drying is not a dependable option. The small fish farmers rarely adopt the dryers powered by fossil fuels due to their high cost. The traditional open sun drying method has some limitations like inadequate drying, fungal attacks, insects and birds catching, unexpected downpour of rain and other adverse weather effects. In such conditions, solar dryers appear to be attractive and cost effective for fish drying. The prawn drying can be done by several methods namely open sun drying, cabinet drying and greenhouse drying. In open sun drying humidity cannot be controlled and hence, it takes considerably a longer time for drying due to the hygroscopic nature of prawn. The drying can also be done with the help of a solar cabinet dryer but the high temperature inside cabinet dryer may burn the products, which is also not desirable. However, the greenhouse dryer provides a controlled environment in terms of moderate temperature and humidity, which is beneficial for the drying of prawn more effectively thus reducing the drying time (Prakash, 2006; Kumar *et al.*, 2006). Mathematical modeling of greenhouse prawn dryer is rarely available in the literature. The principles for drying of prawn are similar to any crop drying inside greenhouse (Bal *et al.*, 2003; Jain and Tiwari, 2004). The present work focuses on the development of a thermal model for prediction of hourly prawn temperature, greenhouse air temperature and the quantity of moisture evaporated under natural convection mode for required drying of prawn inside a solar greenhouse.

## METHODOLOGY

### Experimental set-up:

Wire mesh tray of 0.4x0.24 m$^2$ was used to accommodate 162.9 g samples of prawn, *Macrobrachium lamarri* (H.Milne Edwards). A roof type even span greenhouse with an effective floor covering 1.2´0.78m$^2$ has been made of PVC pipe and UV polythene film. The central height and height of walls were 0.60 and 0.40m, respectively. The inclination of the north and the south roof were 25.90$^0$ and 25.90$^0$, respectively from horizontal plane. The air vent was provided at the roof with an effective opening of 0.0722 m$^2$ for natural convection. The experimental set-up for greenhouse drying in the natural mode is shown in Fig.1. The orientation of the greenhouse was from east-west direction during the experiments.

**Fig. 1 : Experimental set-up for prawn drying inside greenhouse**

## Working principle:

The working principle of the greenhouse prawn drying under natural convection condition is presented in Fig. 2. The plastic covered greenhouse traps the available solar energy in the form of thermal heat within the cover $(\Sigma A_i I_i \tau_i)$ and reduces the convective heat loss. The fraction of trapped energy $(1\text{-}F_n)\ F_p\ (\Sigma A_i I_i \tau_i)$ will be received partly $(1\text{-}F_n)\ (1\text{-}F_p)\ (\Sigma A_i I_i \tau_i)$ by the prawn and partly by the floor and exposed tray area and the remaining solar radiation $[(1\text{-}F_n)\ (1\text{-}F_p)\ (1\text{-}\alpha_g)\ (\Sigma A_i I_i \tau_i)]$ heats the enclosed air inside the greenhouse. The temperature difference between the greenhouse air and ambient air and the vapor pressure difference between the prawn and the greenhouse air, respectively, are responsible for the natural draft and the moisture evaporation from the interior of the prawn.

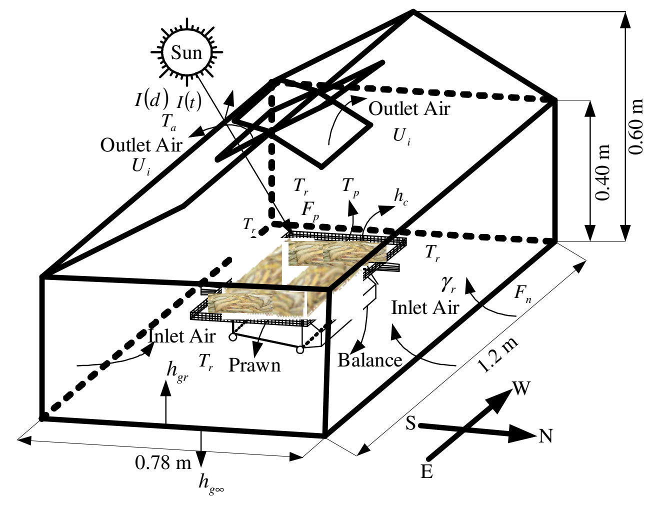

**Fig. 2 : Working principle of greenhouse prawn drying under natural convection mode**

## Instruments used:

A non-contact thermometer (Raytek-AG 42) having least count of 0·1 $^0$C and accuracy of ± 2% on a full scale range of –18 to 260 $^0$C was used for measurement of the prawn surface temperature. 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 of 1 $^0$C). A digital hygrometer (Model: Lutron HT-3003) was used to measure the relative humidity in the greenhouse. Its least count is 0.1% of 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$^2$. The values of the experimental observations for the natural convection greenhouse drying for 162.9g prawns are shown in Table 1.

## Thermal modeling for prediction of temperature of greenhouse air, prawn and amount of moisture evaporation:

### *Assumptions:*

Thermal model for prediction of temperature of prawn and quantity of moisture evaporation was developed with the energy balance equations for greenhouse prawn drying under natural mode. The energy balance equations were written with the following assumptions:

- Heat capacity of tray, greenhouse cover and wall is neglected.
- There is no stratification in greenhouse air temperature
- Absorptivity and heat capacity of the enclosed air is neglected.
- Prawn to prawn conduction is neglected and
- Heat flow is unidirectional

### *Energy balance equations:*

– Energy balance equation at prawn surface (Jain and Tiwari, 2004).

$$(1-F_n)F_p\alpha_p\sum A_iI_i\tau_i = (M_pC_p)\frac{dT_p}{dt} + h_c(T_p - T_r)A_p + 0.016h_c[P(T_p) - \gamma_r P(T_r)]A_p \quad (1)$$

[The rate of thermal energy received at the prawn surface] = [The rate of thermal energy stored by the prawn]+ [The rate of thermal energy lost due to convection loss]+ [The rate of thermal energy lost due to evaporation loss]

**Energy balance equation at ground surface (Jain and Tiwari, 2004):**

$$(1-F_n)(1-F_p)\alpha_g\sum A_iI_i\tau_i = h_{g\infty}\left(T|_{y=0} - T_\infty\right)A_g + h_{gr}\left(T|_{y=0} - T_r\right)(A_g - A_p) \quad (2)$$

[The rate of thermal energy received at the floor surface] = [The rate of thermal energy lost inside ground due to conduction loss] + [The rate of thermal energy lost from floor to greenhouse air due to convection and radiation losses]

**Energy balance equation at greenhouse chamber, using the coefficient of diffusion and difference in vapor pressure due to temperature difference of greenhouse chamber and ambient air (Jain and Tiwari, 2004):**

$$(1-F_n)(1-F_p)(1-\alpha_g)\sum A_iI_i\tau_i + h_c(T_p - T_r)A_p + 0.016h_c[P(T_p - \gamma_r P(T_r))A_p] + h_{gr}\left(T|_{y=0} - T_r\right)(A_g - A_p) = C_dA_v\sqrt{2g\Delta g} \times \Delta P + \sum U_iA_i(T_r - T_a) \quad (3)$$

[The rate of thermal energy received to greenhouse air] + [The rate of thermal energy received from prawn due to convection loss] + [The rate of thermal energy received due to evaporation loss from prawn] + [The rate of thermal energy received from greenhouse floor due to convection and radiation losses] = [The rate of thermal energy lost to the ambient air by natural ventilation] + [The rate of overall heat loss from greenhouse air to ambient air through plastic cover)

The term $C_dA_v\sqrt{2g\Delta g} \times \Delta P$ represents the rate of heat loss through natural vent (Daugherty *et al.,* 1989). The value of $C_d$ was experimentally evaluated and its value is given in Table 2.

$$\Delta H = \frac{\Delta P}{\rho_r g} \quad (4)$$

$$\Delta P = P(T_r) - \gamma_a P(T_a) \quad (5)$$

To simplify the above Eqs (4 and 5), the vapor pressure has been linearised for the small range of temperature between 25 and 55$^0$C, which mostly occurs in solar drying, as

$$P(T) = R_1T + R_2 \quad (6)$$

The vapor pressure of vapor at $T_r$ and $T_a$ can be evaluated from linear regression analysis with help of Eqs. (2), (4), (5) and (6). Equation (3) has been simplified in the form of a third order polynomial equation to determine the greenhouse air temperature ($T_r$) for initial values of prawn and ambient temperature as

$$AT_r^3 + BT_r^2 + CT_r + D = 0 \quad (7)$$

where, $A = \frac{2}{\rho_r}(C_dA_v)^2R^3{}_1$

$$B = \left(\frac{2}{\rho_r}\right)(C_dA_v)^2 3R_1{}^2[R_2 - \gamma_a(R_1T_a + R_2)] - \left[h_cA_p + 0.016h_cA_p\gamma_rR_1 + (UA)_{g\infty} + \sum U_iA_i\right]^2$$

$$C = \left(\frac{2}{\rho_r}\right)(C_dA_v)^2 3R_1{}^2[R_2 - \gamma_a(R_1T_a + R_2)]^2 + 2\left[h_cA_p + 0.016h_cA_p\gamma_rR_1 + (UA)_{g\infty} + \sum U_iA_i\right] \times \begin{bmatrix} I_{effR} + I_{effG}H_G + T_p(h_cA_p + 0.016h_cA_pR_1) + \\ T_a(UA)_{g\infty} + \sum U_iA_i + 0.016h_cA_pR_2(1-\gamma_r) \end{bmatrix}$$

$$D = \left(\frac{2}{\rho_r}\right)(C_dA_v)^2[R_2 - \gamma_a(R_1T_a + R_2)]^3 - \left[I_{effR} + I_{effG}H_G + T_p(h_cA_p + 0.016h_cA_pR_1)\right] + T_a(UA)_{g\infty} + \sum U_iA_i + 0.016h_cA_pR_2(1-\gamma_r)$$

$$I_{eff} = (1-F_n)F_p\alpha_p\sum A_iI_i\tau_i$$

$$I_{effG} = (1-F_n)(1-F_p)\alpha_g\sum A_iI_i\tau_i$$

$$I_{effR} = (1-F_n)(1-F_p)(1-\alpha_g)\sum A_iI_i\tau_i$$

$$H_g = \left[1 + \frac{h_{g\infty}}{h_{gr}(A_g - A_p)}\right]^{-1}$$

$$h_{ce} = h_c + h_r$$

$$h_r = \frac{\sigma\varepsilon\left[(T_p + 273.15)^4 - (T_e + 273.15)^4\right]}{(T_p - T_e)}$$

$$P(T) = \exp\left[25.317 - \frac{5144}{T_i + 273.15}\right]$$

$$(UA)_{g\infty} = \left[\frac{1}{h_{gr}(A_g - A_p)} + \frac{1}{h_{g\infty}A_g}\right]$$

$$\frac{1}{U} = \frac{1}{h_1} + \frac{l_g}{K_g} + \frac{1}{h_2}$$

$$h_1 = h_c + h_r + h_e$$

$$h_2 = 5.7 + 3.8v$$

Using the known values of greenhouse air temperature ($T_r$) in Eq. (1), the prawn temperature ($T_p$) can be determined from the first order differential equation.

$$\frac{dT_p}{dt} + aT_p = f(t) \tag{8}$$

The solution of Eq. (8) for the average $\bar{f}(t)$ for the time 0-1 is

$$T_p = \frac{\bar{f}(t)}{a}\left(1 - e^{-at}\right) + T_{p0}e^{-at} \tag{9}$$

where $a = \frac{h_p A_p (1 + 0.016R_1)}{M_p C_p}$ and

$$f(t) = \frac{I_{effp} + h_c A_p\left[T_r - 0.016\{R_2 - \gamma_r(R_1T_r + R_2)\}\right]}{M_p C_p}$$

Once the temperature of the prawn and greenhouse air temperature are known, the moisture evaporation can be evaluated with the expression.

$$m_{ev} = 0.016\frac{h_c}{\lambda}\left[(R_1T_p + R_2) - \gamma_r(R_1T_r + R_2)\right]A_p t \tag{10}$$

The convective heat transfer coefficient for prawn drying was calculated using regression analysis. The linear curve fitting was used to represent the convective heat transfer coefficient as a function of drying time given by the expression

$$h_c = at + b \tag{11}$$

## Input values for computation:

The mathematical model developed was solved with the help of Matlab 7.0 software to predict hourly prawn temperature, greenhouse air temperature and the amount of moisture evaporated. The average hourly solar radiation on the different walls and roofs of the greenhouse was evaluated from the average hourly solar radiation on a horizontal surface with the help of Liu and Jordan (1962) formula. The average hourly total radiation received by the greenhouse is the sum of the average hourly radiations of the walls and roofs of the greenhouse. Thus, the average hourly total radiation received by the greenhouse and the average hourly ambient air temperature were used as input data to compute the hourly prawn and greenhouse air temperatures and the hourly moisture evaporated (prawn mass during drying). The hourly moisture evaporation was calculated with the help of Eq. (10).The design parameters and the constants used for computation are given in Table 1. The predicted results are validated with the experimental values with coefficient of correlation (r) and root mean square per cent deviation (e) for prawn temperature, greenhouse air temperature and mass of prawn during drying.

**Table 1 : Design parameters and the constants used for greenhouse prawn drying**

| Parameters | Values |
|---|---|
| $A_t$ | $0.096m^2$ |
| $C_a$ | $1012$ J/kg$^0$C |
| $C_p$ | $3598.23$ J/kg$^0$C |
| $C_d$ | 0.0036 |
| $F_p$ | 0.10 |
| g | $9.81m/s^2$ |
| $h_{gr}$ | $8.0$ W/m$^2$ |
| $R_1$ | 397.52 |
| $R_2$ | -7926.90 |
| t | 3600s |
| $\lambda$ | $2.26 \times 10^6$ J/kg |
| $\sigma$ | $5.67 \times 10^{-8}$ W/m$^2$ K$^4$ |
| $\alpha_g$ | 0.60 |
| $\alpha_c$ | 0.70 |
| $\varepsilon$ | 0.90 |
| $\tau$ | 0.90 |

## RESULTS AND DISCUSSION

The drying of prawn inside the greenhouse was conducted during July, 2006. The experiment was started at 10 am and continued till 5 pm. The thermal model developed for greenhouse prawn drying under natural convection was solved from experimental data given in Table 2.

The greenhouse air temperature ($T_r$) was calculated for initial values of prawn and ambient air temperature by using Eq. (7). Then this value of $T_r$ was used to calculate the prawn temperature ($T_p$) by using Eq. (9). Further, these calculated values of $T_r$ and $T_p$ were used to calculate the hourly moisture evaporation from Eq. (10). From Fig. 3, it was observed that during the first day of drying of 162.9 g of prawn, the moisture was evaporated

**Table 2 : 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$^2$ | $T_a$ °C | Greenhouse drying | | | |
|---|---|---|---|---|---|---|---|
| | | | | $T_p$ °C | $T_g$ °C | $\gamma$ (%) | $m_{ev}$ (g) |
| 1st | 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 |

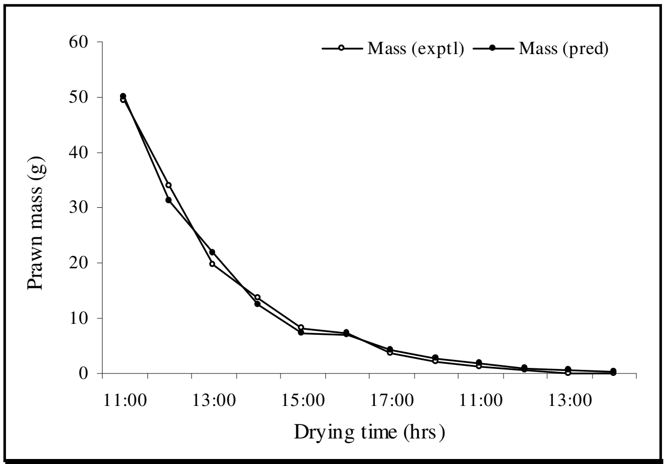

**Fig. 3 : Greenhouse prawn drying curve for natural convection mode**

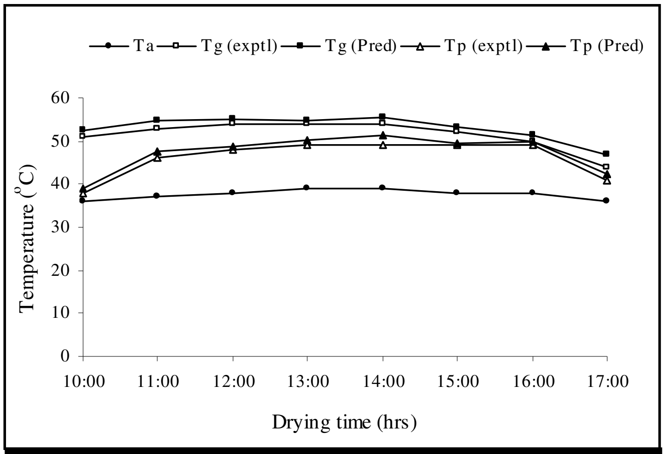

**Fig. 4a : Ambient air, prawn and greenhouse air temperature under natural convection greenhouse drying for first day (162.9g)**

from the surface of the prawn (135.8 g). However, for the second day of drying, the moisture removal was (4 g) and drying occurred from the interior of the prawn due to diffusion from inner to outer surface. It was also observed that the hourly moisture removal was faster for first day and in second day it was remained constant. This may be referred to as constant drying. The value of coefficient of correlation (0.99) and root mean square per cent deviation (26.03%) is mentioned in the same figure. It is observed that predicted values of mass of prawn during drying are in harmony with the observed values in all two days. The thermal behavior of greenhouse prawn drying is shown in Fig. 4a and 4b.

It was also observed that the prawn temperature always exceeded greenhouse air temperature due to direct absorption of solar radiation. The hourly moisture removal

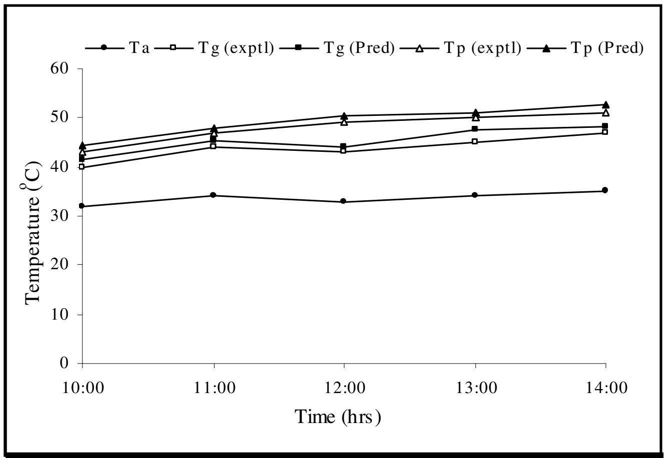

**Fig. 4b : Ambient air, prawn and greenhouse air temperature under natural convection greenhouse drying for second day (162.9g)**

was faster for first few hours and remained constant for rest of time of the experiment. The predicted results exhibited fair agreement with experimental values in terms of coefficient of correlation (r) and root mean square per cent deviation (e %) as shown in the figures.

## Conclusion:

The thermal model developed was validated with the experimental data for the complete drying of prawn under natural convection conditions. The drying time may vary significantly with the type of prawn. This was mainly because of shape, size and initial moisture content. The mathematical model developed successfully predicts the prawn temperature as the function of moisture content of prawn.

## Nomenclature:

A–area ($m^2$), a–coefficient, b–coefficient, C–specific heat (J/kg °c), Cd–coefficient of discharge, d–coefficient, e–root mean square of per cent deviation, f–fraction of solar radiation, f(t) –time dependent derivative, $\Delta$h–difference in pressure head (m), hc–convective heat transfer coefficient ($W/m^{2\circ}c$), hr–radiative heat transfer coefficient, Ii–solar intensity on greenhouse wall/roof ($W/m^2$), I(t) –solar intensity on horizontal surface ($W/m^2$) wall/roof ($W/m^2$), Lg–thickness (m), Kg–thermal conductivity ($W/m^\circ c$), M–mass (kg), mev–moisture evaporated (kg), P(T) –Vapor pressure at temperature T ($N/m^2$), $\Delta$P–difference in vapour pressure, r–coefficient of correlation, t–time (s) and drying time (h), T–Temperature (°C), U–Over all heat loss ($W/m^2$ °C), V–Volume of greenhouse ($m^2$), v–Velocity of air

$\alpha$–absorptivity of crop surface, $\beta$–coefficient of volumetric expansion ($1/^0c$), $\gamma$–relative humidity of air (%), $\varepsilon$–emissivity, $\sigma$–stefan-boltzman constant ($W/m^2k^4$), $\lambda$–latent heat of vaporization (J/kg), $\rho$–density of air ($kg/m^2$), $\mu$–dynamic viscosity of air (kg/m), $\tau$–transmissitivity, 0–initial value, a–ambient air, p–prawn, e–above the prawn surface, g–ground or greenhouse floor, i–greenhouse wall/roof (i=1,2…6), m–mass, n–north wall, r–greenhouse air, v–humid air or vent, ce–crop (prawn) to environment, gr–greenhouse floor to room, $g_\infty$–greenhouse floor to underground, $|_{y=0}$ surface of floor of greenhouse.

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