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Thermal Modeling and Parametric Study of a Forced Convection Greenhouse Drying System for Jaggery: An Experimental Validation

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Abstract: This communication presents the thermal modeling for the greenhouse drying of jaggery under forced convection mode to predict the jaggery temperature, the greenhouse air temperature and the moisture evaporation (jaggery mass during drying). The parametric study has also been performed to find the effects of various parameters namely number of air changes/h, relative humidity and mass of the jaggery. The jaggery cubes (total mass of 2.0 kg) having dimensions of $0.03\times0.03\times0.03$ m^3 has been dried in the roof type even span greenhouse with floor area of 1.20×0.78 m^2 during the month of March, 2004 at IIT Delhi (28°35'N 72°12'E) from 10 am to 5 pm. The jaggery temperature, the greenhouse air temperature and the moisture evaporation have been calculated theoretically in terms of design and climatic parameters by using the MATLAB software. The theoretical results have been experimentally validated and a fair agreement has been observed between the theoretical and experimental results.

Key words: Jaggery, greenhouse forced convection drying, thermal modeling

Introduction

Jaggery or "Gur" contains Proteins, Minerals and Vitamins, which are essential constituents for the body and has great nutritive and medicinal value. It contains 70-85% sucrose, 10-15% reducing sugar, 1-2% minerals like calcium, iron and phosphorous, vitamin A and B, protein and fats (Rao and Lakshminarayana, 1999). Manufacturing of jaggery starts in September/October and continues till March/April in most of the states in India. Jaggery is produced from main cash crop of sugarcane and more than 70% of world's total jaggery is produced in India. It is one of the eco-friendly sweeteners. It is a concentrated form of sugarcane juice produced by the processes of heating and boiling.Bagasses, the extracted biomass of sugarcane and dry leaves serves as fuel. This renewable source of energy promises 3000 MW power potential to be still harvested (Jain, 1996). It has been reported that the storage loss of jaggery is upto the extent of 25% that occurs in the normal storage process. This loss is mainly due to the moisture present in the jaggery which triggers on biochemical activity-thus converting sucrose into reducing sugars (glucose and fructose) which further make jaggery more hygroscopic attracting more moisture and the process continues like chain reaction untill jaggery liquidifies. It is thus necessary to dry jaggery upto certain moisture content before storage.

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Drying of jaggery upto an optimum moisture content thus becomes a pre-requisite for the effective packaging. Freshly prepared jaggery having moisture content in the range of 10-12% takes a considerably longer time for drying, under natural conditions. Thus to reduce drying time considerably, drying of jaggery with warmer air under natural and forced conditions is essential.

Storage is one of the main stages in the production process. Deterioration of considerable quantities of the product may take place during this operation. Drying is widely used industrial preservation method in which water activity of food is decreased to minimize biochemical, chemical and microbiological deterioration (Doymaz and Pala, 2003). Solar crop drying involves the vaporization of moisture within the product by thermal heating and subsequently resulting evaporation of moisture. Thus solar thermal drying is a complex process of simultaneous heat and mass transfer (Dincer, 1998.).

Modeling of crop drying systems has been proved valuable to study their design and management. The use of simulation model is a valuable tool for prediction of performance of solar drying systems (Steifeld and Segal, 1986). The thermal modeling and analytical study of greenhouse drying for grain, fruits and various crops has been reported by several researchers (Ong, 1996; Condorí and Saravia, 1998; Rachmat and Horibe, 1999; Manohar and Chandra, 2000; Condorí *et al*., 2001). Tunnel dryers also come in the category of greenhouse dryer and many researchers have worked on such type of dryers for drying different products (Garg and Kumar, 2000a; Yaldiz *et al*., 2001; Condorí and Saravia, 2003; Bala *et al*., 2003; Jain and Tiwari, 2004). However, no results have been reported on thermal modeling of greenhouse jaggery drying. The previous investigators have not studied the thermal behavior of jaggery under greenhouse drying.

Considering the importance of solar jaggery drying, the specific objectives of the present work are: (i) to develop the thermal model using energy balance equations at jaggery surface, ground surface and at greenhouse chamber for prediction of hourly jaggery temperature, greenhouse air temperature and moisture evaporation under forced convection mode of drying for jaggery and (ii) to examine the effect of number of air changes per hour, relative humidity and jaggery mass (surface area of jaggery) on jaggery temperature, greenhouse air temperature and hourly drying mass of jaggery.

Working Principle of Greenhouse Drying and Experimental Observation

In the phenomenon of greenhouse drying, heat energy is transferred from the surrounding greenhouse air to the jaggery surface in different heat transfer modes thus resulting in the changes in moisture contents, air and jaggery temperature and humidity of air all occurring simultaneously. Due to the propagation of heat energy to the interior of jaggery, the moisture present in jaggery is vaporized through latent heat of vaporization and the jaggery surface temperature is increased (Jain and Tiwari, 2004).

The working principle of the greenhouse drying of jaggery under forced convection is shown in Fig. 1. The plastic covered greenhouse traps the solar energy in the form of thermal heat within the cover ($\sum I_i A_i \tau_i$) and reduces the convective heat loss. The fraction of trapped energy $(1-F_n) F_j (\sum I_i A_i \tau_i)$ will be received partly by the jaggery and partly $\alpha_g (1-F_n) (1-F_j) (\sum I_i A_i \tau_i)$ by the floor and exposed tray area and the remaining solar radiation $((1-F_n) (1-F_j) (1-\alpha_g) (\sum I_i A_i \tau_i))$ will heat the enclosed air inside the greenhouse. Further to reduce the relative humidity inside the greenhouse, an exhaust fan is used which increases the vapor pressure difference hence resulting in the forced mode of drying.

Jaggery pieces having dimensions of $0.03\times0.03\times0.03$ m^3 were kept as thin layers in wire mesh tray of dimensions 0.4×0.24 m^2 under the east west oriented greenhouse for experimentation. A roof type even span greenhouse with 1.20×0.78 m^2 effective floor covering area having the central height

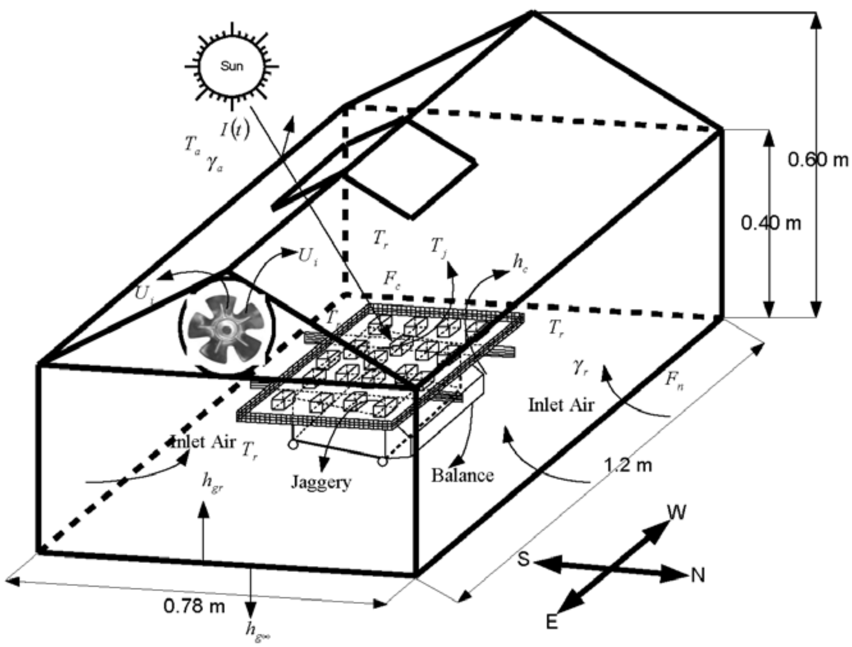

Fig. 1: Working principle of greenhouse jaggery drying under forced convection mode

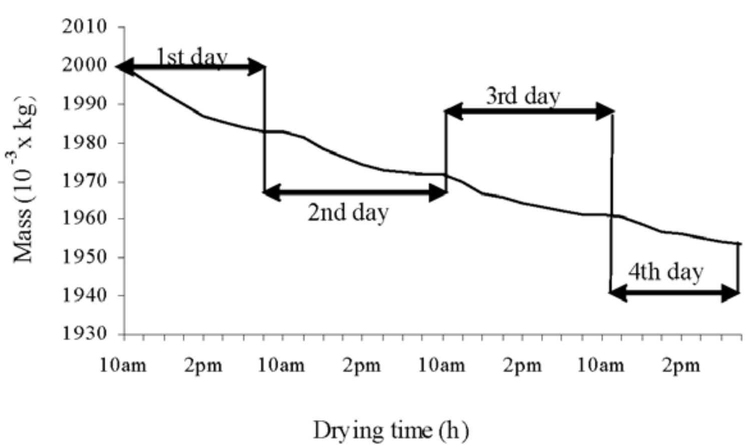

Fig. 2: Greenhouse drying curve for jaggery under forced convection mode

and height of the walls as 0.60 and 0.40 m, respectively, was made of PVC pipe and UV film covering. For forced convection, a fan was provided on the east wall. The data of the experimental observations for the forced convection greenhouse drying for 2.0 kg of jaggery is presented in Table 1. With the help of the experimental observations, the drying behavior of the jaggery for complete drying is as shown in Fig. 2.

Thermal Modeling

Energy Balance

The energy balance equations for the forced mode of drying have been written with the following assumptions:

- Heat capacity of cover and wall material is neglected,
- No stratification in greenhouse air temperature,
- Absorptivity of air is negligible,

(a) Energy balance equation at jaggery surface,

$$(1-F_n)F_j\alpha_j\sum I_i A_i \tau_i = M_j C_j \frac{dT_j}{dt} + h_c(T_j - T_r)A_j + 0.016h_c\left[P(T_j) - \gamma_r P(T_r)\right]A_j \quad (1)$$

(b) Energy balance equation at ground surface

$$(1-F_n)(1-F_j)\alpha_g\sum I_i A_i \tau_i = h_{g\infty}\left(T|_{x=0} - T_\infty\right)A_g + h_{gr}\left(T|_{x=0} - T_r\right)\left(A_g - A_j\right) \quad (2)$$

(c) Energy balance equation at greenhouse chamber

$$\begin{aligned}&(1-F_n)(1-F_j)(1-\alpha_g)\sum I_i A_i \tau_i + h_c(T_j - T_r)A_j + 0.016h_c\left[P(T_j) - \gamma_r P(T_r)\right]A_j \\ &+ h_{gr}\left(T|_{x=0} - T_r\right)\left(A_g - A_j\right) = 0.33NV(T_r - T_a) + \sum U_i A_i (T_r - T_a)\end{aligned} \quad (3)$$

Solution of Thermal Model

To simplify the above equations, the vapor pressure has been linearised for the small range of temperature between 25 and 55°C, which mostly occurs in solar drying, as

$$P(T) = R_1 T + R_2 \quad (4)$$

The linear regression analysis has been used to calculate the vapor pressure at T_r and T_a. With the help of Eq. 2 and 4, Eq. 3 has been simplified to determine the greenhouse room temperature (T_r) for initial values of jaggery temperature and ambient temperature as

$$AT_r = BT_j + CT_a + D \quad (5)$$

where

$$A = \left[h_c A_j + 0.016h_c A_j \gamma_r R_1 + (UA)_{g\infty} + 0.033NV + \sum U_i A_i\right]$$

$$B = h_c A_j + 0.016h_c A_j R_1$$

$$C = \left[(UA)_{g\infty} + \sum U_i A_i + 0.33NV\right]$$

$$D = \left[I_{effR} + I_{effG} H_G + 0.016h_c A_j R_2 (1-\gamma_r)\right]$$

Using the known value of room air temperature (T_r) in Eq. (1), the jaggery temperature (T_j) can be determined from the first order differential equation

$$\frac{dT_j}{dt} + aT_j = f(t) \tag{6}$$

The solution of Eq. 6 for the average $\overline{f(t)}$ for the time 0-t is

$$T_j = \frac{\overline{f(t)}}{a}(1 - e^{-at}) + T_{jo}e^{-at} \tag{7}$$

where,

$$a = \frac{h_j A_j (1 + 0.016R_1)}{M_j C_j}$$

and

$$f(t) = \frac{I_{eff\,j} + h_c A_j \left[T_r - 0.016\{R_2 - \gamma_r(R_1 T_r + R_2)\}\right]}{M_j C_j}$$

Once the temperatures of the jaggery and greenhouse air are known, the moisture evaporation can be evaluated with the expression

$$m_{ev} = 0.016\frac{h_c}{\lambda}\left[\left(R_1 T_j + R_2\right) - \gamma_r\left(R_1 T_r + R_2\right)\right]A_j t \tag{8}$$

Input Values and Computational Procedure

The average hourly total radiation received by the greenhouse, which is the sum of the average hourly radiations of the walls and roofs of the greenhouse was evaluated with the help of Liu and Jordan (1962) formula. Thus, the average hourly total radiation received by the greenhouse and the average hourly ambient air temperature was used as input data to compute the hourly jaggery and greenhouse air temperature and rate of moisture evaporation (jaggery mass during drying). The other design parameters for computation have been given in Table 2. The convective heat transfer coefficient has been calculated for the drying of jaggery by using experimental data given in Table 1 (Tiwari *et al*., 2004; Kumar and Tiwari, 2006).

As the convective heat transfer calculated by the above method varies linearly, hence the linear curve fitting has been used to represent the convective heat transfer as a function of drying time given by the expression

$$h_c = a_1 T + b_1 \tag{9}$$

The coefficient of the linear expression for the forced convection drying for jaggery is presented in Table 2 for all four days of drying. The input values and the constants used in the modeling of jaggery drying are given in Table 3.

The proximity of predicted and experimental values has been presented in terms of coefficient of correlation (R) and root mean square of percent deviation (E) for jaggery temperature, greenhouse air temperature and mass of jaggery during drying.

Table 1: Experimental observation for greenhouse jaggery drying under forced mode during March 1-4, 2004

Day drying	Time	I(t) ($W\ m^{-2}$)	I(d) ($W\ m^{-2}$)	T_a (°C)	T_j (°C)	T_r (°C)	M_j $\times 10^{-3}$ kg	γ_r (%)	γ_a (%)
1st	10 am	480	60	22	26.7	28.1	2000.0	37.8	37.0
	11 am	620	60	25	39.9	37.2	1996.6	34.9	37.1
	12 Noon	720	80	26	43.8	40.5	1992.9	32.7	32.4
	1 pm	700	80	27	45.9	43.3	1990.1	29.7	29.5
	2 pm	640	60	30	47.5	45.8	1987.1	32.1	32.2
	3 pm	500	60	29	49.3	45.7	1985.5	31.2	31.1
	4 pm	340	40	28	42.4	40.9	1984.0	31.5	31.5
	5 pm	100	20	27	42.2	40.2	1982.9	32.3	32.2
2nd	10 am	520	80	21	27.1	29.0	1982.9	40.2	40.3
	11 am	660	80	24	39.6	38.0	1981.1	36.1	36.2
	12 Noon	760	80	26	45.4	43.3	1978.5	30.7	30.6
	1 pm	700	80	28	47.3	46.5	1976.3	30.2	30.7
	2 pm	680	80	29	48.1	47.1	1974.4	27.8	27.4
	3 pm	520	60	28	44.7	42.1	1973.0	28.7	28.6
	4 pm	340	40	27	42.8	38.2	1972.1	28.0	28.0
	5 pm	100	20	26	41.7	33.7	1971.6	31.5	31.4
3rd	10 am	520	80	22	30.7	32.3	1971.6	38.0	37.4
	11 am	620	80	24	43.2	38.9	1970.0	34.9	34.4
	12 Noon	720	80	26	48.6	41.8	1966.7	31.7	31.3
	1 pm	680	80	28	50.7	43.9	1965.6	29.7	29.8
	2 pm	660	80	31	52.6	47.3	1964.4	28.8	28.8
	3 pm	480	80	29	54.1	48.4	1963.3	31.4	31.5
	4 pm	360	60	28	46.1	39.5	1962.2	27.9	27.9
	5 pm	100	20	28	39.8	37.4	1961.3	33.2	33.2
4th	10 am	550	80	22	31.4	35.1	1961.3	41.3	41.7
	11 am	620	80	25	43.4	44.9	1960.7	36.9	36.7
	12 Noon	740	80	27	52.2	46.6	1958.6	32.3	32.5
	1 pm	780	100	29	52.6	47.6	1956.7	31.4	31.1
	2 pm	640	100	31	52.8	47.5	1956.1	29.1	29.9
	3 pm	480	80	31	53.8	46.2	1955.4	28.2	28.5
	4 pm	360	60	30	51.0	43.8	1954.3	29.4	29.4
	5 pm	100	20	30	47.0	40.8	1953.4	30.2	30.3

Results and Discussion

The greenhouse air temperature (T_r) has been calculated for the initial values of jaggery and ambient parameters (Table 1) with the help of Eq. 5. Then this calculated value of T_r was used to calculate the jaggery temperature (T_j) and the moisture evaporated with the help of Eq. 7 and 8 respectively. These values were further used to compute the next set of values and so on. The experimental and theoretical jaggery and greenhouse air temperatures have been plotted against the hourly drying time for four consecutive days of drying (Fig. 3). From Fig. 3 it is observed that the experimental values are in good agreement with the theoretical results. The coefficient of correlation and square root of percent deviation are also presented in the same figures. Figure 4 presents the hourly variation of experimental and theoretical hourly drying mass of jaggery for the four consecutive days with the coefficient of correlation and the square root of percent deviation in the range of 0.96-0.98 and 6.75-12.63%, respectively. Figure 4 shows that the hourly drying mass of jaggery decreases with the increase of the drying days.

Figure 5 shows the effect of number of air changes per hour on jaggery and greenhouse air temperature and the hourly drying mass of jaggery. The number of air changes/hour has been increased theoretically from 60-110 by keeping the other parameters same. It has been observed that the number of air changes/h has a significant effect on the jaggery as well as greenhouse air temperature while it

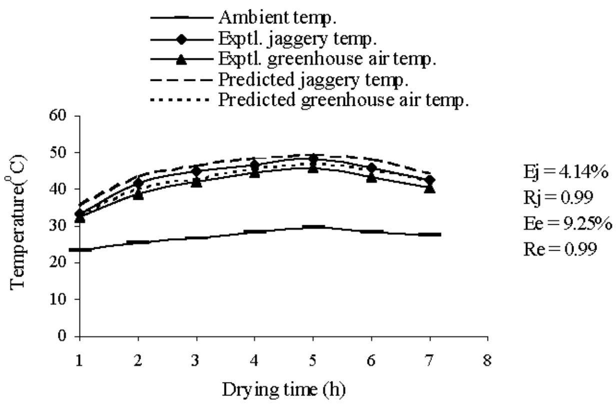

Fig. 3a: Jaggery and greenhouse air temperature under forced convection greenhouse drying for 1st day

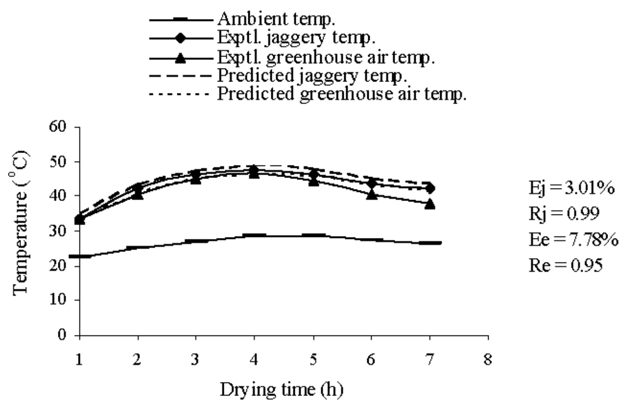

Fig. 3b: Jaggery and greenhouse air temperature under forced convection greenhouse drying for 2nd day

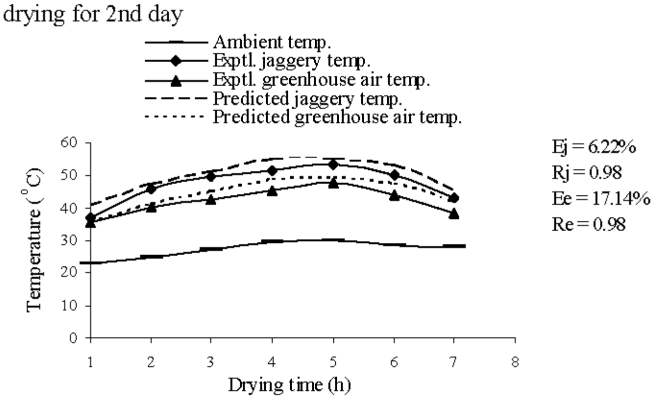

Fig. 3c: Jaggery and greenhouse air temperature under forced convection greenhouse drying for 3rd day

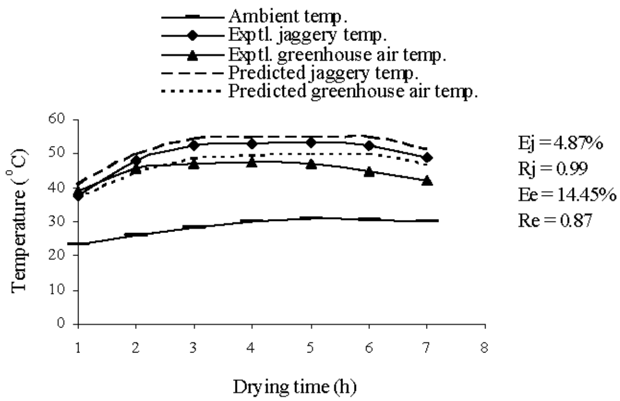

Fig. 3d: Jaggery and greenhouse air temperature under forced convection greenhouse drying for 4th day

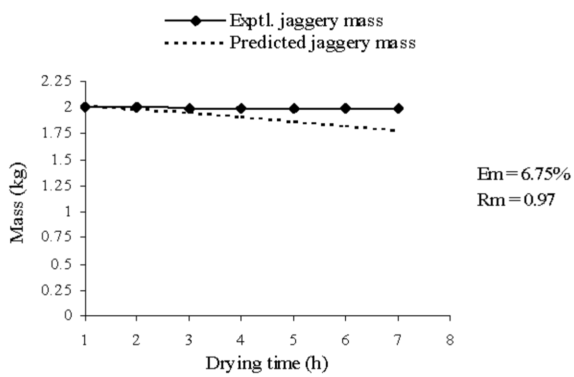

Fig. 4a: Experimental and predicted jaggery mass under forced convection greenhouse drying for 1st day

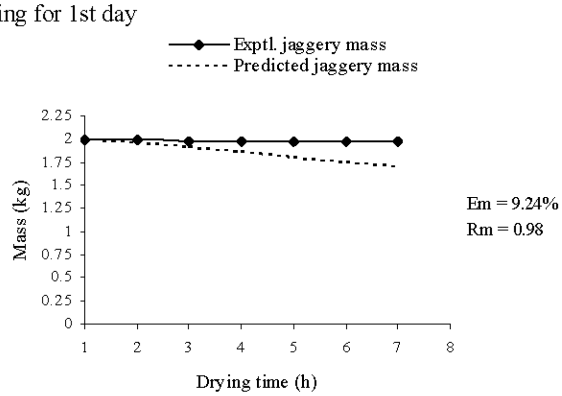

Fig. 4b: Experimental and predicted jaggery mass under forced convection greenhouse drying for 2nd day

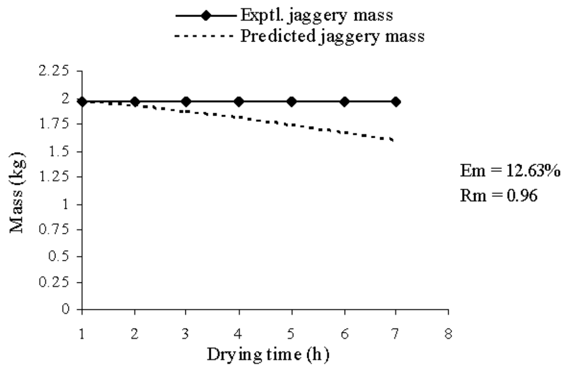

Fig. 4c: Experimental and predicted jaggery mass under forced convection greenhouse drying for 3rd day

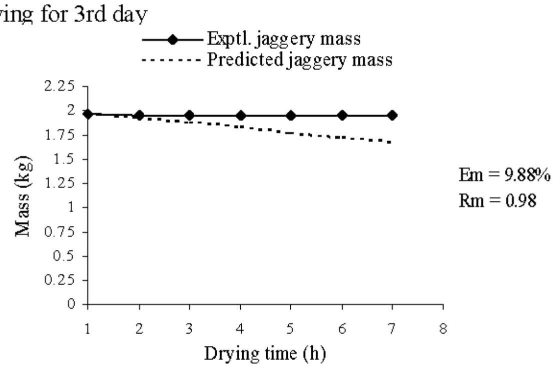

Fig. 4d: Experimental and predicted jaggery mass under forced convection greenhouse drying for 4th day

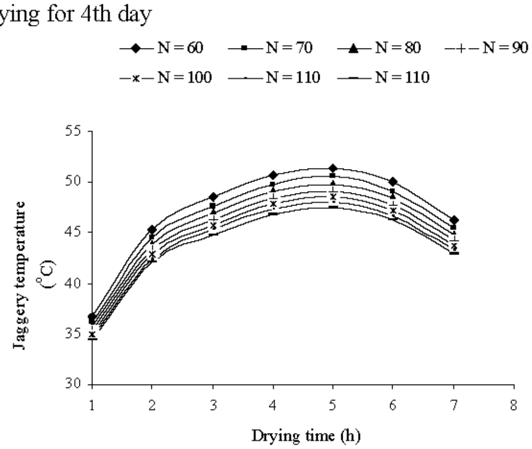

Fig. 5a: Variation in jaggery temperature with number of air exchange per hour

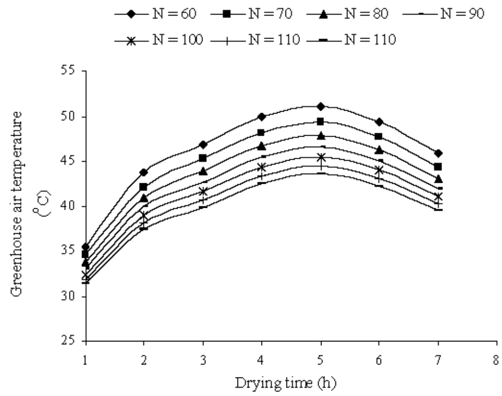

Fig. 5b: Variation in greenhouse air temperature with number of air exchange per hour

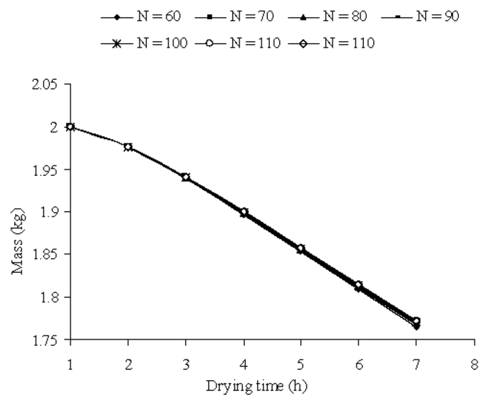

Fig. 5c: Variation in mass of jaggery with number of air exchange per hour

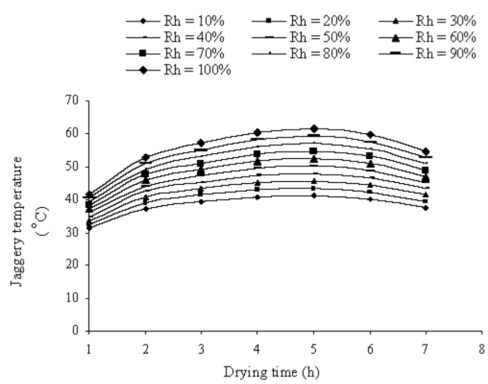

Fig. 6a: Variation in jaggery temperature with relative humidity

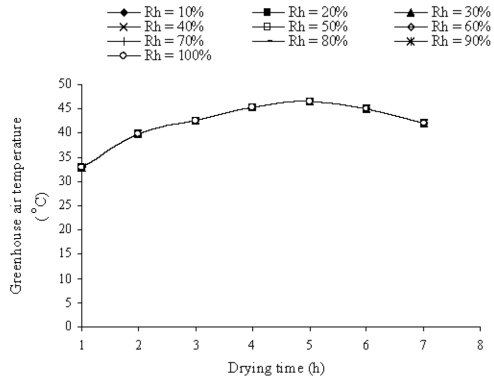

Fig. 6b: Variation in greenhouse air temperature with relative humidity

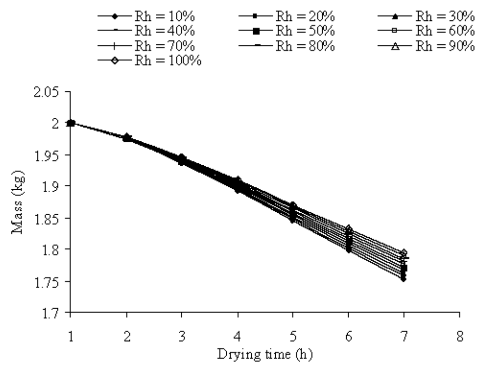

Fig. 6c: Variation in mass of jaggery with relative humidity

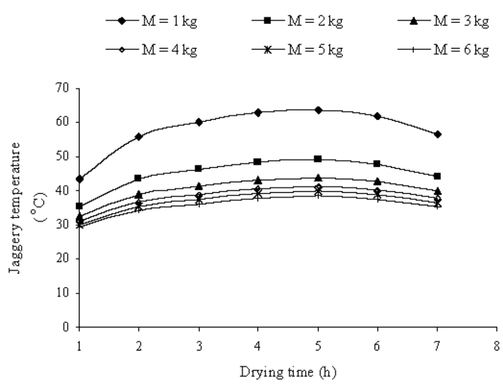

Fig. 7a: Variation in jaggery temperature with mass of jaggery

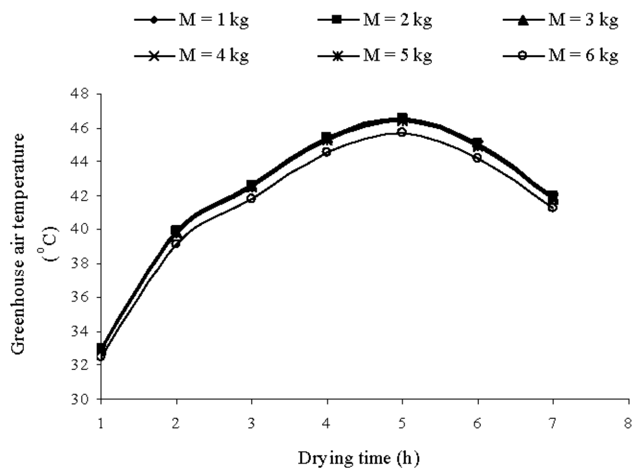

Fig. 7b: Variation in greenhouse air temperature with mass of jaggery

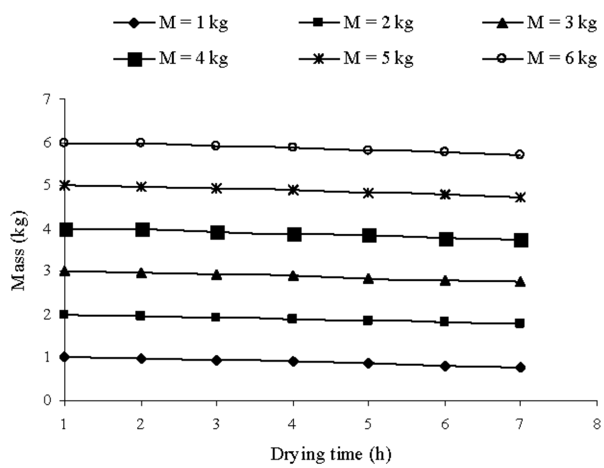

Fig. 7c: Variation in drying rate of jaggery with mass of jaggery

Table 2: Coefficients of linear expression for convective heat transfer coefficient

Day	a_1	b_1
1st	0.0033	0.83
2nd	0.00084	1.3
3rd	0.0024	1.8
4th	0.002	2.7

Table 3: Constant used in modeling of greenhouse jaggery drying

Parameters	Values
C_a	1012 J/kg °C
C_j	2509.9 J/kg °C
F_c	0.10
g	9.81 m/s^2
h_{gr}	8.0 W/m^2 °C
t	3600 s
R_1	397.52
R_2	-7926.90
λ	2.26×10^6 J/kg
σ	5.67×10^{-8} W/m^2 K^4
N	90 rpm
α_g	0.7
α_c	0.6
ε	0.9
τ	0.9

shows a marginal effect on the hourly drying mass of jaggery. The jaggery and greenhouse temperature decreases with increase in the number of air changes/ h due to more withdrawal of greenhouse air, as expected.

The increase in relative humidity increases the jaggery temperature due to lower mass transfer from jaggery but it does not affect the greenhouse air temperature (Fig. 6). The hourly moisture evaporation from the jaggery decreases with increase in relative humidity due to strong hygroscopic nature of jaggery.

The jaggery temperature decreases with the increase of jaggery mass due to the same thermal energy trapped by the greenhouse distributed in more jaggery pieces while it doesn't affect the greenhouse air temperature (Fig. 7). On the other hand moisture removal from the jaggery increases with the increase in mass of jaggery but drying nature remains same due to low moisture content of jaggery.

Conclusions

On the basis of results obtained during study following conclusions are drawn:

- The thermal model developed in this paper is validated with the experimental observations for the drying of jaggery under forced convection mode.
- Number of air changes per hour, relative humidity and jaggery mass (surface area of jaggery) are the effective parameters in greenhouse jaggery drying.
- The present thermal model can be used to develop the design of a greenhouse dryer for the given constants of jaggery and climatic parameters.

In future research, it would be useful, if the model is applied to different shape of greenhouse and different locations. Present study gives a useful idea for designing of economically optimized forced convection greenhouse dryer.

Nomenclature

A Area (m^2), coefficients in Eq. 5
a Derivative of Eq. 6, coefficient of Eq. 9
B Coefficients in Eq. 5
C Specific heat (J kg^{-1} °C^{-1}), coefficient of Eq. 5

D	Coefficient of Eq. 5
E	Root mean square of percent deviation
F	Fraction of solar radiation
f(t)	Time dependent derivative of Eq. 6
h	Total heat transfer coefficient ($Wm^{-2}\ °C^{-1}$)
h_c	Convective heat transfer coefficient of crop ($Wm^{-2}\ °C^{-1}$)
h_{ca}	Convective heat transfer coefficient of air ($Wm^{-2}\ °C^{-1}$)
h_r	Radiative heat transfer coefficient ($Wm^{-2}\ °C^{-1}$)
I(t)	Solar intensity on horizontal surface (Wm^{-2})
I_i	Solar intensity on greenhouse wall/roof i (Wm^{-2})
M	Mass (kg)
N	Number of air changes per hour
m_{ev}	Moisture evaporated (kg)
P(T)	Vapour pressure at temperature T (Nm^{-2})
R	Coefficient of Eq. 4 for linear expression of partial pressure and coefficient of correlation
Rh	Relative humidity
t	Time (s)
T	Temperature (°C)
U	Overall heat loss (Wm^{-2} °C)
V	Volume of greenhouse (m^3)
v	Velocity of air

Greek Letters

α	Absoptivity of crop surface
β	Coefficient of volumetric expansion ($°C^{-1}$)
γ	Relative humidity of air (%)
ε	Emissivity
σ	Stefan-Boltzmann Constant = 5.6696×10^{-8} ($Wm^{-2}K^{-4}$)
λ	Latent heat of vaporization ($J\ kg^{-1}$)
μ	Dynamic viscosity of air ($kg\ m^{-1}$)
ñ	Density of air ($kg\ m^{-3}$)
τ	Transmissivity

Subscripts

0	Initial value
a	Ambient or air
c	crop
e	Green house air
j	Jaggery
g	Ground or greenhouse floor
i	Greenhouse wall/roof (i = 1,2,...,6)
m	mass
n	North wall
r	Greenhouse room air
v	Humid air or vent
ce	Jaggery to environment
gr	Greenhouse floor to room
$g\infty$	Greenhouse floor to underground
$\vert_{x=0}$	Surface of floor of greenhouse

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