Desalination and Water Treatment
www.deswater.com
24 (2010) 38–46
December

doi: 10.5004/dwt.2010.1152

Kinetics of convective heat and mass transfer coefficient of green chilli during open-sun and greenhouse drying

Dilip Jain*, D. Mridula, R.T. Patil, P. Barnwal, Ramesh Kumar

Central Institute of Post Harvest Engineering and Technology, PAU Campus, Ludhiana 141 004, India
Tel. +911612308155, +919478227725; Fax. +911612302370; email: jaindilip25@rediffmail.com, jaindilip25@sify.com

Received 23 February 2009; accepted 30 May 2010

ABSTRACT

The convective heat and mass transfer coefficient of green chilli has been investigated during open-sun (natural convection) and greenhouse (forced convection) drying. Experiments on solar drying of green chilli have been conducted after blanching in sodium hydroxide and sodium chloride solutions. The hourly data were recorded for moisture evaporation, temperature of green chilli and relative humidity of surrounding moist air. Heat transfer analysis is mainly dependent on rate of moisture evaporation and temperature of chilli has been performed during drying process. The average convective heat transfer coefficients evaluated for green chilli blanched in sodium hydroxide and sodium chloride solutions were 3.9499 and 2.448 W m^{-2} K^{-1}, respectively during open sun drying; and 4.333 and 4.520 W m^{-2} K^{-1}, respectively, during greenhouse drying. The convective heat and mass transfer coefficient during drying has been analyzed as the function of moisture content of green chilli and drying time. The logarithmic model has been developed to predict the convictive heat and mass transfer coefficient with moisture content.

Keywords: Open sun drying; Greenhouse drying; Convective heat and mass transfer coefficient; Green chilli

1. Introduction

Chilli (capsicum) is one of the major spices and extensively cultivated throughout the tropical Asia and equatorial America for their edible pungent fruits. India produces 11,85,500 tonnes of chilli from 7,37,500 hectare of land, and also exports of 81,500 tonnes [1]. The consumption of chilli is also very high in India.

The time and stage of harvesting of chilli is governed by the purpose for which it is being used. The fruits are harvested when they are fully developed at green and the red ripe stage. The different stage of ripeness also contributes to variation in color and pungency level of fruit. The green chilli has more Vitamin C and antioxidant properties and finds a different place for preparation of Indian recipes. Therefore the solar drying of green chilli has been studied for powder making.

Drying is a complex process of heat and mass transfer. The removal of moisture takes place due to difference in vapor pressure of the product and surrounding. The desired vapor pressure difference might be induced by applying heat energy to increase the temperature of the product and to vaporize the moisture present in the product through provision of latent heat of vaporization. These parameters may be employed under the controlled conditions of drying

*Corresponding author

for desirable drying rate, which is likely to be uncontrolled with the solar drying, since it is weather dependent process.

The thermal behavior of solar drying has been simulated by several investigators [2,3]. The convective heat transfer coefficient is an important parameter in drying rate simulation since the temperature difference between the air and product varies with this coefficient. Jain and Tiwari have evaluated the convective heat transfer coefficient for some crops and developed a mathematical model for predicting the drying parameters [3]. In another investigation, Jain and Tiwari have studied the dependence of convective heat transfer coefficient on the drying time during complete sun drying [4]. The convective heat transfer coefficient of jaggery under sun drying has been evaluated by Tiwari et al. [5]. The convective heat and mass transfer coefficient of fish has been determined under open sun drying (OSD) by Jain [6]. Recently, the convective heat and mass transfer has been evaluated for kiwi fruit during drying in the mechanical dryer by Kaya et al. [7].

The present studies were undertaken to investigate the kinetics of the convective heat and mass transfer coefficients of the green chilli with different treatments of blanching under the open sun (OSD, natural convection) and greenhouse drying (GHD, forced convection).

2. Theoretical consideration

2.1. Determination of convective heat transfer coefficient

The convective heat transfer coefficient is the most important parameter govern the drying and useful for designing the drying equipment. Therefore, it has been evaluated with the following theoretical consideration.

The Nusselt number (Nu) for natural convection is a function of Grashof (Gr) and Prandtl (Pr) numbers. Similarly, it is a function of the Reynolds and Prandtl numbers for forced convection. A single equation correlates both the laminar and turbulent regimes well [8]

$$\frac{h_c L}{K_v} = Nu = C(Gr.Pr)^n \quad \text{for natural convection} \tag{1a}$$

$$= C(Re.Pr)^n \quad \text{for forced convection} \tag{1b}$$

Thus, the convective heat transfer coefficient can be expressed as

$$h_c = \frac{K_v}{L} C(GrPr)^n \tag{2}$$

The rate of heat utilized (Q_e) to evaporate moisture is given as [9–12]

$$Q_e = 0.016 h_c [P(T_c) - \gamma P(T_e)] \tag{3}$$

The value 0.016 has unit of h_e/h_c, which comes to be kg^{-1} m s^2 K or $[Nm^{-2}\ K^{-1}]^{-1}$.

By substituting h_c from Eq. (2) into Eq. (3) yield

$$Q_e = 0.016 \frac{K_v}{L} C(Gr\,Pr)^n [P(T_c) - \gamma P(T_e)]. \tag{4}$$

The moisture evaporation can be determined by latent heat of vaporization (λ); and multiplying the area of the green chilli in tray (A_t) and time interval (t).

$$m_{ev} = \frac{Q_e}{\lambda} A_t t. \tag{5}$$

Hence

$$m_{ev} = 0.016 \frac{K_v}{L\lambda} C(Gr\,Pr)^n [P(T_c) - \gamma P(T_e)] A_t t. \tag{6}$$

Considering function

$$Z = 0.016 \frac{K_v}{L\lambda} [P(T_c) - \gamma P(T_e)] t A_t,$$

then

$$\frac{m_{ev}}{Z} = C(Gr\,Pr)^n. \tag{7}$$

Eq. (7) can be expressed in the linear form ($Y = mX + C$) by taking logarithm as

$$\ln\left[\frac{m_{ev}}{Z}\right] = n \ln(Gr\,Pr) + \ln C, \tag{8}$$

where $Y = \ln\left[\frac{m_{ev}}{Z}\right], m = n, X = \ln[GrPr]$ (natural convection) or $X = \ln[RePr]$ (forced convection) and $C_0 = \ln C$. Thus, $C = e^{C_0}$

Therefore with the help of observations on moisture evaporation, temperature of green chilli surface, temperature and relative humidity of surrounding moist air in the specific time, the linear regression analysis of Eq. (8) can be performed. Once, the values of C and n are known, the convective heat transfer coefficient is computed by Eq. (2).

2.2. Physical properties of the moist air

The physical properties of air, such as specific heat (C_v), thermal conductivity (K_v), density (ρ_v) and dynamic viscosity (μ_v) and the partial vapor pressure (P) were calculated with the following expressions [3]. For obtaining the physical properties of humid air, T_i is taken as an average temperature of the hourly mean temperatures of chilli ($\overline{T_c}$) and moist air above the chilli surface ($\overline{T_e}$)

$$C_v = 999.2 + 0.1434T_i + 1.101 \times 10^{-4}T_i^2 - 6.7581 \times 10^{-8}T_i^3, \quad (9)$$

$$K_v = 0.0244 + 0.6773 \times 10^{-4}T_i, \quad (10)$$

$$\rho_v = \frac{353.44}{T_i + 273.15}, \quad (11)$$

$$\mu_v = 1.718 \times 10^{-5} + 4.620 \times 10^{-8}T_i, \quad (12)$$

$$P(T) = \exp\left[25.317 - \frac{5144}{T_i + 273.15}\right], \quad (13)$$

2.3. Determination of dependency of convective heat transfer coefficient on mean moisture content

The exponential depletion of moisture content in thin layer drying can simply be defined in the form of Henderson and Pabis as [13]

$$X_d = a_m \exp(-k_m t). \quad (14)$$

The similar exponential expression can be obtained for convective heat transfer coefficient as

$$h_c = a_c \exp(-k_c t). \quad (15)$$

By simplifying Eqs (14) and (15) with elimination of the time 't', the convective heat transfer coefficient can be expressed as the function of mean moisture content and coefficient of drying equation as

$$h_{c,\text{pre}} = \exp\left[(\ln X_d - \ln a_m)\frac{k_c}{k_m} + \ln a_c\right]. \quad (16)$$

Thus, Eq. (16) is an empirical model for prediction of convective heat and mass transfer coefficient.

3. Materials and methods

3.1. Experimental set up

The wire mesh trays of 0.40 x 0.35 m^2 were used to accommodate samples of around 0.8 kg chilli in thin layer. An experimental greenhouse of even span roof with an effective floor covering 1.5 x 1.0 m^2 has been made of PVC pipe and covering of UV film. The central and walls heights were 0.60 and 0.40 m, respectively. A fan of 225 mm sweep diameter with air velocity 5 m s^{-1} was provided on the sidewall of the greenhouse during the experiments of forced convection (Fig. 1).

Fig.1. Experimental greenhouse for drying the green chilli.

3.2. Instrumentation

A digital humidity/temperature meter (model Lutron HT-3003) was used to measure the relative humidity and temperature of ambient air in the greenhouse and above the chilli surface. An infrared non-contact thermometer (Raytek-MT4), having a least count of 0.5°C and accuracy of $\pm 2\%$ on a full-scale range of –18 to 260°C was used for measuring the temperature of chilli. It had a least count of 0.1% relative humidity with accuracy of $\pm 3\%$ on the full scale range of 5–99.9% of relative humidity and 0.1°C temperature with accuracy of $\pm 1\%$ on the full scale range of 10–80°C. A digital balance of 1 kg weighing capacity, having a least count of 0.1 g with $\pm 2\%$ on the full scale was used to weigh the sample during drying. The difference in weight gave the moisture evaporated during the time interval. The air velocity across the greenhouse section during the forced mode drying was measured with an electronic digital vane type anemometer (Mini Thermo-Anemometer make Extech instruments, model 45158). It had a least count of 0.1 m s^{-1} with $\pm 2\%$ on the full scale range of 0.2–28.0 m s^{-1}.

3.3. Processing of chilli

Fresh green chilli were procured from local vegetable market of Ludhiana. The healthy fresh chilli were selected, destalked and washed manually. The blanching of chilli was done in standardized NaOH solution for preservation of the green color in product. NaCl solution was used during blanching of green chilli for getting the clear (removing the greenness) product. The surface water was completely removed after blanching of chilli. The blanched chilli was kept half an hour for conditioning before starting the drying experiments. The samples thus prepared were measured for initial moisture content. The initial moisture contents were 11.25 and 8.30 kg [H_2O]/kg [DM] for the blanched green chilli in the NaOH and NaCl solution, respectively. Therefore, to arrange the thin layer for drying in 0.40 x 0.35 m^2 of tray, the samples were around 0.808 and 0.678 kg of blanched green chilli in NaOH and NaCl solutions, respectively.

3.4. Experimentation of drying

Experiments were conducted in the month of June between 9:00 and 16:00 hours under the climatic conditions of Ludhiana, India (Latitude 30°45N; Longitude 75°48′E). The solar radiation ranged during these hours between 470 and 920 W m^{-1}. All the experiments of GHD have been conducted simultaneously with the OSD. Experiments in the forced mode under GHD were conducted by providing the ventilating fan on the sidewall of the greenhouse. The observations were taken from 9:00 to 16:00 hours at every hour interval for three days of solar drying. The air velocity across the greenhouse was measured as 0.9 m s^{-1} with the help of the anemometer.

3.5. Computational techniques

Temperature of crop (green chilli) was hourly measured with the IR thermometer. Temperature and relative humidity above the crop surface were hourly measured with a digital humidity/temperature meter. Then the hourly temperature and relatively humidity were calculated which is used for evaluation of physical properties of moist air. The hourly convective heat transfer coefficient has been computed based on theory outlined in Section 2. The average surface temperature ($\overline{T_c}$) of green chilli and temperature ($\overline{T_e}$) above the chilli surface were calculated at each hour interval for corresponding moisture evaporated. The physical properties of humid air were evaluated for the mean temperature of $\overline{T_c}$ and $\overline{T_e}$ by using the expressions given in Eqs. (9) to (13). These physical properties were utilized for calculating the Grashof (*Gr*), Prandtl (*Pr*) and Reynolds (*Re*) numbers. The values of C and n in Eq. (2) were obtained by linear regression technique, expressed in Eq. (8) at the increment of every hour of observation. The mean values of h_c were computed at the corresponding hour of drying. The hourly convective heat transfer coefficient and mean moisture content were exponentially correlated individually with drying time. Thus, the coefficients of drying [Eq. (14)] and convective heat and mass transfer coefficient [Eq. (15)] were obtained. Now, the convective heat transfer coefficient can be predicted with the help of Eq. (16) for the given process based on the mean moisture content. The computer program was prepared in the Matlab software 6.1.

4. Results and discussion

Temperature and relative humidity are the main governing parameters in natural convective drying. Whereas, the air velocity is also significant in forced convective drying. The drying was conducted for three days during 9:00 to 16:00 hours (7 h). The hourly drying conditions (mean temperature, mean relative humidity, moisture evaporation), heat transfer parameters (Grashof, Reynolds and Prandtl numbers), coefficients C and n, and convective heat and mass transfer coefficient for OSD and GHD of green chilli after blanching in NaOH and NaCl solutions are compiled in Tables 1–4. It may be noticed that there is no certain trend in variation in temperature and relative humidity. However, the higher product temperature and low relative humidity can be observed at the end of drying, which is obvious at low moisture content of product. The moisture evaporations in the GHD were observed higher than the OSD for both the samples. This resulted the faster drying in greenhouse. The lower moisture contents were obtained in GHD as 0.245 and 0.092 kg [H_2O]/kg [DM] of green chilli blanched in NaOH and NaCl solutions, respectively. Whereas for the same duration under OSD, the moisture contents of green chilli were 0.342 and 0.198 kg [H_2O]/kg [DM] blanched in NaOH and NaCl solutions, respectively. The maximum value of Grashof and Reynolds number were computed as 4.125×10^6 and 5.244×10^3 under natural and forced convective drying. The product of Grashof and Prandtl numbers ($Gr{\cdot}Pr \leq 10^7$) under natural convection and Reynolds and Prandtl numbers ($Re{\cdot}Pr \leq 10^5$) under forced convection describe that the entire dryings fall within laminar flow regime [4,14].

The convective heat and mass transfer coefficients were decreasing with decrease in moisture content in the green chilli and increase in drying time for both the drying methods. The convective heat and mass transfer coefficients were observed higher in the GHD over the OSD for both of the blanched green chilli samples. The maximum and minimum convective heat and mass transfer coefficients were 7.967 and 1.269 W m^{-2} K^{-1} in the GHD and OSD of NaCl blanched green chilli. However, the average convective heat transfer coefficient under GHD and OSD were computed as 3.95 and 4.33 W m^{-2} K^{-1}, respectively, of green chilli blanched in NaOH solution; and 2.448 and 4.520 W m^{-2} K^{-1}, respectively of green chilli blanched in NaCl solution.

The moisture content of drying has been established as the function of drying time. The standard Henderson and Pabis model appropriately represents the

Table 1
Hourly observations and heat transfer coefficients of green chilli blanched with NaOH solution and open sun drying (Initial weight, 0.8085 kg; initial X_d, 11.25 kg [H_2O]/kg [DM]; final X_d, 0.3424 [H_2O]/kg [DM]; mean h_c, 3.9499 W m^{-2} K^{-1})

Day	Drying time, h	$\overline{T_c}$ (°C)	$\overline{T_e}$ (°C)	$\overline{Y}$	m_{ev} (x10^{-3}, kg)	X_d, (kg[H_2O] /kg[DM])	Gr (x10^6)	***Pr***	C	n	h_c (W m^{-2} K^{-1})
1st	1	38.00	42.25	0.465	60.5	10.791	2.968	0.7055	1.000	0.214	6.550
	2	41.40	45.10	0.475	67.2	9.824	2.315	0.7057	0.999	0.212	6.267
	3	44.35	48.85	0.457	66.7	8.809	2.517	0.7059	0.999	0.207	5.851
	4	44.10	51.80	0.402	54.9	7.888	4.125	0.7060	1.008	0.200	5.451
	5	41.75	46.90	0.377	52.1	7.078	3.106	0.7057	1.009	0.195	5.074
	6	39.25	39.05	0.381	47.8	6.321	0.144	0.7054	1.038	0.194	4.794
	7	35.10	35.60	0.355	46.6	5.606	0.418	0.7052	1.049	0.195	4.674
2nd	8	34.15	37.60	0.305	45.7	4.906	2.827	0.7053	1.058	0.192	4.583
	9	38.35	41.75	0.276	43.5	4.231	2.381	0.7055	1.068	0.187	4.346
	10	40.05	45.05	0.288	40.1	3.597	3.204	0.7056	1.092	0.181	4.118
	11	38.40	43.15	0.309	28.2	3.072	3.240	0.7055	1.120	0.174	3.857
	12	39.50	44.45	0.318	26.4	2.651	3.236	0.7056	1.147	0.167	3.624
	13	44.65	51.75	0.324	25.2	2.260	3.773	0.7060	1.189	0.159	3.375
	14	44.10	48.65	0.327	24.2	1.886	2.564	0.7059	1.200	0.154	3.159
3rd	15	40.25	43.40	0.348	23.7	1.523	2.070	0.7056	1.197	0.151	3.021
	16	37.75	39.50	0.350	18.7	1.202	1.291	0.7054	1.170	0.149	2.883
	17	37.95	39.30	0.333	13.0	0.962	0.996	0.7054	1.114	0.149	2.704
	18	44.00	46.00	0.302	11.7	0.775	1.179	0.7058	1.059	0.147	2.490
	19	49.30	50.60	0.232	10.5	0.606	0.654	0.7061	0.934	0.150	2.264
	20	51.55	52.00	0.178	8.5	0.462	0.214	0.7062	0.716	0.163	2.057
	21	51.65	53.00	0.175	3.7	0.370	0.632	0.7062	0.599	0.167	1.801

Table 2
Hourly observations and heat transfer coefficients of green chilli blanched with NaOH solution and greenhouse drying (Initial weight, 0.8099 kg; initial X_d, 11.25 kg [H_2O]/ kg [DM]; final X_d, 0.2449 [H_2O]/kg [DM]; mean h_c, 4.333 W m^{-2} K^{-1})

Day	Drying time, h	$\overline{T_c}$ (°C)	$\overline{T_e}$ (°C)	$\overline{Y}$	m_{ev} (x10^{-3}, kg)	X_d, (kg[H_2O]/ kg[DM])	Gr (x10^6)	***Pr***	C	n	h_c (W m^{-2} K^{-1})
1st	1	38.35	41.15	0.487	76.9	10.669	5.100	0.7055	1.000	0.403	7.866
	2	41.40	47.00	0.471	62.5	9.615	4.975	0.7057	0.999	0.399	7.072
	3	43.90	47.75	0.462	64.5	8.654	4.930	0.7058	0.999	0.375	6.260
	4	43.05	50.30	0.436	58.2	7.726	4.907	0.7059	0.998	0.371	6.050
	5	40.25	48.45	0.407	46.7	6.933	4.971	0.7057	0.998	0.366	5.810
	6	37.75	41.55	0.345	45.1	6.238	5.103	0.7055	1.000	0.356	5.359
	7	34.15	36.65	0.295	43.4	5.569	5.227	0.7052	1.002	0.349	5.073
2nd	8	33.90	38.15	0.298	42.7	4.918	5.209	0.7053	1.003	0.344	4.902
	9	37.50	42.35	0.327	39.7	4.295	5.095	0.7055	1.003	0.339	4.675
	10	39.70	45.30	0.312	38.3	3.705	5.022	0.7056	1.003	0.332	4.429
	11	38.35	43.85	0.272	34.2	3.156	5.061	0.7055	1.003	0.325	4.187
	12	39.45	43.70	0.299	30.3	2.669	5.048	0.7056	1.003	0.318	3.942
	13	44.70	50.50	0.363	25.3	2.248	4.882	0.7059	0.999	0.301	3.674
	14	44.70	49.55	0.322	26.2	1.859	4.895	0.7059	0.996	0.302	3.434
3rd	15	40.80	43.15	0.286	22.4	1.491	5.037	0.7056	0.996	0.294	3.218
	16	36.90	38.80	0.257	18.4	1.182	5.155	0.7054	0.999	0.286	3.031
		37.50	40.10	0.269	17.2	0.913	5.127	0.7054	1.001	0.279	2.864
	18	44.75	46.80	0.375	14.5	0.666	4.932	0.7058	0.997	0.271	2.667
	19	50.30	51.80	0.461	8.7	0.483	4.791	0.7061	0.987	0.260	2.420
	20	52.15	53.20	0.388	6.0	0.372	4.749	0.7062	0.972	0.247	2.151
	21	52.50	53.20	0.248	5.4	0.285	4.744	0.7062	0.956	0.234	1.900

Table 3
Hourly observations and heat transfer coefficients of green chilli blanched with salt solution and open sun drying (Initial weight, 0.6784 kg; initial X_d, 8.30 kg [H_2O]/kg [DM]; final X_d, 0.1981 [H_2O]/ kg [DM]; mean h_c, 2.448 W m^{-2} K^{-1})

Day	Drying time, h	$\overline{T_c}$ (°C)	$\overline{T_e}$ (°C)	$\overline{Y}$	m_{ev} (x10^{-3}, kg)	X_d, (kg[H_2O]/ kg[DM])	Gr (x10^6)	***Pr***	C	n	h_c (W m^{-2} K^{-1})
1st	1	42.50	43.00	0.493	48.5	7.970	0.318	0.7056	1.000	0.202	3.521
	2	43.85	45.70	0.485	47.4	7.311	1.099	0.7058	1.013	0.189	3.460
	3	46.10	48.95	0.449	49.8	6.642	1.547	0.7059	1.027	0.180	3.323
	4	45.55	51.70	0.395	47.6	5.972	3.225	0.7060	1.049	0.172	3.279
	5	43.30	47.80	0.355	43.3	5.340	2.606	0.7058	1.064	0.166	3.144
	6	41.10	39.95	0.339	40.8	4.755	0.791	0.7055	1.057	0.165	2.992
	7	36.65	35.70	0.294	38.0	4.213	0.769	0.7053	1.055	0.164	2.931
2nd	8	36.35	37.70	0.295	34.9	3.712	1.058	0.7053	1.054	0.163	2.878
	9	40.25	42.05	0.291	29.5	3.269	1.212	0.7056	1.055	0.159	2.722
	10	41.65	45.25	0.280	27.2	2.879	2.237	0.7057	1.084	0.152	2.564
	11	40.25	43.35	0.298	25.8	2.514	2.039	0.7056	1.102	0.147	2.452
	12	44.15	44.10	0.247	23.7	2.174	0.030	0.7057	1.024	0.151	2.321
	13	48.35	51.35	0.258	23.1	1.852	1.514	0.7061	1.049	0.143	2.147
	14	45.00	49.70	0.301	21.8	1.543	2.566	0.7059	1.094	0.136	2.041
3rd	15	40.80	44.30	0.281	19.3	1.260	2.243	0.7056	1.125	0.130	1.959
	16	37.20	39.50	0.287	18.8	0.998	1.714	0.7054	1.136	0.128	1.909
	17	38.60	39.40	0.266	15.4	0.763	0.582	0.7054	1.104	0.127	1.834
	18	44.15	46.10	0.218	11.8	0.569	1.145	0.7058	1.101	0.122	1.708
	19	48.90	50.60	0.195	8.6	0.422	0.860	0.7061	1.062	0.118	1.556
	20	50.30	52.05	0.179	6.3	0.320	0.848	0.7061	1.019	0.114	1.403
	21	50.55	52.60	0.178	5.7	0.237	0.981	0.7062	0.998	0.108	1.269

Table 4
Hourly observations and heat transfer coefficients of green chilli blanched with salt solution and greenhouse drying (Initial weight, 0.6788 kg; initial X_d, 8.30 kg [H_2O]/ kg [DM]; final X_d, 0.0922 [H_2O]/ kg [DM]; mean h_c, 4.520 W m^{-2} K^{-1})

Day	Drying time, h	$\overline{T_c}$ (°C)	$\overline{T_e}$ (°C)	$\overline{Y}$	m_{ev} (x10^{-3}, kg)	X_d, (kg[H_2O]/ kg[DM])	Gr (x10^6)	***Pr***	C	n	h_c (W m^{-2} K^{-1})
1st	1	39.10	43.15	0.584	51.8	7.953	5.061	0.7056	1.000	0.404	7.967
	2	39.15	47.00	0.467	53.7	7.227	5.006	0.7057	1.000	0.402	7.803
	3	38.60	47.75	0.415	54.3	6.485	5.003	0.7057	0.999	0.398	7.564
	4	39.70	50.30	0.372	53.3	5.746	4.953	0.7058	0.999	0.391	7.168
	5	38.35	48.45	0.340	42.2	5.088	4.997	0.7057	0.999	0.379	6.496
	6	33.35	41.55	0.330	38.2	4.535	5.167	0.7053	1.000	0.372	6.121
	7	33.05	36.65	0.337	37.9	4.012	5.244	0.7052	1.002	0.363	5.718
2nd	8	35.85	38.15	0.342	32.3	3.529	5.180	0.7053	1.004	0.351	5.201
	9	39.20	42.35	0.341	27.9	3.115	5.071	0.7055	1.004	0.338	4.673
	10	40.30	45.30	0.336	26.1	2.743	5.014	0.7056	1.003	0.327	4.261
	11	40.75	46.85	0.327	25.3	2.390	4.986	0.7057	1.001	0.318	3.940
	12	42.35	46.70	0.327	24.6	2.046	4.966	0.7057	0.999	0.308	3.636
	13	42.90	47.50	0.337	22.4	1.723	4.947	0.7058	0.997	0.299	3.373
	14	40.75	46.55	0.349	21.2	1.423	4.990	0.7057	0.996	0.293	3.194
3rd	15	36.10	43.15	0.343	20.6	1.136	5.104	0.7055	0.997	0.289	3.101
	16	35.80	39.80	0.327	18.2	0.869	5.156	0.7054	0.998	0.284	2.971
	17	38.90	41.10	0.286	16.3	0.632	5.093	0.7055	0.999	0.276	2.793
	18	41.40	46.80	0.252	12.2	0.436	4.978	0.7057	0.997	0.267	2.585
	19	44.05	49.80	0.239	7.8	0.298	4.900	0.7059	0.990	0.255	2.337
	20	44.65	51.30	0.232	5.3	0.208	4.872	0.7060	0.982	0.243	2.092
	21	42.05	52.50	0.228	5.8	0.132	4.891	0.7059	0.976	0.233	1.920

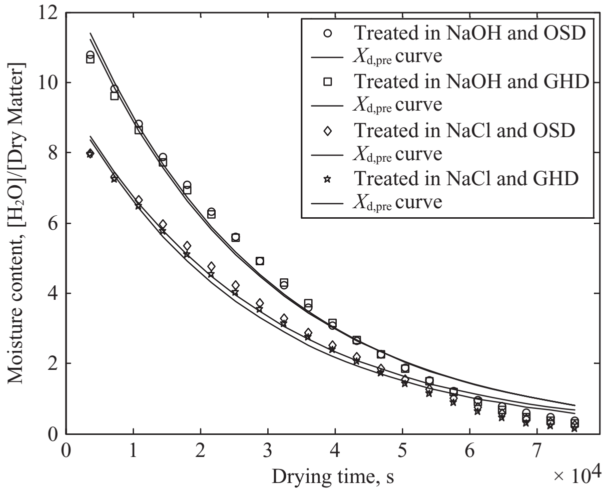

Fig. 2. Moisture content with drying time of the green chilli drying under open sun (OSD) and greenhouse drying (GHD) after blanching in NaOH and NaCl solutions.

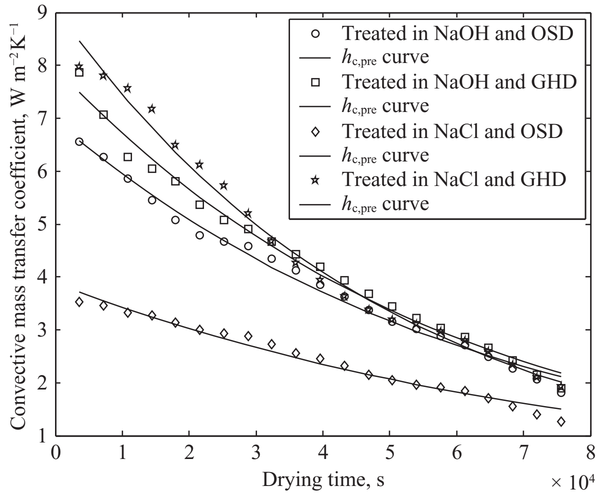

Fig. 3. Convective heat transfer coefficient with drying time of the green chilli drying under open sun (OSD) and greenhouse drying (GHD) after blanching in NaOH and NaCl solutions.

drying process. The trends of drying under natural and GHD of green chilli are shown in Fig. 2. From Tables 1–4, it can be observed that the convective heat and mass transfer coefficient also depends on drying time and moisture content. The dependency of convective heat and mass transfer coefficient on drying time is shown in Fig. 3. Therefore, an attempt has been made to establish the dependency of convective heat and mass transfer coefficient on the hourly mean moisture content. The theoretical concept is developed with Eqs (14)–(16). Thus, the exponential regressions of mean moisture content and convective heat transfer coefficients were done to evaluate the model coefficients (a_m, a_c, k_m and k_c). The coefficient of drying and convective heat and mass transfer coefficient models and their correlation parameters for all drying experiments are presented in Table 5. The exponential regression for

Table 5
Coefficients and error for the different model equations

Model equation	$X_d = a_m \exp(-k_m t)$		$h_c = a_c \exp(-k_c t)$		$h_{c,pre} = \exp\left[\left(\log X_d - \log a_m\right)\frac{k_c}{k_m} + \log a_c\right]$	
Treatment	Parameter	Value	Parameter	Value	Parameter	Value
NaOH blanched and OSD	a_m	13.01	a_c	6.964		
	$k_m(s^{-1})$	3.669×10^{-5}	$k_c(s^{-1})$	1.575×10^{-5}		
	r^2	0.9889	r^2	0.9915	r^2	0.9912
	e_s	2.411	e_s	0.3324	e_s	0.3321
	E_{RSM}	0.3562	E_{RSM}	0.1323	E_{RSM}	0.1289
NaOH blanched and GHD	a_m	12.79	a_c	7.979		
	$k_m(s^{-1})$	3.644×10^{-5}	$k_c(s^{-1})$	1.715×10^{-4}		
	r^2	0.9861	r^2	0.9900	r^2	0.9899
	e_s	2.964	e_s	0.5447	e_s	0.544
	E_{RSM}	0.395	E_{RSM}	0.1693	E_{RSM}	0.1649
NaCl blanched and OSD	a_m	9.607	a_c	3.889		
	$k_m(s^{-1})$	3.530×10^{-5}	$k_c(s^{-1})$	1.26×10^{-5}		
	r^2	0.9864	r^2	0.9771	r^2	0.9759
	e_s	1.622	e_s	0.2268	e_s	0.2264
	E_{RSM}	0.2921	E_{RSM}	0.1093	E_{RSM}	0.1064
NaCl blanched and GHD	a_m	9.565	a_c	9.1		
	$k_m(s^{-1})$	3.697×10^{-5}	$k_c(s^{-1})$	2.00×10^{-5}		
	r^2	0.9865	r^2	0.9905	r^2	0.9904
	e_s	0.6010	e_s	0.7600	e_s	0.7589
	E_{RSM}	0.2903	E_{RSM}	0.2000	E_{RSM}	0.1948

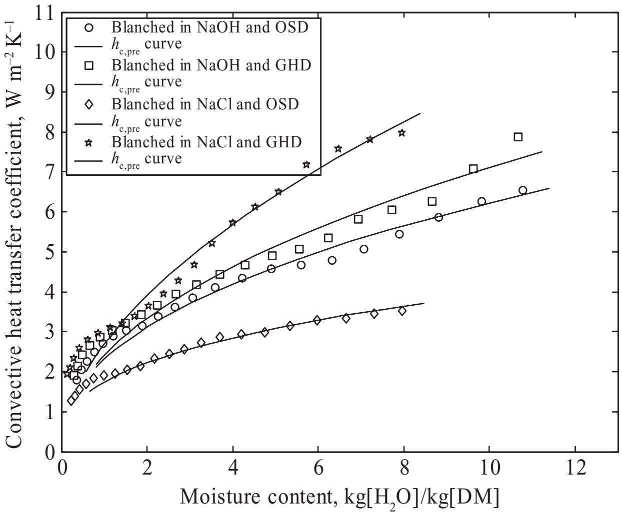

Fig. 4. Convective heat transfer coefficient as a function of mean moisture content of the green chilli drying under open sun (OSD) and greenhouse drying (GHD) after blanching in NaOH and NaCl solutions.

moisture content and convective heat and mass transfer coefficient with drying time corroborated with higher coefficient of determination ranged from 0.991 to 0.977 and lower E_{RMS} as 0.395. With the help of Eq. (16), the convective heat and mass transfer coefficient can be predicted with the knowledge of moisture content. The results of computed h_c from the experimental data and predicted $h_{c,pre}$ from developed model for all four drying experiments are presented in Fig. 4. It is clear from Fig.4 that convective heat and mass transfer is higher at the higher moisture content of chilli. This reveals that while moisture content of the product is lower, the availability of moisture for evaporation is also lower. Hence the heat utilized for drying is lower due to predominant effect of evaporation. The correlation and error parameters of the predictive model of $h_{c,pre}$ with computed h_c are shown in Table 5. The predicted $h_{c,pre}$ from model Eq. (16) is good agreement with the computed h_c from experimental data for all the drying experiments with the r^2 more than 0.975 and E_{RMS} less than 0.1948.

5. Conclusion

Solar drying of blanched green chilli has been studied for investigation of convective heat and mass transfer coefficient under natural and forced convection. The green chilli blanched with NaCl and dried in greenhouse under forced convection enhanced the convective heat transfer coefficient. The green chilli blanched in NaCl has the lowest convective heat transfer coefficient under OSD and lowest moisture content under GHD.

Symbols

a_c	coefficient of exponential model of convective heat transfer coefficient
a_m	coefficient of drying model
A_t	area of green chilli (tray), m^2
C	coefficient of Eq. (1)
C_v	specific heat of humid air, J kg^{-1} K^{-1}
e_s	standard error
E_{RMS}	root mean square error
g	acceleration due to gravity, m s^{-2}
Gr	Grashof number ($= \beta g L^3 \rho_v{}^2 \triangle T^1/\mu^2$)
h_c	convective heat transfer coefficient of green chilli, W m^{-2} K^{-1}
$h_{c,pre}$	Predicted convective heat transfer coefficient of green chilli, W m^{-2} K^{-1}
k_c	exponential coefficient of convective heat transfer coefficient, s^{-1}
k_m	drying coefficient, s^{-1}
K_v	thermal conductivity of moist air, W m^{-1} K^{-1}
L	characteristic dimension, m
m_{ev}	moisture evaporated, kg
n	coefficient of Eq. (1)
Nu	Nusselt number ($= h_c L/K_v$)
Pr	Prandtl number ($= \mu_v C_v/K_v$)
$P(T)$	partial vapour pressure at temperature T, N m^{-2}
Q_e	rate of heat utilized to evaporate moisture, J m^{-2} s^{-1}
Re	Reynolds number ($=\rho_v\, Lv/\mu_v$)
r^2	coefficient of determination
t	time, s
T_c	temperature of green chilli, °C
T_e	temperature humid air above the green chilli surface, °C
T_i	average of green chilli and humid air temperature, °C
$\triangle T^{-1}$	effective temperature difference, K
v	velocity of air, m s^{-1}
X_d	moisture content of green chilli, kg [H_2O]/kg[dry matter (DM)]
β	coefficient of volumetric expansion, K^{-1}
γ	relative humidity (fraction, range 0–1)
σ	Stefan-Boltzmann constant ($= 5.6696 X 10^{-8}$), W m^{-2} K^{-4}
λ	latent heat of vaporization, J kg^{-1}
μ_v	dynamic viscosity of humid air, kg m^{-1} s^{-1}
ρ_v	density of humid air, kg m^{-3}

Reference

[1] Anonymous, Spices board, Ministry of Commerce and Industry & Ministry of Agriculture, Govt. of India 2007.
[2] S. Timoumi, D. Mihoubi and F. Zagrouba, Simulation model for solar drying process, Desalination, 168 (2004) 111–115.
[3] D. Jain and G.N. Tiwari, Thermal aspect of open sun drying of various crops, Energy, 28 (2003) 37–54.
[4] D. Jain and G.N. Tiwari, Effect of greenhouse on crop drying under natural and forced convection I: Evaluation of convective mass transfer coefficient, Energy Conv. Manag., 45 (2004) 765–783.
[5] G.N. Tiwari, S. Kumar and O. Prakash, Evaluation of convective mass transfer coefficient during drying of jaggery, J. Food Eng., 63 (2004) 219–227.
[6] D. Jain, Determination of convective heat and mass transfer coefficients of solar drying of fish, Biosyst. Eng., 94 (3) (2006) 429–435.
[7] A. Kaya, O. Aydın and I. Dincer, Experimental and numerical investigation of heat and mass transfer during drying of Hayward kiwi fruits (Actinidia Deliciosa Planch), J. Food Eng., 88 (2008) 323–330.
[8] D.R. Pitts and L.E. Sissom, Theory and Problems of Heat Transfer. McGraw-Hill Book Company, 1977.
[9] W.K. Lewis, The evaporation of a liquid into a gas. Trans. ASAE, 44 (1922) 325.
[10] W.K. Lewis, Evaporation of a liquid into a gas –a correction. Mech. Eng., 55 (1933) 567.
[11] M.A.S. Malik, G.N. Tiwari, A. Kumar and M. S. Sodha, Solar Distillation. Oxford: Pergamon Press, 1982.
[12] P.I. Cooper, The maximum efficiency for single effect solar still. Solar Energy, 15 (1973) 205–217.
[13] D. Jain and P.B. Pathare, Study the drying kinetics of open sun drying of fish, J. Food Eng., 78 (2007) 1315–1319.
[14] J.P. Holman, Heat transfer, 7th ed. SI Unit. McGraw Book Company, Berlin, 1992.