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FORCED CONVECTION GREENHOUSE PAPAD DRYING: AN EXPERIMENTAL STUDY

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Abstract

In this research paper, the behavior of heat and mass transfer phenomenon during greenhouse papad drying under forced convection mode has been investigated. Various experiments were performed during the month of April 2010 at Guru Jambheshwar University of Science and Technology Hisar (29^{o}5'5" N 75^{o}45'55" E). Experimental data obtained for forced convection greenhouse drying of papad were used to determine the constants in the Nusselt number expression by using the simple linear regression analysis and, consequently, the values of convective and evaporative heat transfer coefficients were evaluated. The average values of experimental constants *C* and *n* were determined as 0.996 and 0.194 respectively. The average values of convective and evaporative heat transfer coefficients were determined as 0.759 W/m^2 ^{o}C and 23.48 W/m^2 ^{o}C respectively. The experimental error in terms of percentage uncertainty was also evaluated.

Keywords: Papad, Papad drying, Heat transfer coefficient, Convective, Evaporative, Forced convection greenhouse.

1. Introduction

Papad is the most popular adjuncts in the diet and it is consumed in most Indian homes. India is the largest papad producing country and about 95 percentage of the total production of papad is prepared at household level or in cottage scale. It is prepared from dough consisting of different pulses flour along with additives. It is prepared by rolling the dough balls of low moisture contents (27% to 30%) by using rolling pin in the form of circular disc (130 mm to 210 mm diameter) of thickness generally varying from 0.4 mm to 0.7 mm [1-3]. Papad drying is a simultaneous heat and mass transfer process in which heat is transferred by

Nomenclatures

A_t	Area of tray, m^2
C	Experimental constant
C_v	Specific heat of humid air, J/kg ^{o}C
g	Acceleration due to gravity, m/s^2
h_c	Convective heat transfer coefficient, W/m^2 ^{o}C
$h_{c,av}$	Average convective heat transfer coefficient, W/m^2 ^{o}C
h_e	Evaporative heat transfer coefficient, W/m^2 ^{o}C
$h_{e,av}$	Average evaporative heat transfer coefficient, W/m^2 ^{o}C
K_v	Thermal conductivity of humid air, W/m ^{o}C
m_{ev}	Mass evaporated, kg
N	Number of observations in each set
N_o	Number of sets
Nu	Nusselt number = $h_c X/K_v$
n	Experimental constant
$P(T)$	Partial vapor pressure at temperature T, N/m^2
Pr	Prandtl number = $\mu_v C_v/K_v$
$\dot{Q}_e$	Rate of heat utilized to evaporate moisture, J/m^2 s
Re	Reynolds number = $\rho_v V X/\mu_v$
T_e	Temperature just above the papad surface, ^{o}C
T_g	Greenhouse temperature, ^{o}C
T_p	Temperature of papad surface, ^{o}C
t	Time, s
V	Air velocity inside greenhouse, m/s
X	Characteristic dimension, m
Greek Symbols	
β	Coefficient of volumetric expansion (K^{-1})
γ	Relative humidity (%)
λ	Latent heat of vaporization, J/kg
μ_v	Dynamic viscosity of humid air, N s/m^2
ρ_v	Density of humid air, kg/m^3
σ	Standard deviation

convection and radiation to papad-air interface and by conduction to the interior of papad. Water is transferred by diffusion from inside the papad to papad-air interface and from the interface to the air stream by convection. Thus, papad drying involves removal of moisture in order to preserve it.

Open sun drying is the most primitive (traditional) method of papad drying. However, this traditional method of drying suffers from high product losses due to inadequate drying, fungal growth, encroachments of insects, rodents, birds, and other contamination resulting in poor product quality. In spite of many disadvantages, open sun drying is still practiced in places throughout the world. Although the hot air industrial driers are available to get the good quality of the product but they consume large amount of energy. The scarcity of fossil fuels with their rising cost of production and environmental pollution emphasize the need on the utilization of solar energy as an alternative source for low temperature drying applications, especially in the regions, where this source is abundantly available. Solar energy is preferred to other energy sources because it is abundant, non-pollutant, inexhaustible, environmentally benign, free of cost, and renewable which can be effectively used for drying purposes, if harvested properly [4-6].

An advanced and alternative technique to the traditional method is greenhouse drying, in which the product is placed in trays and receives solar radiation through the plastic cover, while moisture is removed by natural convection or forced air flow. The uses of appropriate greenhouse dryers improve the quality of the product, prevent the contamination by insects, microorganisms and bacteria, and lead to reduction of drying time interval [7-9].

The convective heat transfer coefficient is an important parameter in drying rate simulation, since the temperature difference between the air and the product varies with this coefficient [10]. The convective heat transfer coefficient is not a property of the fluid. It is an experimentally determined parameter whose value depends on the physical properties of the humid air surrounding the papad (product) and the temperature difference between the papad surface and the air.

The convective heat transfer coefficients for various shapes and sizes of jaggery pieces [11, 12] were evaluated under natural and forced convection greenhouse drying. These were observed to vary from 0.73 -1.41 W/m^2 ^{o}C and 0.80-1.47 W/m^2 ^{o}C under natural and forced convection greenhouse drying mode respectively for eight hundred gram samples.

The effect of the greenhouse on the convective heat and mass transfer under natural and forced modes of drying for cabbage and peas drying were studied [13]. The convective mass transfer coefficient under forced convection mode was reported double as compared to natural convection greenhouse drying. Kumar and Tiwari [14] reported that the value of convective mass transfer coefficient depends significantly on the mass of the onion flakes to be dried under open sun and greenhouse drying. They found that the values of convective heat transfer coefficient under forced convection mode are constant.

The convective heat transfer coefficients for khoa pieces [15] were evaluated in a controlled environment under natural and forced convection greenhouse drying modes which were reported to vary from 0.86-1.09 W/m^2 ^{o}C and 0.54-1.03 W/m^2 ^{o}C respectively. Recently, Kumar et al. [3] evaluated the convective heat transfer coefficients of papad drying under open sun and indoor forced convection conditions. The values of convective heat transfer coefficients under open sun and forced convection drying modes were reported to be 3.54 W/m^2 ^{o}C and 1.56 W/m^2 ^{o}C respectively.

The usage of greenhouse for papad drying is a new approach in the papad preservation. This may pave a new path in the field of food industry. To the best knowledge of the author, so far, no such work has been reported in the literature on greenhouse papad drying. Therefore, the present study has been undertaken to evaluate the convective and evaporative heat transfer coefficients of papad for greenhouse drying under forced convection mode. This study would be helpful in designing a dryer for drying papad to its optimum storage moisture level of about 15%.

2. Materials and Methods

2.1. Experimental set-up and instrumentation

A roof type even span greenhouse of 1.2×0.8 m^2 effective floor area was fabricated of PVC pipe and a UV film covering of 200 microns. The central height and the walls were maintained as 0.6 m and 0.4 m respectively. A fan of 225 mm sweep diameter and 1340 rpm with a rated air velocity of 5 m/s was provided on the sidewall of the greenhouse for the forced convection experiments. A photograph of the experimental setup for greenhouse drying in the forced mode is shown in Fig. 1 and its schematic view is shown in Fig. 2.

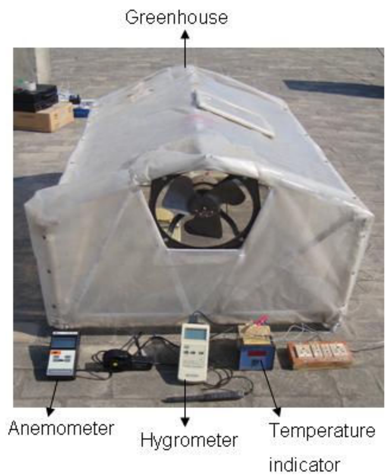

Fig. 1. Experimental Set-up of Greenhouse Papad Drying under Forced Convection Mode.

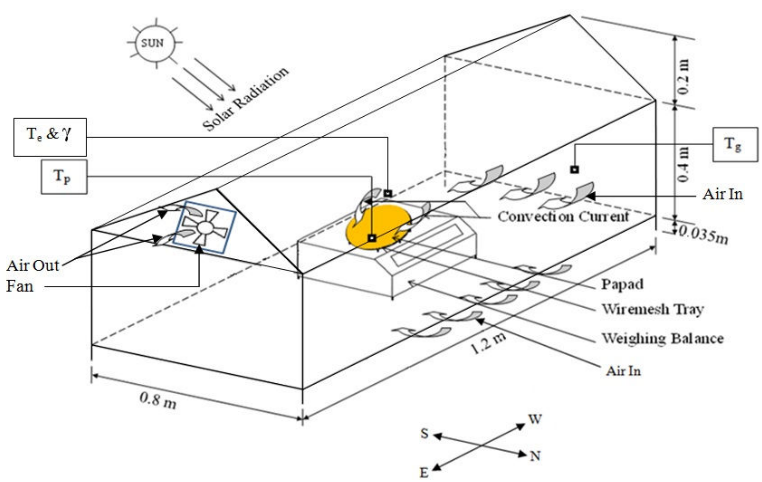

Fig. 2. Schematic View of Greenhouse Papad drying under Forced Convection Mode.

A circular shaped wire mesh tray of diameter 0.180 m was used to accommodate the papad for single layer drying. It was kept directly over the digital weighing balance of 6 kg capacity (model TJ-6000, Scaletech, made in India) having a least count of 0.1 g. The papad surface temperature (T_p) and air temperature at different locations were measured by calibrated copper-constantan thermocouples connected to a ten channel digital temperature indicator with a least count of 0.1^{o}C (accuracy ±0.1%). The relative humidity, γ and the temperature just above the papad surface, T_e, were measured by a digital humidity/temperature meter (model Lutron-HT 3006, made in Taiwan). It had a least count of 0.1% relative humidity (an accuracy of ±3% on the full scale range of 10 to 95% of RH) and 0.1^{o}C temperature (an accuracy of ± 0.8^{o}C on the full scale range of 50^{o}C). The air velocity across the greenhouse section was measured with an electronic digital anemometer (model AM-4201, made in Taiwan). It had a least count of 0.1 m/s with an accuracy of ±2% on the full scale range of 0.2 to 30.0 m/s.

Calibration of thermocouples

Copper-constantan thermocouples connected to ten channel digital temperature indicator were used to record the papad surface temperature and air temperature at different locations. The thermocouples tend to deviate from the actual data after a long period, so it is necessary to calibrate with respect to a standard thermometer, the ZEAL thermometer, which gives accurate readings.

2.2. Sample preparation and experimental observations

Papad was freshly prepared by taking the flour of moong bean (Indian trade name - moong) and phaseolus mungo (Indian trade name - urad dal) mixed with 27.5% water content per kg of papad weight. The flour was purchased locally, and that fraction of flour which passed through an eighty five mesh (180 microns) British Standard sieve was used for making papad. The dough was kneaded and rolled in circular shape of 0.7 mm thickness and 180 mm diameter with the help of pastry-board and pastry-roller. The freshly prepared papad of 23.5 g was used for each run of the forced convection greenhouse papad drying.

Experiments were performed during the month of April 2010 at Guru Jambheshwar University of Science and Technology Hisar (29^{o}5'5" N 75^{o}45'55" E). The orientation of the greenhouse during the experimentation was kept east-west because sunlight availability is more in comparison to north-south. Experimental setup was located on the open floor of a three-floor building to have a good exposure to the solar radiation. Each observation was taken for papad drying after half an hour time interval. The papad sample was kept in the wire mesh tray over the digital weighing balance. The moisture evaporated was calculated by taking the difference of mass of papad between two consecutive readings. The papad sample was dried till no variation in its mass was observed. In order to obtain accurate results, the above mentioned experimentation procedure was repeated four times for each freshly prepared similar papad sample of same size (i.e., 180 mm diameter and 0.7 mm thickness) on consecutive days at the same timing. The initial mass of papad sample for each run of drying was kept constant (i.e., 23.5 g).

2.3. Thermal modeling

The convective heat transfer coefficient under forced convection can be defined as [3, 15, 16]:

$$h_c = \frac{K_v}{X} C(\text{Re}\,\text{Pr})^n \tag{1}$$

The rate of heat utilized to evaporate moisture is given as [17]

$$\dot{Q}_e = 0.016\, h_c \left[P(T_p) - \gamma\, P(T_e)\right] \tag{2}$$

On substituting h_c from Eq. (1), Eq. (2) becomes

$$\dot{Q}_e = 0.016 \frac{K_v}{X} C(\text{Re}\,\text{Pr})^n \left[P(T_p) - \gamma\, P(T_e)\right] \tag{3}$$

The moisture evaporated is determined by dividing Eq. (3) by the latent heat of vaporization (λ) and multiplying the area of the papad drying tray (A_t) and time interval (t).

$$m_{ev} = \frac{\dot{Q}_e}{\lambda} A_t\, t = 0.016 \frac{K_v}{X\lambda} C(\text{Re}\,\text{Pr})^n \left[P(T_p) - \gamma\, P(T_e)\right] A_t\, t \tag{4}$$

Let

$$0.016 \frac{K_v}{X\lambda} \left[P(T_p) - \gamma\, P(T_e)\right] A_t\, t = Z$$

$$\frac{m_{ev}}{Z} = C(\text{Re}\,\text{Pr})^n \tag{5}$$

Taking the logarithm of both sides of Eq. (5),

$$\ln\left[\frac{m_{ev}}{Z}\right] = \ln C + n \ln(\text{Re}\,\text{Pr}) \tag{6}$$

This is the form of a linear equation,

$$Y = mX_0 + C_0 \tag{7}$$

where

$$Y = \ln\left[\frac{m_{ev}}{Z}\right],$$

$$m = n,$$

$X_0 = \ln(\text{Re}\,\text{Pr})$, and

$$C_0 = \ln C$$

Thus, $C = e^{C_o}$

Values of m and C_o in Eq. (7) are obtained by using the simple linear regression method by using the following formulae

$$m=\frac{N\sum X_0Y-\sum X_0\sum Y}{N\sum X_0^{\;2}-\left(\sum X_0\right)^2} \tag{8}$$

and

$$C_0=\frac{\sum X_0^{\;2}\sum Y-\sum X_0\sum X_0Y}{N\sum X_0^{\;2}-\left(\sum X_0\right)^2} \tag{9}$$

Then the constant 'C' and exponent 'n' can be obtained from the above equations. The values of these constant were considered further to determine the convective heat transfer coefficient. After knowing the convective heat transfer coefficient (h_c), the evaporative heat transfer coefficient (h_e) can also be calculated from Eq. (10) as follows [16]:

$$h_e=0.016\;h_c\left[\frac{P(T_p)-\gamma P(T_e)}{T_p-T_e}\right] \tag{10}$$

2.4. Physical properties of humid air

The following expressions were used for determining the values of the physical properties of humid air, such as specific heat (C_v), thermal conductivity (K_v), density (ρ_v), viscosity (μ_v), and partial vapor pressure, $P(T)$ [3, 10, 15]:

$$C_v=999.2+0.1434T_i+1.101\times10^{-4}T_i^2-6.7581\times10^{-8}T_i^3 \tag{11}$$

$$K_v=0.0244+0.7673\times10^{-4}T_i \tag{12}$$

$$\rho_v=\frac{353.44}{\left(T_i+273.15\right)} \tag{13}$$

$$\mu_v=1.718\times10^{-5}+4.620\times10^{-8}T_i \tag{14}$$

$$P(T)=\exp\left[25.317-\frac{5144}{\left(T_i+273.15\right)}\right] \tag{15}$$

where $T_i=\left(T_p+T_e\right)/2$

2.5. Experimental error

The experimental method used for determining the convective heat transfer coefficient is an indirect approach based on the mass of moisture evaporated from the papad. This indirect approach has a considerable degree of experimental uncertainty in the estimated convective heat transfer coefficient. The experimental error was evaluated in terms of percentage uncertainty (internal + external) for the moisture evaporated. The following two equations were used for internal uncertainty [16-19]:

$$U_I = \frac{\sqrt{{\sigma_1}^2 + {\sigma_2}^2 + \ldots {\sigma_N}^2}}{N_o} \tag{16}$$

and $$\sigma = \sqrt{\frac{\sum\left(X - \bar{X}\right)^2}{N}} \tag{17}$$

Therefore, the percentage internal uncertainty was determined using the following expression:

% internal uncertainty = (U_I/mean of the total observations) ×100 (18)

For external uncertainty, the least counts of all the instruments used in measuring the observation data were considered.

2.6. Computation technique

The average of papad surface temperature (T_p) and temperature above the papad surface (T_e) inside greenhouse were calculated at half an hour time interval for corresponding moisture evaporated. The air velocity across the greenhouse section during the forced convection drying mode was measured with an anemometer. The physical properties of humid air were evaluated for the mean temperature (T_i) of T_p and T_e by using Eqs. (11) to (15). These physical properties of humid air and velocity of air were used for determining the values of the Reynolds number (Re) and Prandtl number (Pr). The values of C and n in Eq. (1) were determined by simple linear regression analysis, and then the values of convective heat transfer coefficient (h_c) were calculated at the increment of every half an hour of observation. The evaporative heat transfer coefficients were evaluated by using Eq. (10).

3. Results and Discussion

The experimental data obtained for papad drying under forced convection greenhouse mode are given in Tables 1(a) to (d).

The data given in Tables 1(a) to (d) were used to determine the values of constant C and exponent n in the Nusselt number expression by simple linear regression analysis. Then the values of the constant C and exponent n were used further for determining the values of the convective heat transfer coefficient by Eq. (1). The values of convective heat transfer coefficients were used to determine the evaporative heat transfer coefficients by Eq. (10). The values of constants (C and n), convective heat transfer coefficients (h_c), and evaporative heat transfer coefficients (h_e) for papad drying under forced convection greenhouse mode are summarized in Table 2. The ranges of Reynolds and Prandtl numbers have also been given. The product of Reynolds and Prandtl number indicates that the entire drying for forced convection greenhouse mode falls within a laminar flow, because $\mathrm{Re}\,\mathrm{Pr} \leq 10^5$ [20].

It is observed from Table 2 that the values of constant C and exponent n vary from 0.995 to 0.997 and 0.192 to 0.197 respectively. The convective and evaporative heat transfer coefficients were observed to vary from 0.739 W/m^2 ^{o}C to 0.786 W/m^2 ^{o}C and 21.91 W/m^2 ^{o}C to 25.42 W/m^2 ^{o}C respectively. It is observed that different values of convective and evaporative heat transfer coefficients were obtained for similar papad sample dried on consecutive days. This variation may be due to change in operating conditions on each day. The variation in values of the convective and evaporative heat transfer coefficient is observed to be 6.08% and 23.97% respectively for all the papad samples.

Table 1. Observations for Forced Greenhouse Drying of

(a) First Papad Sample (April 7, 2010).

Time	T_p (°C)	T_e (°C)	$m_{ev} \times 10^{-3}$ (kg)	γ (%)
9.30 am	44.6	41.2	2.8	37.8
10.00 am	47.4	43.3	2.0	34.7
10.30 am	49.6	44.9	2.5	31.2
11.00 am	51.2	46.2	1.2	30.9
11.30 am	52.4	47.4	1.6	30.1

(b) Second Papad Sample (April 8, 2010).

Time	T_p (°C)	T_e (°C)	$m_{ev} \times 10^{-3}$ (kg)	γ (%)
9.30 am	44.0	40.6	3.5	37.2
10.00 am	46.1	42.2	2.1	35.8
10.30 am	49.0	44.3	2.2	34.6
11.00 am	50.2	45.2	1.0	32.8
11.30 am	51.1	46.2	1.2	31.3

(c) Third Papad Sample (April 9, 2010).

Time	T_p (°C)	T_e (°C)	$m_{ev} \times 10^{-3}$ (kg)	γ (%)
9.30 am	43.5	40.6	2.4	35.2
10.00 am	45.8	42.2	2.1	35.1
10.30 am	48.8	44.6	2.0	34.0
11.00 am	49.9	45.5	2.1	33.8
11.30 am	50.9	46.3	1.1	30.1

(d) Fourth Papad Sample (April 10, 2010).

Time	T_p (°C)	T_e (°C)	$m_{ev} \times 10^{-3}$ (kg)	γ (%)
9.30 am	44.0	40.9	3.0	36.7
10.00 am	46.4	42.6	2.1	35.2
10.30 am	49.1	44.7	2.2	33.3
11.00 am	50.4	45.6	1.4	32.5
11.30 am	51.5	46.7	1.3	30.5

Table 2. Values of Experimentally Evaluated Parameters and the Convective Heat Transfer Coefficients.

C	n	Re	Pr	h_c (W/m^2 °C)	h_e (W/m^2 °C)
First Papad Sample (April 7, 2010)					
0.996	0.192	5053.35 - 5252.45	0.695-0.696	0.740-0.749	21.91-24.88
Second Papad Sample (April 8, 2010)					
0.995	0.192	5088.06 - 5270.06	0.695-0.696	0.739-0.747	21.37-23.44
Third Papad Sample (April 9, 2010)					
0.997	0.197	5089.46 - 5277.43	0.695-0.696	0.777-0.786	24.02-26.22
Fourth Papad Sample (April 10, 2010)					
0.996	0.196	5075.52 - 5265.65	0.695-0.696	0.764-0.773	23.14-25.42

The variation in convective and evaporative heat transfer coefficients with drying time is illustrated in Figs. 3 and 4 respectively. The variation in convective heat transfer coefficients with respect to drying time for all the individual samples is found to lie in between 1.09% to 1.22% whereas for the evaporative heat transfer coefficient it is observed to lie in between 9.16% to 13.55%. It is inferred that the evaporative heat transfer coefficients changes significantly with the change in convective heat transfer coefficients.

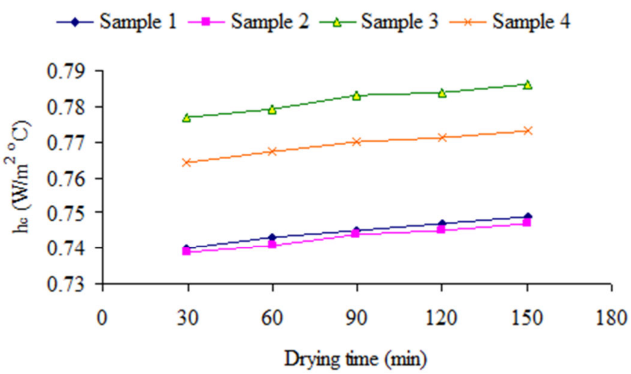

Fig. 3. Variation of the Convective Heat Transfer Coefficients with Respect to Drying Time.

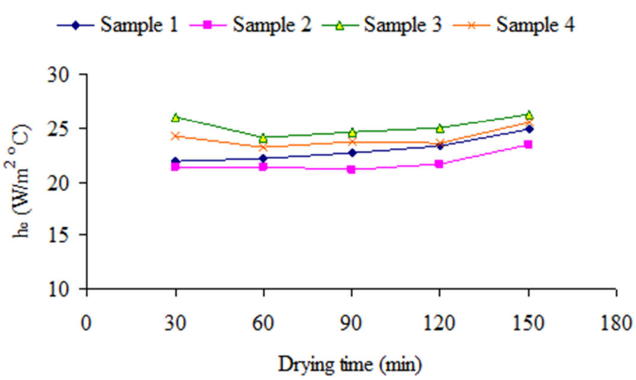

Fig. 4. Variation of the Evaporative Heat Transfer Coefficients with Respect to Drying Time.

The average values of constants (*C* and *n*) and the convective and evaporative heat transfer coefficients were also calculated which are reported in Table 3.

Table 3. Average Values of Constants (*C* and *n*) and the Convective and Evaporative Heat Transfer Coefficients.

C	n	$h_{c,av}$ (W/m^2 °C)	$h_{e,av}$ (W/m^2 °C)
0.996	0.194	0.759	23.48

The percentage uncertainty (internal + external) was found to be within the range of 23.23% to 44.88% for the forced greenhouse papad drying and the different values of convective and evaporative heat transfer coefficients were found to be within this range. The experimental percentage uncertainties for papad drying under forced greenhouse mode are presented in Table 4. The magnitude of these uncertainties is comparable with the uncertainties found in the measurements of heat transfer coefficients of other products (10, 13). The error bars for the convective and evaporative heat transfer coefficients are illustrated in Figs. 5 and 6 respectively.

Table 4. Experimental Percentage Uncertainties.

Papad Sample Number	Internal uncertainty (%)	External uncertainty (%)	Total uncertainty (%)
First	28.76	0.5	29.26
Second	44.38	0.5	44.88
Third	22.73	0.5	23.23
Fourth	30.82	0.5	31.32

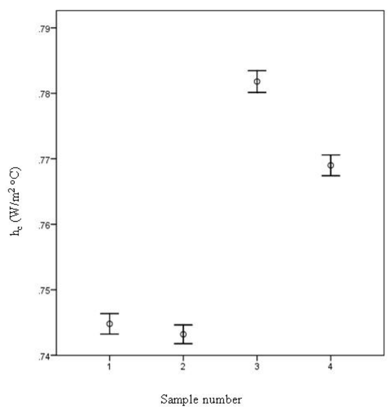

Fig. 5. The Error Bars for Convective Heat Transfer Coefficients.

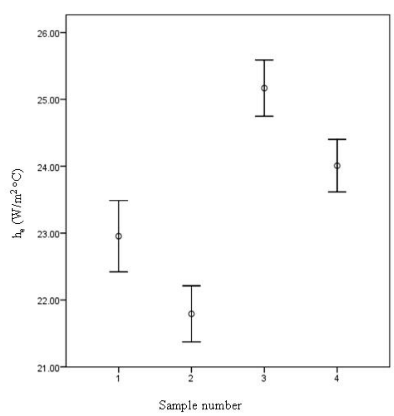

Fig. 6. The Error Bars for Evaporative Heat Transfer Coefficients.

4. Conclusions

The convective and evaporative heat transfer coefficients for papad under forced convection greenhouse drying mode were evaluated by using the values of the constants (*C* and *n*) in the Nusselt number expression obtained for papad based on experimental data by using simple linear regression analysis. The values of the constant *C* and exponent *n* were found to be 0.996 and 0.194 respectively. The values of convective and evaporative heat transfer coefficients were observed to vary from 0.739 $W/m^2\ ^oC$ to 0.786 $W/m^2\ ^oC$ and 21.37 $W/m^2\ ^oC$ to 25.42 $W/m^2\ ^oC$ respectively. The average values of convective and evaporative heat transfer coefficients for papad drying under forced convection greenhouse mode were found to be 0.759 $W/m^2\ ^oC$ and 23.48 $W/m^2\ ^oC$ respectively. These values would be useful in designing a dryer for drying papad to its optimum storage moisture level. The experimental errors were found to be in the range of 23.23% to 44.88%.

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