An Experimental Study On Open Sun Drying Of Corn Kernels

Ravinder Kumar Sahdev

Mechanical Engineering Department, University Institute of Engineering & Technology, Maharshi Dayanand UniversityRohtak,

Sandeep

Mechanical Engneering Department, University Institute of Engineering & Technology, Maharshi Dayanand University Rohtak, India

Mahesh Kumar

Mechanical Engineering Department, Guru Jambheshwar University of Sciences & Technology, Hisar, India

Abstract

In this research paper, an attempt has been made to determine the convective heat transfer coefficient of corn kernels under open sun drying mode. The experiments were conducted in the month of June 2013 for open sun drying of corn kernels in the climatic conditions of Rohtak (28° 40': 29 05'N 76° 13': 76° 51'E). The corn kernels werwe dried from initial moisture content 43 % dry basis. Experimental data were used to evaluate the values of constants (C and n) in the Nusselt number expression by using linear regression analysis and consequently convective heat transfer coefficients were determined. The average value of convective heat transfer coefficient was found to be 3.91 W/m^2 °C for corn kernels. The experimental error in terms of percent uncertainty has also been evaluated.
Keywords: Corn kernels; Convective heat transfer coefficient; Open sun drying.

Nomenclature

A_t	area of circular wire mesh tray, m^2
C	constant
C_v	specific heat of humid air, J/kg °C
g	acceleration due to gravity, m/s^2
Gr	Grashof number $= \beta g X^3 \rho_v^2 \Delta T / \mu_v^2$
h_c	convective heat transfer coefficient, W/m^2 °C
$h_{c,av}$	average convective heat transfer coefficient, W/m^2 °C
K_v	thermal conductivity of humid air, W/m °C
m_{ev}	moisture evaporated, kg
n	constant
Nu	Nusselt number $= h_c X / K_v$
Pr	Prandtl number $= \mu_v C_v / K_v$
$P(T)$	partial vapor pressure at temperature *T*, N/m^2
Q_e	rate of heat utilized to evaporate moisture, J/m^2 s
t	time, s
T_c	corn kernel surface temperature, °C
T_e	temperature just above corn kernel surface, °C
$\bar{T}_c$	average corn kernel surface temperature, °C
$\bar{T}_e$	average temperature of humid air, °C
T_i	average of corn kernel surface and humid air temperature, °C
ΔT	effective temperature difference, °C
X	characteristic dimension, m

Greek symbols

β	coefficient of volumetric expansion, 1/ °C
γ	relative humidity, %
$\bar{\gamma}$	average relative humidity, %
λ	latent heat of vaporization, J/kg
μ_v	dynamic viscosity of humid air, kg/m.s
ρ_v	density of humid air, kg/m^3

1. INTRODUCTION

Corn is a popular food throghout the world in many forms. It is used in breakfast cereals in the western world (as corn flake) and it is a grain that can be eaten raw off the cob.

Open sun drying is the most primitive methods of corn kernels drying. Corn kernels drying involves a heat and mass transfer phenomenon in which heat energy supplied to the corn kernels surface is utilized in two different ways: (i) to increase the corn kernels temperature in the form of sensible heat and (i) to vaporize the moisture present in corn kernels through provision of the latent heat of vaporization. The removal of moisture from the interior of the corn kernels takes place due to induced vapor pressure difference between the corn kernel and surrounding medium. The moisture from the interior diffuses to the corn kernels surface to replenish the evaporated surface moisture.

The convective heat transfer coefficient is an important parameter in drying rate simulation since the temperature difference between the air and corn kernel varies with this coefficient. Sodha et al. [1] presented a simple analytical model based on simultaneous heat and mass transfer at the product surface and included the effect of wind speed, relative humidity, product thickness, and heat conducted to the ground for open sun drying and for a cabinet dryer. Miketinac et al. [2] studied the drying of thin layer of barley and formulated five models simulating the process of simultaneous heat and mass transfer. Depending upon the form of drying model the heat transfer coefficient was found to vary between 43 and 59 W/m^2 ^{o}C. Goyal and Tiwari [3] have studied heat and mass transfer in product drying systems and have reported the values of convective heat transfer coefficient for wheat and gram as 12.68 and 9.62 W/m^2 ^{o}C, respectively, by using the simple regression and 9.67 and 10.85 W/m^2 ^{o}C respectively, for same products while using the multiple regression technique. Anwar and Tiwati [4] studied the open sun drying of some crops (green chillies, green peas, white gram, onion flakes, potato slices and cauliflower) and found the values of convective heat transfer coefficients which were to vary from 3.71 – 25.98 W/m^{2o}C. Togrul [5] have determined the convective heat transfer coefficients of some crops dried under open sun conditions which were found to vary with a range of 0.768 to 3.292 W/m^2 ^{o}C. Akpinar [6] determined the convective heat transfer coefficient of various agricultural products, namely, mulberry, strawberry, apple, garlic, potato, pumpkin, eggplant, and onion under open sun drying. The convective heat transfer coefficient of these crops was found to vary from crop to crop with a range of 1.136 – 11.323 W/m^{2o}C. Togrul [7] determined the convective heat transfer coefficient of apricots in open sun drying conditions which were found to vary from 0.0374 to 2.046 W/m^{2o}C. Dilip Jain [8] studied the solar drying of Indian minor fish species, such as prawn (Macrobrachium lamarrei) and carp (chelwa) (Oxygaster bacaila). The convective mass transfer coefficients were found to vary from 8.958 to 0.402 μms^{-1} for prawn and from 7.613 to 0.320 μms^{-1}for chelwa fish. Jaishree Akhilesh Prasad [9] studied the drying of *Tinospora cordifolia (herb), Curcuma longa L. and Zingiber officinale (spices)* in open sun drying mode. The maximum values of convective heat transfer coefficient were found to be 3.9, 3.4 and 3.3 W/m^{2o}C for *T. cordifolia, C. longa L. and Z. officinale* under open sun drying, respectively. Kumar et al. [10] studied the drying of papad in open sun and indoor forced convection drying modes. The convective heat transfer coefficients of papad were found to be 3.54 and 1.56 W/m^2 ^{o}C under open sun drying and indoor forced convection drying modes respectively. Sahdev et al. [11] studied the open sun drying of vermicelli of different diameters and found the convective heat transfer coefficient to be 5.61 and 4.13 for vermiceli of diameter 2 mm and 1.25 mm respectively.

In the present research paper, the convective heat transfer coefficient has been found by determining the values of the constants (C and n) in the Nusselt number expression for corn kernels dried under open sun drying mode. This value would be helpful in designing a dryer to dry corn kernels to its optimum storage moisture level of about 16 %.

1. MATERIALS AND METHODS

Experimental set-up and Procedure

A circular shaped wire mesh tray of diameter 150 mm was used to accommodate the corn kernels. A digital weighing balance (Smart, Aqua Series) of 6 kg capacity having a least count of 0.1g was used to measure the mass of moisture evaporated. A non-contact (infra-red thermometer) thermometer (Raytek-MT4) having a least count of 0.2 ^{o}C with an accuracy of ± 2% on a full scale range of -1 to 400 ^{o}C was used to measure the corn kernels surface temperature. An eight channel digital temperature indicator (0-200^{o}C, least count of 0.1 ^{o}C) with a calibrated thermocouple was used to measure the ambient temperature. A digital hygrometer (model Lutron HT-315) was used to measure the relative humidity and temperature of air just above the corn kernels surface.

Experiments were conducted in the month of June 2013 for open sun drying mode in the climatic conditions of Rohtak (28^o 40': 29 05'N 76^o 13': 76^o 51'E). The corn kernels were kept on the weighing balance using the wire mesh tray. A digital hygrometer was kept just above the corn kernels surface with its probe facing downwards towards the corn kernels surface to measure the humidity and temperature of the air. Every time it was kept on 1 minute before reading the observations. All the observations were recorded at every 10 minute time intervals. The whole unit was kept in open sun at a place with negligible wind velocity. The difference in weight directly gave the quantity of water evaporated during that time interval. Average values of corn kernels surface temperature $\left(\overline{T_c}\right)$, exit air temperature $\left(\overline{T_e}\right)$ and relative humidity $\left(\overline{\gamma}\right)$ were calculated from the two consecutive values for that time interval and were used in the calculations. The photograph of the experimental set up under open sun drying mode is shown in Figure 1.

Figure 1: A photograph of experimental set-up for open sun drying mode.

Sample Preparation

Corn cobs were purchased from the local market and its grains (corn kernels) were separated from it. The corn kernels of 72.0 grams were used for open sun drying mode.

Thermal modeling

The convective heat transfer coefficient for open sun drying mode can be calculated using the expression for Nusselt number as [12, 10]:

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

or

$$h_c = \frac{K_v}{X} C(Gr\,\mathrm{Pr})^n \quad (1)$$

The rate of heat utilized to evaporate moisture is given as [13].

$$Q_e = 0.016 h_c [P(T_c) - \gamma P(T_e)] \quad (2)$$

On substituting h_c from equation (1), equation (2) becomes

$$Q_e = 0.016 \frac{K_v}{X} C(Gr\,\mathrm{Pr})^n [P(T_c) - \gamma P(T_e)] \quad (3)$$

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

$$m_{ev} = \frac{Q_e}{\lambda} t A_t = 0.016 \frac{K_v}{X\lambda} C(Gr\,\mathrm{Pr})^n [P(T_c) - \gamma P(T_e)] t A_t \quad (4)$$

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

$$\frac{m_{ev}}{Z} = C(Gr\,\mathrm{Pr})^n \quad (5)$$

Taking logarithm on both sides of equation (5)

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

This is the form of a linear equation,

$$Y = mX_0 + C_0$$

Where

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

$$X_0 = \ln(Gr\,\mathrm{Pr}), \qquad C_0 = \ln C$$

Thus, $C = e^{C_0}$

By using the data of Table 1, the values of Y and X_0 were evaluated for different time intervals and then the constants C and n were obtained from the above equations. The values of constants C and n were further used to evaluate convective heat transfer coefficient from Equation (1). The physical properties of humid air, i.e., specific heat (C_v), thermal conductivity (K_v), density (ρ_v), viscosity (μ_v) and partial vapor pressure were calculated using the following expressions [4, 10]:

$$C_v = 999.2 + 0.1434T_i + 1.101\times10^{-4}T_i^2 - 6.7581\times10^{-8}T_i^3 \tag{7}$$

$$K_v = 0.0244 + 0.7673\times10^{-4}T_i \tag{8}$$

$$\rho_v = \frac{353.44}{T_i + 273.15} \tag{9}$$

$$\mu_v = 1.718\times10^{-5} + 4.620\times10^{-8}T_i \tag{10}$$

$$P(T) = \exp\left[25.317 - \frac{5144}{(T + 273.15)}\right] \tag{11}$$

Where

$$T_i = \frac{\overline{T}_c + \overline{T}_e}{2}$$

The values of constants C and n have been determined by linear regression analysis by using measured data of the corn kernels and exit air temperature, exit air relative humidity and moisture evaporated during a certain time period. The following linear regression formulae have been used to calculate *C* and *n*

$$n = \frac{N_o\sum X_0Y - \sum X_0\sum Y}{N_o\sum X_0^{\,2} - (\sum X_0)^2} \tag{12}$$

and

$$C_0 = \frac{\sum X_0^{\,2}\sum Y - \sum X_0\sum X_0Y}{N_o\sum X_0^{\,2} - (\sum X_0)^2} \tag{13}$$

The experimental error were also calculated in terms of % uncertainty (internal + external).The following equations were used to evaluate % uncertainty [14]

$$U = \frac{\sqrt{\sigma_1^{\,2} + \sigma_2^{\,2} + \sigma_3^2 .... + \sigma_n^{\,2}}}{N} \tag{14}$$

Where σ is the standard deviation and is given as

$$\sigma = \sqrt{\frac{\sum(X_i - \overline{X}_i)^2}{N_0}} \tag{15}$$

Where X_i is the moisture evaporated and $(X_i - \overline{X}_i)$ is the deviation of the observations from the mean. N and N_o are the number of sets and number of observations in each set, respectively.

The % uncertainty was determined using the following expression.

$$\%\,\text{internal uncertainty} = \frac{U}{\text{Average of total number of observations}} \times 100 \quad (16)$$

The values of observations recorded for open sun drying mode are recorded in Tables 1 for corn kernels.

2. EXPERIMENTAL RESULTS AND DISCUSSION

Table 1: Observations for corn kernels under open sun drying mode

Drying time (min.)	Wt (gms)	$T_c\left({}^oC\right)$	$T_e\left({}^oC\right)$	$\gamma(\%)$	m_{ev} (gm)	$\overline{T_c}\left({}^oC\right)$	$\overline{T_e}\left({}^oC\right)$	$\overline{\gamma}(\%)$
0	72.0	34.2	34.4	0.5648	-	-	-	-
10	71.1	33.9	33.1	0.5219	0.0009	34.1	33.75	0.5434
20	69.5	34.8	34.7	0.5199	0.0016	34.4	33.92	0.5209
30	68.2	32.9	32.5	0.5206	0.0013	33.9	33.61	0.5203
40	67.6	33.6	34.7	0.5498	0.0006	33.3	33.58	0.5352
50	65.2	33.2	34.4	0.5626	0.0024	33.4	34.55	0.5562
60	64.2	35.2	34.9	0.5341	0.0010	34.2	34.68	0.5484
70	63.5	36.6	37.8	0.4885	0.0007	35.9	36.35	0.5113
80	62.6	37.8	38.2	0.4793	0.0009	37.2	37.96	0.4839
90	62.0	36.8	36.5	0.5085	0.0006	37.3	37.33	0.4939
100	61.2	37.0	38.1	0.4776	0.0008	36.9	37.32	0.4931
110	59.4	37.2	37.0	0.4953	0.0018	37.1	37.57	0.4865
120	58.8	36.9	36.5	0.5021	0.0006	37.1	36.76	0.4987
130	58.2	38.0	37.1	0.4888	0.0006	37.5	36.80	0.4955
140	57.8	37.9	38.2	0.4714	0.0004	38.0	37.64	0.4801
150	57.1	36.0	37.9	0.4857	0.0007	37.0	38.06	0.4786
160	56.4	36.8	37.7	0.4779	0.0007	36.4	37.82	0.4818
170	55.9	37.0	37.2	0.4757	0.0005	36.9	37.43	0.4768
180	55.1	37.0	38.9	0.3718	0.0008	37.0	38.06	0.4238
190	54.5	41.6	41.5	0.3820	0.0006	39.3	40.20	0.3769
200	54.1	42.8	44.1	0.3552	0.0004	42.2	42.78	0.3686
210	53.6	41.8	42.2	0.3520	0.0005	42.3	43.16	0.3536
220	52.7	38.6	39.7	0.4130	0.0009	40.2	40.96	0.3825
230	51.8	34.8	37.5	0.4738	0.0009	36.7	38.59	0.4434
240	50.9	31.0	31.9	0.4845	0.0009	32.9	34.69	0.4792
250	50.3	33.2	33.2	0.4628	0.0006	32.1	32.52	0.4737

The average of corn kernel surface temperature $\left(\overline{T}_c\right)$, exit air temperature $\left(\overline{T}_e\right)$ and exit air relative humidity $\left(\overline{\gamma}\right)$ were used to calculate the physical properties of the humid air which were further used to evaluate the values of Grashof number and Prandtl number. The values of ‘C’ and ‘n’ in equation (1) were obtained by simple linear regression analysis, and, thus the values of h_c were determined as tabulated in Table 2.

Table 2: Values of C, n and the convective heat transfer coefficients

	C	n	h_c (W/m^2 ^{o}C)	$h_{c\ avg}$ (W/m^2 ^{o}C)
corn kernels	0.99	0.24	2.45 – 5.16	3.91

The variation of convective heat transfer coefficient with respect to time for open sun drying mode is shown in Figures 2.

An estimate of internal uncertainty was carried out for experimental observations. The external uncertainty has also been calculated by taking into account the errors which occurred during measurements of mass evaporated, temperatures and relative humidity which were considered by taking the least count of all the measuring instruments. The value of percent uncertainty (internal+external) was found to be within 40 %.

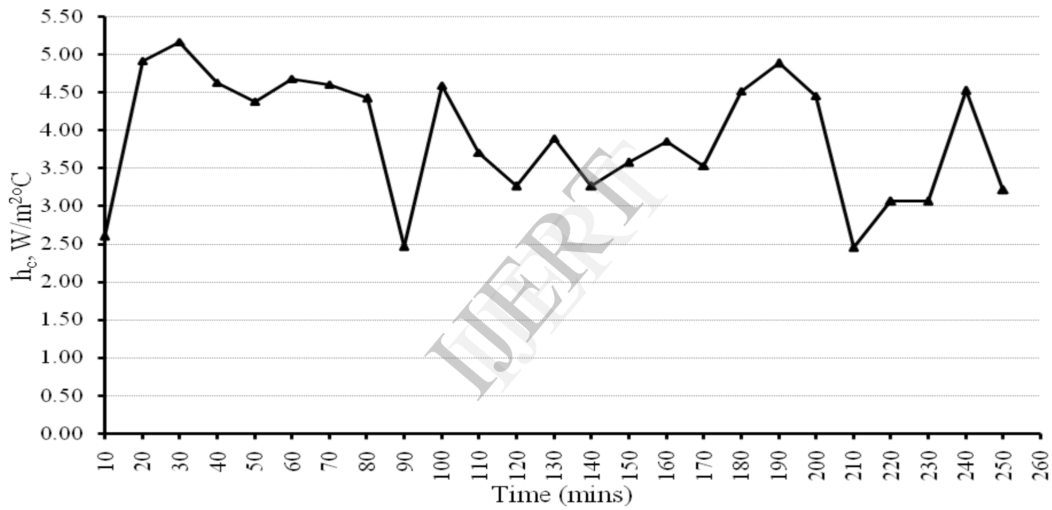

Figure 2: h_c vs time for corn kernels under open sun drying mode.

3. CONCLUSION

The convective heat transfer coefficients for corn kernels under open sun drying mode was determined using the values of the constants, ‘C’ and ‘n’ in the expression of Nusselt number by using the linear regression technique. The average value of convective heat transfer coefficient under open sun drying mode has been found to be 3.91 W/m^2 ^{o}C. The experimental error for open sun drying has been found to be within 40 %.

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