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Research Paper

CONVECTIVE HEAT TRANSFER COEFFICIENT FOR INDOOR FORCED CONVECTION DRYING OF CORN KERNELS

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In this present research paper, an attempt has been made to determine the convective heat transfer coefficient of corn kernels under indoor forced convection drying mode. The experiments were conducted in the month of May 2013 in the climatic conditions of Rohtak (28° 40’: 29 05’N 76° 13’: 76° 51’E). Corn kernels were dried from initial moisture content 43% dry-basis. Experimental data was used to evaluate the values of constants (C and n) in Nusselt number expression by using linear regression analysis and consequently convective heat transfer coefficient was determined. The convective heat transfer coefficient for corn kernels was found to be 1.04 W/m^2 °C. The experimental error in terms of percent uncertainty has also been calculated.

Keywords: Corn kernels, Convective heat transfer coefficient, Indoor forced convection drying

INTRODUCTION

Corn is one of the main agricultural products in many countries. It is an important industrial raw material in the starch industry (Haros and Surez, 1997; and Soponronnarit *et al.*, 1997a). It is also a grain that can be eaten raw off the cob. Traditionaly corn kernels are dried in open atmosphere exposing them to the sun. Open sun drying is the most primitive methods of corn kernels drying. The removal of moisture from the interior of the corn kernels takes place due to induced vapor pressure difference between the corn kernels and surrounding medium.

The convective heat transfer coefficient is an important parameter in drying rate simulation since the temperature difference between the air and corn kernels varies with this coefficient. Sodha *et al.* (1985) presented a simple analytical model based on simultaneous heat and mass transfer at the

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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. Goyal and Tiwari (1998) 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 °C, respectively, by using the simple regression and 9.67 and 10.85 W/m^2 °C respectively, for same products while using the multiple regression technique. Anwar and Tiwari (2001a) studied the drying of six crops (green chilies, green peas, white gram, onion flakes, potato slices and cauliflower) under forced convection drying mode. The values of convective heat transfer coefficients were found to vary between 1.31 and 12.80 W/m^2 °C and between 1.25 and 10.94 W/m^2 °C in indoor open and closed conditions under forced mode respectively. Akpinar (2004) determined the convective heat transfer coefficient of various agricultural products, namely, mulberry, strawberry, apple, garlic, potato, pumpkin, eggplant, and onion under indoor forced convection drying mode. The convective heat transfer coefficient of these crops was found to vary from crop to crop between 0.644-7.121 W/m^2 °C. Togrul (2003 and 2005) have determined the convective heat transfer coefficients of some crops dried under open sun conditions. Kumar *et al.* (2011) 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 °C under open sun drying and indoor forced convection drying modes respectively. Anwar *et al.* (2012) studied the drying of Indian goosberry (Embica officinalis) in three forms (shrede, slices and pieces) under forced convection mode. The values of convective heat transfer coefficient for shredded, slice and pieces forms were found to be 30.39, 25.88, and 18.67 W/m^2 °C respectively. Ravinder *et al.* (2012) studied the drying of vermicelli in indoor forced convection drying mode. The convective heat transfer coefficient was found to vary from 0.98-1.10 W/m^2 °C.

In the present research paper, the convective heat transfer coefficient has been found for corn kernels under indoor forced convection drying mode. The value would be helpful in designing a dryer to dry corn kernels to its optimum storage moisture level of about 16%.

MATERIALS AND METHODS

Experimental Set-Up and Procedure

A rectangular shaped wire mesh tray of dimension 196×155 mm^2 was used to accommodate the corn kernels. A digital weighing balance (Smart, Aqua Series) of 6 kg capacity having a least count of 0.1 g 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 °C with an accuracy of ± 2% on a full scale range of –1 to 400 °C was used to measure the surface temperature of corn kernels. An eight channel digital temperature indicator (0-200 °C, least count of 0.1 °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 exit air. A heat convector (Usha Shriram, model FH-812T, 230V) was used to blow hot air over the corn kernels surface during the forced convection mode.

Experiments were conducted in the month of May 2013 for indoor forced convection drying mode in the climatic conditions of Rohtak (28° 40’: 29 05’N 76° 13’: 76° 51’E). The corn kernels were kept on the weighing balance using the wire mesh tray. A digital hygrometer was kept after corn kernels surface with its probe facing the exit air to measure the humidity and temperature of the exit air. Every time it was kept on 1 minute before reading the observations. The air velocity of heat convector was measured with the help of digital anemometer (model Lutron AM-4201) and it was observed to be 1.5 m/s. All the observations were recorded at every 10 minute time interval. The difference in weight directly gave the quantity of water evaporated during that time interval. Average values of corn kernels surface temperature $(\overline{T_c})$, exit air temperature $(\overline{T_e})$ and relative humidity $(\overline{\text{¥}})$ 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 indoor forced convection drying mode is shown in Figure 1. The experiment was repeated twice for obtaining more accurate results.

Figure 1: A Photograph of Experimental Set-Up for Indoor Forced Convection Drying Mode

Sample Preparation

Corn cobs were purchased from the local market and grains (corn kernels) were separated from it. The corn kernels of 82.9 grams were used for indoor forced convection drying mode.

Thermal Modeling

The convective heat transfer coefficient for indoor forced convection drying mode has been calculated by using the expression for Nusselt number as (Tiwari and Suneja, 1977; and Kumar *et al.*, 2011):

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

or

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

The rate of heat utilized to evaporate moisture is given as (Malik *et al.*, 1982)

$$Q_e = 0.016 h_c [P(T_c) - \text{¥}\, P(T_e)] \quad ...(2)$$

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

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

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

$$m_{ev} = \frac{Q_e}{\text{a}} t A_t$$

$$= 0.016 \frac{K_v}{X \text{a}} C(\mathrm{Re\,Pr})^n [P(T_c) - \text{¥}\, P(T_e)]\, t A_t \quad ...(4)$$

Let $0.016\frac{K_v}{X^{\text{a}}}\left[P(T_c)-\text{¥}\,P(T_e)\right]t\,A_t=Z$

$$\frac{m_{ev}}{Z}=C(\mathrm{RePr})^n \quad ...(5)$$

Taking logarithm on both sides of equation

$$\ln\left[\frac{m_{ev}}{Z}\right]=\ln C+n\ln(\mathrm{RePr}) \quad ...(6)$$

This is the form of a linear equation,

$$Y=mX_0+C_0$$

where

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

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

Thus, $C=e^{C_0}$

The experimental constants (*C* and *n*) were obtained from the above equations which were further used to determine the convective heat transfer coefficient.

The physical properties of humid air, i.e., specific heat (C_v), thermal conductivity (K_v), density (°_v), viscosity («_v) and partial vapor pressure were calculated using the following expressions (Anwar and Tiwari, 2001b; and Kumar *et al.*, 2011):

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

$$K_v=0.0244+0.7673\times10^{-4}T_i \quad ...(8)$$

$$\text{°}_v=\frac{353.44}{T_i+273.15} \quad ...(9)$$

$$\text{«}_v=1.718\times10^{-5}+4.620\times10^{-8}T_i \quad ...(10)$$

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

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*

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

and

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

The experimental error was also calculated in terms of % uncertainty (internal + external). The following equations were used to evaluate % uncertainty (Nakra and Choudhary, 1991).

$$U=\frac{\sqrt{\pm_1^{\,2}+\pm_2^{\,2}+\pm_3^{\,2}....+\pm_n^{\,2}}}{N} \quad ...(14)$$

where ± is the standard deviation and is given as:

$$\pm=\sqrt{\frac{\sum(X_i-\overline{X}_i)^2}{N_0}} \quad ...(15)$$

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.

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

EXPERIMENTAL RESULTS AND DISCUSSION

The values of observations for indoor forced convection drying mode are recorded in Table 1.

Table 1: Observations for Corn Kernels Under Indoor Forced Convection Drying Mode

Drying Time (min.)	Wt (gms)	$T_c(^oC)$	$T_e(^oC)$	¥(%)	m_{ev}(gm)	$\overline{T}_c(^oC)$	$\overline{T}_e(^oC)$	$\overline{¥}$(%)
0	82.9	36.9	38.79	0.4131	-	-	-	-
10	80.4	59.4	62.94	0.1045	0.0025	48.15	50.87	0.2588
20	77.5	60.4	64.81	0.0891	0.0029	59.90	63.88	0.0968
30	75.1	60.8	65.30	0.0853	0.0024	60.60	65.06	0.0872
40	72.5	60.9	65.32	0.0826	0.0026	60.85	65.31	0.0840
50	69.9	60.9	65.64	0.0812	0.0026	60.90	65.48	0.0819
60	67.8	61.0	65.71	0.0801	0.0021	60.95	65.68	0.0807
70	65.3	60.9	65.70	0.0815	0.0025	60.95	65.71	0.0808
80	63.0	60.8	65.36	0.0775	0.0023	60.85	65.53	0.0795
90	60.6	60.9	65.32	0.0732	0.0024	60.85	65.34	0.0754
100	58.2	60.4	64.56	0.0749	0.0024	60.65	64.94	0.0741
110	56.1	60.3	64.62	0.0729	0.0021	60.35	64.59	0.0739
120	54.1	60.2	64.56	0.0710	0.0020	60.25	64.59	0.0720
130	52.1	60.3	64.54	0.0702	0.0020	60.25	64.55	0.0706
140	50.3	61.0	65.33	0.0690	0.0018	60.65	64.94	0.0696
150	48.4	61.3	65.81	0.0606	0.0019	61.15	65.57	0.0648
160	46.5	61.4	66.01	0.0579	0.0019	61.35	65.91	0.0593
170	44.8	61.7	66.45	0.0540	0.0017	61.55	66.23	0.0560

The average of corn kernels surface temperature $(\overline{T}_c)$, exit air temperature $(\overline{T}_e)$ and exit air relative humidity $(\overline{¥})$ were used to calculate the physical properties of the humid air which were further used to evaluate the values of Reynolds 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 given in Table 2.

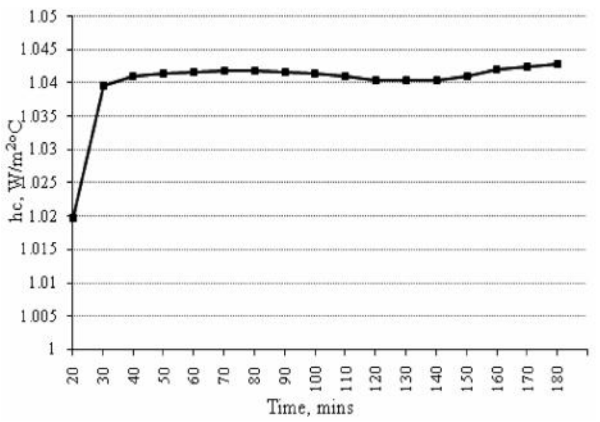
The convective heat transfer coefficients for corn kernels under indoor forced convection drying mode has been observed to be 1.04 W/m^2 °C. It can be seen from the Table 2 that the convective heat transfer coefficient does not change much. The variation of convective heat transfer coefficient with respect to time for indoor forced convection drying mode is

Table 2: Values of C, n and Convective Heat Transfer Coefficients

	C	**n**	$h_{c,av}$ **(W/m² °C)**	h_c **(W/m² °C)**
Corn Kernels	1.00	0.20	1.04	1.0197-1.0428

shown in Figure 2. From the Figure 2, it is observed that the convective heat transfer coefficient for corn kernels under forcd convection drying mode is observed to be almost constant.

Figure 2: h_c vs Time for Corn Kernels Under Indoor Forced Convection Drying Mode



The experimental errors were calculated in terms of percent uncertainty (internal + external) for the mass of water evaporated. The value of percent uncertainty (internal + external) was found to be within 15%.

CONCLUSION

The convective heat transfer coefficient for corn kernels under indoor forced convection drying mode was determined using the values of the constants, 'C' and 'n' in the Nusselt number expression by using the linear regression technique. The convective heat transfer coefficient was observed to be 1.04 W/m^2 °C. The experimental error was found to be within 15%.

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