Convective heat transfer coefficient for indoor forced convection drying of vermicelli

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ABSTRACT

In this present research paper, an attempt has been made to determine the convective heat transfer coefficient of vermicelli under indoor forced convection drying mode. The experiments were conducted in the month of March 2012 in the climatic conditions of Rohtak (28° 40': 29 05'N 76° 13': 76° 51'E). 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 coefficients were determined. The convective heat transfer coefficient values for vermicelli were found to vary from 0.98 to 1.10 W/m² °C. The experimental error in terms of percent uncertainty has also been calculated.

Keywords: - **Convective heat transfer coefficient, Indoor forced convection drying, Vermicelli**.

NOMENCLATURE

A_t area of rectangular wire mesh tray, m²

C constant

C_v specific heat of humid air, J/kg °C

h_c convective heat transfer coefficient, W/m² °C

$h_{c,av}$ average convective heat transfer coefficient, W/m² °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 $= \mu_v \, C_v / K_v$

Re Reynolds number $= \rho \, V \, X / \mu$

$P(T)$ partial vapor pressure at temperature T, N/m²

Q_e rate of heat utilized to evaporate moisture, J/m² s

t time, s

T_v vermicelli surface temperature, °C

T_e temperature just above vermicelli surface, °C

$\overline{T}_v$ average vermicelli surface temperature, °C

$\overline{T}_e$ average temperature of humid air, °C

T_i average of vermicelli surface and humid air temperature, °C

X characteristic dimension, m

V air velocity, m/s

Greek symbols

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

Vermicelli is a traditional food item which is prepared in household level by extruding the dough (wheat semolina with suitable quantity of water contents) with a cylindrical hand extruder. The extruded product is dried by different means. Open sun drying is the most primitive methods of vermicelli drying. The removal of moisture from the interior of the vermicelli takes place due to induced vapor pressure difference between the vermicelli and surrounding medium.

The convective heat transfer coefficient is an important parameter in drying rate simulation since the temperature difference between the air and vermicelli 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. Goyal and Tiwari [2] 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 Tiwari [3] 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 ^{o}C and between 1.25 and 10.94 W/m^{2o}C in indoor open and closed conditions under forced mode respectively. Akpinar [4] 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 ^{o}C. Togrul [5, 6] have determined the convective heat transfer coefficients of some crops dried under open sun conditions. Kumar et al. [7] 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.

In the present research paper, the convective heat transfer coefficients have been found for vermicelli of diameter 2mm dried under indoor forced convection drying mode. These values would be helpful in designing a dryer to dry vermicelli to its optimum storage moisture level of about 9%.

2. EXPERIMENTAL SET-UP AND PROCEDURE

A rectangular shaped wire mesh tray of dimension 196×155 mm^2 was used to accommodate the vermicelli. 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 ^{o}C with an accuracy of ± 2% on a full scale range of -1 to 400 ^{o}C was used to measure the surface temperature of vermicelli. An eight channel digital temperature indicator (0-200°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 exit air. A heat convector (Usha Shriram, model FH-812T, 230V) was used to blow hot air over the vermicelli surface during the forced convection mode.

Experiments were conducted in the month of March 2012 for indoor forced convection drying mode in the climatic conditions of Rohtak (28° 40': 29 05'N 76° 13': 76° 51'E). The vermicelli was kept on the weighing balance using the wire mesh tray. A digital hygrometer was kept after vermicelli 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 5 minute time interval. The difference in weight directly gave the quantity of water evaporated during that time interval. Average values of vermicelli surface temperature $\left(\overline{T_v}\right)$, 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 indoor forced convection drying mode is shown in Fig. 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

3. SAMPLE PREPARATION

Vermicelli was freshly prepared by taking wheat semolina flour mixed with 30% of water content per kg of vermicelli weight. The flour was purchased locally, and that fraction of flour which passes through a 40-mesh sieve (610 microns) was used for making vermicelli. Dough was made and extruded in cylindrical hand extruder of 59 mm diameter and 118 mm height (Fig. 2). The bottom of extruder is attached with steel die plates of 57 mm diameter having holes of 2 mm diameter (Fig. 3). The freshly prepared vermicelli of 25.7 grams and 24.5 grams of 2mm diameter respectively were used for indoor forced convection drying mode.
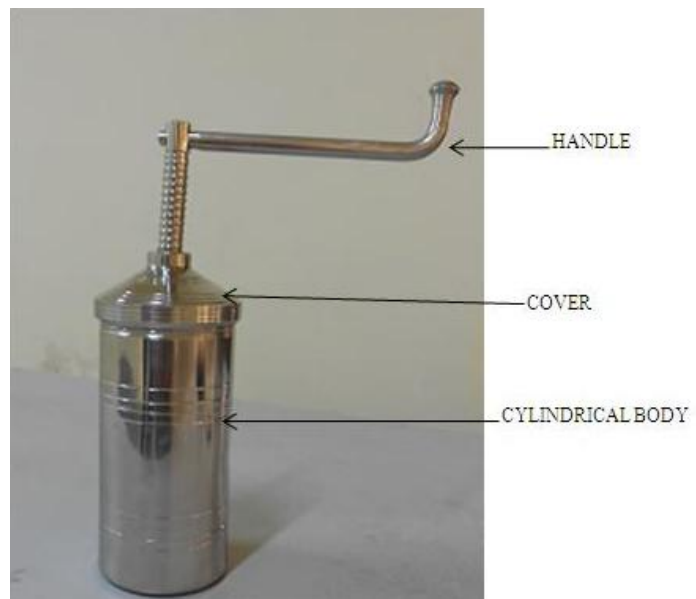

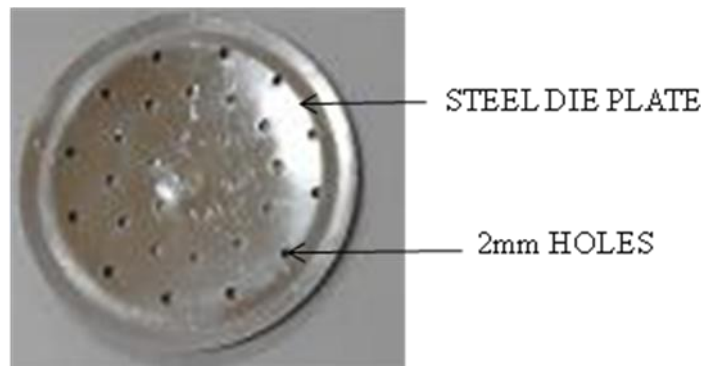Figure 2: A photograph of cylindrical hand extruder

Figure 3: A photograph of Steel die plate

4. THERMAL MODELING

The convective heat transfer coefficient for indoor forced convection drying mode has been calculated by using the expression for Nusselt number as [7, 8]:

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

Or

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

The rate of heat utilized to evaporate moisture is given as [9]

$$: Q_e = 0.016 \, h_c \left[P(T_v) - \gamma \, P(T_e) \right] \tag{2}$$

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

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

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)

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

Let: $0.016 \dfrac{K_v}{X\lambda} \left[P(T_v) - \gamma \, P(T_e) \right] t \, A_t = Z$

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

Taking logarithm on both sides of equation (5)

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

This is the form of a linear equation,

$$: Y = mX_0 + C_0$$

Where

$$: Y = \ln\left[\frac{m_{ev}}{Z}\right], \qquad : m = n, \qquad : X_0 = \ln(\text{Re Pr}), \qquad : C_0 = \ln C$$

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 (ρ_v), viscosity (μ_v) and partial vapor pressure were calculated using the following expressions [10, 7]:

$$: C_v = 999.2 + 0.1434 T_i + 1.101 \times 10^{-4} T_i^2 - 6.7581 \times 10^{-8} T_i^3 \qquad (7)$$

$$: K_v = 0.0244 + 0.7673 \times 10^{-4} T_i \qquad (8)$$

$$: \rho_v = \frac{353.44}{T_i + 273.15} \qquad (9)$$

$$: \mu_v = 1.718 \times 10^{-5} + 4.620 \times 10^{-8} T_i \qquad (10)$$

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

Where

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

The values of constants C and n have been determined by linear regression analysis by using measured data of the vermicelli 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*

$$: n = \frac{N_o \sum X_0 Y - \sum X_0 \sum Y}{N_o \sum X_0^{\,2} - \left(\sum X_0\right)^2} \qquad (12)$$

And

$$: C_0 = \frac{\sum X_0^{\,2} \sum Y - \sum X_0 \sum X_0 Y}{N_o \sum X_0^{\,2} - \left(\sum X_0\right)^2} \qquad (13)$$

The experimental error were also calculated in terms of % uncertainty (internal + external).The following equations were used to evaluate % uncertainty [11].

$$: U = \frac{\sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 \ldots + \sigma_n^2}}{N} \qquad (14)$$

Where σ is the standard deviation and is given as

$$: \sigma = \sqrt{\frac{\Sigma(X_i - \overline{X}_i)^2}{N_0}} \qquad (15)$$

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.

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

5. EXPERIMENTAL RESULTS AND DISCUSSION

The values of observations for indoor forced convection drying mode are recorded in Tables 1 and 2 for vermicelli of 2 mm diameter.

TABLE 1
Observations for vermicelli under indoor forced convection drying mode (Set1:28-03-2012)

Drying time (min.)	Wt (gms)	$T_v(^oC)$	$T_e(^oC)$	$\gamma(\%)$	m_{ev}(gm)	$\overline{T_v}(^oC)$	$\overline{T_e}(^oC)$	$\overline{\gamma}(\%)$
0	25.7	31.7	33.18	0.3225	-	-	-	-
5	24.4	35.2	34.99	0.2805	1.3	33.4	34.09	0.3015
10	23.5	37.1	35.57	0.2642	0.9	36.1	35.28	0.2724
15	22.8	38.4	35.90	0.2619	0.7	37.8	35.74	0.2631
20	22.3	38.7	36.25	0.2550	0.5	38.6	36.08	0.2585
25	21.9	39.1	36.18	0.2531	0.4	38.9	36.22	0.2541
30	21.5	39.4	36.11	0.2525	0.4	39.3	36.15	0.2528
35	21.2	39.5	36.43	0.2493	0.3	39.5	36.27	0.2509
40	20.9	39.7	36.53	0.2482	0.3	39.6	36.48	0.2488
45	20.7	41.1	36.78	0.2432	0.2	40.4	36.66	0.2457
50	20.5	39.8	36.44	0.2461	0.2	40.4	36.61	0.2447
55	20.3	39.7	36.40	0.2482	0.2	39.7	36.42	0.2472
60	20.1	39.9	36.46	0.2457	0.2	39.8	36.43	0.2470
65	19.9	40.0	36.31	0.2485	0.2	40.0	36.39	0.2471

TABLE 2

Observations for vermicelli under indoor forced convection drying mode (Set2:29-03-2012)

Drying time (min.)	Wt (gms)	$T_v(^oC)$	$T_e(^oC)$	$\gamma(\%)$	m_{ev}(gm)	$\overline{T_v}(^oC)$	$\overline{T_e}(^oC)$	$\overline{\gamma}(\%)$
0	24.5	31.48	30.98	0.3640	-	-	-	-
5	23.1	34.70	33.40	0.3150	1.4	33.1	32.19	0.3395
10	22.2	35.35	33.75	0.3029	0.9	35.0	33.58	0.3090
15	21.6	36.43	34.45	0.2917	0.6	35.9	34.10	0.2973
20	21.1	36.78	34.17	0.2953	0.5	36.6	34.31	0.2935
25	20.7	37.45	33.76	0.2998	0.4	37.1	33.97	0.2976
30	20.3	37.80	33.89	0.2984	0.4	37.6	33.83	0.2991
35	20.0	37.75	33.90	0.2963	0.3	37.8	33.90	0.2974
40	19.7	37.85	34.36	0.2907	0.3	37.8	34.13	0.2935
45	19.5	37.58	34.66	0.2905	0.2	37.7	34.51	0.2906
50	19.3	38.23	34.47	0.2865	0.2	37.9	34.57	0.2885
55	19.1	38.28	34.72	0.2827	0.2	38.23	34.60	0.2846
60	18.9	38.40	34.59	0.2822	0.2	38.3	34.66	0.2825
65	18.8	39.50	34.73	0.2787	0.1	39.0	34.66	0.2805
70	18.6	38.25	34.60	0.2784	0.2	38.9	34.67	0.2786
75	18.5	38.33	34.60	0.2804	0.1	38.3	34.60	0.2794
80	18.4	38.65	34.46	0.2768	0.1	38.5	34.53	0.2786

The average of vermicelli surface temperature $\left(\overline{T_v}\right)$, 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 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 3.

TABLE 3

Values of C, n and convective heat transfer coefficients

Diameter (2mm)	C	n	h_c(W/m^2 ^oC)
Set 1	1.00	0.21	1.09 – 1.10
Set 2	0.99	0.20	0.98 – 0.99

The convective heat transfer coefficients for vermicelli under indoor forced convection drying mode have been observed to vary from 0.98 to 1.10 W/m^2 ^oC. This variation could be due to change in operating conditions. It can be seen from Table 3 that the convective heat transfer coefficient does not change much for both the sets. The variation of convective heat transfer coefficient with respect to time for indoor forced convection drying mode is shown in Fig. 4 and 5.
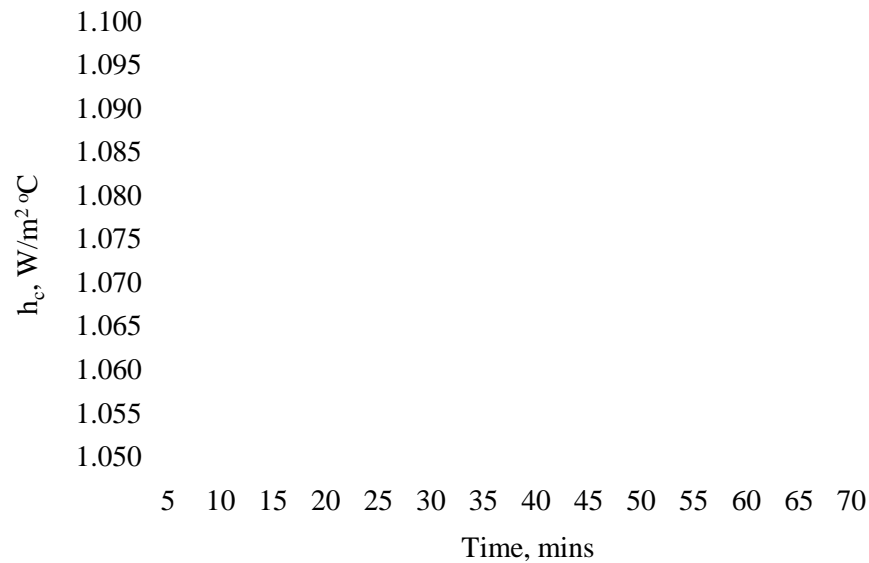
Figure 4: h_c vs time for vermicelli under indoor forced convection drying mode (set 1)
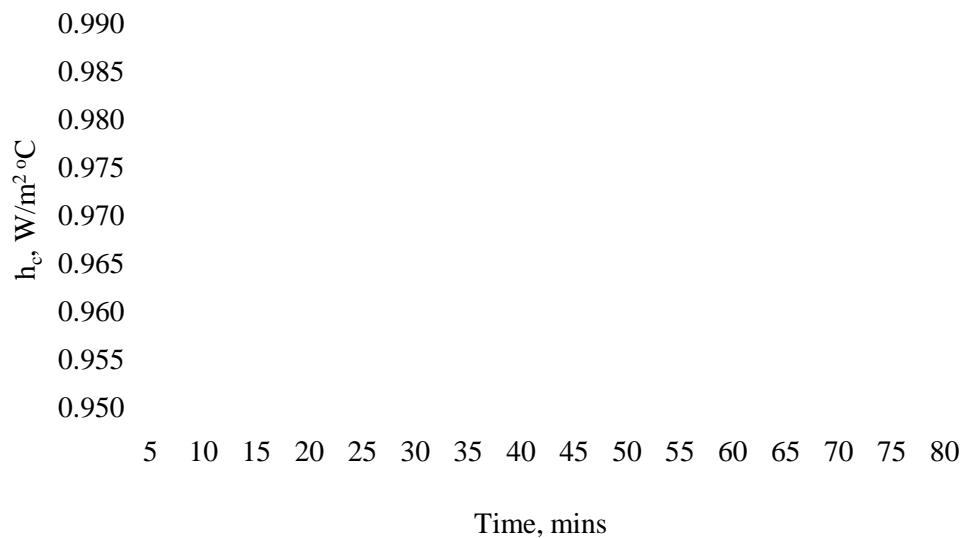

Figure 5: h_c vs time for vermicelli under indoor forced convection drying mode (set 2)

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 with in 79.87 %.

6. CONCLUSION
The convective heat transfer coefficients for vermicelli under indoor forced convection drying mode were 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 coefficients were observed to vary from 0.98 to 1.10 W/m^2 ^{o}C. The experimental errors were found to be within 79.87 %.

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