American Journal of

Food Technology

ISSN 1557-4571

Academic Journals Inc.

www.academicjournals.com

American Journal of Food Technology 1 (1): 1-18, 2006
ISSN 1557-4571

Effect of Mass on Convective Heat Transfer Coefficient During Onion Flakes Drying

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Abstract: In this present study an open sun and greenhouse drying of onion flakes has been performed to study the effect of mass on convective heat transfer coefficient. Three sets of experiments with total quantity of onion as 300, 600 and 900 g were done. The onion was continuously dried for 33 h both in open sun and in the roof type even span greenhouse with floor area of 1.2×0.78 m^2. Experiments were carried out during the months of October to December 2003 at IIT Delhi (28°35'N 72°12'E). Experiments were started at 8 am. The data obtained from experimentation under open sun and greenhouse conditions have been used to determine values of the constant 'C' and exponent 'n' by regression analysis and consequently, convective heat transfer coefficient. It is observed that there is a significant effect of mass on convective heat transfer coefficient for open as well as greenhouse drying. It is also observed that the rate of moisture evaporation in case of greenhouse drying is more than that in open sun drying during the off sunshine hours due to the stored energy inside the greenhouse. The experimental observations were analyzed in terms of percentage uncertainty also.

Key words: Convective heat transfer coefficient, onion flakes, greenhouse drying

Introduction

Onion, *Allium cepa*, L., is considered as one of the most important crops in all countries. Onion ranks third highest in production in the world among seven major vegetables, namely onion, garlic, cauliflower, green peas, cabbage, tomato and green beans. The four major onion producing countries in the world are China with largest production of 3.93 million tones, followed by India with 3.35 million tones, USA 2.45 million tones and Turkey 1.55 million tones. In India, about 35-40% of onion is lost during post harvest, due to the lack of proper processing and storage facilities (Sarsavadia *et al*., 1999). In India, deterioration of considerable quantities of onion takes place during storage operation. Various preservative methods have been employed to minimize this loss. The most primitive method employed in preserving onion deterioration is that onion flakes are spread on the ground such as wheat, raisins, fig or apricot, exposed to the sun in order to be dried. This method is commonly known as Open Sun Drying (OSD). The dried crop can be stored for a considerable period without the fear of its deterioration. The rate of drying (moisture evaporation) depends on a number of external parameters (solar radiation, ambient temperature, wind velocity and relative humidity) and internal parameters (initial moisture contents, type of crops, crop absorptivity, mass of product per unit exposed area etc.). An advanced and alternative method to the traditional techniques is Greenhouse

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Drying (GHD), in which the product is placed in trays receiving solar radiation through the plastic cover, while moisture is removed by natural convection or forced air flow (Condorí and Luis, 1998). This double function, greenhouse and dryer, improves the rate of the initial investment (Condorí *et al*., 2001), thus maintaining the good quality, increasing the storage capacity and reducing the wastage of the crop simultaneously (Tiwari, 2003).

Mathematical modeling of crops drying under solar energy is a multifaceted problem relating simultaneous heat and mass transfer in a nonisotropic and nonhomogeneous nature of the agricultural products along with their irregular shape and changes in shape during drying of crop. Convective heat transfer coefficient is one of the most decisive parameters required for analysis and simulation of the drying process (Thompson *et al*., 1968.). Sodha *et al.* (1985) 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. Smith and Sokhansanj (1990) have developed a natural convection heat transfer model in which the density of air was assumed to be a function of temperature and absolute humidity. Ratti and Crapiste (1995) evaluated the heat transfer coefficient under forced convection from the data on crop drying and heat and mass balances. The experimental heat transfer coefficients were correlated by dimensionless expressions with Nusselt and Reynolds numbers. The experimental heat transfer coefficient values ranged from 25 to 90 $Wm^{-2} K^{-1}$ for potatoes, apples and carrots. Goyal and Tiwari (1998) have studied heat and mass transfer in crop drying systems and have reported the values of convective heat transfer coefficient for wheat and gram as 12.68 and 9.62 $Wm^{-2}\,°C^{-1}$, respectively, by using the simple regression and 9.67 and 10.85, respectively, for the same crops while using the multiple regression technique. Anwar and Tiwari (2001b) determined the convective heat transfer under open sun drying by using the linear regression technique. However, their study was limited to constant rate drying from 11 to 13.30 h of the day for the month of May and June for composite climate of New Delhi. Further they have reported that the value of convective heat transfer coefficient is of the order of 14.0 $Wm^{-2}\,°C^{-1}$. Anwar and Tiwari (2001a) evaluated the convective heat transfer coefficients for some crops under a simulated condition of forced mode in indoor open and closed conditions. Jain and Tiwari (2003) evaluate the convective heat transfer coefficients for open sun drying for various crops and they developed a mathematical model to predict the crop temperature, moisture removal and solair temperature for a steady state condition.

The present studies were undertaken to determine convective heat transfer coefficients for different mass at each stage of drying time for onion flakes with the following conditions:

- Open Sun Drying (OSD) under natural convection.
- Greenhouse Drying (GHD) under natural convection.
- Greenhouse Dying (GHD) under forced convection.

The crop with high moisture content i.e., onion, is taken to see the effect of greenhouse on continuous drying of onion under natural and forced mode and the results have been compared with the open sun drying.

Materials and Methods

Experimental Set up

Different mass of onion flakes were kept in wire mesh tray having dimensions of 0.4×0.24 m^2. Three sets of experiment with total quantity of onion flakes as 300, 600 and 900 g were done. The thickness of onion flakes of 3 mm was spread as thin layers were used for each set of experimentation. A roof type even span greenhouse with 1.20×0.78 m^2 effective floor covering area was made of PVC

Fig. 1: Onion drying under opens sun and natural convection mode in greenhouse

Fig. 2: Onion drying under force convection mode in greenhouse

pipe and UV film covering. The central height and height of the walls were 0.60 and 0.40 m, respectively. An air vent with an effective opening of 0.0722 m^2 was provided at the roof for natural convection. The experimental set up for open sun and greenhouse drying in the natural mode is shown in Fig. 1. For forced convection a fan of 120 mm sweep diameter with air velocity 5 m s^{-1} was provided on the sidewall of the greenhouse during the experiments Fig. 2. The orientation of the greenhouse was taken as east-west during the experiments.

Instrumentation

A six-channel digital temperature indicator with least count of 0.1°C (accuracy ±0.1%) having 125°C range with calibrated copper-constantan thermocouples was used to measure the onion and air temperature. To measure the relative humidity a digital humidity meter (model Lutron HT-3003) was used. It had a least count of 0.1% relative humidity with accuracy of ±3% on the full-scale range of 5-99.9% of relative humidity. A top loading digital balance of 6 kg weighing capacity, having a least count of 0.1 g with ±2% on the full scale was used to weight the sample during drying.

Sample Preparation

Fresh onions were peeled and cut with the help of hand slicer in the form of flakes of 3 mm thickness. The same sizes of samples were maintained simultaneously for open sun drying and inside the greenhouse in all cases.

Experimentation

Experiments were carried out during the months of October to December 2003 at IIT Delhi (28°35'N 72°12'E). The prepared samples of onion were kept in the wire mesh tray for the experiments. Observations were taken for open sun and inside the greenhouse under natural as well as forced mode from 8 am at every hour interval for the 33 h of continuous drying. Natural convection under GHD was done with the air vent provided at the roof of the greenhouse. Experiments in the forced mode under GHD were conducted by providing the ventilating fan on the sidewall of the greenhouse.

The data of the experimental observations for the open sun and greenhouse drying for open as well as both modes natural and forced are presented in Table 1-9.

Table 1: Experimental data and results for convective heat transfer coefficient for onion drying under open sun on Oct 3-4, 2003 (300 g)

Time	T_c (°C)	T_e (°C)	m_{ev}x10^{-3} kg	γ (%)	Gr×10^5	Pr	C	n	Nu	h_c (Wm^{-2} °C^{-1})
8-9am	28.6	27.2	16.5	27	2.61	0.69	1.234	0.087	3.54	1.25
9-10am	31.8	29.5	26.6	32.4	3.26	0.69			3.61	1.29
10-11am	41.9	43.8	40.4	23.5	4.02	0.69			3.68	1.35
12-Nov	41.5	44.1	40.8	31	3.86	0.69			3.67	1.35
12-1pm	43.5	45.8	36.5	20.4	4.52	0.69			3.72	1.38
1-2pm	46.7	43.1	23	22.7	5.97	0.69			3.81	1.41
2-3pm	47.3	44.7	17.7	26.6	5.35	0.69			3.77	1.4
3-4pm	44.5	46.3	11.8	25.3	4.23	0.69			3.69	1.37
4-5pm	41.1	43	6.7	37	3.3	0.69			3.62	1.33
5-6pm	35.1	37.4	2.6	48.6	2.56	0.69			3.54	1.28
6-7pm	29.9	32	0.7	54.6	2.09	0.69			3.47	1.24
7-8pm	29.8	31.7	0.2	59	1.87	0.69			3.44	1.23
8-9pm	30.8	32.6	0.1	59.6	1.84	0.69			3.44	1.23
9-10pm	31.5	33.5	0.2	58.3	1.98	0.69			3.46	1.24
10-11pm	30.9	33.2	0.3	53	2.25	0.69			3.5	1.25
12-Nov	31.2	33	0.6	54.7	2	0.69			3.46	1.24
12-1am	31.2	32.8	0.1	68.5	1.51	0.69			3.38	1.21
1-2am	31	32.7	0.1	73.5	1.4	0.69			3.36	1.2
2-3am	29.3	31.2	0.2	70.3	1.55	0.69			3.39	1.2
3-4am	27.9	29.6	0.3	61	1.69	0.69			3.41	1.21
4-5am	26.5	28.1	0.5	64.5	1.53	0.69			3.38	1.19
5-6am	26.1	27.5	0.6	61.3	1.5	0.69			3.38	1.19
6-7am	29	30.5	0.1	60	1.65	0.69			3.4	1.21
7-8am	32.6	34.5	1	48.7	2.28	0.69			3.5	1.26
8-9am	49.2	46.4	4.6	40.8	5.03	0.69			3.75	1.4
9-10am	41.3	38.7	4.5	35.5	4.18	0.69			3.69	1.35
10-11am	44.4	42.7	4.2	33.3	4.14	0.69			3.69	1.36
12-Nov	45.1	43.7	3	27.8	4.32	0.69			3.7	1.37
12-1pm	45.9	45.1	2.6	25	4.26	0.69			3.7	1.37
1-2pm	49.4	43.9	2.2	23.8	7.37	0.69			3.88	1.44
2-3pm	47	43.5	1.3	24.6	5.88	0.69			3.8	1.41
3-4pm	46.1	46.7	1.1	28.8	3.88	0.69			3.67	1.36
4-5pm	43.4	44.3	0.8	38.1	3.15	0.69			3.6	1.33

Numerical Computation

Determination of Convective Heat Transfer Coefficient

The convective heat transfer coefficient (h_c) under natural convection can be evaluated as (Anwar and Tiwari, 2001a; Jain and Tiwari, 2003):

$$h_c = \frac{k}{X_0} C(GrPr)^n \tag{1a}$$

And under forced convection can be defined as:

$$h_c = \frac{k}{X_0} C(RePr)^n \tag{1b}$$

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

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

On substituting h_c from Eq. 1 and Eq. 2 becomes:

$$\dot{Q}_e = 0.016 \frac{k}{X_0} C(GrPr)^n [P(T_c) - \gamma P(T_e)] \tag{3}$$

Evaporated moisture can be determined by dividing Eq. 3 with the latent heat of vaporization (λ) and multiplying the area of Onion drying tray (A_t) and time interval (t):

$$m_{ev} = \frac{\dot{Q}_e}{\lambda} A_t t = 0.016 \frac{k}{X_0 \lambda} C(GrPr)^n [P(T_c) - \gamma P(T_e)] A_t t \tag{4}$$

Let $0.016 \frac{k}{X_0 \lambda}[P(T_c) - \gamma P(T_e)]t\, A_t = Z$ 7 than Eq. 4 becomes:

$$\frac{m_{ev}}{Z} = C(GrPr)^n \tag{5}$$

Taking logarithm on both sides Eq. 5 can be written:

$$\ln \frac{m_{ev}}{Z} = \ln C + n \ln(GrPr) \tag{6a}$$

This is the form of a linear equation:

$$y = mx + c \tag{6b}$$

Where:

$$y = \ln \frac{m_{ev}}{Z} \quad \text{and} \quad x = \ln[\text{Gr Pr}] \tag{7a}$$

With

$$m = n \quad \text{and} \quad c = \ln[C] \text{ gives } C = e^c \tag{7b}$$

Similarly in the case of forced convection mode:

$$y = \ln \frac{m_{ev}}{Z} \quad \text{and} \quad x = \ln[\text{Re Pr}] \tag{8a}$$

With

$$m = n \text{ and } c = \ln[C] \text{ gives } C = e^c \tag{8b}$$

By using the data from Table 1 to 9 for T_c, T_e γ and m_{ev}, the values of y and x can be evaluated for different time interval and then the constant 'C' and exponent 'n' can be obtained from above Eq. 7 and 8 for natural and forced mode of drying. The constants 'C' and 'n' will be further used to evaluate convective heat transfer coefficient from Eq. 1 under natural and forced convection mode (Table 1-9).

Table 2: Experimental data and results for convective heat transfer coefficient for onion drying under natural mode on Oct 3-4, 2003 (300 g)

Time	T_c (°C)	T_e (°C)	m_{ev}x10^{-3} kg	γ (%)	Gr×10^5	Pr	C	n	Nu	h_c (Wm^{-2} °C^{-1})
8-9am	25.1	34.5	20.6	32	5.95	0.69	0.512	0.164	4.29	1.52
9-10am	27.5	37.2	28.3	33	5.97	0.69			4.29	1.53
10-11am	45.6	52.9	40.4	26.7	5.94	0.69			4.28	1.61
12-Nov	42	51.6	42.7	28.5	6.24	0.69			4.32	1.61
12-1pm	46	52.1	37.8	22.4	5.93	0.69			4.28	1.61
1-2pm	51.6	52.3	23.4	23.5	5.15	0.69			4.18	1.58
2-3pm	48	50.3	17.1	27.1	4.77	0.69			4.13	1.55
3-4pm	48.8	51.1	10.6	25.9	4.97	0.69			4.16	1.56
4-5pm	43.8	47.5	5.5	38.1	4.06	0.69			4.02	1.49
5-6pm	37.5	41.2	2.3	49.5	3.13	0.69			3.86	1.41
6-7pm	31.4	35.7	1.2	55.8	2.97	0.69			3.83	1.37
7-8pm	31	34.9	0.9	59.6	2.69	0.69			3.76	1.35
8-9pm	32	35.5	0.7	59.8	2.54	0.69			3.73	1.34
9-10pm	33.3	36.6	0.7	60	2.47	0.69			3.71	1.34
10-11pm	31.9	35.2	0.8	54	2.65	0.69			3.75	1.35
12-Nov	32.3	35.7	0.7	55.6	2.64	0.69			3.75	1.35
12-1am	32.5	35.8	0.5	68.5	2.17	0.69			3.63	1.31
1-2am	32.7	35.7	0.4	73.5	1.9	0.69			3.55	1.28
2-3am	31.4	34.2	0.3	70.1	1.93	0.69			3.56	1.28
3-4am	29.2	32.5	0.1	63.2	2.33	0.69			3.68	1.31
4-5am	27.7	31.1	0.2	66	2.3	0.69			3.67	1.3
5-6am	27.3	30.7	0.1	63.5	2.37	0.69			3.69	1.31
6-7am	30.1	32.6	0.2	61	2.08	0.69			3.61	1.29
7-8am	33.5	35.5	1.2	48.3	2.38	0.69			3.69	1.33
8-9am	52.4	52.8	3.7	41.5	4	0.69			4.01	1.52
9-10am	45.8	47.1	2.7	35.6	3.69	0.69			3.96	1.47
10-11am	53.9	53	2.8	34.5	5.13	0.69			4.18	1.59
12-Nov	57	52.3	1.9	28.4	8.2	0.69			4.52	1.72
12-1pm	59.3	54.3	1.2	25.6	9.11	0.69			4.59	1.76
1-2pm	60	54	0.9	23.9	9.93	0.69			4.66	1.78
2-3pm	53.3	51.6	0.8	25	6.07	0.69			4.3	1.63
3-4pm	53.3	52.9	0.3	29.2	5.12	0.69			4.18	1.58
4-5pm	47.2	49.5	0.1	38.7	3.96	0.69			4.01	1.5

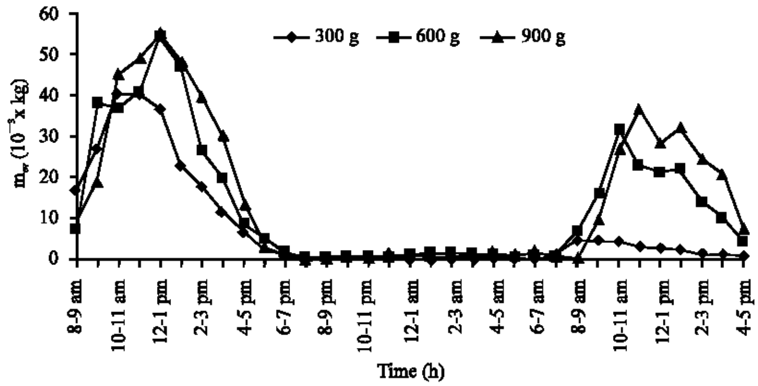

Fig. 3a: Rate of moisture evaporation in onion drying under open sun for different mass

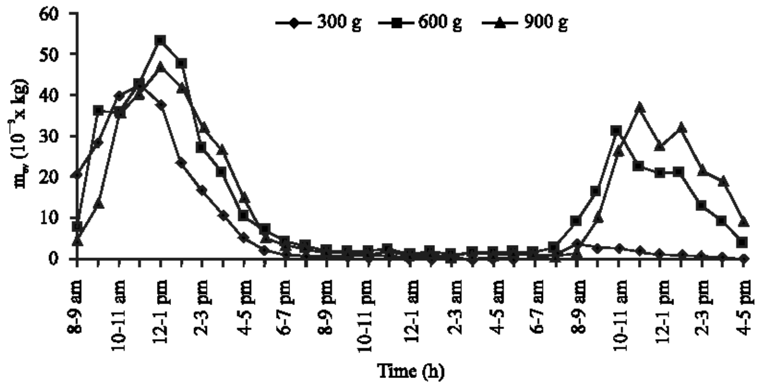

Fig. 3b: Rate of moisture evaporation in onion drying under natural mode for different mass using greenhouse

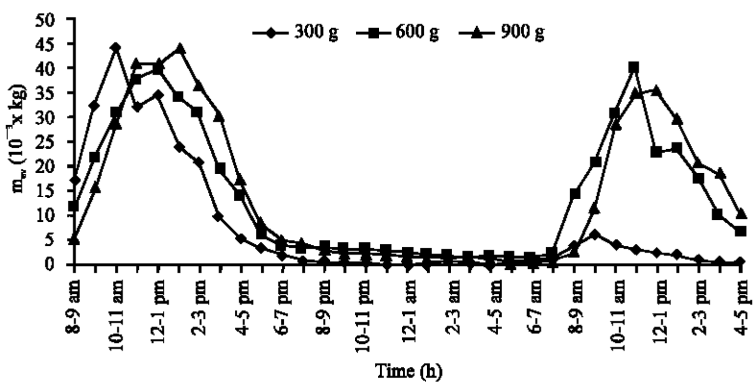

Fig. 3c: Rate of moisture evaporation in onion drying under force mode for different mass using greenhouse

Computation Technique

The rate of moisture evaporated corresponding to the onion temperature (T_c) and temperature above the crop surface (T_e) were calculated at each hour interval for each case and its values are given in Table 1 to 9 and also shown in Fig. 3. The physical properties of humid air were evaluated for the

Appendix A

The following expressions were used for calculating values of the physical properties of air, such as specific heat (c_p), thermal conductivity (k), density (ρ) and dynamic viscosity (μ) and the vapour pressure (P) (Anwar and Tiwari, 2001a; Jain and Tiwari, 2003; Tiwari, 2003). For obtaining the physical properties of humid air, T_i is taken as the mean of the onion temperature T_c and the temperature just above the onion surface T_e.

$$c_p = 999.2 + 0.1434\ T_i + 1.101\quad 10^{-4}\ T_i^2 - 6.7581\quad 10^{-8}\ T_i^3$$

$$k = 0.0244 + 0.7673\quad 10^{-4}\ T_i$$

$$\rho = \frac{353.44}{T_i + 273.15}$$

$$\mu = 1.718\quad 10^{-5} + 4.620\quad 10^{-8}\ T_i$$

$$P(T) = \exp\ 25.317 - \frac{5144}{T + 273.15}$$

Appendix B

Calculation of Experimental percentage uncertainty (U) (Anwar and Tiwari, 2001a).

$$U_1 = \frac{\sqrt{\sigma_1^{\ 2} + \sigma_1^{\ 2} + \quad + \sigma^2_{\ n}}}{N}$$

Where, σ is the standard deviation expressed as:

$$\sigma = \frac{\sqrt{\quad (X_i - \bar{X})^2}}{N_0}$$

Where, $(X_i - \bar{X})$ is the deviation from the mean and N and N_0, number of set and number of observations in each set, respectively.

$$\%\ \text{Internal uncertainty} = \frac{U_I}{\text{mean of total obsevation}} \quad 100$$

The external uncertainty is taken as the least count of the measuring instruments.

mean temperature of T_c and T_e by using the expressions given in the Appendix A. The values of C and n were obtained from Eq. 7b and 8b for natural and forced mode by using the linear regression analysis at increments of every hour of observation and thus, the values of convective heat transfer coefficient (h_c) were computed from Eq. 1 at the corresponding hour of drying. The computer program was prepared in the MATLAB software to evaluate convective heat transfer coefficient (Chapman, 2003).

The experimental error has been determined in terms of percent uncertainty (internal+external) for the most sensitive parameter, i.e., the rate of moisture evaporation (Appendix B).

Table 3: Experimental data and results for convective heat transfer coefficient for onion drying under forced mode on Oct 3-4, 2003 (300 g)

Time	T_c (°C)	T_e (°C)	m_{ev}x10^{-3} kg	γ (%)	Re×10^5	Pr	C	n	Nu	h_c (Wm^{-2} °C^{-1})
8-9am	37.8	40	17.3	43.3	2.23	0.69	1.12	0.137	3.06	1.12
9-10am	40.2	43.1	32.2	39.8	2.2	0.69			3.06	1.12
10-11am	41.7	48	44.2	31	2.16	0.69			3.05	1.13
12-Nov	41	46.8	32.3	29.5	2.17	0.69			3.05	1.13
12-1pm	43.2	48.8	34.7	26.2	2.15	0.69			3.05	1.13
1-2pm	46.2	49.2	24	25.2	2.13	0.69			3.04	1.14
2-3pm	48	47.7	20.7	25.1	2.12	0.69			3.04	1.14
3-4pm	45.9	54.9	9.7	27.1	2.09	0.69			3.04	1.14
4-5pm	40	43.9	5.3	34.4	2.2	0.69			3.06	1.12
5-6pm	31.5	36.1	3.5	45.5	2.3	0.69			3.08	1.1
6-7pm	29.8	33.6	1.7	58.4	2.33	0.69			3.08	1.1
7-8pm	29.4	32.7	0.9	64.3	2.34	0.69			3.08	1.1
8-9pm	29	32.2	0.3	69.5	2.34	0.69			3.09	1.1
9-10pm	28.9	32	0.4	74	2.34	0.69			3.09	1.1
10-11pm	28	31.1	0.2	68.2	2.36	0.69			3.09	1.09
12-Nov	28.5	31	0.1	76	2.35	0.69			3.09	1.1
12-1am	28.3	30.8	0.1	83.3	2.36	0.69			3.09	1.09
1-2am	29.4	30.1	0.2	87.4	2.35	0.69			3.09	1.1
2-3am	28.8	29.7	0.6	87.6	2.36	0.69			3.09	1.09
3-4am	28.6	29.3	0.3	87.8	2.36	0.69			3.09	1.09
4-5am	28.5	29.4	0.1	88	2.36	0.69			3.09	1.09
5-6am	28	29	0.4	88.2	2.37	0.69			3.09	1.09
6-7am	30.2	30.9	0.3	72.6	2.34	0.69			3.09	1.1
7-8am	33.4	33.6	1.2	54.8	2.3	0.69			3.08	1.1
8-9am	47.1	44.1	3.8	39.5	2.15	0.69			3.05	1.13
9-10am	48.3	45.3	6.1	37.5	2.14	0.69			3.05	1.13
10-11am	49.8	49.5	3.9	39	2.1	0.69			3.04	1.14
12-Nov	55.1	55.3	2.9	24.2	2.04	0.69			3.03	1.15
12-1pm	55.7	54.1	2.2	29	2.04	0.69			3.03	1.15
1-2pm	57.6	53.8	1.8	23.6	2.04	0.69			3.02	1.15
2-3pm	55.5	49.2	0.8	24.7	2.07	0.69			3.03	1.15
3-4pm	55.6	51.4	0.5	30	2.06	0.69			3.03	1.15
4-5pm	46.3	48.5	0.4	49.4	2.13	0.69			3.04	1.13

Results and Discussion

The results of convective heat transfer coefficient by using the values of ‘C’ and ‘n’ are also given in Table 1 to 9 for open sun drying and greenhouse drying.

The values of C and n as obtained by Anwar and Tiwari (2001b) for open sun drying for 602.9 g onion flakes are 1.00 and 0.31, respectively. While those obtained by Jain and Tiwari (2003) for open sun drying for 600 g onion flakes are 1.0064 and 0.2579, respectively. However, the values of C and n as obtained by present work are 0.472 and 0.17 respectively for open sun drying for 600 g onion flakes. The variation in the values may be due to the different drying hours of the experiment. The present work is based on continuous drying for 33 h and the observations are taken after one hour interval. While the drying hours for the experiment done by Anwar and Tiwari (2001b) and Jain and Tiwari (2003) were for 2 h and 30 min with observations taken at 15 min interval.

In the case of indoor open simulation under forced mode, Anwar and Tiwari (2001a) found the values of C and n as 0.99 and 0.75, respectively for 625.3 g of onion flakes. However, in case of indoor closed simulation under forced mode, they found these values as 0.99 and 0.59, respectively. In our present work for 600 g of onion flakes for greenhouse drying under forced mode, the values of C and n are calculated as 0.936 and 0.298, respectively. This variation in the values is due to different environmental conditions of both the experiments performed.

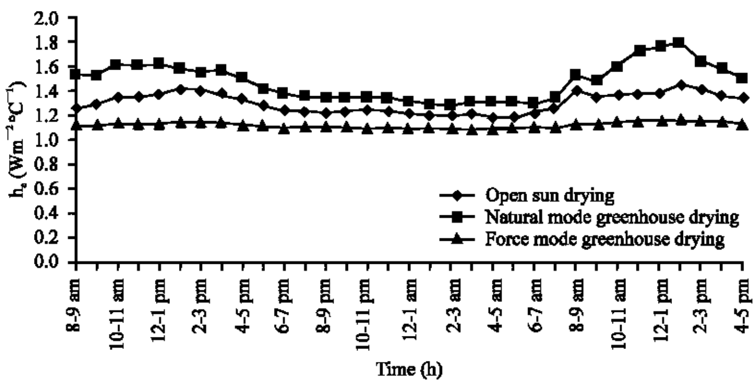

Fig. 4: Variation in convective heat transfer coefficient for different modes of drying (300 g)

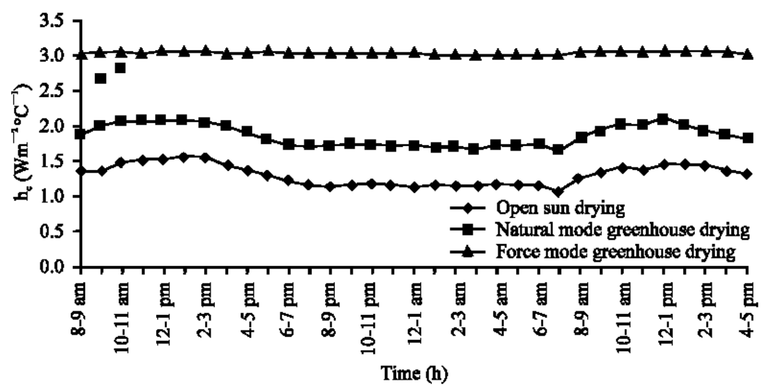

Fig. 5: Variation in convective heat transfer coefficient for different modes of drying (600 g)

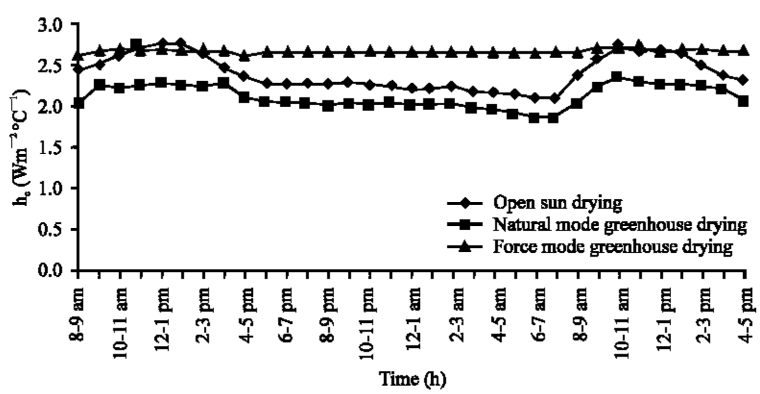

Fig. 6: Variation in convective heat transfer coefficient for different modes of drying (900 g)

Table 1 to 3 demonstrates the values of convective heat transfer coefficient for 300 g onion under open sun as well as greenhouse drying. It has been observed that the values of h_c are constant for forced mode of operation. However convective heat transfer coefficient varies for open sun and greenhouse drying under natural mode. Further it is important to note that the convective heat transfer coefficient is more in natural mode as compared to forced mode greenhouse as well as open sun drying due to more

Table 4: Experimental data and results for convective heat transfer coefficient for onion drying under open sun on Oct 18-19, 2003 (600 g)

Time	T_c (°C)	T_e (°C)	m_{ev}x10^{-3} kg	γ (%)	Gr×10^5	Pr	C	n	Nu	h_c (Wm^{-2} °C^{-1})
8-9am	39.2	40.6	7.3	40.8	2.8	0.69	0.472	0.17	3.75	1.37
9-10am	39.4	41.2	38	40.4	2.97	0.69			3.79	1.38
10-11am	39.9	43.8	37	28.8	4.27	0.69			4.03	1.48
12-Nov	42.2	46.9	40.8	26.9	4.84	0.69			4.11	1.52
12-1pm	42.7	47.9	54.1	25.6	5.12	0.69			4.15	1.54
1-2pm	43.5	48.9	46.8	27.6	5.14	0.69			4.16	1.55
2-3pm	42.8	51.3	26.2	33.2	5.65	0.69			4.22	1.57
3-4pm	42.6	45.7	19.6	39	3.73	0.69			3.94	1.45
4-5pm	40.1	42.1	8.5	48.8	2.73	0.69			3.73	1.37
5-6pm	36.5	38.8	4.9	58.4	2.25	0.69			3.61	1.31
6-7pm	29.9	31.7	1.4	65.6	1.65	0.69			3.43	1.22
7-8pm	29	30.5	0.3	72.7	1.32	0.69			3.3	1.17
8-9pm	28.5	30.1	0.4	73.5	1.33	0.69			3.31	1.17
9-10pm	27.7	29.1	0.5	69.7	1.33	0.69			3.31	1.17
10-11pm	27.4	29.3	0.5	71	1.52	0.69			3.38	1.19
12-Nov	26.8	28.5	0.5	72	1.4	0.69			3.33	1.18
12-1am	26.7	28.3	1.1	78.4	1.2	0.69			3.25	1.14
1-2am	25.8	27.6	1.7	78.2	1.29	0.69			3.29	1.16
2-3am	26	27.7	1.4	79.4	1.22	0.69			3.26	1.15
3-4am	25.7	27.5	1.2	80.5	1.24	0.69			3.27	1.15
4-5am	25.4	27	1	67.2	1.45	0.69			3.35	1.18
5-6am	25.5	27.1	0.5	75.3	1.27	0.69			3.28	1.15
6-7am	25.7	27.2	0.6	74.2	1.25	0.69			3.27	1.15
7-8am	29.1	30.2	0.3	83	0.88	0.69			3.08	1.09
8-9am	39.6	39.9	7.1	60.1	1.67	0.69			3.43	1.25
9-10am	40.1	41.9	15.8	54.7	2.41	0.69			3.65	1.34
10-11am	41	43.9	31.4	45.6	3.22	0.69			3.84	1.41
12-Nov	40.4	42.9	22.8	43.8	3.14	0.69			3.82	1.4
12-1pm	43.2	46.6	21.3	42	3.71	0.69			3.93	1.46
1-2pm	41.8	46.2	22.1	44.2	3.8	0.69			3.95	1.46
2-3pm	41.8	46	14	48.6	3.51	0.69			3.89	1.44
3-4pm	42.1	44.4	10.1	51.9	2.81	0.69			3.75	1.38
4-5pm	39.2	40.9	3.7	56.7	2.24	0.69			3.61	1.32

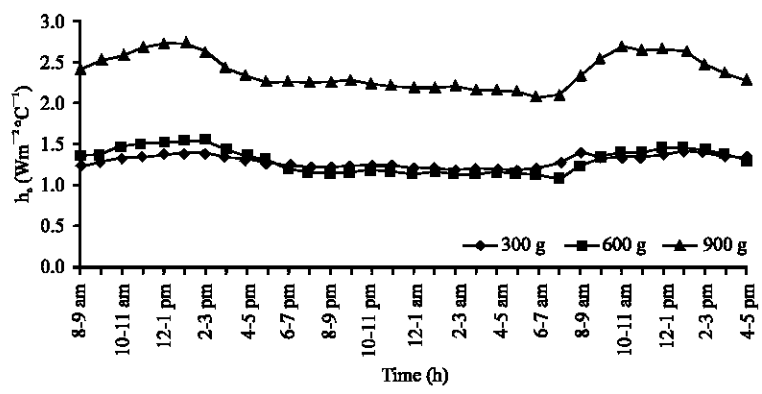

Fig. 7a: Variation in convective heat transfer coefficient in onion drying under open sun for different mass

Table 5: Experimental data and results for convective heat transfer coefficient for onion drying under natural mode on Oct 18-19, 2003 (600 g)

Time	T_c (°C)	T_e (°C)	m_{ev}x10^{-3} kg	γ (%)	Gr×10^5	Pr	C	n	Nu	h_c (Wm^{-2} °C^{-1})
8-9am	37.5	39.4	8.1	44.6	2.7	0.69	0.96	0.139	5.19	1.89
9-10am	40.7	45.2	35.9	42	3.88	0.69			5.46	2.01
10-11am	42.9	47.4	35.9	31.5	4.59	0.69			5.59	2.07
12-Nov	43.8	48.1	43.1	29	4.75	0.69			5.61	2.09
12-1pm	48.9	49.6	53.6	27	4.45	0.69			5.56	2.09
1-2pm	47.9	49.4	47.7	29.6	4.37	0.69			5.55	2.08
2-3pm	46.4	48.7	27.3	34.6	4.11	0.69			5.5	2.05
3-4pm	44.8	47.2	21.1	42	3.56	0.69			5.39	2.01
4-5pm	42.2	43.9	10.2	52	2.63	0.69			5.17	1.91
5-6pm	38.3	40.1	7.4	60.8	2.06	0.69			5	1.82
6-7pm	31.1	33.4	4.1	68	1.8	0.69			4.91	1.76
7-8pm	30.2	32.5	2.9	74.5	1.6	0.69			4.83	1.72
8-9pm	29.6	31.9	1.8	75.6	1.57	0.69			4.82	1.72
9-10pm	28.8	31.6	1.8	71.5	1.89	0.69			4.94	1.76
10-11pm	28.5	31	1.8	70.7	1.79	0.69			4.9	1.74
12-Nov	28	30.5	2.1	73.5	1.71	0.69			4.87	1.73
12-1am	27.5	30.2	1.3	79.2	1.65	0.69			4.85	1.72
1-2am	26.8	29.4	1.4	79.3	1.61	0.69			4.83	1.71
2-3am	27.1	29.7	1.2	82.2	1.53	0.69			4.8	1.7
3-4am	26.9	29.3	1.4	81.6	1.47	0.69			4.77	1.69
4-5am	26.6	29.1	1.5	70.5	1.79	0.69			4.91	1.73
5-6am	26.7	29.3	1.6	76.8	1.68	0.69			4.86	1.72
6-7am	26.8	29.4	1.5	76.2	1.69	0.69			4.87	1.72
7-8am	30.3	32.2	2.8	83.7	1.18	0.69			4.63	1.65
8-9am	39.6	41.9	9	62	2.22	0.69			5.05	1.85
9-10am	41.5	44.8	16.6	56.8	2.82	0.69			5.22	1.93
10-11am	44.1	49.8	31.7	48.8	4	0.69			5.48	2.04
12-Nov	44	47.8	22.5	46	3.66	0.69			5.42	2.01
12-1pm	50.8	48	20.8	43.5	5.11	0.69			5.67	2.13
1-2pm	48.8	48.4	21.1	46.7	3.31	0.69			5.34	2
2-3pm	47.1	47.5	13.1	50.2	2.79	0.69			5.21	1.95
3-4pm	46.3	46.7	9.3	56.3	2.38	0.69			5.1	1.9
4-5pm	42.7	43.3	3.7	60.4	1.95	0.69			4.96	1.83

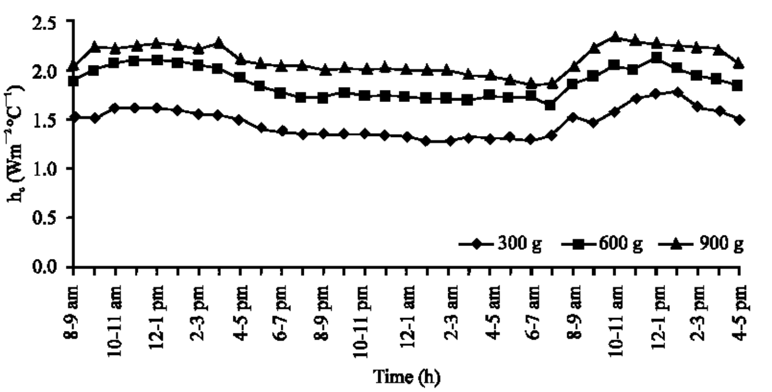

Fig. 7b: Variation in convective heat transfer coefficient in onion drying under natural mode for different mass using greenhouse

Table 6: Experimental data and results for convective heat transfer coefficient for onion drying under forced mode on Oct 23-24, 2003 (600 g)

Time	T_c (°C)	T_e (°C)	m_{ev}x10^{-3} kg	γ (%)	Re×10^5	Pr	C	n	Nu	h_c (Wm^{-2} °C^{-1})
8-9am	36	37	11.4	53	2.26	0.69	0.936	0.298	8.42	3.05
9-10am	38.2	40	21.7	42.9	2.23	0.69			8.38	3.06
10-11am	41.7	42.8	31	37.6	2.19	0.69			8.34	3.07
12-Nov	38.7	39.7	37.8	36.7	2.23	0.69			8.38	3.06
12-1pm	41.4	43.1	40	34.2	2.19	0.69			8.34	3.07
1-2pm	41.2	42.1	33.7	37	2.2	0.69			8.35	3.07
2-3pm	41.8	42.5	30.9	42.2	2.19	0.69			8.34	3.07
3-4pm	39.8	41.1	19.6	47	2.21	0.69			8.36	3.06
4-5pm	37.7	39	14	62.1	2.24	0.69			8.4	3.06
5-6pm	46.3	37.2	6.2	73.3	2.2	0.69			8.35	3.07
6-7pm	34.3	35.9	3.8	76.4	2.28	0.69			8.44	3.05
7-8pm	33	34.6	3.5	76.2	2.3	0.69			8.46	3.04
8-9pm	32.7	34.5	3.4	79.4	2.3	0.69			8.47	3.04
9-10pm	32.1	33.6	2.9	84	2.31	0.69			8.48	3.04
10-11pm	31.9	33.3	3	85.5	2.31	0.69			8.48	3.04
12-Nov	31.3	32.6	2.6	78.3	2.32	0.69			8.49	3.04
12-1am	30.9	32.5	2.3	80.3	2.33	0.69			8.5	3.04
1-2am	28.8	30.5	1.8	89.5	2.35	0.69			8.53	3.03
2-3am	28.5	30.2	1.5	90.2	2.36	0.69			8.53	3.03
3-4am	28.4	29.8	1	91.1	2.36	0.69			8.59	3.03
4-5am	28.3	29.3	1.4	92.2	2.37	0.69			8.54	3.03
5-6am	28.2	29.1	1.2	92.6	2.37	0.69			8.54	3.03
6-7am	28.6	29.6	1.3	92.7	2.36	0.69			8.53	3.03
7-8am	30.8	31.9	1.8	93	2.33	0.69			8.5	3.03
8-9am	41.4	42.8	14.3	55	2.19	0.69			8.34	3.07
9-10am	41.1	42.5	20.7	40	2.2	0.69			8.35	3.07
10-11am	41.4	46.7	30.8	32.2	2.17	0.69			8.31	3.08
12-Nov	39.2	42.1	40.4	37.2	2.21	0.69			8.36	3.07
12-1pm	39.6	42.6	22.8	30	2.21	0.69			8.36	3.07
1-2pm	40.2	42.5	23.6	28.5	2.2	0.69			8.35	3.07
2-3pm	40.3	42.8	17.3	33.8	2.2	0.69			8.35	3.07
3-4pm	42.3	43.7	10.2	35	2.18	0.69			8.33	3.07
4-5pm	38.7	40.7	6.4	53.1	2.22	0.69			8.38	3.06

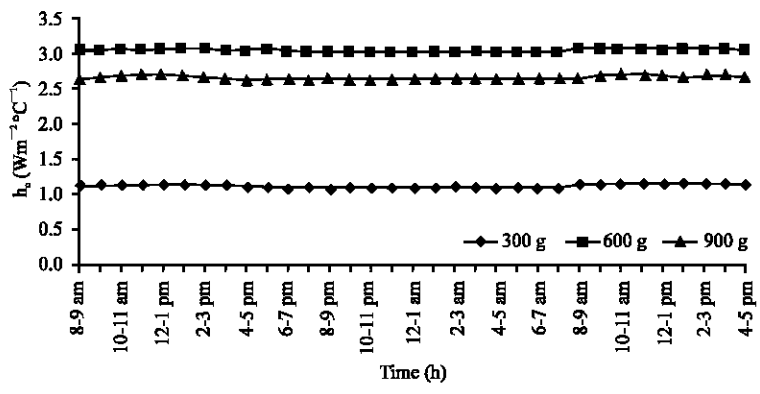

Fig. 7c: Variation in convective heat transfer coefficient in onion drying under force mode for different mass using greenhouse

Table 7: Experimental data and results for convective heat transfer coefficient for onion drying under open sun on Nov 21-22, 2003 (900 g)

Time	T_c (°C)	T_e (°C)	m_{ev}x10^{-3} kg	γ (%)	Gr×10^5	Pr	C	n	Nu	h_c (Wm^{-2} °C^{-1})
8-9am	26	30.1	9.8	40.8	3.28	0.69	0.899	0.164	6.86	2.42
9-10am	33.3	37.2	18.8	32.1	3.69	0.69			6.99	2.52
10-11am	35	40.1	45.2	31.5	4.28	0.69			7.16	2.6
12-Nov	35.9	42.4	49.1	26.6	5.06	0.69			7.36	2.69
12-1pm	34.8	43.3	54.9	24.3	5.86	0.69			7.54	2.75
1-2pm	32.9	41.7	47.9	22.8	6	0.69			7.57	2.75
2-3pm	34.7	40.3	39.8	22.4	4.83	0.69			7.31	2.65
3-4pm	33.5	35.3	30.3	23.1	3.12	0.69			6.8	2.45
4-5pm	28	30.5	13.5	37	2.68	0.69			6.64	2.35
5-6pm	23.9	26.6	3	50.7	2.33	0.69			6.49	2.27
6-7pm	22.2	25.3	1	55.2	2.42	0.69			6.53	2.28
7-8pm	20.7	23.9	0.1	57.8	2.42	0.69			6.53	2.27
8-9pm	20.5	23.8	0.3	60	2.43	0.69			6.53	2.27
9-10pm	19.9	23.5	0.9	59.7	2.6	0.69			6.6	2.29
10-11pm	19.6	22.8	0.9	60.4	2.38	0.69			6.51	2.26
12-Nov	19	22	1.1	61.6	2.25	0.69			6.45	2.23
12-1am	19	21.8	1.3	62.3	2.13	0.69			6.39	2.21
1-2am	18.9	21.7	1	63.4	2.12	0.69			6.38	2.21
2-3am	18.8	21.9	1.1	64.8	2.25	0.69			6.45	2.23
3-4am	18.5	21.4	1.2	78.2	1.91	0.69			6.28	2.17
4-5am	18.3	21.3	1.1	82	1.91	0.69			6.28	2.17
5-6am	18.4	21.3	1	83	1.83	0.69			6.24	2.15
6-7am	19.5	21.9	1.7	83.8	1.53	0.69			6.05	2.09
7-8am	22.1	24.5	0.6	84.2	1.48	0.69			6.02	2.1
8-9am	26.2	30	0.2	57	2.72	0.69			6.65	2.35
9-10am	36.8	40.9	9.8	34.3	3.88	0.69			7.05	2.57
10-11am	40.1	45.1	26.7	19.6	5.13	0.69			7.38	2.72
12-Nov	39.8	43.9	36.7	22.2	4.65	0.69			7.26	2.67
12-1pm	38.7	43.3	28.2	21.8	4.75	0.69			7.29	2.67
1-2pm	34.1	40	32.2	24	4.85	0.69			7.31	2.65
2-3pm	37.1	38.4	24.4	21.3	3.32	0.69			6.87	2.5
3-4pm	33.6	34.3	20.9	26	2.55	0.69			6.58	2.37
4-5pm	28.7	30.6	7.5	41.2	2.32	0.69			6.48	2.3

operating temperature inside the greenhouse. While in open sun drying, more convective heat transfer coefficient occurs than forced mode due to high wind velocity. These results have also been depicted in Fig. 4.

The results of convective heat transfer coefficient for 600 g onion for different drying modes reported in Table 4 to 6 have been shown in Fig. 5. It is important to note that the convective heat transfer coefficient is constant under forced mode unlike natural mode in greenhouse and open sun drying. Further it is observed that convective heat transfer coefficient for forced mode is more for 600 g onion in comparison with other modes due to decrease in relative humidity inside the greenhouse resulting in increased partial pressure. The convective heat transfer coefficient for greenhouse drying in natural mode is higher than open sun drying due to high operating temperature (Fig. 5) as also concluded earlier for 300 g (Fig. 4).

The results of Table 7 to 9 for 900 g onion have been shown in Fig. 6 for all cases. The trends of variation of convective heat transfer coefficient are similar to the case of 600 g except for few hours at the beginning. The value of convective heat transfer coefficient is reduced from 3 to 2.5 Wm^{-2} °C^{-1} for greenhouse drying under forced mode. It may be due to non exposure of some onion flakes due to higher layer thickness in case of 900 g. It is also important to observe that the convective heat transfer

Table 8: Experimental data and results for convective heat transfer coefficient for onion drying under natural mode on Nov 21-22, 2003 (900 g)

Time	T_c (°C)	T_e (°C)	m_{ev}x10^{-3} kg	γ (%)	Gr×10^5	Pr	C	n	Nu	h_c (Wm^{-2} $°C^{-1}$)
8-9am	27.5	29.5	4.7	42	2.3	0.69	1.067	0.14	5.76	2.04
9-10am	32.2	37.1	13.2	33.3	4.01	0.69			6.23	2.24
10-11am	36.9	39.6	36	33.1	3.41	0.69			6.09	2.22
12-Nov	40.8	42	40.7	28.1	3.42	0.69			6.09	2.24
12-1pm	42.1	43.6	46.9	26.2	3.77	0.69			6.18	2.28
1-2pm	42.5	42.8	42.1	25	3.45	0.69			6.1	2.25
2-3pm	37.5	39.3	32.3	23.7	3.48	0.69			6.11	2.22
3-4pm	35.4	39.6	26.6	25.2	4.2	0.69			6.27	2.28
4-5pm	30.2	32.7	14.9	40.1	2.69	0.69			5.89	2.1
5-6pm	26	29.1	5.4	53.8	2.48	0.69			5.88	2.06
6-7pm	24.2	27.2	3.6	56.4	2.35	0.69			5.78	2.03
7-8pm	22.8	26.1	2.6	60	2.42	0.69			5.8	2.03
8-9pm	22.1	25.2	1.8	61.6	2.29	0.69			5.76	2.01
9-10pm	21.8	25	1.8	60.7	2.36	0.69			5.78	2.02
10-11pm	21.2	24.4	1.2	62.1	2.33	0.69			5.78	2.01
12-Nov	20.6	24	2	63.7	2.41	0.69			5.8	2.02
12-1am	20.6	23.8	0.6	65	2.28	0.69			5.76	2
1-2am	20.4	23.6	1	66.2	2.26	0.69			5.75	2
2-3am	20	23.3	0.9	67.1	2.3	0.69			5.76	2
3-4am	19.8	23	1.1	79.1	2.02	0.69			5.66	1.96
4-5am	19.9	23	1.1	82.4	1.91	0.69			5.62	1.95
5-6am	20.2	22.7	1	83.1	1.58	0.69			5.47	1.9
6-7am	21.5	23.5	1.3	83.8	1.3	0.69			5.32	1.85
7-8am	23.7	25.7	0.9	84.5	1.26	0.69			5.3	1.85
8-9am	27	30	1.5	58.8	2.31	0.69			5.77	2.04
9-10am	36.3	39.9	10.4	36.2	3.58	0.69			6.13	2.23
10-11am	39.5	43.2	26.5	21	4.53	0.69			6.34	2.33
12-Nov	42.4	44.1	37.1	24.5	3.96	0.69			6.22	2.29
12-1pm	43.4	43.2	28	24.6	3.59	0.69			6.13	2.26
1-2pm	40.1	41.6	31.9	25.6	3.56	0.69			6.13	2.25
2-3pm	38.5	40.1	22.1	23.2	3.52	0.69			6.12	2.23
3-4pm	35	37.8	19.1	28.2	3.49	0.69			6.11	2.21
4-5pm	30.8	32.8	9.5	45.3	2.35	0.69			5.78	2.06

coefficient in open sun drying is slightly more than greenhouse drying under natural mode due to wind effect outside greenhouse.

In order to see the effect of mass of onion on convective heat transfer coefficient, the results of Fig. 4 to 6 have been further shown in Fig. 7. One can easily conclude from Fig. 7 that the convective heat transfer coefficient strongly depends on the mass and thickness of layer of onion flakes. The convective heat transfer coefficient increases by 90 and 135%, respectively as the mass of onion flakes is increased from 300 to 900 g in case of open sun drying and greenhouse drying under forced mode due to faster rate of moisture removal. However this increase is reduced to 30% in case of greenhouse drying under natural mode. It may be due to lower coefficient of diffusion of the greenhouse resulting in the increased relative humidity inside greenhouse.

The above results are found to be within the percent uncertainty of 21.71, 19.94 and 20.40 for open sun drying, greenhouse drying under natural mode and greenhouse drying under forced mode, respectively as given in Table 10.

Table 9: Experimental data and results for convective heat transfer coefficient for onion drying under forced mode on Dec 4-5, 2003 (900 g)

Time	T_c (°C)	T_e (°C)	m_{ev}x10^{-3} kg	γ (%)	Re×10^5	Pr	C	n	Nu	h_c (Wm^{-2} °C^{-1})
8-9am	16.1	17.9	5.4	53.6	2.54	0.69	1.004	0.271	7.66	2.62
9-10am	29.2	28.5	15.6	35.5	2.37	0.69			7.51	2.66
10-11am	38.7	38.6	28.8	32	2.24	0.69			7.39	2.69
12-Nov	33.4	34.8	40.8	26.9	2.3	0.69			7.44	2.68
12-1pm	41	43	40.8	26.5	2.19	0.69			7.35	2.7
1-2pm	34.3	35.5	44.2	24.5	2.28	0.69			7.44	2.68
2-3pm	28.4	29.3	37	23.6	2.37	0.69			7.51	2.66
3-4pm	24.8	26.5	30.8	27.6	2.41	0.69			7.55	2.65
4-5pm	17.8	21.1	17.4	45.2	2.5	0.69			7.63	2.63
5-6pm	24.6	27.8	8.1	65.6	2.4	0.69			7.54	2.65
6-7pm	24.1	27.1	4.7	68.1	2.41	0.69			7.55	2.65
7-8pm	23.5	26.5	4.3	66.5	2.42	0.69			7.56	2.65
8-9pm	22.8	25.6	3.1	74.6	2.43	0.69			7.57	2.65
9-10pm	22.4	25.3	2.2	74	2.44	0.69			7.57	2.64
10-11pm	22.1	25	2.1	75.3	2.44	0.69			7.58	2.64
12-Nov	22.1	24.8	1.9	73.4	2.44	0.69			7.58	2.64
12-1am	21.6	24.3	1.6	73.6	2.45	0.69			7.58	2.64
1-2am	21.1	23.7	1.4	75.5	2.46	0.69			7.59	2.64
2-3am	20.5	23	1.2	76.2	2.47	0.69			7.6	2.64
3-4am	20.3	23	1.2	77	2.47	0.69			7.6	2.64
4-5am	20.2	22.7	1.2	77.6	2.47	0.69			7.6	2.64
5-6am	20.4	22.7	0.4	78	2.47	0.69			7.6	2.64
6-7am	20.3	22.7	0.7	78.4	2.47	0.69			7.6	2.64
7-8am	22.2	24	0.7	78.8	2.45	0.69			7.58	2.64
8-9am	25.6	25.5	2.3	58.2	2.41	0.69			7.55	2.65
9-10am	37.5	34.8	11.6	34.4	2.27	0.69			7.42	2.69
10-11am	43.6	41.1	28.4	30.2	2.19	0.69			7.35	2.71
12-Nov	43.7	44.2	34.8	27	2.17	0.69			7.33	2.71
12-1pm	33.6	33.6	35.9	23.6	2.3	0.69			7.45	2.68
1-2pm	28.1	29.5	29.4	26	2.37	0.69			7.51	2.66
2-3pm	36.9	36.8	20.2	27.8	2.26	0.69			7.41	2.69
3-4pm	35	35.5	18.6	31.8	2.28	0.69			7.43	2.68
4-5pm	30	32.2	10.1	51	2.34	0.69			7.48	2.67

Table 10: Experimental percent uncertainties under different modes of drying

Mode of drying	Uncertainty (%)		
	Internal (%)	External (%)	Total (%)
Open sun drying	21.31	0.4	21.71
Greenhouse natural mode drying	19.54	0.4	19.94
Greenhouse forced mode drying	20.00	0.4	20.40

Conclusions

On the basis of the present studies, the following conclusions were made:

The value of convective heat transfer coefficient

- Depends significantly on the mass of the onion to be dried and the mode of drying.
- There is 30-135% increase in the convective heat transfer as the mass of the onion flakes is increased from 300 to 900 g for different modes of drying.

Nomenclature

A_t Area of onion flakes tray (m^2)
C Experimental constant
c Intersection in straight line equation
c_p Specific heat of humid air ($Jkg^{-1}\ °C^{-1}$)
g Acceleration due to gravity ($m\ s^{-2}$)
Gr Grashof number = $\frac{g\,\beta X_0^3 \rho^2 \Delta T}{\mu^2}$
h_c Convective heat transfer coefficient ($Wm^{-2}\ °C^{-1}$)
k Thermal conductivity of humid air ($Wm^{-1}\ °C^{-1}$)
m Slope in straight line equation
m_{ev} Moisture evaporation (kg)
n Exponent
Nu Nusselt number = $h_c X_0/k$
Pr Prandtl number of humid air = $\mu c_p/k$
P (T) Vapor pressure at temperature T (Nm^{-2})
Q The rate of heat utilized to evaporate moisture ($Jm^{-2}\ s^{-1}$)
Re Reynolds number = $\rho v X_0/\mu$
t Time (s)
T_e Temperature above onion flakes (°C)
T_c Temperature of onion (°C)
T_i Mean temperature of the T_c and T_e (°C)
ΔT Effective temperature difference (°C)
X_0 Characteristic dimension (m)

Greek Letters

β Coefficient of volumetric expansion ($°C^{-1}$)
γ Relative humidity (%)
λ Latent heat of vaporization ($J\ kg^{-1}$)
μ Dynamic viscosity ($N\ s\ m^{-2}$)
ρ Density ($kg\ m^{-3}$)

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