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CONVECTIVE HEAT TRANSFER COEFFICIENT OF INDIAN GOOSEBERRY (*EMBLICA OFFICINALIS*) DRIED IN THREE DIFFERENT FORMS UNDER FORCED CONVECTION MODE

S. I. ANWAR*, R.D. SINGH

Division of Agricultural Engineering, Indian Institute of Sugarcane Research, Lucknow – 226002 (U.P.), India
*Corresponding Author: sianwar@yahoo.co.in

Abstract

In this paper, convective heat transfer coefficient of Indian gooseberry (*Emblica officinalis*), in three different forms (shreds, slices and pieces), under forced convection mode has been determined. These forms were dried in laboratory drier. Values of constants *C* and *n* have been determined using experimental data and regression analysis for calculating values of convective heat transfer coefficient. It was found that the convective heat transfer coefficient varies with form of commodity being dried and decreases as the drying progresses. The value of convective heat transfer coefficient was highest for shredded form (30.39 $W/m^{2o}C$) followed by slices (25.88 $W/m^{2o}C$) and pieces (18.67 $W/m^{2o}C$) when compared at certain final moisture content. The data were also analyzed for per cent uncertainty.

Keywords: Crop drying, Forced convection, Convective heat transfer, Indian gooseberry.

1. Introduction

Indian gooseberry (*Emblica officinalis*), locally named '*Aonla/Amla'*, is a typical fruit having hard skin, fibre outside and hard stone inside. It contains 600-1000 milligram vitamin C per 100 gram pulp. Due to its nutritional and medicinal qualities, it is extensively used in *Ayurvedic* system of Indian medicines [1]. It could be utilized for preparation of various beverages viz. ready- to - serve nectar, squashes, syrups etc. either alone or after blending with other fruit juices and jams [2, 3]. There is 80-82% moisture content in the fresh fruit [4]. This is either used fresh or in dried form for making its different preparations.

Nomenclatures

A_t	Area of tray, m^2
C	Constant
C_v	Specific heat of humid air, J/kg°C
d	Hydraulic diameter, m
h_c	Convective heat transfer coefficient, W/m^2°C
K_v	Thermal conductivity of humid air, W/m°C
m.c.	Moisture content, % dry basis
m_{ev}	Moisture evaporated, kg
n	Constant
Nu	Nusselt number = h_cX/K_v
Pr	Prandtl number = μ_vC_v/K_v
$P(T)$	Partial vapour pressure at temperature T, N/m^2
Q_e	Rate of heat utilized to evaporate moisture, J/m^2 s
Re	Reynolds number = $\rho_v v d/\mu_v$
t	Time, s
T_c	Crop temperature, °C
$\overline{T}_c$	Average crop temperature, °C
T_e	Exit air temperature, °C
$\overline{T}_e$	Average temperature of humid air, °C
T_i	Average of crop and humid air temperature, °C
v	Air velocity, m/s
X	Characteristic dimension, m

Greek Symbols

γ	Relative humidity, %
$\overline{\gamma}$	Average relative humidity, %
λ	Latent heat of vaporization, J/kg
μ_v	Dynamic viscosity of humid air, kg/ms
ρ_v	Density of humid air, kg/m^3

Crop drying is one of the oldest methods of preservation. Drying is basically a heat and mass transfer phenomenon. Drying of Indian gooseberry as a whole is difficult hence before drying, the stone is removed and the pulp is cut into small pieces or slices. It is either dried under open sun or in suitable mechanical/solar dryer. In drying, part of heat used propagates to the interior of the crop (causing a rise in temperature and formation of water vapour) and the remaining amount is utilized in evaporation of moisture from the surface. Forced convection helps in quick removal of water vapour. The moisture from the interior diffuses to the 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 crop varies with this coefficient [5]. On the basis of crop bed thickness, drying can be classified into two categories: thin bed and deep bed drying. Generally, crop drying with a bed thickness up to 20 cm falls under thin bed, whereas when the thickness is more, it is known as deep bed drying [6]. The heat transfer coefficient can be determined on the basis of (a) area of the crop for thin bed and (b) volume of the crop for deep bed drying. Smith and Sokhansanj [7] 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. Garrote et al. [8] studied the effect of retort temperature, rotation speed, headspace and radius of rotation on mean convective heat transfer coefficient during sterilisation of canned evaporated whole milk. The model developed for heat transfer coefficient was adequate, showing no significant lack of fit and satisfactory coefficient of determination.

Sokhansanj [9] used experimental data for thin layer drying of barley to show that a model of coupled heat and mass transfer within a single kernel of grain improve prediction of the drying rate. Miketinac et al. [10] formulated five models simulating the process of simultaneous heat and mass transfer in drying a thin layer of barley. The heat transfer coefficient was found to vary from 43 to 59 $W/m^2/K$ depending on the form of drying model.

Sodha et al. [11] 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. Jaturonglumlert and Kiatsiriroat [12] have carried out studies on heat and mass transfer of fruit leather drying with combination of hot air and far-infrared and the heat and mass transfer coefficients were analyzed by heat-mass analogy. Wang et al. [13] measured the convective heat transfer coefficient for a packed bed of rice. Kumar and Tiwari [14] and Tiwari et al. [15] have developed models for getting the values of C and n and convective mass transfer for solar distillation. Goyal and Tiwari [16] have developed an empirical expression for heat and mass transfer for thin layers of crops like wheat and gram. Anwar and Tiwari [17] evaluated convective heat transfer coefficient by determining the values of C and n for six crops, namely, green chillies, green peas, white gram (Indian trade name – *Kabuli chana*), onion flakes, potato slices and cauliflower under open sun drying conditions and for *Kabuli chana* under natural cooling. Anwar and Tiwari [18] also determined values of C and n and thus convective heat transfer coefficient of these crops in forced convection also in open and closed simulated conditions. It was found that the values of convective heat transfer coefficient varied from crop to crop and method of drying.

These values would be useful in designing a dryer for a given range of crops. Basunia and Abe [19] conducted experiments on thin layer solar drying of rough rice in natural convection and determined the drying rate by using the Page equation. Manohar and Chandra [20] studied the drying process in greenhouse type solar dryer using natural as well as forced ventilation and the drying data were represented with the Page drying equation. Yaldiz et al. [21] presented various mathematical models of thin layer solar drying of sultana grapes on the basis of regression analysis of the experimental data. Mulet et al. [22] proposed a method of standardizing open sun drying time by defining the equivalent time based on the average solar radiation input. Goyal and Tiwari [23] presented a thermal model to predict the crop parameters for a reverse absorber cabinet type solar dryer. Ratti and Majumdar [24] developed a simulation code to predict the batch drying performance of a packed bed of particles (carrots or apple slices). The model was used to predict the crop temperature and moisture ratio with respect to drying time in a cabinet solar dryer.

The present study has been undertaken to determine convective heat transfer coefficient of Indian gooseberry dried in three different forms. The values would be useful for predicting drying parameters and designing a suitable drier as in variety of preparations Indian gooseberry is used in dried form.

2. Materials and Methods

2.1. Sample preparation

For conducting the experiment, fresh and healthy fruits of Indian gooseberry (average weight per fruit - 36.3 g) were taken. The fruits were of elliptical shape with mean larger diameter of 35.5 mm (SD = 1.51), mean smaller diameter of 42.13 mm (SD = 1.57) and mean diameter of 38.93 (SD = 1.14).

Initial moisture content of fruit pulp was determined by gravimetric method. The fruits were washed and excess water was wiped of using clean cloth. Stainless steel shredder was used for shredding of fruits. Shreds of 15-18 mm length and 2 mm thickness were made. Slices (5 mm thick) were made by cutting fruits using stainless steel knife. For piece form, pieces of about 12 mm size were made. Cutting of slices/pieces and grating was done manually. The stones after shredding and cutting in slices/pieces were discarded. The representative samples are shown in Fig.1.

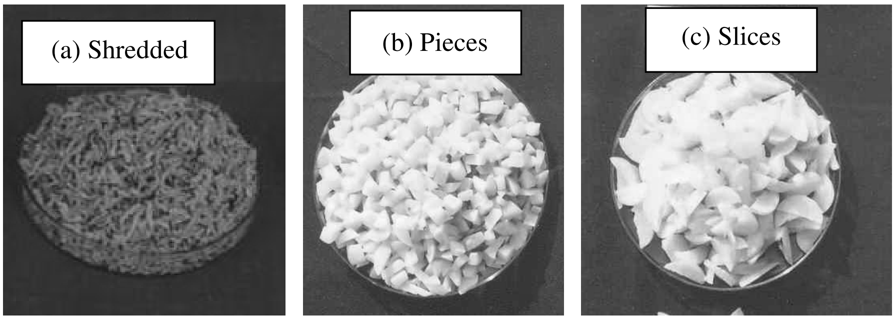

Fig. 1. Different Forms of Indian Gooseberry Taken for Experiment.

2.2. Experimental setup and instrumentation

All the above forms were dried up to about 17 per cent moisture content (dry basis) under forced convection mode using hot air blower (Usha Shriram, model FH-812, 230 V A.C., two heating coils of 1 kW each and air speed 0.4 m/s). To avoid excessive heating only one heating coil was used. The experimental set-up for shredded form is shown in Fig. 2. Samples were placed in the drying channel in which a thermocoal sheet (30 cm × 60 cm) was also placed and samples kept over it were considered as representative sample. The thickness of samples was uniform in all the cases. Thermocoal pieces were placed in the drying channel for distribution of drying air to all part of channel. Channel was covered with glass to have a view of samples. Samples were stirred at regular interval to avoid over-drying of samples nearer to blower outlet. Temperature of samples and exit air were recorded using mercury thermometer and the weight of representative sample was noted down at 10-minute interval using an electronic balance (Dolphin make) of least count 0.01 g. The quantity of moisture evaporated was determined by the weight loss in representative sample and multiplying it with the total area of samples. The moisture content was again calculated by the weight loss in samples. Humidity of exit air was also recorded at regular interval by dial type hair thermo-hygrometer (Hugor make) placed at the channel exit. The set up is shown in Fig. 2.

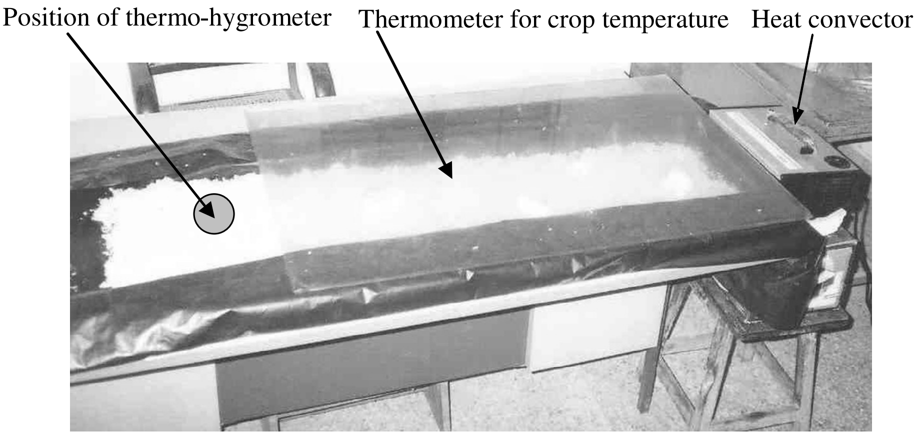

Fig. 2. Drying of Shreds of Indian Gooseberry under Forced Convection Mode.

2.3. Computation procedure

The convective heat transfer coefficient, h_c, can be determined using the expression for Nusselt no. as below:

$$h_c = \frac{NuKv}{X}$$

or

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

The rate of heat utilized to evaporate moisture from horizontally wetted surface is given as [25]:

$$Qe = 0.016\, h_c \{P(T_c) - \gamma P(T_e)\} \tag{2}$$

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

$$Qe = 0.016 \frac{Kv}{X} C(\mathrm{Re}\, \mathrm{Pr})^n \{P(T_c) - \gamma P(T_e)\} \tag{3}$$

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

$$m_e v = \frac{Qe}{\lambda} A_t t$$

or

$$m_{ev} = 0.016 \frac{Kv}{X\lambda} C(\mathrm{Re\,Pr})^n \{P(T_c) - \gamma P(T_e)\} A_t t \tag{4}$$

Putting

$$0.016 \frac{Kv}{X\lambda} \{P(T_c) - \gamma P(T_e)\} A_t t = Z$$

Eq. (4) becomes

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

Taking the logarithm of both sides,

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

Equation (6) is the analogy of an equation of a straight line, $Y = b_0 + b_1 X$,

where $Y = \ln\left(\frac{m_{ev}}{Z}\right)$, $b_1 = n$, $X = \ln(\mathrm{Re\,Pr})$, and $b_0 = \ln C$, thus $C = e^{b_0}$.

The values of constants C and n have been determined by linear regression analysis by using measured data of crop and exit air temperature and humidity and moisture evaporated during 10-minute time period. The percent uncertainty (internal + external) of data was determined for error analysis [26].

The physical properties of humid air; specific heat, C_v, thermal conductivity, K_v, density, ρ_v and viscosity, μ_v and the partial vapour pressure, P, can be calculated using the expressions given in *Appendix A*.

3. Results and Discussion

The average values of five observations for all the forms of Indian gooseberry are shown in Tables 1 to 3.

Here $\overline{T}_c$, $\overline{T}_e$ and $\overline{\gamma}$ are the average of respective T_c, T_e and γ values of that particular time and preceding time.

The physical properties of humid air were determined by using average crop temperature, $\overline{T}_c$, exit air temperature, $\overline{T}_e$ and exit air relative humidity, and $\overline{\gamma}$. These properties were used for calculating Reynolds number and Prandtl number. Linear regression analysis was done for determining values of constants C and n. Convective heat transfer coefficient, h_c, for all the forms of samples was calculated using Eq. (1). The values of C, n and convective heat transfer coefficient on hourly basis (cumulative) for all the three forms have been summarized in Tables 4 to 6.

Table 1. Observations for Shredded Form.

Time	T_c	T_e	γ	Weight of crop	m_{ev}	m.c.	$\bar{T}_c$	$\bar{T}_e$	$\bar{\gamma}$
min.	ºC	ºC	%	g	g	%db	ºC	ºC	%
0	25.0	36.0	48	2368.00	…..	601.75	…..	…..	…..
10	25.0	37.0	46	2293.27	74.73	579.60	25.00	36.5	47.0
20	24.0	37.0	36	2195.74	97.53	550.70	24.50	37.0	41.0
30	24.0	38.0	31	2111.08	84.66	525.61	24.00	37.5	33.5
40	25.0	39.0	28	2021.73	89.35	499.13	24.50	38.5	29.5
50	25.0	38.0	24	1958.45	63.28	480.38	25.00	38.5	26.0
60	26.5	38.0	25	1886.52	71.93	459.06	25.75	38.0	24.0
70	25.5	39.0	24	1812.58	73.94	437.15	26.00	38.5	24.5
80	25.5	39.0	24	1728.56	84.02	412.2	25.50	39.0	24.0
90	27.0	39.0	23	1648.24	80.32	388.45	26.25	39.0	23.5
100	27.0	39.0	23	1574.14	74.1	366.49	27.00	39.0	23.0
110	28.5	40.0	23	1488.75	85.39	341.18	27.75	39.5	23.0
120	27.5	40.0	23	1398.71	90.04	314.50	28.00	40.0	23.0
130	28.0	40.0	21	1330.21	68.5	294.20	27.75	40.0	22.0
140	30.0	40.0	20	1251.41	78.8	270.85	29.00	40.0	20.5
150	27.5	42.0	20	1172.94	78.47	247.59	28.75	41.0	20.0
160	28.0	42.0	20	1101.74	71.2	226.49	27.75	42.0	20.0
170	28.0	41.0	19	1028.49	73.25	204.7	28.00	41.5	19.5
180	27.5	41.0	19	959.83	68.66	184.44	27.75	41.0	19.0
190	27.0	41.0	19	891.64	68.19	164.23	27.25	41.0	19.0
200	27.0	40.0	19	826.46	65.18	144.92	27.00	40.5	19.0
210	27.5	40.0	18	758.33	68.13	124.73	27.25	40.0	18.5
220	27.5	41.0	18	691.02	67.31	104.78	27.50	40.5	18.0
230	28.0	40.0	17	636.49	54.53	88.62	27.75	40.5	17.5
240	28.0	40.0	17	590.51	45.98	74.99	28.00	40.0	17.0
250	27.5	41.0	17	552.14	38.37	63.62	27.75	40.5	17.0
260	27.5	41.0	17	514.3	37.84	52.41	27.5	41.0	17.0
270	27.0	41.0	16	493.43	20.87	46.22	27.25	41.0	16.5
280	27.0	41.0	17	459.42	34.01	36.14	27.00	41.0	16.5
290	28.0	42.0	16	422	37.42	25.05	27.5	41.5	16.5
300	28.5	42.0	16	412.2	9.8	22.15	28.25	42.0	16.0
310	28.5	42.0	15	402.8	9.4	19.36	28.50	42.0	15.5
320	29.0	43.0	15	394.9	7.9	17.02	28.75	42.5	15.0

Table 2. Observations for Slice Form.

Time	T_c	T_e	γ	Weight of crop	m_{ev}	m.c.	$\bar{T}_c$	$\bar{T}_e$	$\bar{\gamma}$
min.	ºC	ºC	%	g	g	%db	ºC	ºC	%
0	25.0	37.0	55	2368	0	601.75	…..	…..	…..
10	27.0	36.0	53	2328.99	39.01	590.19	26.00	36.50	54.0
20	27.0	32.0	46	2255.72	73.27	568.48	27.00	34.00	49.5
30	29.0	36.0	43	2199.56	56.16	551.83	28.00	34.00	44.5
40	27.5	38.0	39	2130.81	68.75	531.46	28.25	37.00	41.0
50	31.0	39.0	38	2059.04	71.77	510.19	29.25	38.50	38.5
60	31.0	39.0	38	1988.16	70.88	489.18	31.00	39.00	38.0
70	31.0	39.0	38	1915.95	72.21	467.78	31.00	39.00	38.0
80	30.0	40.0	37	1842.92	73.03	446.14	30.50	39.50	37.5
90	31.0	39.0	36	1767.97	74.95	423.93	30.50	39.50	36.5
100	29.0	39.0	35	1692.29	75.68	401.50	30.00	39.00	35.5
110	28.0	38.0	33	1611.42	80.87	377.54	28.50	38.50	34.0
120	28.5	38.0	33	1536.11	75.31	355.22	28.25	38.00	33.0
130	28.5	38.0	35	1461.35	74.76	333.06	28.50	38.00	34.0
140	28.0	38.0	35	1387.05	74.30	311.05	28.25	38.00	35.0
150	28.0	39.0	35	1314.02	73.03	289.40	28.00	38.50	35.0
160	28.5	39.0	36	1237.44	76.58	266.71	28.25	39.00	35.5
170	28.5	39.0	38	1159.81	77.63	243.70	28.50	39.00	37.0
180	29.0	40.0	38	1079.98	79.83	220.05	28.75	39.50	38.0
190	29.0	40.0	37	1007.12	72.86	198.45	29.00	40.00	37.5
200	29.0	40.0	37	927.38	79.74	174.82	29.00	40.00	37.0
210	29.0	40.0	38	848.28	79.10	151.38	29.0	40.00	37.5
220	28.5	40.0	38	802.34	45.94	137.77	28.75	40.00	38.0
230	28.5	40.0	38	758.26	44.08	124.70	28.5	40.00	38.0
240	28.5	40.0	38	716.28	41.98	112.26	28.5	40.00	38.0
250	28.5	41.0	38	678.45	37.83	101.05	28.5	40.50	38.0
260	28.0	40.0	39	634.75	43.70	88.10	28.25	40.50	38.5
270	28.5	41.0	39	601.26	33.49	78.18	28.25	40.50	39.0
280	28.0	40.0	38	561.23	40.03	66.31	28.25	40.50	38.5
290	28.0	41.0	39	536.48	24.75	58.98	28.0	40.50	38.5
300	27.5	41.0	39	512.27	24.21	51.81	27.75	41.0	39.0
310	27.5	41.0	39	498.38	13.89	47.69	27.5	41.0	39.0
320	27.5	41.0	38	481.29	17.09	42.62	27.5	41.0	38.5
330	27.0	41.0	37	464.39	16.90	37.62	27.25	41.0	37.5
340	27.5	41.0	38	451.28	13.11	33.73	27.25	41.0	37.5
350	27.5	41.0	38	441.16	10.12	30.73	27.5	41.0	38.0
360	27.5	41.0	37	431.26	9.90	27.80	27.5	41.0	37.5
370	27.0	42.0	37	425.28	5.98	26.03	27.25	41.50	37.0
380	27.0	42.0	37	420.18	5.10	24.51	27.0	42.00	37.0
390	27.0	42.0	36	415.29	4.89	23.07	27.0	42.00	36.5
400	26.5	42.0	36	411.29	4.00	21.88	26.75	42.00	36.0
410	26.5	42.0	35	407.23	4.06	20.68	26.5	42.00	35.5
420	26.5	42.0	35	403.26	3.97	19.50	26.5	42.00	35.0
430	26.5	42.0	35	399.02	4.24	18.24	26.5	42.00	35.0
440	26.5	42.0	35	397.1	1.92	17.68	26.5	42.00	35.0
450	26.5	42.0	35	396.28	0.82	17.43	26.5	42.00	35.0

Table 3. Observations for Piece Form.

Time	T_c	T_e	γ	Weight of crop	m_{ev}	m.c.	$\overline{T}_c$	$\overline{T}_e$	$\overline{\gamma}$
min.	°C	°C	%	g	g	%db	°C	°C	%
0	24.0	40.0	37	2368	0	601.75	…..	…..	…..
10	22.0	40.0	35	2284.5	83.5	577.00	23.00	40.00	36.0
20	24.5	40.0	37	2202.2	82.3	552.61	23.25	40.00	36.0
30	25.5	40.0	33	2126.9	75.3	530.30	25.00	40.00	35.0
40	25.0	40.0	29	2054.6	72.3	508.87	25.25	40.00	31.0
50	25.0	40.0	29	1992.1	62.5	490.35	25.00	40.00	29.0
60	25.0	40.0	30	1930.9	61.2	472.22	25.00	40.00	29.5
70	24.5	40.0	29	1865.1	65.8	452.72	24.75	40.00	29.5
80	26.5	42.0	29	1792.5	72.6	431.20	25.50	41.00	29.0
90	27.0	42.0	30	1720.2	72.3	409.77	26.75	42.00	29.5
100	27.5	42.0	28	1650.5	69.7	389.12	27.25	42.00	29.0
110	27.5	42.0	28	1571.2	79.3	365.62	27.50	42.00	28.0
120	27.0	42.0	27	1490	81.2	341.56	27.25	42.00	27.5
130	28.0	42.0	29	1430.1	59.9	323.80	27.50	42.00	28.0
140	27.0	42.5	28	1352.8	77.3	300.90	27.75	42.25	28.5
150	27.0	42.5	27	1283.1	69.7	280.24	27.50	42.50	27.5
160	28.0	42.0	27	1219.9	63.2	261.51	27.75	42.25	27.0
170	28.0	42.5	26	1157.8	62.1	243.11	28.00	42.25	26.5
180	28.0	43.0	25	1098.4	59.4	225.50	28.00	42.75	25.5
190	28.5	43.0	26	1042.1	56.3	208.82	28.25	43.00	25.5
200	28.5	43.0	25	987.5	54.6	192.64	28.50	43.00	25.5
210	28.5	43.0	24	931.3	56.2	175.98	28.5	43.00	24.5
220	28.5	43.0	23	880	51.3	160.78	28.5	43.00	23.5
230	29.0	43.0	23	830.8	49.2	146.20	28.75	43.00	23.0
240	28.5	43.5	24	788.5	42.3	133.67	28.75	43.25	23.5
250	28.0	43.5	22	747.3	41.2	121.46	28.25	43.50	23.0
260	28.0	43.5	18	711	36.3	110.70	28.0	43.50	20.0
270	28.5	43.5	19	681.8	29.2	102.05	28.25	43.50	18.5
280	29.0	44.0	18	660.3	21.5	95.67	28.75	43.75	18.5
290	29.5	44.0	17	610.5	49.8	80.92	29.25	44.00	17.5
300	29.0	44.5	16	571.3	39.2	69.30	29.25	44.25	16.5
310	28.5	44.0	16	542.1	29.2	60.65	28.75	44.25	16.0
320	29.0	44.0	15	510.9	31.2	51.40	28.75	44.00	15.5
330	29.5	44.5	16	482.6	28.3	43.01	29.25	44.25	15.5
340	28.5	44.5	15	458.4	24.2	35.84	28.75	44.50	15.5
350	29.5	45.0	16	441.2	17.2	30.74	28.75	44.75	15.5
360	30.0	45.0	15	432.9	8.3	28.28	29.75	45.00	15.5
370	31.5	45.0	14	426.4	6.5	26.36	30.75	45.00	14.5
380	31.0	46.0	15	418.8	7.6	24.11	31.25	45.50	14.5
390	31.0	45.5	15	412.6	6.2	22.27	31.0	45.75	15.0
400	31.0	45.5	15	407.3	5.3	20.70	31.0	45.50	15.0
410	31.5	45.5	14	402.5	4.8	19.28	31.25	45.50	14.5
420	32.5	45.0	15	398.6	3.9	18.12	32.0	45.25	14.5
430	32.0	45.5	14	395.5	3.1	17.20	32.25	45.25	14.5

It may be seen from above tables that the values of *C*, *n* and convective heat transfer coefficient, h_c, in all cases, go on decreasing as the drying of samples progresses. This is due to decreasing moisture content of samples with time. The values of convective heat transfer coefficient for shredded, slice and piece forms at the end of drying came out to be 30.39, 25.88 and 18.67 respectively. Therefore, convective heat transfer coefficient varies with the form, which is due to difference in physical characteristics. During initial stage of drying (up to 60 minutes), the higher value of h_c in piece form was probably due to surface conditions which suited drying but it was not lasted during later part of drying. Shredded form has highest values of convective heat transfer coefficient due to higher cut ends thus exposure of more wet area to drying air and higher rate of moisture removal. Slices follow next due to comparatively less cut area than pieces and so piece form. The per cent uncertainty (internal + external) was found to be in the range 28-30% and the different values of *C* and *n* were found to be within this range.

Table 4. Values of *C*, *n* and Convective Heat Transfer Coefficient, h_c, for Shredded Form.

Time up to, min.	*m.c.*, %db	*C*	*n*	h_c, W/m^2 °C
60	459.06	0.9986	1.0650	86.22
120	314.50	0.9951	1.0126	59.02
180	184.44	0.9897	0.9819	47.09
240	74.99	0.9871	0.9596	40.08
300	22.15	0.9801	0.9232	30.72
320	17.02	0.9790	0.9219	30.39

Table 5. Values of *C*, *n* and Convective Heat Transfer Coefficient, h_c, for Slice Form.

Time up to, min.	*m.c.*, %db	*C*	*n*	h_c, W/m^2 °C
60	489.18	0.9972	1.0245	64.33
120	355.22	0.9947	0.9930	51.15
180	220.05	0.9945	0.9952	51.95
240	112.26	0.9941	0.9902	50.07
300	51.81	0.9929	0.9793	46.26
360	27.80	0.9909	0.9554	38.97
420	19.50	0.9869	0.9210	30.40
480	17.29	0.9850	0.8986	25.88

Table 6. Values of *C*, *n* and Convective Heat Transfer Coefficient, h_c, for Piece Form.

Time up to, min.	*m.c.*, %db	*C*	*n*	h_c, W/m^2 °C
60	472.22	0.9983	1.1080	116.55
120	341.56	0.9948	1.0584	81.42
180	225.50	0.9902	1.026	64.55
240	133.67	0.9833	0.9961	51.52
300	69.30	0.9738	0.9621	40.06
360	28.28	0.9591	0.9254	30.41
420	18.12	0.9210	0.8728	20.09
430	17.20	0.9132	0.8636	18.67

4. Conclusions

The values of convective heat transfer coefficient, h_c, for three forms (shredded, pieces and slices) were determined using values of constants, *C* and *n*, obtained for these forms based on experimental data and the linear regression analysis. The value of h_c was found to vary from form to form and the values decrease as the drying progresses. At common moisture content, the value is higher in case of shredded form (30.39 W/m$^{2\circ}$C) followed by slices (25.88 W/m$^{2\circ}$C) and pieces (18.67 W/m$^{2\circ}$C). Experimental error in terms of per cent uncertainty was found to be in the range of 28 to 30%.

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Appendix A

The following expressions were used for calculating values of the physical properties of humid air such as specific heat, C_v, thermal conductivity, K_v, density, ρ_v and dynamic viscosity, μ_v and the partial vapour pressure, P [27].

For obtaining the physical properties of humid air, T_i is taken as the average of crop temperature, T_c, and the temperature just above the crop surface, T_e:

$$C_v = 999.2 + 0.1434\,T_i + 1.101\times10^{-4}\,T_i^{\,2} - 6.7581\times10^{-8}\,T_i^{\,3} \tag{A.1}$$

where $T_i = (T_c + T_e)/2$

$$K_v = 0.0244 + 0.6773 \text{ x } 10^{-4}\,T_i \tag{A.2}$$

$$\rho_v = \frac{353.44}{(T_i + 273.15)} \tag{A.3}$$

$$\mu_v = 1.718\times10^{-5} + 4.620\times10^{-8}\,T_i, \tag{A.4}$$

$$P(T) = \exp\left(25.317 - \frac{5144}{T_i + 273.15}\right) \tag{A.5}$$