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THERMAL KINETICS OF THIN LAYER DRYING OF INDIAN GOOGEBERRY OR ANOLA FLAKS (PHYLLANTHUS EMBLICA)

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ABSTRACT

The aonla flacks (*Phyllanthusemblica*), a fruit rich in vitamin-C, has very high medicinal importance in human life. Further, it is regarded as a highly perishable commodity due to its high moisture content. So it needs special attention for its preservation. Drying of aonla in the form of flacks and powder is one of the widely used methods of its preservation. Longer storage life, and substantial volume reduction are the main reasons of the popularity of its fruits and herbs in dried form. In thin layer drying model for drying a hygroscopic material the moisture ratio during the drying period is calculated by the Half Life Time Method, It is assumed that the material layer is thin enough and the air velocity is high so that the conditions of the drying air (humidity and temperature) are kept constant throughout the material at the average velocity of 0.48 m/s and relative humidity 35% of drying air and the drying air temperature in the range between 400 °C to 750°C. The drying models, namely Newton's Model, Page Model, Modified Page Model etc. were compared on the basis of to their statistical coefficients such as Root Mean Square Error RMSE, chi-square and Efficiency EF to see how close the predicted values were to experimental one. The results indicated that out of these models the values of RMSE and the reduced, chi-square χ^2 were found the lowest and values of EF highest with Henderson & Pabis model, defined by$\frac{M}{M_0} = Ae^{-kt}$where M and M_0 are the instantaneous and initial moisture contents respectively, The two constants namely shape factor and constant k were obtained using curve fitting for different drying air temperatures in the range $400\,℃–750\,℃$. Using the experimental and predicted values, the resulting RMSE was found to lie between 0.0382 and 0.0094, reduced χ^2between 0.000132 and 0.00761 and EF between 0.9598 and 0.9985. Analysis of the effect of dryingair temperature at constant velocity and relative humidity, revealed the adopted Henderson and Pabis modelswas in good agreement with the experimental results for all drying conditions taken up in the present study of aonla flacks. This model, can therefore, used to predict the moisture content of the aonla at any time during thin layer of drying process, with reasonable accuracy.

Keywords: aonla, phyllanthusemblica, drying, drying kinetics, hygroscopic material, half life time method, Indian gooseberry, thin layer drying.

INTRODUCTION

Drying is one of the most energy-intensive processes. Drying and dehydration are important operations in chemical and food industries, in storage and processing of cereal grains and have received a due place in the literature. Whereas dehydration is the removal of moisture to very low moisture content, nearly a dry-bone condition[16], the basic objective of drying food fruit is the removal of moisture to a level, which would prevent the growth of moulds and insects that normally cause spoilage [6], yet retaining the germination capacity.

A large amount of energy is consumed in drying process every year all over the world. Therefore understanding the drying process is necessary in establishing design requirements for an energy efficient drying system. Drying may be accomplished by adsorption, mechanical separation, vaporization, chemical means or a combination of two or more of these methods. In this paper, only artificial drying of hygroscopic fruits using heated air as a drying medium will be considered.

The study of drying behavior of different materials has been a subject of various investigations during the past 60 years and has contributed significantly to the development of various food processing industries. Liquid solutions and gels are non-porous. In these materials, transport of water is considered only due to the relatively simple phenomena of molecular diffusion. Most solid food materials can be treated as hygroscopic and capillary-porous.

In hygroscopic materials, there is a large amount of physically bound water and the material often shrinks during heating. For them there is a level of moisture saturation below which the internal vapor pressure is a function of temperature. These relationships are called equilibrium moisture isotherms. Above this moisture saturation, the vapor pressure is a function of temperature only expressed by the Clapeyron equation, and is independent of the moisture level. Thus, above certain moisture level, all materials behave as non-hygroscopic. Transport of water in hygroscopic materials is complex.

The liquid diffusion is considered to take place due to concentration difference and vapour diffusion due to vapour pressure gradient. on the other hand, [7] thought that both liquid and vapour diffusions may occur simultaneously due to moisture and vapour concentration gradients.[4] suggested that drying is due to vapour pressure gradient rather than moisture concentration gradient. However, [6] pointed out that moisture flow due to a pressure gradient is significant only in drying at product temperature well above the temperature employed in cereal-grain drying. [33]&[6] concluded that temperature gradients need not be considered in predicting drying rate in falling rate period where thermal diffusing is large compared to molecular diffusivity.

Lewis [19] proposed a model analogous to Newton's Law of cooling

$$\frac{dM}{dt} = -k(M - M_0) \tag{1}$$

The thin layer drying experiment was conducted with air of given humidity and temperature. Moisture content, M during drying, was taken on dry basis.

The moisture ratio $\left(\frac{M}{M_0}\right)$ was calculated from the moisture content (%db). The thermal kinetics during drying the relationship between moisture ratios and drying instants was determined. Based on the Lewis proposal, seven models were proposed by researchers.

EXPERIMENTAL SETUP AND PROCEDURE

The experimental set-up for carrying out the thin-layer drying is shown in Figure 1. It consists of three main units: Humidification chamber, Air heating system, and drying unit. The humidification chamber was constructed of galvanized iron sheet in two cylindrical parts, which were joined together by means of an air-tight flange-joint. The lower part of the humidification chamber is of 0.3 m diameter and 1 m height. A float valve is employed in order to maintain a desired level of water in the lower portion of the chamber. An overhead water tank supplies water to the chamber. The air suction pipe, 3 m long and 106 mm in diameter, is connected to the humidification chamber through an orifice-meter just above the water level. The lower part of the humidification chamber is also provided with a water level indicator, a drain valve, two 2-kW electric immersion heaters, a water pump and a 12 mm diameter perforated spray tube .

Figure-1. The experimental set-up for carrying out the thin-layer drying.

It was intended that the atmospheric air be given a water bath by means of a fine spray produced in the humidification chamber using the perforated tube and the water pump to saturate it to a desired dew point. At the top of the humidification chamber two sets of louvers are provided to trap the water droplets from the moist air. Figure-2 shows the insulated humidification chamber, which is attached to the suction side of the blower.

Figure-2. Humidification chamber.

The air heating system was fabricated in three parts. The central portion is a 1 m long cylinder with two diffusers at each end. Two 2-kW and three 1-kW heaters are fitted into the cylindrical portion to raise the temperature of the air, coming out from the humidification chamber, to a desired value. Figure-3 shows the unit which is connected to the delivery side of the blower.

Figure-3. Air heating unit.

Thin-layer drying unit consists of three sections a plenum chamber, a base plate with five openings and an exposure chamber. The plenum chamber is a cylindrical chamber fitted with a 300 diffuser of 0.5m height.

The drying unit is connected to the air heating unit with the help of a 900, 150 mm pipe bend to the diffuser A 3 mm thick mild steel base plate having five equispaced holes, each of 185 mm diameter, is fitted to the top of the plenum chamber. The openings are provided with rubber gaskets to prevent any leakage of air from the sides when drying pans are placed over them. To facilitate proper placement of the drying pans four small ball bearings are attached to the plate around each of the openings.

Preparation of the fruit samples

A batch of 50 kg of Aonla fruits was obtained in September 2005 and October 2006. The fruit was cleaned, sorted and graded before it was used for the experiment. The fruit samples at the desired moisture were obtained by adding calculated amounts of distilled water to the fruit and then sealed in separate bags. The samples were kept at 278 K in a refrigerator for a week to enable the moisture to become uniformly distributed throughout the material. Before starting a test, the required quantity of the fruit was taken out of the refrigerator and was allowed to warm up to the room temperature.

Thin-layer drying

To obtain thermal kinetics during drying the desired values of velocity, temperature and relative humidity of the drying air, airflow rate and energy supplied to the water-heater and air heaters were suitably adjusted. It was ensured that the system achieved steady state conditions; it was only after about one hour that the drying experiments could be started. About 1kg of Aonla flakes was weighed and distributed uniformly in a thin-layer, one flake high, in each of the drying pans. The drying pans were then placed on the openings in the base plate in the exposure chamber. As the drying continued, the samples were weighed periodically. The duration between two consecutive weighing was 6 min during the first hour and 12 min thereafter. As the drying proceeded, the drying rate decreased. The time interval beyond 12h of drying was increased to 30 min. The drying was continued until the weight difference between two consecutive readings of a drying sample was negligible The experimental observations were obtained for the following conditions: Initial moisture content was about 35%, Average air velocity of drying air 0.48 m/s, Drying air temperature: 323K, 333K, 338K, 343K, 348K, 353K & 358K with two dew-point temperatures (approximately 293K and 303K).

METHOD OF SOLUTION

The initial moisture contents and the equilibrium moisture content are given in Table-1

Table-1. Values of initial moisture and final moisture with drying air at various temperatures.

Temp.	Initial Moisture Content, M_o *(g)*	Final Moisture Content *(g)*	Duration *(hours)*
50°C	874.00	80.50	48
55°C	872.33	67.67	44
60°C	870.80	58.25	40
65°C	868.90	49.39	36
70°C	866.57	41.86	32
75°C	864.38	36.26	28

Experimental observation may be reported in Table-3.2.

Table-2. Experimental moisture ratio$MR = \frac{M}{M_0}$ at different drying time (hr.).

Drying Time *(hours)*	50°C	55°C	60°C	65°C	70°C	75°C
0	1.000	1.000	1.000	1.000	1.000	1.000
4	0.696	0.670	0.642	0.618	0.572	0.497
8	0.484	0.458	0.416	0.382	0.345	0.279
12	0.336	0.296	0.274	0.241	0.201	0.146
16	0.226	0.206	0.183	0.148	0.124	0.082
20	0.148	0.139	0.118	0.096	0.068	0.044
24	0.108	0.082	0.076	0.059	0.043	0.019
28	0.067	0.063	0.049	0.036	0.022	0.000
32	0.046	0.046	0.034	0.021	0.000	-
36	0.031	0.034	0.021	0.000	-	-

Analytical determination of drying coefficient "k" by half life method

To determine the thermal kinetics of drying thin layer, an Analytical determination of drying coefficient 'k' by Half Life Method. The drying equations used by researchers [11, 21] were of the following type:

$$MR = \frac{M - M_e}{M_0 - M_e} = Ae^{-kt} \tag{2}$$

By plotting the value of natural log of experimental MR against drying time for a given drying air temperature, they found the plot to be a straight line, the slopes gives the drying coefficient and the intercept the natural logarithmic value of the shape factor for the temperature under consideration. It is assumed that the types of equation remain the same when the definition of Moisture Ratio is changed to MR=M/Mo and therefore, MR becomes

$$MR = \frac{M}{M_0} = Ae^{-kt} \tag{3}$$

The value of *'k'* can be determined analytically by the half-life Method. Half–life period is the time of one-half response in a drying process and can be defined as the number of hours necessary to obtain a moisture ratio of one-half. Using the experimental results on drying of Aonla obtained in the present work, with drying air at 50 °C, drying time at which MR is half, (i.e. ½) can be found by linear interpolation at 4 and 8 hours' time, as given below.

$$\left(\frac{t_{1/2}-4}{8-4}\right)=\left(\frac{0.5-0.696}{0.484-0.696}\right)$$

$t_{1/2} = 7.54\ hrs.$ and similarly, $t_{1/4} = 715.09\ hrs.$ Therefore, using the expressions for half time $t_{1/2}$ and quarter time $t_{1/4}$, from the following equations:

$\left(\frac{1}{2}\right) = e^{-kt_{1/2}}$ (or) $t_{1/2} = \left(\frac{\ln 2}{k}\right)$, and

$\left(\frac{1}{4}\right) = e^{-kt_{1/4}}$ (or) $t_{1/4} = \left(\frac{\ln 4}{k}\right)$

drying coefficient $k_{1/2}$ and $k_{1/4}$can be calculated as shown below:

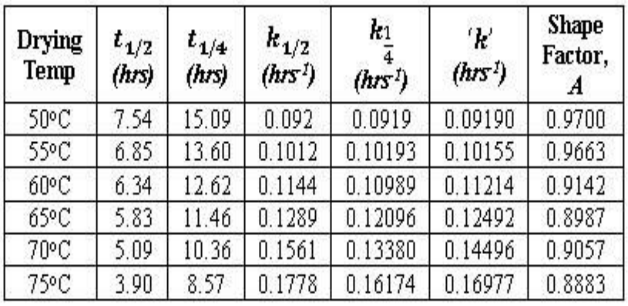
$k_{1/2} = \left(\frac{\ln 2}{t_{1/2}}\right) = 0.09193\ h^{-1}andk_{1/4} = \left(\frac{\ln 4}{t_{1/4}}\right) = 0.09187h^{-1}$

hence, value of *'k'*, which is the average of $k_{1/2}\&k_{1/4}$ is found as:

$$k = \frac{k_{1/2}+k_{1/4}}{2} = \left(\frac{0.09193+0.09187}{2}\right) = 0.0919h^{-1}$$

Similarly $t_{1/2},\ t_{1/4},\ k_{1/2},\ k_{1/4}$ and *'k'* at temperature 55 °C, 60 °C, 65 °C, 70 °C and 75 °C were calculated as above and are tabulated in Table-3.

Table-3. Drying coefficient and shape factor at diff. temp.



Drying Temp	$t_{1/2}$ (hrs)	$t_{1/4}$ (hrs)	$k_{1/2}$ (hrs^{-1})	$k_{\frac{1}{4}}$ (hrs^{-1})	'k' (hrs^{-1})	Shape Factor, A
50°C	7.54	15.09	0.092	0.0919	0.09190	0.9700
55°C	6.85	13.60	0.1012	0.10193	0.10155	0.9663
60°C	6.34	12.62	0.1144	0.10989	0.11214	0.9142
65°C	5.83	11.46	0.1289	0.12096	0.12492	0.8987
70°C	5.09	10.36	0.1561	0.13380	0.14496	0.9057
75°C	3.90	8.57	0.1778	0.16174	0.16977	0.8883

Hence the exponential model was fitted best with the above values of *'k'* and shape factor *'A'*, obtained from using MR values from table 3.2, for various drying temperatures are found as given below:

$k = 0.0267e^{0.0243T}$ and $A = 2.4095T^{-0.2325}$

thus the drying equation:

$$MR = \left(\frac{M}{M_o}\right) = (2.4095T^{-0.2325})e^{-(0.0267e^{0.0243T})t} \qquad (4)$$

Where *'t'* is the drying time in hours, and *'T'* is the drying air temperature in °C**.**

Thin layer drying models, namely the Henderson &Pabis model, the Lewis model, the Page model, and the modified Page model were also used to describe drying process during drying of aonla flakes. The models were evaluated on the basis of root mean square error (RMSE), reduced χ^2-square and model efficiency (EF) for the primary criterion to select the best equation to account for variation in the drying curves of the dried samples [1], [2] and [17].

Reduced χ^2 are used to determine the goodness of the fit. The lower the values of the reduced χ^2, the better the goodness of the fit. The RMSE gives the deviation between the predicted and experimental values and it is required to reach zero. The EF also gives the ability of the model to its highest value is 1.These statistical values can be calculated as follows:

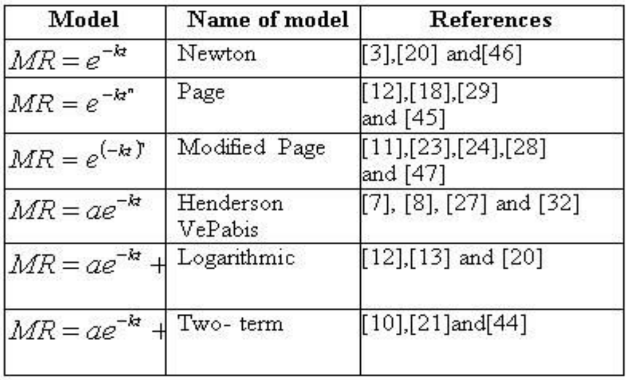
$$\chi^2 = \sum_{i=1}^{n} \frac{\left(MR_{i,exp} - MR_{i,pre}\right)^2}{N-n} \qquad (5)$$

$$RMES = \sqrt{\frac{\sum_{i=1}^{n}\left(MR_{i,Pre} - MR_{i,exp}\right)^2}{N}} \qquad (6)$$

$$EF = \frac{\sum_{i=1}^{n}\left(MR_{i,exp} - MR_{i,exp_{mean}}\right)^2 - \sum_{i=1}^{n}\left(MR_{i,Pre} - MR_{i,exp}\right)^2}{\sum_{i=1}^{n}\left(MR_{i,exp} - MR_{i,exp_{mean}}\right)^2} \qquad (7)$$

where, $MR_{exp,i}$ is the i^{th} experimental moisture ratio, $MR_{pre,i}$ is the i^{th} predicted moisture ratio, N is the number of observations, n is the number of constants in the drying model and $MR_{exp,mean}$ is the mean value of experimental moisture ratio.

Table-4. Mathematical models for drying.



Model	Name of model	References
$MR = e^{-kt}$	Newton	[3],[20] and[46]
$MR = e^{-kt^n}$	Page	[12],[18],[29] and [45]
$MR = e^{(-kt)^n}$	Modified Page	[11],[23],[24],[28] and [47]
$MR = ae^{-kt}$	Henderson VePabis	[7], [8], [27] and [32]
$MR = ae^{-kt} +$	Logarithmic	[12],[13] and [20]
$MR = ae^{-kt} +$	Two- term	[10],[21]and[44]

MODELS FOR THE DRYING OF AONLA FLAKES

There are number of mathematical models as given below:

- Newton Model: $MR = e^{-kt}$,
- Page Model: $MR = e^{-kt^n}$,
- Modified Page Model: $MR = e^{(-kt)^n}$ etc.

From Page Model: $MR = e^{-kt^n}$, the values of χ^2, RMSE and EF for various values of empirical constant (n) at a given drying air temperature 50°C, it was found that the value n = 1 has maximum EF (efficiency) and minimum RMSE value shown in Figure 4.

Table-5. Values of statistical parameters for various Constant (n) at a constant air temp 50 °C.

Temp.(°C)	Value of n	X^2	RMSE	EF
50	0.6	0.15628	0.36050	-0.70640
50	0.7	0.08546	0.26638	0.07438
50	0.8	0.03573	0.17129	0.61621
50	0.9	0.00923	0.08568	0.90170
50	1	0.00042	0.01781	0.99554
50	1.1	0.00157	0.03083	0.98359
50	1.2	0.00718	0.06327	0.92544

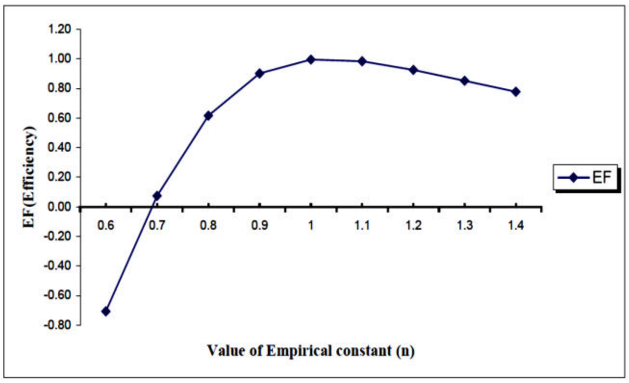


Figure-4. Efficiency EF at various values of constant, n at a drying temp 50 °C.

RESULTS AND DISCUSSIONS

For values of RMSE and EF (Efficiency) Newton Model & Modified Page Model are equal from 50^{0}C to 75^{0}C (higher temperature) whereas the value of χ^2 is different for air temperatures above 65 ^{0}C onwards. RMSE values for Page Model varies between 0.0067 to 0.0766 and the EF (efficiency) is highest at the temperature 55^{0}C(0.9989) and the least value at the temperature 75 ^{0}C (0.8841) where as with the Modified page Model, the RMSE values varies between 0.0087 (at 50 ^{0}C) to 0.0844(at 75 ^{0}C) and the EF (efficiency) is highest at the temperature 50^{0}C (0.9988) and the least at the temperature 75^{0}C (0.8564). It shows that the Page Model and Modified Page Model are suitable up to 55^{0}C (low temperature).

Table-6. Curve fitting criteria for semi-theoretical thin layer drying model for the drying of Aonla flacks.

Model	Temp. (°C)	χ^2	RMSE	EF
Newton Model $MR = e^{-kt}$	50	0.0001	0.0087	0.9988
	60	0.002	0.0355	0.9769
	65	0.0047	0.0537	0.9458
	70	0.0083	0.07	0.9048
	75	0.0125	0.0844	0.8564
Page Model $MR = e^{-kt^n}$	50	0.0004	0.0178	0.9955
	60	0.0012	0.0268	0.9869
	65	0.0036	0.0452	0.9622
	70	0.0069	0.0618	0.9271
	75	0.011	0.0766	0.8841
Modified Page $MR = e^{(-kt)^n}$	50	0.0001	0.0087	0.9988
	60	0.0022	0.0355	0.9769
	65	0.0051	0.0537	0.9458
	70	0.009	0.07	0.9048
	75	0.0136	0.0844	0.8564
Henderson VePabis $MR = ae^{-kt}$	50	0.0001	0.0094	0.9985
	60	0.0008	0.0191	0.9911
	65	0.0013	0.0239	0.985
	70	0.0018	0.0248	0.9814
	75	0.0039	0.0382	0.9598

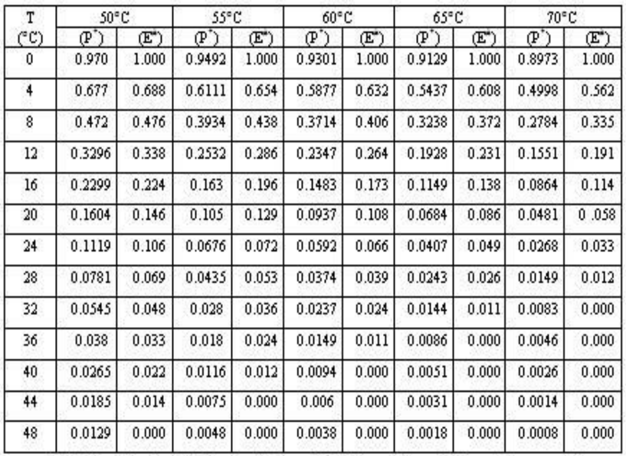
Table–7. Maximum value of EF (efficiency) at different temperature.

Temp (°C)	50°C	55°C	60°C	65°C	70°C	75°C
Newton Model	0.9988	0.9956	0.9769	0.9458	0.9048	0.8564
Page Model	0.9955	0.9989	0.9869	0.9622	0.9271	0.8841
Modified Page	0.9988	0.9956	0.9769	0.9458	0.9048	0.8564
Henderson VePabis	0.9985	0.9966	0.9911	0.9850	0.9814	0.9598

Table–8. Minimum RMSE values at different temperature.

Temp(°C)	50°C	55°C	60°C	65°C	70°C	75°C
Newton Model	0.0087	0.0154	0.0355	0.0537	0.0700	0.0844
Page Model	0.0178	0.0067	0.0268	0.0452	0.0618	0.0766
Modified Page	0.0087	0.0154	0.0355	0.0537	0.0700	0.0844
Henderson VePabis	0.0094	0.0112	0.0191	0.0239	0.0248	0.0382

Table–9. Details of Experimental data (E*) and Predicted data (P*) of moisture ratio at different time and temperatures.



T	50°C		55°C		60°C		65°C		70°C	
(°C)	(P^*)	(E^*)	(P^*)	(E^*)	(P^*)	(E^*)	(P^*)	(E^*)	(P^*)	(E^*)
0	0.970	1.000	0.9492	1.000	0.9301	1.000	0.9129	1.000	0.8973	1.000
4	0.677	0.688	0.6111	0.654	0.5877	0.632	0.5437	0.608	0.4998	0.562
8	0.472	0.476	0.3934	0.438	0.3714	0.406	0.3238	0.372	0.2784	0.335
12	0.3296	0.338	0.2532	0.286	0.2347	0.264	0.1928	0.231	0.1551	0.191
16	0.2299	0.224	0.163	0.196	0.1483	0.173	0.1149	0.138	0.0864	0.114
20	0.1604	0.146	0.105	0.129	0.0937	0.108	0.0684	0.086	0.0481	0 .058
24	0.1119	0.106	0.0676	0.072	0.0592	0.066	0.0407	0.049	0.0268	0.033
28	0.0781	0.069	0.0435	0.053	0.0374	0.039	0.0243	0.026	0.0149	0.012
32	0.0545	0.048	0.028	0.036	0.0237	0.024	0.0144	0.011	0.0083	0.000
36	0.038	0.033	0.018	0.024	0.0149	0.011	0.0086	0.000	0.0046	0.000
40	0.0265	0.022	0.0116	0.012	0.0094	0.000	0.0051	0.000	0.0026	0.000
44	0.0185	0.014	0.0075	0.000	0.006	0.000	0.0031	0.000	0.0014	0.000
48	0.0129	0.000	0.0048	0.000	0.0038	0.000	0.0018	0.000	0.0008	0.000

(P) Predicted moisture ratio and (E*) Experimental moisture ratio*

Whereas it shown in Table 3.7the value of EF (efficiency) is highest at the temperature 55 ^{o}C (0.9989) and the least value at the temperature 75 ^{o}C (0.8841).

Whereas, Modified page Model, the RMSE values varies between 0.0087 (at 50 ^{o}C) to 0.0844(at 75 ^{o}C) and the EF (efficiency) is highest at the temperature 50 ^{o}C (0.9988) and the least at the temperature 75 ^{o}C (0.8564). It shows that the Page Model and Modified Page Model are suitable up to 55 ^{o}C (low temperature).

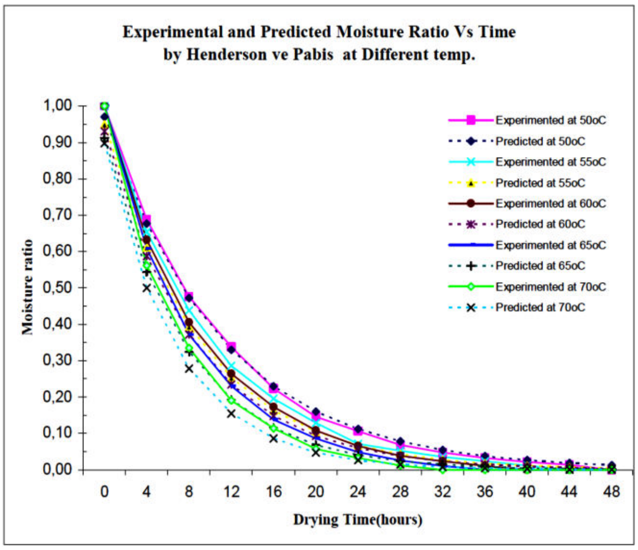


Figure-5. Experimental and predicted moisture ratio at different temperatures.

CONCLUSIONS

In thin layer drying model, and two –dimensional approach for drying a hygroscopic material as 5mm thick aonla flakes of three maturity level of aonla fruits, the moisture ratio during the drying period is calculated by the Half Life Time Method and It is assumed that the material layer is thin enough and the air velocity is high so that the conditions of the drying air (humidity and temperature) are kept constant throughout the material at the average velocity of 0.48m/s of drying air and the drying air temperature in the range between 400 ^{0}C to 750 ^{0}C.

For modeling and numerical approach of drying the hygroscopic material (aonla flakes), the experimental moisture content data was used on the dry weight basis. These moisture content data at any time of drying process obtained at different drying air temperature and a constant velocity condition were made non-dimensional by dividing it by initial moisture content and denoted by MR. Moisture ratio was then fitted against the drying time.
The drying models, namely Newton's Model, Page Model, Modified Page Model etc. were compared on the basis of to their statistical coefficients such as Root Mean Square Error RMSE, chi-square and Efficiency EF to see how close the predicted values were to experimental one.

The results indicated out of these models the values of RMSE and chi-square were found lowest and values of EF highest with Henderson &Pabis model. The definition of MR in the actual model is changed from (M-Me)/(Mo-Me) to M/Mo in the adopted model, Here Mo and Me are the initial moisture content and equilibrium moisture content, respectively as determination of the EMC was not included in the scope of the work. Even with the changed definition of MR, the form of equation MR= A exp(-ktn) was maintained and the shape factor(empirical constant) A; and constant k determined from Half Life Method, were found for a given drying air temperature at different time instants the curve fitting was done for different drying air temperatures in the range (400C-750C), the two constants namely shape factor and constant k were obtained. The resulting equation as given below:

$$MR = \left(\frac{M}{M_o}\right) = (2.4095T^{-0.2325})e^{-(0.0267e^{0.0243T})t}$$

The instants between the experimental and predicted values resulting RMSE changed between 0.0382 and 0.0094, chi-square between 0.000132 and 0.00761 and EF between 0.9598 and 0.9985. On analysis of the effect of drying air temperature at constant velocity of air and relative humidity the adopted Henderson and Pabis models was found to be in good agreement with the experimental results for all drying conditions taken up in the present study of aonla flakes.

According to the results of thin layer drying of aonlaflakes , Henderson and Pabis Modified by the author , and called adopted Henderson and Pabis model, could be used to predict the moisture content of the product at any time of drying process with reasonable accuracy between drying air temperatures between 40 and 750C with 0.48m/s air velocity. This numerical approach of drying of sample can be used to calculate two-dimensional heat mass transfer during drying of any hygroscopic materials after applying some relative parameters.

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