# Influence Collector Inclination of Solar Dryer on Apple 'Golab' Chips Drying

Omid Reza ROUSTAPOUR [1(✉)]
Hamid Reza GAZOR [2]

## Summary

Thin layer of apple chips ('Golab') with 73.4% (wet basis) moisture content were dried in a hybrid solar dryer. A new mechanism was designed to change inclination of the collector. Drying experiments were run in three levels of airflow rates and two levels of collector tilted angle. In order to describe the thin layer drying, ten different models were selected. The goodness of fitting was evaluated by calculating and comparing the statistical values for each model. The approximation of diffusion and the Midilli model were chosen for 30, and 45 degrees of tilted angle, respectively. Besides, five linear and nonlinear equations were derived in order to establish the best relationship for every empirical coefficient with temperature and airflow rate. Results revealed that the 2nd polynomial equations were suitable to predict these coefficients. Comparison between moisture ratio data in different inclination evidenced that more drying intensity occurred with 30 degrees of slope angle and airflow 0.018 $m^3 \cdot s^{-1}$.

## Key words

solar dryer, variable collector, drying model, apple

[1] Agricultural Engineering Research Center, Zarghan, Fars Province, Iran
✉ e-mail: roustapour@farsagres.ir
[2] Agricultural Engineering Research Institute, Karaj, Iran

Received: December 20, 2014 | Accepted: April 23, 2015

ACKNOWLEDGEMENTS
The authors are pleased to acknowledge Agricultural Engineering Department of Fars Province for preparing some facilities for this project. They also thank Mr. Sayyahi for improving the English text quality.

## Introduction

With regard to the current energy crisis, it is appropriate to be able to dry agricultural products with minimum energy consumption. This issue has been led to the development of various models of solar dryer in recent years (Pangavhane et al., 2002; El-Sebaii et al., 2002). Usually, drying agricultural products is accomplished at low temperatures; therefore, solar drying method can be a great alternative to the conventional drying methods. Increasing products quality and decreasing the drying period is one of the benefits of solar drying method (Sharma et al., 1995). Apple fruit contains a high percentage of water. Accordingly, it exhibits relatively high metabolic activity in comparison with other plant-derived food such as seed. This metabolic activity continues after harvesting, thus making most fruits as highly perishable commodities (Atungulu et al., 2004). Mathematical modeling of drying under different conditions is necessary to obtain better control of drying operation and overall improvement of the quality of the final product. Models are often employed to study the variables involved in the process, predict drying kinetics of the product, and optimize the operating parameters (Karathanos and Belessiotis, 1999). The thin-layer drying equations were utilized to estimate the drying period of several products and also to generalize drying curves. Several investigators had proposed numerous mathematical models for the thin-layer drying of many agricultural products (Yaldiz et al., 2001; Togrul and Pehlivan, 2002; Doymaz, 2004; Sacilik and Elicin, 2006; Wang et al., 2006; Aghabashlo et al., 2008; Zomorodian and Moradi, 2010).

A mathematical model was developed to solve the heat and mass transfer equations for convective drying of Banana fruit. The shrinkage of material and dependency of moisture content variation and shrinkage phenomenon were taken into account by the model. According to the results, the model agreed closely with the experimental values (Karim and Hawlader, 2005). A vacuum- belt drying technology was applied to dry natural- herb extract. The performance of different mathematical models describing the drying process were tested and compared. In conformity with the results, the Logarithmic model provided better prediction than the other models (Liu et al., 2009). Drying kinetics of olive cake during the convective dehydration process was modeled. Air temperature showed a significant effect on drying rates. Based on the statistical tests results, the Modified Henderson and Pabis equation was the most suitable model to describe the experimental drying curves (Vega-Galvez et al., 2010). A one-dimensional unsteady state mathematical model of coupled heat and mass transfer equations was developed to simulate the convective drying of the thin layer of carrot slices. A semi-analytical proposed-solution method took fundamentals of the drying process into consideration. The predicted temperature and moisture history of food in drying process was validated with a set of experimental data. A remarkable agreement was observed between the theoretical and the experimental data (Barati and Esfahani, 2012). Using of solar dryer for drying of apple chips is suitable and safe in rural areas.

Modification of solar dryer can help to increasing of drying rate and managing of energy consumption. The collector inclination has different effects on drying behavior of products, so the objective of the current study is to determine the effect of the inclination, drying air temperature, and air flow rate on the drying characteristics and dehydration ratio of apple chips (‘Golab’). ‘Golab’ apple has the synonym ‘Kohanz’ and is a native apple variety of Iran. This type has small fruit size (50 ± 10 mm diameter) with suitable smell and taste and grows in mountain area of Iran (Lak, 2011).

## Materials and methods

### Material

Apples were harvested form local Garden of Zarghan, Fars Province. Suitable models were selected in order to describe the thin-layer drying process. Samples of apple slices with 3 mm thickness were prepared by a precise cutter device. Before drying process, the initial wet basis moisture content of samples was measured using moisture analyzer (AND MX50 model). The moisture content of apple slices was 73.4±2% (w.b.).

### Experimental setup

The experiments were undertaken in an active and mixed mode solar dryer with capacity of 10 kg/batch. This dryer consisted of a collector unit, diffuser, chamber, and a centrifugal fan. Fig. 1 portrays the solar dryer with variable inclination mechanism. The collector unit contained an absorber black plate with dimensions of 1×2 m. Air passed through both sides of the collector and absorbed the solar heat energy. After that, hot air is directed into the chamber by the diffuser. The chamber consisted of two trays where slices of apples were placed. The chamber had a channel to connect the air supply fan. In order to reduce heat loss, the collector and the chamber were made of plywood and insulated by a 5 cm- thick glass wool. The maximum airflow rate of dryer was about 4500 $m^3/h$ that was achieved using centrifugal fan with 1400 rpm and 0.7 kW. The air flow rate was also changed by an inverter that was installed in the fan circuit. A galvanized pipe 1000 mm long, and 152 mm in diameter was utilized at the outlet of the fan to obtain a fully developed flow. The air velocity was measured at the end of the outlet pipe by a hot wire anemometer (Lutron AM-4202). In order to measure the variation of temperature during drying process, three K-type thermocouples were employed in collector, chamber and outlet pipe of the dryer. Temperature data was recorded via a data acquisition system (Data Shuttle/ USB 56 model) at regular 5 second intervals. Two electrical heaters (2×1 kW) were installed in the


**Figure 1.** Solar dryer components

diffuser part of the dryer that assisted the solar heater system when there was not enough solar radiation energy for drying. The solar dryer was considered as a hybrid type dryer.

The chamber was located above the dryer to absorb the solar radiation directly by a glass cover of 4 mm thickness that was placed over the chamber with 45 degrees of tilt. The slope angle of collector depends on the latitude of the region. There is not any appropriate equation to determine the inclination of collector. The best collector tilt angle has to be determined experimentally for every region. This angle (α) is equal to latitude angle ± 15 degrees (Duffie and Beckman, 1991). The solar radiation angle changes in different seasons, so drying process will be more efficient if the tilted angle of the collector can be changed according to the radiation angle. In summer, the steepness of solar radiation increases; consequently, it is better to decrease the inclination of the collector and vice versa in winter, the inclination should be increased. In this dryer, a new mechanism is designed to change the slope angle of the collector. On the top edge of the collector a joint was mounted that allowed the lower part of the collector to move up and down. It allowed the change of the tilted angle of the collector. Experiments were carried out in Zarghan region near Shiraz. Shiraz is a capital city of Fars Province. It is located in the south west of Iran and the latitude of this region is about 30 degrees, so the inclination of the collector varies from 15 to 45 degrees.

### Procedure

The average initial moisture content of apple chips was about 73.4% (w.b.) Drying process was accomplished continuously in each test for a uniform 120 minutes period in the dryer. Three levels of airflow rate (0.018, 0.036 and 0.072 $m^3 \cdot s^{-1}$) and two levels of the collector slope angle (30 and 45 degrees) were adopted and all the experiments were carried out in July from 10:30 to 12:30. In conformity with the test conditions, the final average moisture content of apple chips was about 12% (w.b.) During the experiments, the ambient air temperature was about 30°C (±5°C), and the relative humidity was about 26±2%. Due to the short drying period (120 minutes), the inlet air temperature did not experience any considerable fluctuations. As a result, the air temperature inside the drying chamber only depended upon the airflow rate and tilted angle of the collector through the drying process. The lower the airflow rate, the higher the drying air temperature. As the airflow rate increased from 0.018 to 0.072 $m^3 \cdot s^{-1}$, the average inlet air temperature to the chamber decreased from 51.5 to 36.6°C when the collector slope angle equals 30 degrees and the average inlet air temperature also drops from 44 to 36.4°C when the slope angle reaches to 45 degrees. The solar radiation intensity was measured and recorded utilizing a solarimeter (Kimo Co. - SL100 model- Japan) whose probe was located on the glass cover of the collector. The average solar intensity during the test in July was 800±145 $W \cdot m^{-2}$. The moisture content variation was measured based on decreasing weight of samples during the drying process. Weighing of samples was performed over different intervals of 30 minutes applying a precise scale with 0.1 g precision (AND Co.- EK-6000i model- Japan).

### Data analysis

The thin layer drying procedure has been found to be the most appropriate tool for characterizing the drying parameters (Akgun and Doymaz, 2005; Akpinar et al., 2003). There are three types of the thin layer drying models to describe the drying rate of agricultural products; theoretical, semi-theoretical, and empirical models (Midilli et al., 2002; Demirats et al., 1998). The theoretical approach concerns either the diffusion equation or simultaneous heat and mass transfer equations. The empirical model neglects the fundamentals of drying processes and presents a direct relationship between average moisture and drying time by means of regression analysis (Ozdemir and Devres, 1999). The semi-theoretical model is also a trade-off between the theoretical and empirical ones deriving from a widely applying simplification of the Fick's second law of diffusion or modification of the simplified model, such as the Lewis model, the Page model, the Modified Page model, and the Henderson model. In order to model the thin layer drying by semi- theoretical method, it is required to calculate the variation of moisture ratio of products. The moisture ratio (*MR*) is defined as follows (Mujumdar, 2004):

$$MR = \left(M - M_e\right)/\left(M_0 - M_e\right) \qquad (1)$$

The values of $M_e$ are relatively small compared to $M$ or $M_0$ in the drying period, thus the *MR* can be simplified to $MR= M/M_0$ (Akpinar et al., 2003; Midilli et al., 2002). To examine the drying characteristics of apple fruit, it was essential to model the drying behavior effectively. The experimental thin layer drying data for apple chips at different drying air temperatures and flow rates were fitted into 10 commonly used drying models illustrated in Table (1).

Goodness of fitting was validated by applying three statistical criteria as root of mean square error (RMSE), reduced Chi-square ($\chi^2$), and coefficient of determination ($R^2$). They were calculated using Minitab software (version 15, Minitab Inc.

**Table 1.** Mathematical models for thin layer drying

| Model name | Model equation | References |
|---|---|---|
| Newton | MR = exp(-kt) | (Westerman *et al.,* 1973) |
| Page | MR = exp(-kt$^n$) | (Guarte, 1996) |
| Modified Page | MR = exp(-kt)$^n$ | (Yaldiz and Ertkin, 2001) |
| Henderson and Pabis | MR = a. exp(-kt) | (Yagcioglu *et al.,* 1999) |
| Logarithmic | MR = a.exp(-kt) +c | (Akpinar *et al.,* 2003) |
| Two term | MR = a.exp(-$k_0$t)+ b.exp(-$k_1$t) | (Rahman, 1998) |
| Exponential two term | MR = a.exp(-kt)+ (1-a).exp(-$k_a$t) | (Yaldiz *et al.,* 2001) |
| Wang and Sing | MR = 1 + at + bt$^2$ | (Ozdemir and Devres, 1999) |
| Approximation of diffusion | MR = a.exp(-kt)+ (1-a).exp(-kbt) | (Akpinar *et al.,* 2003) |
| Midilli et al. | MR = a.exp(-kt$^n$)+ bt | (Sacilik *et al.,* 2006) |

USA). The higher $R^2$ value and the lower $\chi^2$ and RMSE values were better for goodness of fit (Yaldiz and Ertekin, 2001; Yaldiz et al., 2001). These parameters have been calculated as follows (Madamba et al., 1996):

$$RMSE = \left[ \frac{1}{N} \sum_{i=1}^{N} (MR_{pre,i} - MR_{\exp,i})^2 \right]^{1/2} \quad (2)$$

$$\chi^2 = \left[ \frac{\sum_{i=1}^{N} (MR_{\exp,i} - MR_{pre,i})^2}{N - P} \right] \quad (3)$$

$$R^2 = \left[ 1 - \frac{\sum_{i=1}^{N} (MR_{\exp,i} - MR_{pre,i})^2}{\sum_{i=1}^{N} (MR_{\exp,i})^2} \right] \times 100 \quad (4)$$

The influence of the drying parameters on these coefficients was checked using pair wise method by Minitab software to establish an equation for every empirical coefficient in the chosen thin layer models. For this reason, five linear and nonlinear equations were derived for every empirical coefficient.

The best subset regression method was applied to classify the best model. Since this method is based on the maximum coefficient of determination, setup models were checked for other necessary post tests, such as t value of regression coefficients, sum square of error (*SSE*), and adjusted coefficient of determination ($R^2_{adj}$).

$$SSE = \sum_{i=1}^{N} (M_{\exp,i} - M_{pre,i})^2 \quad (5)$$

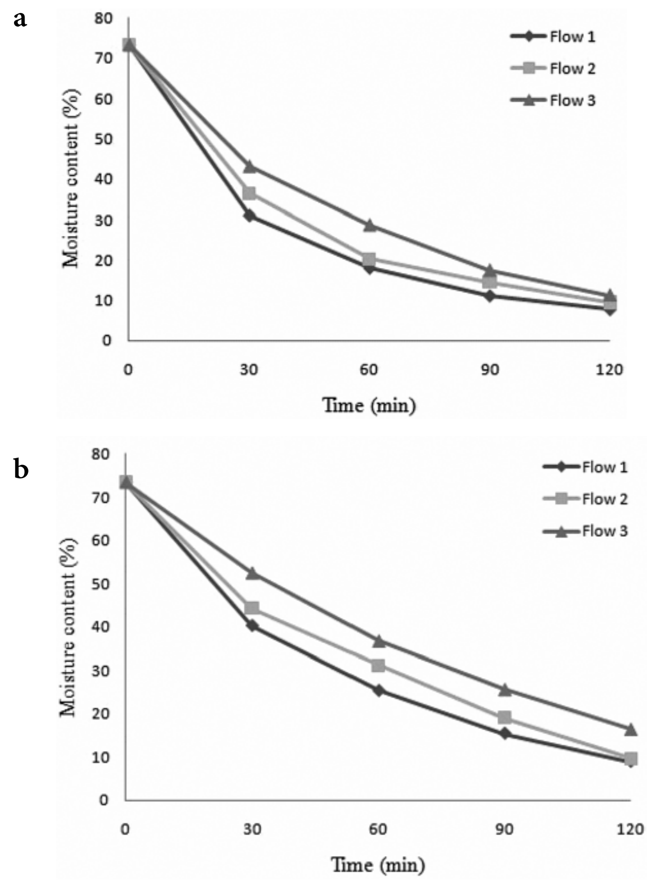


**Figure 2.** Variations of experimental moisture content versus drying time for apple at three airflow rate and collector tilted angle (a: 30° and b: 45°)

## Results and Discussion

Apple chips were dried in a hybrid solar dryer equipped with an adjustable inclination mechanism for the collector. The moisture content values versus drying period at three airflow rates and in two levels of inclination were showed in Figs. 2a and 2b. The results obtained proved that an increase in air flow rate caused a decrease in the intensity of drying down to 30 percent in every tilted angle. Because, reduction of airflow rate increased the drying air temperature entered into the chamber. It causes to increase drying efficiency in solar dryer.

Comparisons between moisture ratio variations in levels of collector inclination angle and airflows indicated that intensity rate of drying increased when inclination angle and airflow were 30 degrees and 0.018 $m^3 \cdot s^{-1}$, respectively. It was similar to the results gained by Zomorodian and Moradi (2010) during the drying process of cumin. Moisture ratio (*MR*) data at different drying air flow rates and the collector inclination were fitted into 10 commonly applied drying models. Empirical coefficients in all models for the thin layer drying of apple chips were determined in two levels of collector slope angle. Approximation of diffusion and Midilli models showed the best curve fitting results $\chi^2$ respectively in 30 and 45 degrees with the highest $R^2$, and the lowest RMSE (Tables 2 and 3).

Consequently, these two models were selected to represent the thin layer solar drying characteristics of apple chips. In another research performed by Liu et al. (2009), Logarithmic model predicted the drying process of natural herb extract in a vacuum- belt dryer better than the other models. Coefficients of approximation of diffusion model (a, k and b) and Midilli model (a, k, n and b) changed according to the influence of airflow rate and drying air temperature in different inclinations.

Different equations were established for empirical coefficients of Approximation and Midilli models were analyzed by considering the "t" values, the residual diagnosis consisted of $R^2$, $R^2adj.$, and *SSE* in two levels of the collector tilted angle (Asadi et al., 2012).Table 4 show five equation models discussing three coefficients in the approximation of diffusion model for 30 degrees of inclination. In conformity with the results, it is clarified that the third model had the lowest *SSE*, and the other residual diagnostic tests had the highest values for a, k, and b coefficients. On the other hand, "t" values were significant at 1% level.

Also, four coefficients in the Midilli model, which described drying in 45 degrees of the collector slope angle, were examined by five models. Due to the lowest *SSE,* the highest values of

**Table 2.** Statistical results obtained from various thin layer drying models for the collector slope angle of 30º

| Model name | Model coefficients | $R^2$ | RMSE | $\chi^2$ |
|---|---|---|---|---|
| Newton | k = 0.019776 | 0.972 | 0.0541 | 0.0031 |
| Page | k = 0.047812, n = 0.784166 | 0.980 | 0.0448 | 0.0023 |
| Modified Page | k = 0.140628, n = 0.0.140628 | 0.972 | 0.0541 | 0.0034 |
| Henderson and Pabis | a = 0.981667, k = 0.019403 | 0.973 | 0.0535 | 0.0033 |
| Logarithmic | a = 0.897722, k = 0.025657, c = 0.09948 | 0.982 | 0.0459 | 0.0026 |
| Two term | a = 0.951531, $k_0$= 0.018788, b = 0.048469, $k_1$ = 0.649982 | 0.975 | 0.0526 | 0.0037 |
| Exponential two term | a = 0.037537, k = 0.378843 | 0.981 | 0.0454 | 0.0026 |
| Wang and Sing | a = -0.01669, b = 0.000081 | 0.964 | 0.0599 | 0.0041 |
| Approximation of diffusion | a = 0.0333411, k = 0.056994, b = 0.239712 | 0.994 | 0.0447 | 0.0025 |
| Midilli et al. | a = 2.017841, k = 0.338971, n = 0.409167, b = -0.00044 | 0.992 | 0.0448 | 0.0027 |

**Table 3.** Statistical results obtained from various thin layer drying models for the collector slope angle of 45º

| Model name | Model coefficients | $R^2$ | RMSE | $\chi^2$ |
|---|---|---|---|---|
| Newton | k = 0.014845 | 0.962 | 0.0545 | 0.0037 |
| Page | k = 0.0170981, n = 0.966606 | 0.964 | 0.0543 | 0.0036 |
| Modified Page | k = 0.121838, n = 0.121838 | 0.961 | 0.0545 | 0.0035 |
| Henderson and Pabis | a = 0.994961, k = 0.014761 | 0.974 | 0.0544 | 0.0035 |
| Logarithmic | a = 0.997216, k = 0.014686, c = -0.002501 | 0.973 | 0.0545 | 0.0037 |
| Two term | a = 0.988383, $k_0$= 0.014672, b = 0.010631, $k_1$ = 0.051716 | 0.969 | 0.0544 | 0.0040 |
| Exponential two term | a = 0.037537, k = 0.378843 | 0.970 | 0.0541 | 0.0037 |
| Wang and Sing | a = -0.012731, b = 0.000041 | 0.968 | 0.0578 | 0.0039 |
| Approximation of diffusion | a = 0.037545, k = 0.405949, b = 0.035031 | 0.981 | 0.0540 | 0.0035 |
| Midilli et al. | a = 0.876594, k = 0.009305, n = 1.033711, b = -0.00064 | 0.985 | 0.0532 | 0.0033 |

**Table 4.** Different regression models for empirical coefficients in 30º of the collector inclination

| No | Regression Equation (t value) | $R^2$ | $R^2_{adj}$ | SSE |
|---|---|---|---|---|
| 1 | a = 3.91 - 0.0709 (T) - 17.2 (Q)<br>(14.75)*** (-11.91)*** (-19.31)*** | 0.986 | 0.981 | 0.035344 |
| 2 | a = 1.96 - 0.118 (T) - 0.928 ln(Q)<br>(6.15)*** (-8.50)*** (-11.17)*** | 0.959 | 0.945 | 0.060152 |
| 3 | a = 2.63 - 0.0479 (T) – 155 $(Q)^2$<br>(18.63)*** (-14.20)*** (-28.91)*** | 0.994 | 0.991 | 0.023716 |
| 4 | a = 11.8 - 17.4 (Q) - 2.90 ln(T)<br>(13.26)*** (-20.02)*** (-12.40)*** | 0.987 | 0.982 | 0.034000 |
| 5 | a = 2.46 - 17.0 (Q) - 0.000865 $(T)^2$<br>(16.28)*** (-18.52)*** (-11.38)*** | 0.984 | 0.979 | 0.036932 |
| 1 | k = - 1.40 + 0.0293 (T) + 9.68 (Q)<br>(-12.81)*** (11.91)*** (26.29)*** | 0.994 | 0.992 | 0.0146613 |
| 2 | k = - 0.312 + 0.0563 (T) + 0.524 ln(Q)<br>(-2.06)* (-8.50)*** (13.27)*** | 0.976 | 0.968 | 0.028601 |
| 3 | k = - 0.684 + 0.0163 (T) - 87 $(Q)^2$<br>(-14.21)*** (14.20)*** (47.75)*** | 0.998 | 0.997 | 0.008072 |
| 4 | k = -4.65 + 9.76 (Q) – 1.20 ln(T)<br>(-12.68)*** (27.18)*** (12.40)*** | 0.994 | 0.992 | 0.014058 |
| 5 | k = -0.805 – 9.60 (Q) - 0.000358 $(T)^2$<br>(-12.88)*** (25.29)*** (11.38)*** | 0.993 | 0.991 | 0.015270 |
| 1 | b = - 1.11 - 0.0178 (T) – 5.77 (Q)<br>(16.65)*** (-11.91)*** (-25.81)*** | 0.993 | 0.991 | 0.008879 |
| 2 | b = 0.457 - 0.0339 (T) - 0.313 ln(Q)<br>(5.00)*** (-8.50)*** (-13.14)*** | 0.975 | 0.967 | 0.017222 |
| 3 | b = 0.679 - 0.0100 (T) - 51.9 $(Q)^2$<br>(22.88)*** (-14.20)*** (-46.20)*** | 0.998 | 0.997 | 0.004977 |
| 4 | b = 3.08 - 5.82 (Q) - 0.728 ln(T)<br>(13.83)*** (-26.69)*** (-12.40)*** | 0.994 | 0.992 | 0.008541 |
| 5 | b = 0.744 - 5.73 (Q) - 0.000217 $(T)^2$<br>(19.60)*** (-24.82)*** (-11.38)*** | 0.993 | 0.990 | 0.009278 |

* - Significant at 10%; ** - Significant at 5%; *** - Significant at 1%

**Table 5.** Different regression models for empirical coefficients in 45º of the collector inclination

| No | Regression Equation (t value) | $R^2$ | $R^2_{adj}$ | SEE |
|---|---|---|---|---|
| 1 | a = - 8.86 + 0.200 (T) + 52.0 (Q) | 0.898 | 0.864 | 0.130681 |
| | (-5.86)*** (7.28)*** (6.96)*** | | | |
| 2 | a = - 0.74 + 0.302 (T) + 3.13 Ln(Q) | 0.358 | 0.144 | 0.328430 |
| | (-0.47)*** (1.70)*** (1.62)*** | | | |
| 3 | a = - 4.72 + 0.136 (T) + 379 $(Q)^2$ | 0.956 | 0.941 | 0.086120 |
| | (-7.86)*** (11.32)*** (10.93)*** | | | |
| 4 | a = - 39.1 + 61.7 Q + 10.2 Ln(T) | 0.845 | 0.793 | 0.161308 |
| | (-5.42)*** (5.54)*** (5.72)*** | | | |
| 5 | a = - 3.60 + 44.3 Q + 0.00195 $(T)^2$ | 0.925 | 0.900 | 0.112393 |
| | (-5.36)*** (8.09)*** (8.58)*** | | | |
| 1 | k = - 0.176 + 0.0122 T + 2.31 Q | 0.949 | 0.932 | 0.008008 |
| | (-1.90) (7.28)*** (5.05)*** | | | |
| 2 | k = 0.198 + 0.0150 T + 0.120 Ln(Q) | 0.788 | 0.717 | 0.016352 |
| | (2.55)** (1.70) (1.25) | | | |
| 3 | k = 0.0032 + 0.00948 T + 17.1 $(Q)^2$ | 0.971 | 0.962 | 0.006013 |
| | (0.08) (11.32)*** (7.06)*** | | | |
| 4 | k = - 2.03 + 2.91 Q + 0.627 Ln(T) | 0.922 | 0.897 | 0.009885 |
| | (-4.59)*** (4.26)*** (5.72)*** | | | |
| 5 | k = 0.146 + 1.84 Q + 0.000120 $(T)^2$ | 0.962 | 0.950 | 0.006888 |
| | (3.54)*** (5.48)*** (8.58)*** | | | |
| 1 | n = - 1.20 + 0.0269 T + 6.53 Q | 0.905 | 0.874 | 0.017610 |
| | (-5.91)*** (7.28)*** (6.49)*** | | | |
| 2 | n = - 0.178 + 0.0387 T + 0.382 Ln(Q) | 0.457 | 0.276 | 0.042181 |
| | (-0.89) (1.70) (1.54) | | | |
| 3 | n = - 0.688 + 0.0189 T + 47.7 $(Q)^2$ | 0.956 | 0.941 | 0.012009 |
| | (-8.21)*** (11.32)*** (9.87)*** | | | |
| 4 | n = - 5.28 + 7.83 Q + 1.38 Ln(T) | 0.856 | 0.808 | 0.021737 |
| | (-5.43)*** (5.22)*** (5.72)*** | | | |
| 5 | n = - 0.496 + 5.49 Q + 0.000263 $(T)^2$ | 0.930 | 0.907 | 0.015146 |
| | (-5.48)*** (7.44)*** (8.58)*** | | | |
| 1 | b = - 0.0301 + 0.000513 T + 0.124 Q | 0.906 | 0.875 | 0.000335 |
| | (-7.76)*** (7.28)*** (6.46)*** | | | |
| 2 | b = - 0.0106 + 0.000736 T + 0.00725 Ln(Q) | 0.463 | 0.284 | 0.000801 |
| | (-2.79)** (1.70) (1.54) | | | |
| 3 | b = - 0.0203 + 0.000361 T + 0.905 $(Q)^2$ | 0.956 | 0.941 | 0.000229 |
| | (-12.70)*** (11.32)*** (9.82)*** | | | |
| 4 | b = - 0.108 + 0.149 Q + 0.0262 Ln(T) | 0.857 | 0.809 | 0.000414 |
| | (-5.82)*** (5.21)*** (5.72)*** | | | |
| 5 | b = - 0.0166 + 0.104 Q + 0.000005 $(T)^2$ | 0.930 | 0.907 | 0.000288 |
| | (-9.64)*** (7.41)*** (8.58)*** | | | |

* - Significant at 10%; ** - Significant at 5%; *** - Significant at 1%

$R^2$, and $R^2adj.$, the third model were selected. As for the results obtained, “t” values were also significant at 1% level (Table 5).

Zomorodian and Dadashzadeh (2009) found the linear correlations for constant coefficients of Page model with air temperature and velocity during the drying process of sultana grape in a mixed mode solar dryer with 45 degrees of the collector tilted angle. Experimental and predicted variation of moisture ratio versus the drying period are displayed for different air flow rate in Figs. 3 and 4 for 30 and 45 degrees of the collector inclination, respectively.

The established models for each drying condition provided a satisfactory agreement between experimental and predicted moisture ratio values. A comparison between moisture ratio variations for different inclination angle illustrated an increase in the intensity rate of drying process when this angle was 30 degrees (Fig. 5).

In summer, the tilted angle of sunlight radiation increases, so in order to receive radiation energy more efficiently, the tilted angle should be lowered. Uniform variation of observation order

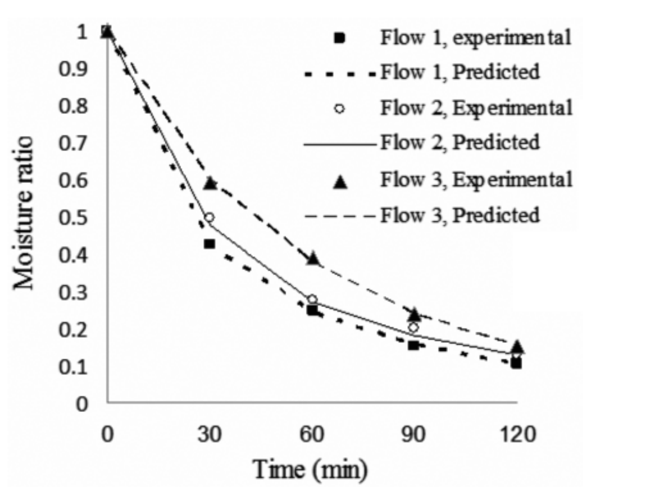


**Figure 3.** Variation of experimental and predicted moisture ratio versus drying period at three levels of flow rate for 30º of the collector inclination angle

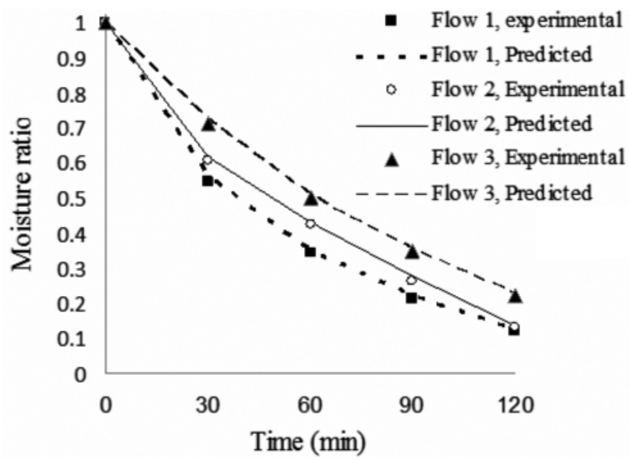


**Figure 4.** Variation of experimental and predicted moisture ratio versus drying period at three levels of flow rate for 45° of the collector inclination angle

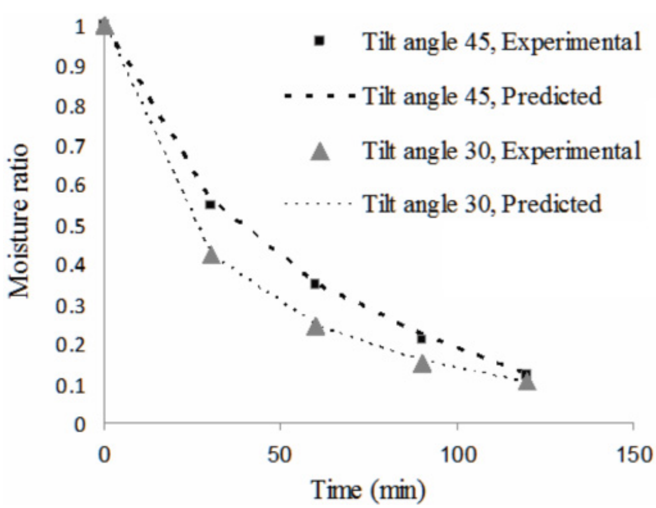


**Figure 5.** Comparison between moisture ratio variations in different inclination of the collector

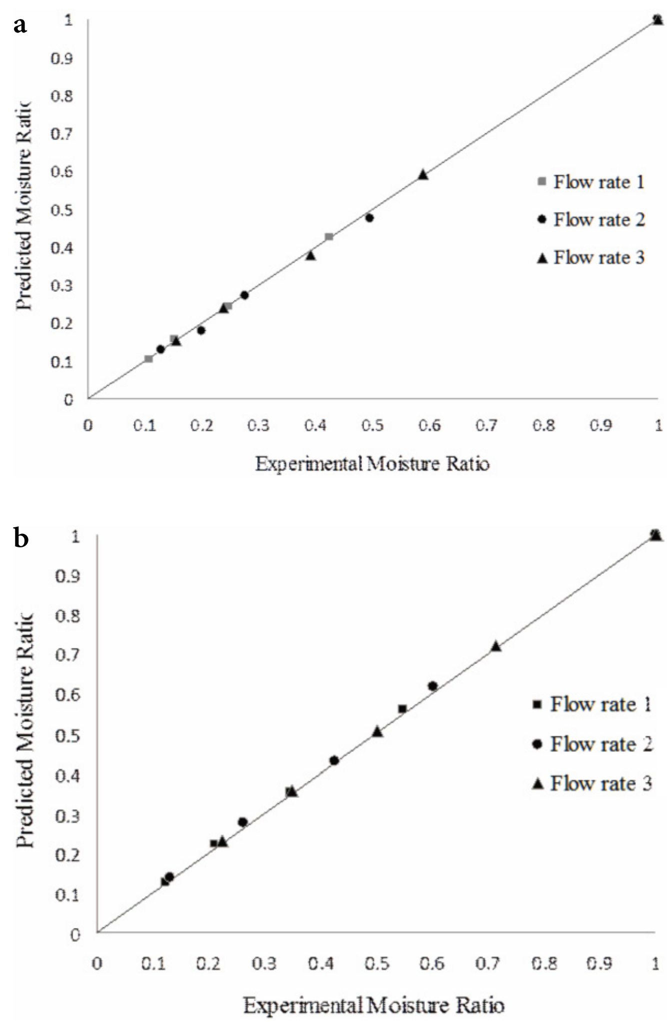


**Figure 6.** Comparison between experimental and Predicted Moisture Ratio values for two levels of tilted angle of the collector (a: 30° and b: 45°

and fitted value revealed that the assumption of uniformity of variance among residuals was held (Figs. 6a and 6b). In other words, homoscedasticity of residuals was proved according Asadi et al., (2012) method. Although most of models had good agreement with experimental data, but the approximation of diffusion model (Fig. 6a) and the Midilli model (Fig. 6b) were better than others for describing the drying behavior of apple chips.

## Conclusion

Acquired results showed that the approximation of diffusion and the Midilli models had the best curve fitting for observation values when the collector slope angle was 30 and 45 degrees, respectively. In this research we concluded that an increase in airflow rate caused a decrease in the intensity of drying down to 30 percent in every tilted angle. Results showed that when the 2$^{nd}$ polynomial equations were selected, there was a good agreement between observation and predicted data. Comparisons between moisture ratio variations in levels of collector inclination angle and airflows indicated that, intensity rate of drying increased when inclination angle and airflow were 30 degrees and 0.018 $m^3.s^{-1}$, respectively. Uniform variation of observation and predicted values revealed that the predicted *MR* out of the approximation of diffusion model and Midilli model was acceptable to describe the drying behavior of apple chips.

## References

Aghabashlo M., Kianmehr M.H., Khani S. (2008) Mathematical modeling of carrot thin layer drying using new model. Energy Convers. Manage., 49, 201–212.

Akgun N., Doymaz I. (2005) Modeling of olive cake thin-layer drying process. J. Food. Eng., 68, 455–461.

Akpinar E. K., Bicer Y., Midilli A. (2003) Modeling and experimental study on drying of apple slices in a convective cyclone dryer. J. Food. Process Eng., 26, 515–541.

Asadi V., Raoufat M.H., Nassiri, S.M. (2012) Fresh egg mass estimation using machine vision technique. Int. Agrophysics, 26, 229–234.

Atungulu G., Nishiyama Y., Koide S. (2004) Electrode configuration and polarity effects on physiochemical properties of electric field treated apples post harvest. Biosyst. Eng., 87, 313–323.

Barati E., Esfahani J.A. (2012) Mathematical simulation of convective drying: Spatially distributed temperature and moisture in carrot slab. Int. J. Therm. Sci., 56, 86-94.

Demirats C., Ayhan T., Kaygusuz K. (1998) Drying behavior of hazelnuts. J. Sci. Food Agric., 76, 559–564.

Doymaz I. (2004) Convective air drying characteristics of thin layer carrots. J. Food. Eng., 61, 359–364.

Duffie J.A., Beckman W.A. (1991) Solar engineering of thermal processes. John Wiley & Sons Inc., New York.

El-Sebaii A.A., Aboul-Enein S., Ramadan MRI, El-Gohary H.G. (2002) Experimental investigation of an indirect type natural convection solar dryer. Energy Convers. Manage., 43, 2251–2266.

Guarte R. (1996) Modeling the drying behavior of copra and development of a natural convection dryer for production of high quality copra in the philippines. Ph.D. Thesis, Dissertation, 287, Hohenheim University, Stuttgart, Germany.

Karathanos V.T. Belessiotis V.G. (1999) Application of a thin layer equation to drying data fresh and semi-dried fruits. J. Agr. Eng. Res., 74, 355–361.

Karim M.A, Hawlader M.N.A. (2005) Mathematical modeling and experimental investigation of tropical fruits drying. Int. J. Heat Mass Transfer, 48, 4914–4925.

Lak M.B. (2011) Geometric properties of Kohanz apple fruits. CIGR journal, Vol.13, No.4

Liu X, Qiu Z, Wang L, Cheng Y, Qu H, Chen Y. (2009) Mathematical modeling for thin layer vacuum belt drying of Panaxnotoginseng extract. Energy Convers. Manage., 50, 928–932.

Madamba P., Driscoll R., Buckle K. (1996) The thin layer drying characteristics of garlic slices. J. Food. Process Eng., 29, 75–97.

Midilli A., Kucuk H., Yapar Z.A. (2002) New model for single-layer drying. Drying Technol., 20, 1503–1513.

Mujumdar A.S. (2004) Guide to industrial drying. 1st Ed. Color Publications Pvt. Ltd., Mumbai, India.

Ozdemir M., Devres Y. (1999) The thin layer drying characteristics of hazelnuts during roasting. J. Food. Eng., 42, 225–233.

Pangavhane D.R.,Sawhney R.L., Sarsavadia P.N.(2002) Design, development and performance testing of a new natural convection solar dryer. Energy, 27, 579–90.

Rahman M. (1998) Desorption isotherm and heat pump drying kinetics of peas. Food Res. Int., 30, 485–491.

Sacilik K., Keskin R., Elicin A. (2006) Mathematical modeling of solar tunnel drying of thin layer organic tomato. J. Food. Eng., 73, 231–238.

Sacilik K., Elicin A.K. (2006) The thin layer drying characteristics of organic apple slices. J. Food. Eng., 73, 281–289.

Sharma V.K., Colangelo A., Spagna G. (1995) Experimental investigation of different solar dryers suitable for fruit and vegetable. Renew. Energy, 6, 413–424.

Togrul I.T., Pehlivan, D. (2002) Mathematical modeling of solar drying of apricots in thin layers. J. Food. Eng., 55, 209–216.

Vega-Galvez A., Miranda M., Diaz L.P., Lopez L., Rodriguez K., Di Scala K. (2010) Effective moisture diffusivity determination and mathematical modeling of the drying curves of the olive-waste cake. Bioresour. Technol., 101, 7265–7270.

Wang Z., Sun J., Liao X., Chen F., Zhao G., Wu J., Hu X. ( 2006) Mathematical modeling on hot air drying of thin layer apple pomace. J. Food. Eng., 40, 39–46.

Westerman P, White W. (1973) Relative Humidity Effect on the High Temperature Drying of Shelled Corn. Trans. ASAE, 16, 1136–1139.

Yagcioglu A., Degirmencioglu A., Cagatay F. (1999) Drying characteristics of laurel leaves under different drying conditions. Proceeding of the 7th International Conference on Agricultural Mechanics and Energy, Adana, Turkey, 565–569.

Yaldiz O., Ertekin C. (2001) Thin layer solar drying of some different vegetables. Drying Technol., 19, 583–596.

Yaldiz O., Ertekin C., Uzun H.I. (2001) Mathematical modeling of thin layer solar drying of Sultana grapes. Energy, 26, 457–465.

Zomorodian A.A., Moradi M. (2010) Mathematical modeling of forced convection thin layer solar drying for Cuminumcyminum. J. Agr. Sci. Tech., 12, 401–408.

Zomorodian A.A., Dadashzadeh M. (2009) Indirect and mixed mode solar drying mathematical models for sultana grape. J. Agr. Sci. Tech., 11, 391–400.

## Nomenclature

| | |
|---|---|
| a, b, c, k, $k_0$, $k_1$, n | Empirical coefficients in models |
| $M$ | Moisture content (kg water/kg dry solids) |
| $M_e$ | Equilibrium moisture content (kg water/kg dry solids) |
| $M_0$ | Initial moisture content (kg water/kg dry solids) |
| $MR$ | Moisture ratio |
| $MR_{exp}$ | Experimental moisture ratio |
| $MR_{pred}$ | Predicted moisture ratio |
| $N$ | Number of observations |
| $P$ | Number of parameters |
| $R^2$ | Coefficient of determination |
| $R^2_{adj.}$ | Adjusted coefficient of determination |
| $RMSE$ | Root of mean square error |
| $SSE$ | Error sum squares |
| T | Drying time, s |
| T | Average temperature in chamber, °C |
| Q | Air flow rate, $m^3/s$ |
| $\chi^2$ | Reduced chi-square |

acs80_14