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MATHEMATICL MODELLING OF SOLAR DRYING OF TOMATO IN THIN LAYERS

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ABSTRACT

The aim of this research is to develop and evaluate the solar drying method to dry tomato and improve tomato product quality. Also to study the behavior of tomato drying rate compared with some drying mathematical models. The solar dryer is used to dry tomato under different levels of air velocity (0.5, 1.0, 1.5, and 2.0 m/sec) and three different slices thickness (3, 4, 5 mm). The solar dryer performance is determined by studying the effect of the mentioned studied variables on air specifications and product quality. The maximum temperature recorded inside the dryer chamber was 56°C during the corresponding ambient temperature and relative humidity were 34°C and 30.8%, with 3mm thickness and 0.5 m/s air velocity, respectively. During the test period, the experimental results revealed that the reduction in tomatoes moisture content from 91.78 to 3.463203 % was obtained using drying air velocity of 1 m/s and slices thickness of 5 mm. The modified Henderson and Pabis's model is the most proper model to describe the drying behavior of tomato slices.

Key words: Solar energy, solar dryer, mixed-mode dryer, tomato drying, performance evaluation.

INTRODUCTION

Drying is one of the important food preservation methods especially for the sensitive commodities crops as tomato fruits. In Egypt the annually tomato production is about 8,105,260 Mg (Statistical FAO, 2011). Tomato have a short duration crop, giving high yield. But the excess production results in a glut in the market and reduction in tomato prices. Also, it is highly perishable in the fresh state leading to wastage and losses during the peak harvesting period. The prevention of these losses and wastage is very much important especially due to subsequent imbalance in supply and demand at the harvesting off-season and economic consideration.

Tomato, as other vegetables, can be dried using various methods. In any tomato drying technique the required time for drying the product depends on many parameters such as tomato variety, the soluble solids content of the fresh product, the size of the tomato segments, the air specifications (humidity temperature and velocity) and the efficiency of drying system. The drying rate affects the product quality (Andritsos *et al.,* 2003). They added that, dried tomatoes undergo the following process steps: pre-drying treatments (such as size selection, washing and tray placing), drying or dehydration, and post-dehydration treatments, such as inspection, screening and packaging. Karim and Hawlader (2005) said that dried products have gained commercial importance and their growth on a commercial scale has become an important in agricultural industry. Goula and Adamopoulos (2006) determined a mathematical model for the reaction kinetics of ascorbic acid degradation to describe the rate of vitamin "C" loss in a drying process of tomato halves or tomato pulp. Alonge and Hammed (2007) designed, constructed and tested a direct passive solar dryer using available local materials. The angle of collector inclination varied depending on the location and season. The results of no load test condition gave the maximum of 59°C inside the dryer while outside the dryer was 38°C. Gurlek *et al.* (2008) explained the drying behavior of tomato under twelve different mathematical models. There were compared according to their coefficient of

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determination values. According to the results, the two-term model could adequately describe the solar drying behavior of tomato in a new designed solar tunnel dryer, the experimental data obtained for air at temperature ranging from 32 to 59°C. During there experiments, the time to reach final moisture content of 5% for solar tunnel were found to be 96 hours.

The aim of this research is to develop and evaluate the solar drying method to dry tomato and improve the product quality. Also to study the behaviour of tomato drying rate compared with other mathematical models.

MATERIALS AND METHODS

The experiments were carried out in Zagazig Univ. on September and October (2011 and 2012). The solar dryer Fig. 1 was constructed at local workshop in Tanta city. It consisted of:

1. Solar collector which made from wood and fixed at the front side of the dryer. The collector dimensions are of 1840 × 920 × 150 mm with the slope of 30°. A corrugated black painted iron sheet of 0.5 mm thickness was used to increase the efficiency of energy collection. The top surface of the solar collector was covered by a glass of 5 mm thickness. The front side was made from a perforated stainless steel sheet as a window for air inlet. The window's dimensions are 920 × 150 mm at the north side. The collector was oriented North-South.
2. The drying chamber was constructed as the pyramid shape. The gross dimensions of the chamber were 920 × 920 mm. The base of the drying chamber consists of frame, suction fan, air suction duct, four levels to put one tray with net surface area of 0.65, 0.435, 0.25 and 0.105 m^2 respectively, the dryer was covered by black plastic sheet and four legs are used as a stand.

No.	Part Name	No. of Parts
1	Solar collector	1
2	Glass cover of solar collector	2
3	Corrugated sheet of absorber plate	1
4	Trays	3
5	Chimney	1
6	Air suction fan	1
7	Charging and discharging door	1
8	The drying chamber	1
9	Plastic cover of the drying chamber	4
10	Dryer stand	1

All dimensions in mm

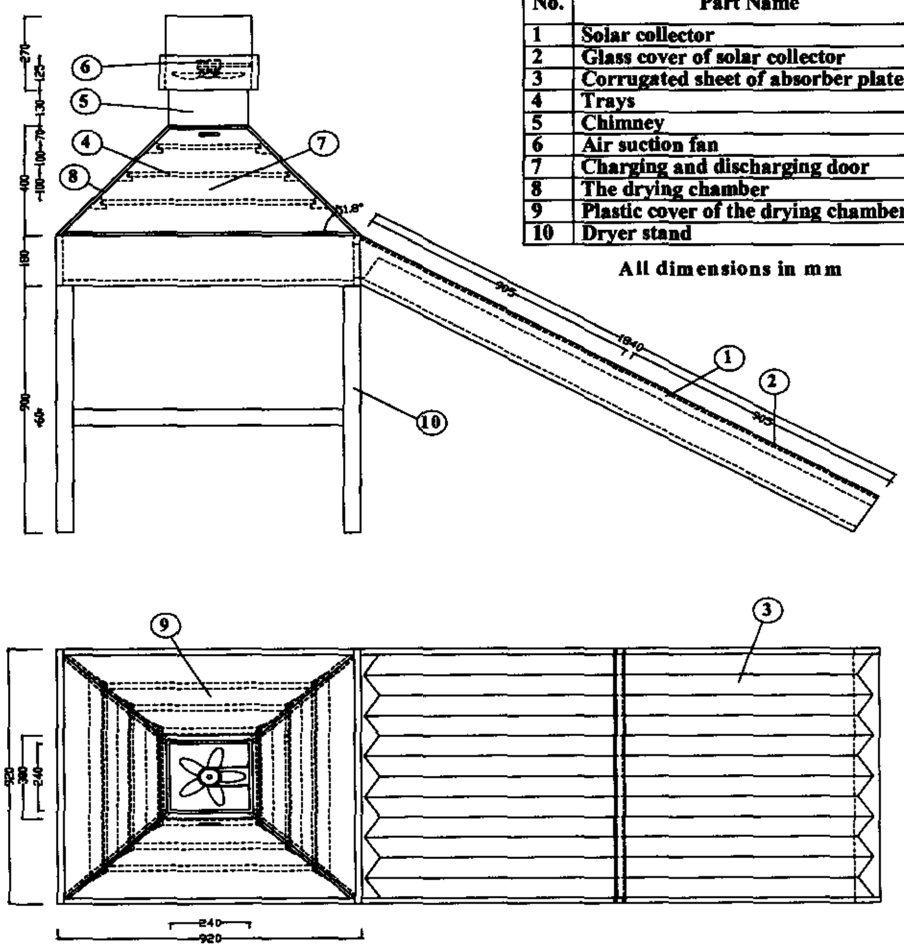

Fig. 1. Elevation and plan of the solar dryer

Experimental Procedure

The dryer prepared by adjusting the air velocity before each run, the slices of tomato loaded on trays as one layer. Performance of the drying process was tested under the following variables:

1. Four different air velocities (0.5, 1.0, 1.5 and 2.0 m/sec) represents air flow rates of 81.617, 163.233, 244.850 and 326.466 m^3/min.
2. Three different thicknesses of tomato slices (3, 4 and 5 mm).

Measurements

1. Air specifications as temperature, velocity, relative humidity were recorded every 5 min along the 1st hour, then every 10 min along the 2nd hour, then every 15 min along the 3rd hour, then every 20 min along the 4th hour, then every 30 min along the 5th hour and finally every 1 hour up to the end of the run.
2. During the drying process, tomato slice moisture content was measured before the drying process and throughout the drying period at different places of the drying trays by taking slice of tomato sample in four replicates and using the electric oven at 70°C for 24 h.

Experimental Measurement and Measuring Equipment

Mass of tomato slices

Mass of tomato slices was conducted using an electrical digital balance ±0.1 g accuracy.

Air temperature, air velocity and relative humidity

The digital device (Tri-SENSE) model No. 37000-00 used to measures temperature, humidity and air velocity. The range for air velocity form (0 to 25 m/sec) with accuracy of (±0.2 m/sec) and the range for temperature from (-29 to 70 °C) with accuracy of (±1.5 °C). Hygro Thermo- Anemometer measures temperature, humidity and air velocity. The range for air velocity from (0.4 to 25 m/sec) with accuracy of (±0.2 m/sec), the range for temperature from (0 to 50°C) with accuracy of (±0.8°C) and the range for relative humidity from (10 to 70 RH) with accuracy of (±3 RH) and from (70 to 95 RH) with accuracy of (±4 RH).

Measurement of the hourly total solar radiation (I_T)

The solar radiation data were collected from the weather station "Watchdog" model 900 ET. The Weather station measures wind speed (0-175 m/h) ± 5%, wind direction (2° increments) ± 7°, temperature (-30° : 100°C), relative humidity (20-100%) ± 3%, rainfall (0.01-0.25 cm) ± 2% and solar radiation (1- 1250 W/m^2).

Estimation of the moisture ratio (*MR*) and drying rate

The moisture ratio (*MR*) and drying rate were calculated by using the following equations:

$$MR = \frac{M_t - M_e}{M_i - M_e}, \text{ decimal}$$

$$M_e=(M_i+M_f)-(Mm)^2/(Mi+M_f)-2(Mm)$$

(Callaghan and Nellist,1971)

$$Drying\ rate= \frac{M_{t-dt} - M_t}{dt}, \ kg\ water/min$$

Where:

M_i, M_f are Initial and final moisture contents (db%), *Mm* is moisture content at half time(db%), M_e is Material moisture content in equilibrium with the drying air (db%), M_{t-dt} and M_t are the moisture contents at *t-dt* and *t*, respectively (db%), and dt is the drying time period (min.).

Thin Layer Drying Equations

In this study three drying models were examined to check their applicability in describing the drying behavior of tomato slice (Table 1).

Statistical Analysis

Regression analyses were done by using the statistical routine. The coefficient of correlation (r) was one of the primary criterions for selecting the best equation to define the thin layer drying curves of tomato slices (O'Callaghan *et al.*, 1971). In addition to r, the various statistical parameters such as; reduced chi-square (χ^2), mean bais error (MBE) and root mean square error (RMSE) were used to

Table 1. The examined models included

1- Lewis's model (Lewis, 1921)	$MR=\frac{M-M_f}{M_o-M_f}=\exp(-kt)$
2- Henderson and Pabis's model, Chhninman (1984) and Westerman *et al.* (1973)	$MR=\frac{M-M_f}{M_o-M_f}=A\exp(-kt)$
3- Page's model (Page, 1949)	$MR=\frac{M-M_f}{M_o-M_f}=A\exp(-kt^u)$
4- Logarithmic model (Yagcıoglu *et al.*, 1999)	$MR=\frac{M-M_f}{M_o-M_f}=A\exp(-kt)+C$
5- Two term model, Henderson (1974) and Rahman *et al.* (1998)	$MR=\frac{M-M_f}{M_o-M_f}=A\exp(-k_1t)+B\exp(-k_2t)$
6- Modified Henderson and Pabis's model (Karathanos, 1999)	$MR=\frac{M-M_f}{M_o-M_f}=A\exp(-k_1t)+B\exp(-k_2t)+C\exp(-k_3t)$

Where: *MR:* moisture ratio. *k:* the drying coefficient. *M:* moisture content at time t
Mo: initial moisture content *Mf:* final moisture content *t:* drying time
K, k_1, k_2, k_3, A, B and C: the drying constants.
k_H: drying constant, 1/min A_H: equation constant, dimensionless

determine the quality of the fit model. These parameters can be calculated as following:

$$X^2=\frac{\sum_{i=1}^{N}\left(MR_{obs,i}-MR_{calc,i}\right)^2}{N-n}$$

$$MBE=\frac{1}{N}\sum_{i=1}^{N}\left(MR_{obs,i}-MR_{calc,i}\right)$$

$$RMSE=\left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{obs,i}-MR_{calc,i}\right)^2\right]^{\frac{1}{2}}$$

Where:

$MR_{obs.,i}$: stands for the observed moisture ratio found in any measurement

$MR_{calc.,i}$: is the calculated moisture ratio for this measurement.

N and *n* are the number of observations and constants, respectively (Pangavhane *et al.*, 2002).

Biochemical Quality

Food quality is the sum of all desirable attributes which make a food acceptable for consumption. For tomato slices the parameters such as colour and nutrient content in terms of PH and ascorbic acid are considered to be appropriate for evaluation using a standard methods.

RESULTS AND DISCUSSION

Influence of Drying Time and Air Velocity on Air Temperature Behaviour

Figs. 2 and 3 illustrate the behaviour of air temperature related to drying time at different levels of drying air velocity. As shown in Fig. 2, increasing drying time from 0.0 to 240 minutes, the air temperature increased from 49 to 56, 44 to 51, 42 to 49 and 39 to 47°C at air velocities of 0.5, 1.0, 1.5 and 2 m/s respectively. While by increasing drying time from 240 to 480 minutes, the air temperature decreased from 56, 51, 49 and 47 to 26°C respectively at air velocities of 0.5, 1.0, 1.5 and 2 m/sec. They were varied with the drying air velocity. On the other hand it can be seen from Fig. 2 that the highest air temperature occurred at the lowest air velocity and visa versa with the highest air velocity. These results may be due to: at the lowest air velocity the air exposed to heat long time compared with the high air velocity. Furthermore, the same trend was found during measuring the air temperature at the end of drying collector (Fig. 3), but the temperature increased from 54 to 62, 49 to58, 47 to 56 and 45 to 54 °C respectively at air velocities of 0.5,

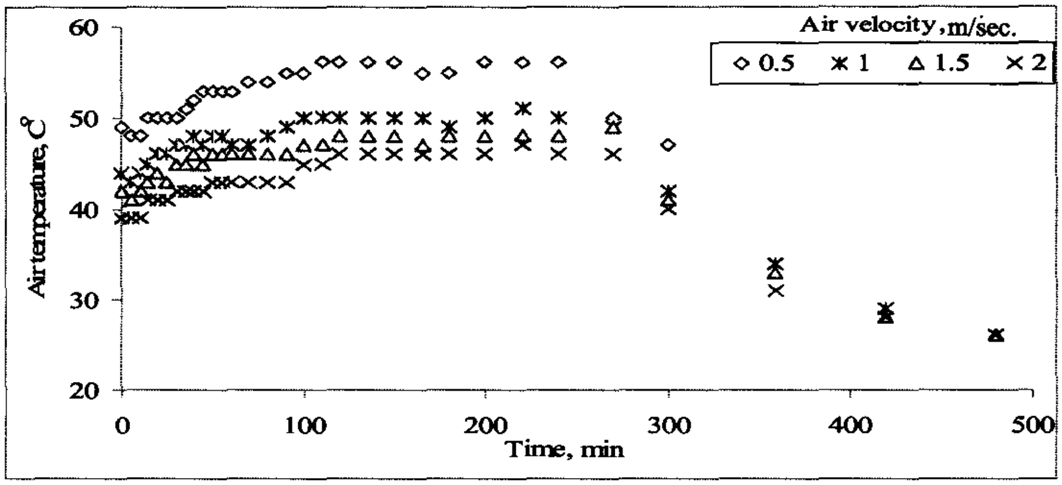

Fig. 2. Temperature distribution via drying time under different air velocities at the black cover

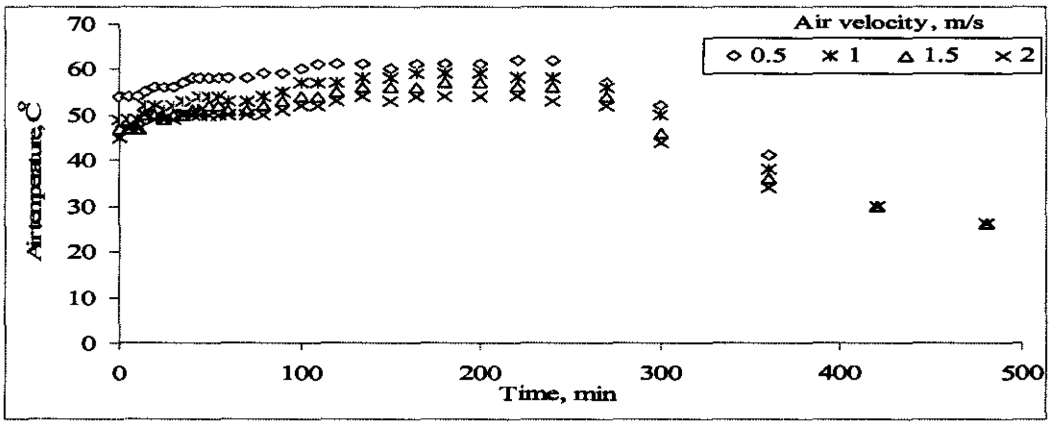

Fig. 3. Temperature distribution via drying time under different air velocities at the end of the drying collector

1.0, 1.5 and 2 m/sec. at the first 240 minutes. While the increasing in time from 240 to 480 minutes, the air temperature decreased from 62, 58, 56 and 54 to 26 °C respectively at air velocities of 0.5, 1.0, 1.5 and 2 m/sec.

Influence of Drying Time and Air Velocity on Tomato Moisture Content

As shown in the Fig. 4, the reduction in tomato moisture content was varied with the increase of slice thickness, while it was decreased with the increase of slices thickness.

Drying Rate Constant

The drying rate constants for the six mathematical models are shown in Table 2. From the table it is clear that the modified Henderson and Pabis's model found to be the most proper model during describing the drying behavior of tomato slices. Where it have the highest value for R^2 and had the lowest values chi-square (χ^2), mean bias error (MBE) and root mean square error (RMSE). Also, Figs. from 4 to 15 show the comparison between the observed and calculated moisture contents which calculated from the tested models at all drying air velocities, slices thickness and with black cover. From the figures, it can be seen that the differences between the observed moisture contents and the predicted using the Page, Lewis, Henderson and Logarithmic equations, were wide, but the differences were narrow for both models, two term and Modified Henderson & Pabis equations. From the Figs. 5, 6, 7 and 8 it can be concluded that the best model which can be used to describe the drying behaviour of tomato under

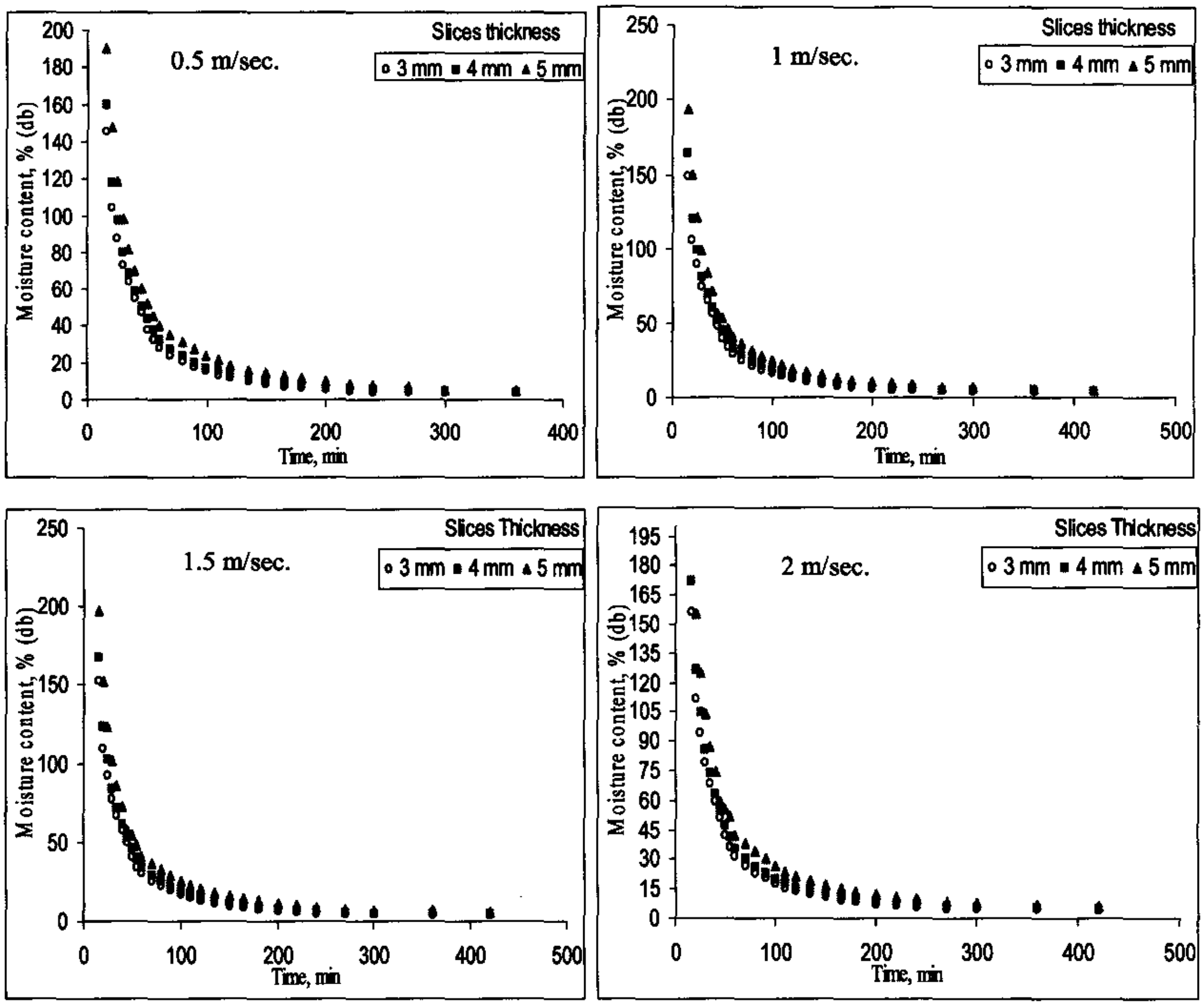

Fig. 4. Influence of drying tomato moisture content under different slices thickness

Table 2. Average of drying rate constant

The model	Regression coefficient (R^2)	χ^2	MBE	RMSE
Lewis	0.949	0.085	0.208	0.287
Henderson and Pabis	0.949	0.027	-0.036	0.158
Page	0.991	0.085	0.221	0.243
The Logarithmic	0.960	0.002	-0.022	0.041
The Two Term	0.999	0.000	-0.002	0.006
The Modified Henderson and Pabis	1.000	0.000	-0.000	0.002

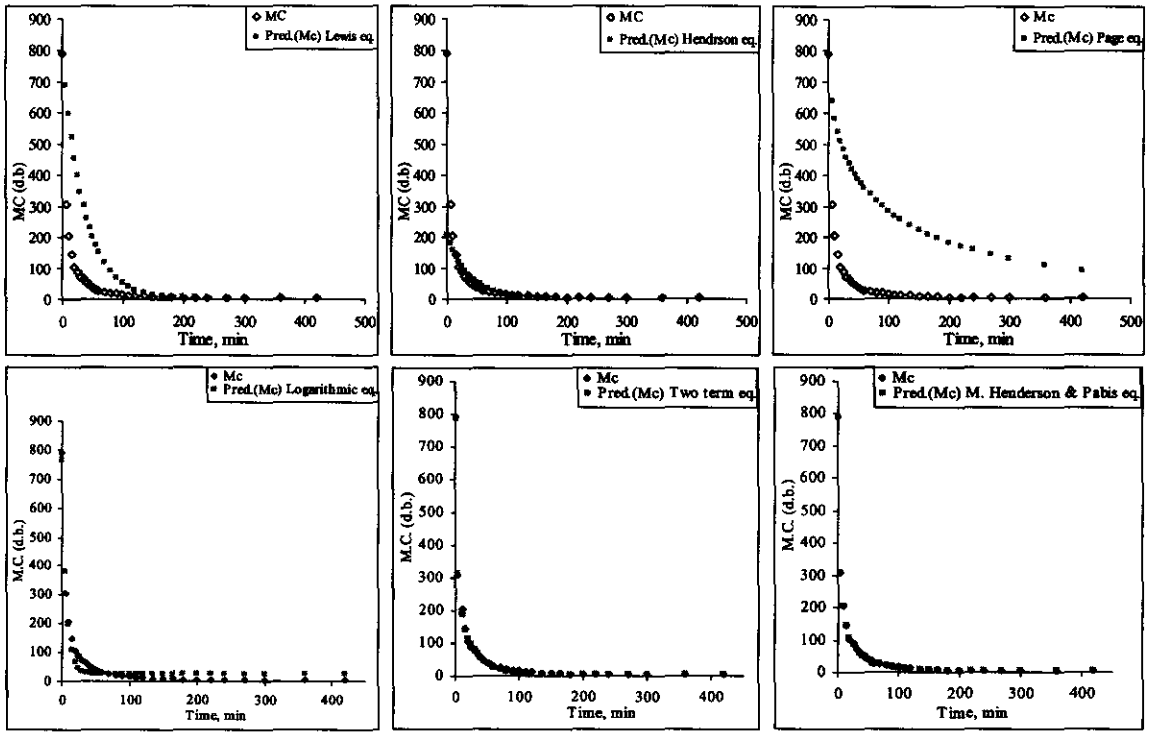

Fig. 5. Comparison between the observed and calculated moisture content which calculated from the tested models at 0.5 m/sec. drying air velocity and 3 mm slice thickness

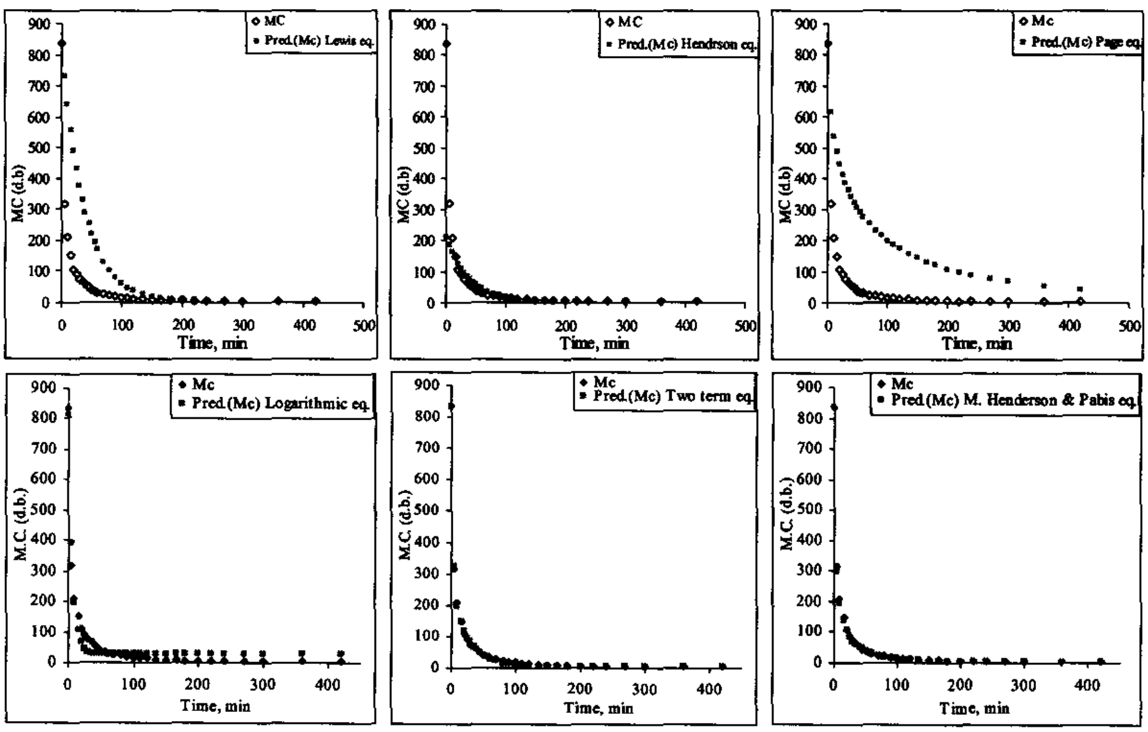

Fig. 6. Comparison between the observed and calculated moisture content which calculated from the tested models at 1 m/sec. drying air velocity and 3 mm slice thickness

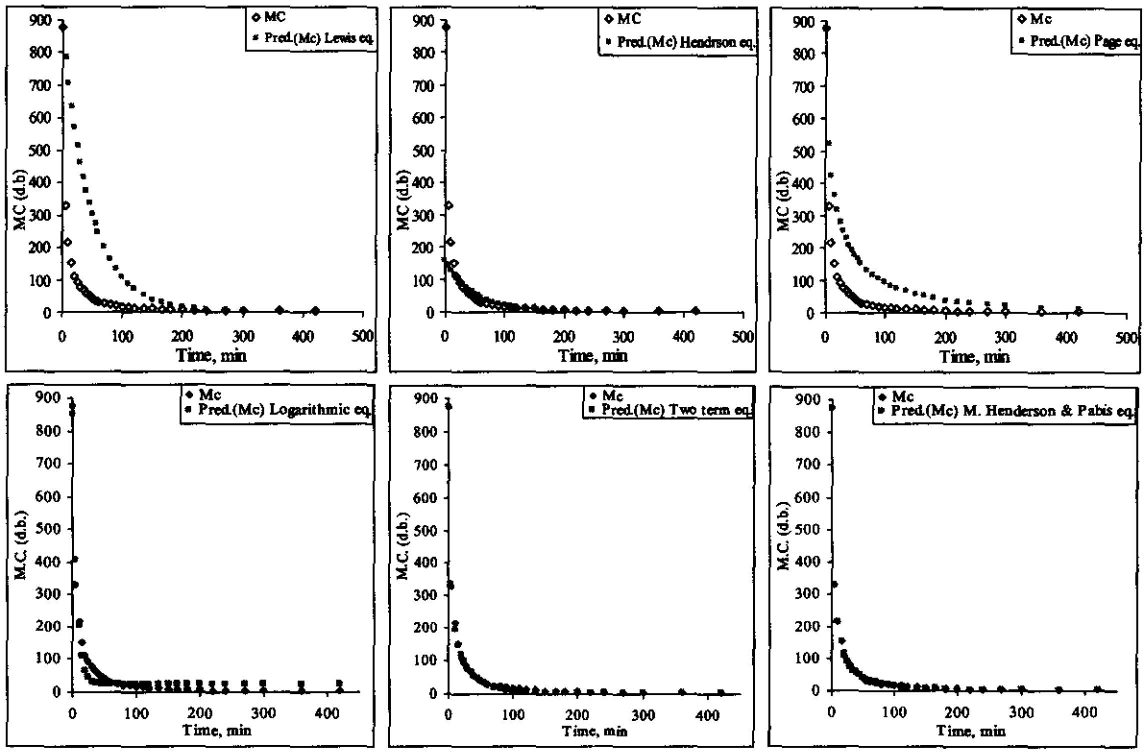

Fig. 7. Comparison between the observed and calculated moisture content which calculated from the tested models at 1.5 m/sec. drying air velocity and 3 mm slice thickness

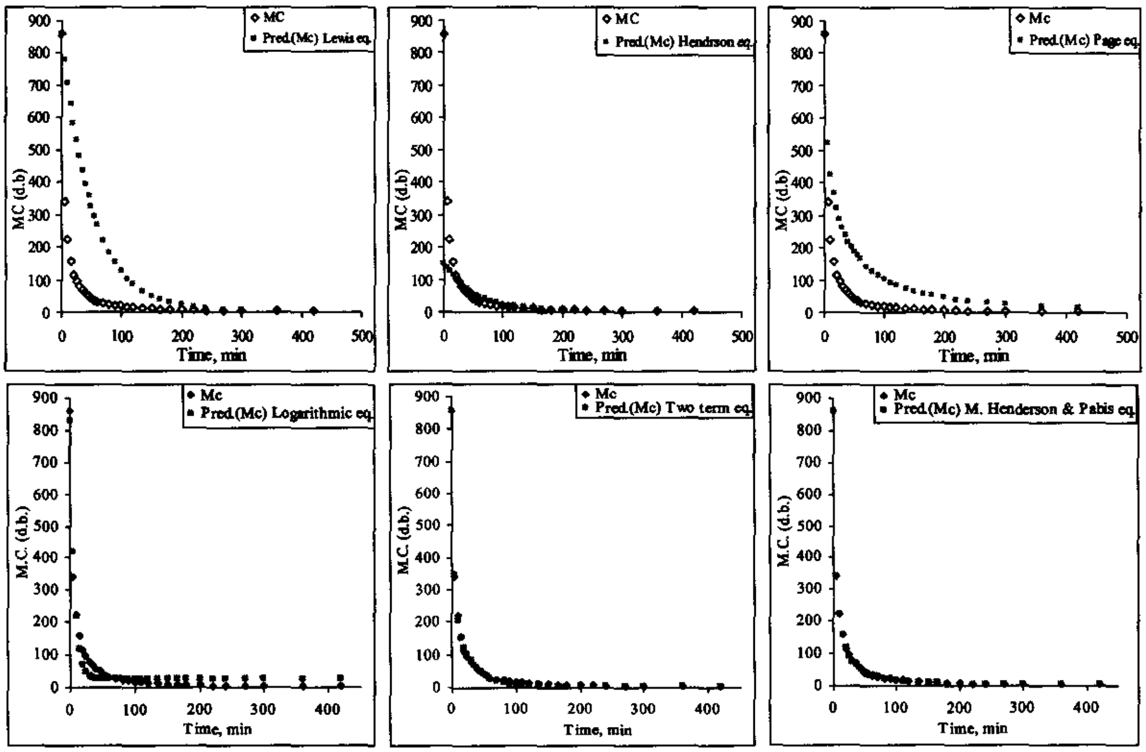

Fig. 8. Comparison between the observed and calculated moisture content which calculated from the tested models at 2 m/sec. drying air velocity and 3 mm slice thickness

the tested range of air velocities from 0.5 to 2 m/sec. with 3 mm slice thickness is Modified Henderson and Pabis model. It was becouse of the values of the Regression coefficient (R^2) between the measured values and the predicted values of the Two Term model was 0.998925, 0.9989, 0.99885 and 0.9988 at air velocity of 0.5, 1.0, 1.5 and 2 m/sec. respectively, while they were 0.99985, 0.999825, 0.999825 and 0.9998, respectively at Modified Henderson & Pabis model.

From the Figs. 9, 10, 11 and 12, it can be concluded that, the best model can be used to describe the drying behaviour of tomato under ranged air velocities from 0.5 to 2 m/s and 4 mm slice thickness is Modified Henderson & Pabis equation where the values of the Regression coefficient (R^2) between the measured values and the predicted values of the Two Term model were 0.998825, 0.9988, 0.9988and 0.998775 respectively at air velocity of 0.5, 1.0, 1.5 and 2 m/sec. while it was 0.9999 for all values of air velocity at Modified Henderson & Pabis model.

From the Figs. 13, 14, 15 and 16 it can be concluded that the best equation which can be used to describe the drying behaviour of tomato under the tested ranges of air velocities from 0.5 to 2 m/sec. and 5 mm slice thickness is Modified Henderson & Pabis equation where the values of the Regression coefficient (R^2) between the measured values and the predicted values of the Two Term model were 0.99845, 0.998325, 0.9983 and 0.99815 respectively at air velocity of 0.5, 1.0, 1.5 and 2 m/sec. while they were 1, 0.999975, 0.999925and 0.9999 respectively at Modified Henderson & Pabis model.

From the previous results it can be concluded that the best equation which can be used to describe the drying behaviour of tomato under the tested ranges of experimental treatments is M. Henderson & Pabis equation.

Conclusions

From the obtained results it can be concluded that:

1. The maximum temperature recorded inside the dryer chamber was 56°C during the corresponding ambient temperature and relative humidity were 34°C and 30.8%, at 3mm thickness and 0.5 m/sec. air velocity respectively.
2. During the test period, the experimental results revealed that the reduction in tomato moisture content from 91.78 to 3.463203% was obtained using drying air velocity of 1 m/sec. and slices thickness of 5 mm.
3. The modified Henderson and Pabis's model is the most proper model to describe the drying behavior of tomato slices.

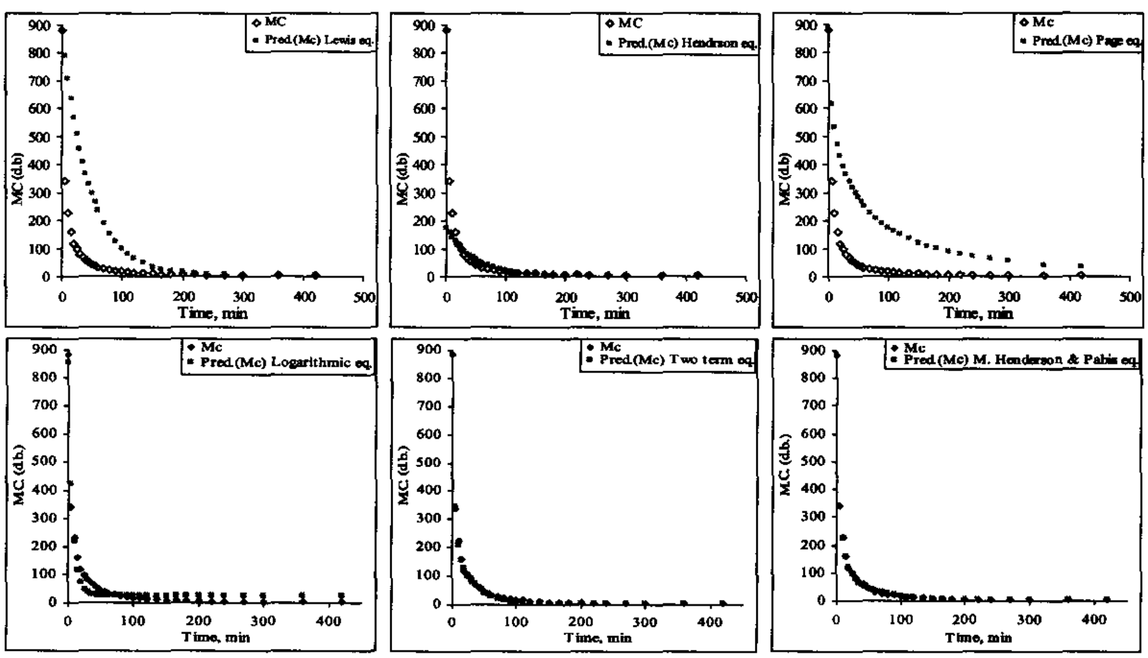

Fig. 9. Comparison between the observed and calculated moisture content which calculated from the tested models at 0.5 m/sec. drying air velocity and 4 mm slice thickness

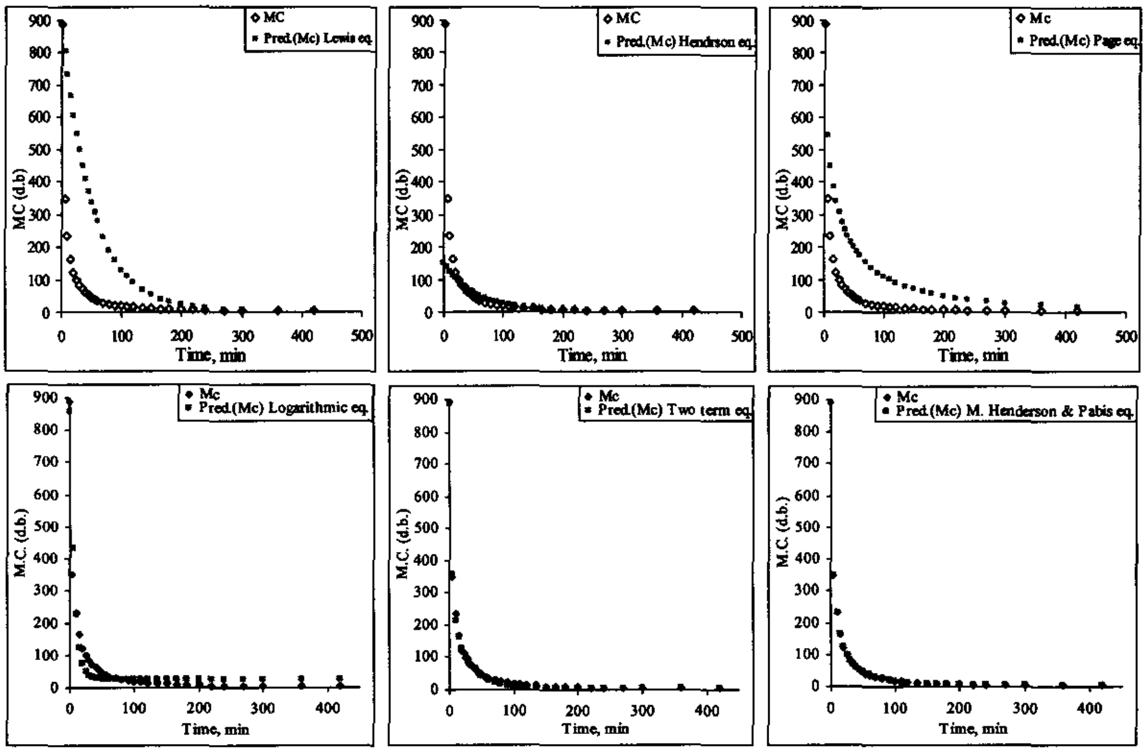

Fig. 10. Comparison between the observed and calculated moisture content which calculated from the tested models at 1 m/sec. drying air velocity and 4 mm slice thickness

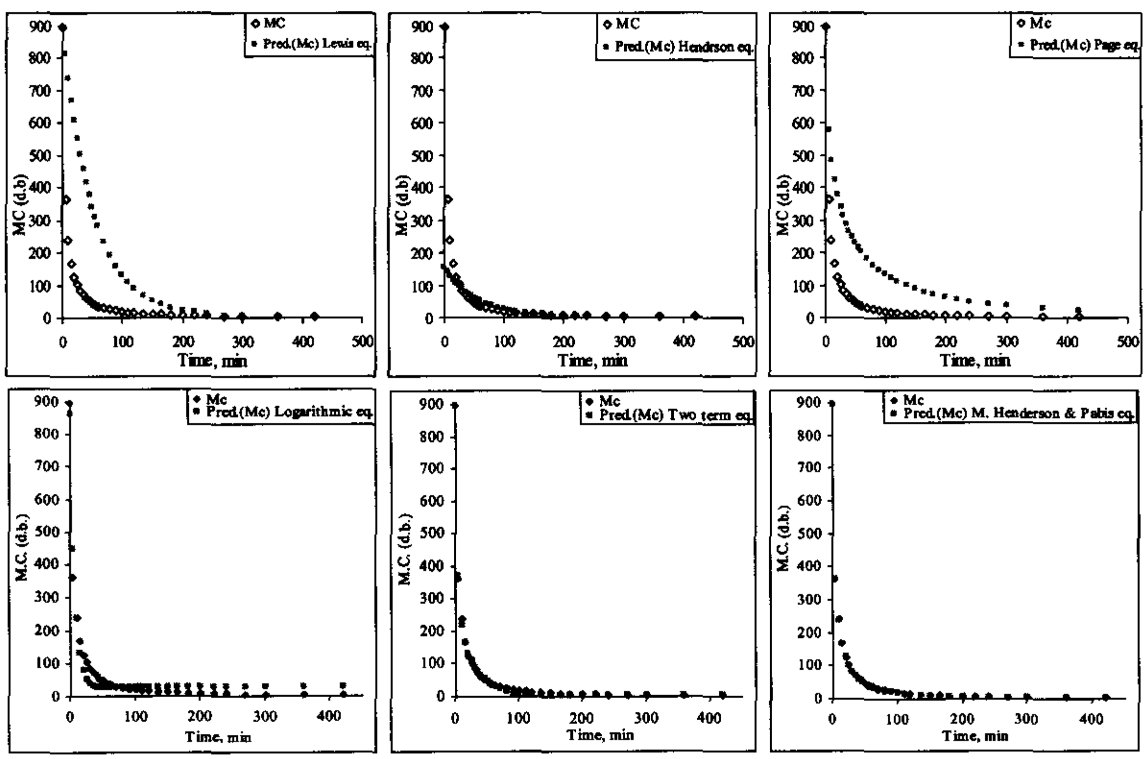

Fig. 11. Comparison between the observed and calculated moisture content which calculated from the tested models at 1.5 m/sec. drying air velocity and 4 mm slice thickness

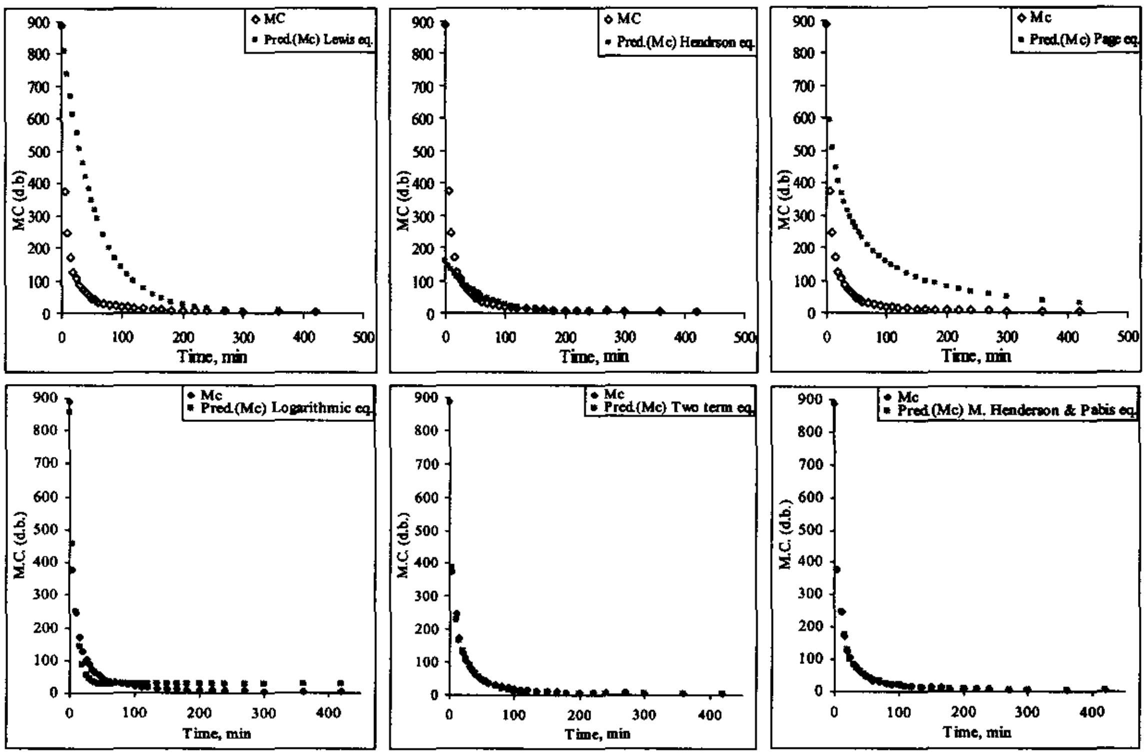

Fig. 12. Comparison between the observed and calculated moisture content which calculated from the tested models at 2 m/sec. drying air velocity and 4 mm slice thickness

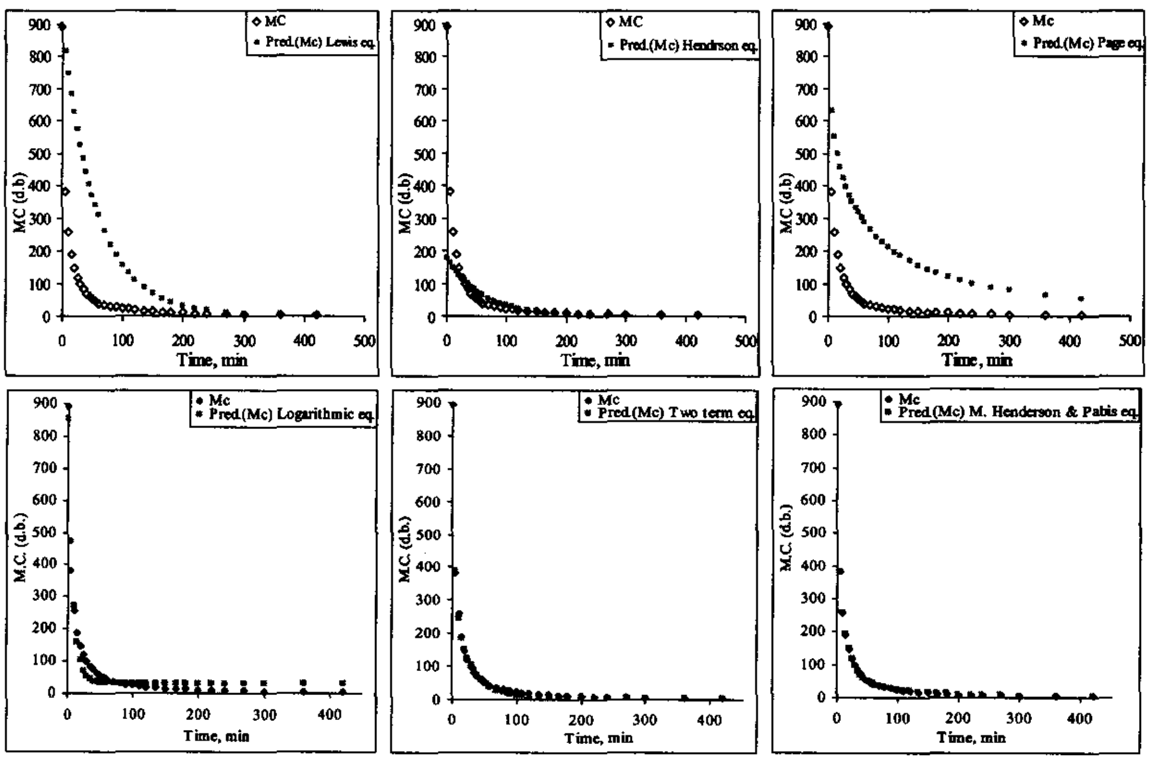

Fig. 13. Comparison between the observed and calculated moisture content which calculated from the tested models at 0.5 m/sec. drying air velocity and 5 mm slice thickness

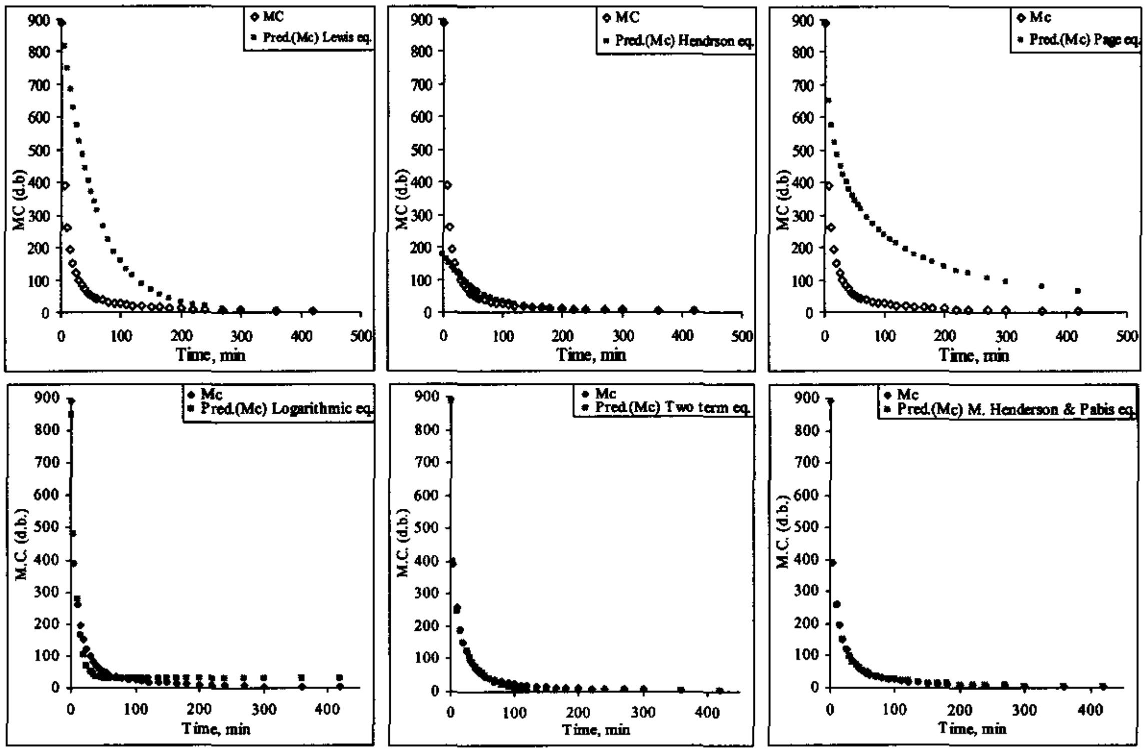

Fig. 14. Comparison between the observed and calculated moisture content which calculated from the tested models at 1 m/sec. drying air velocity and 5 mm slice thickness

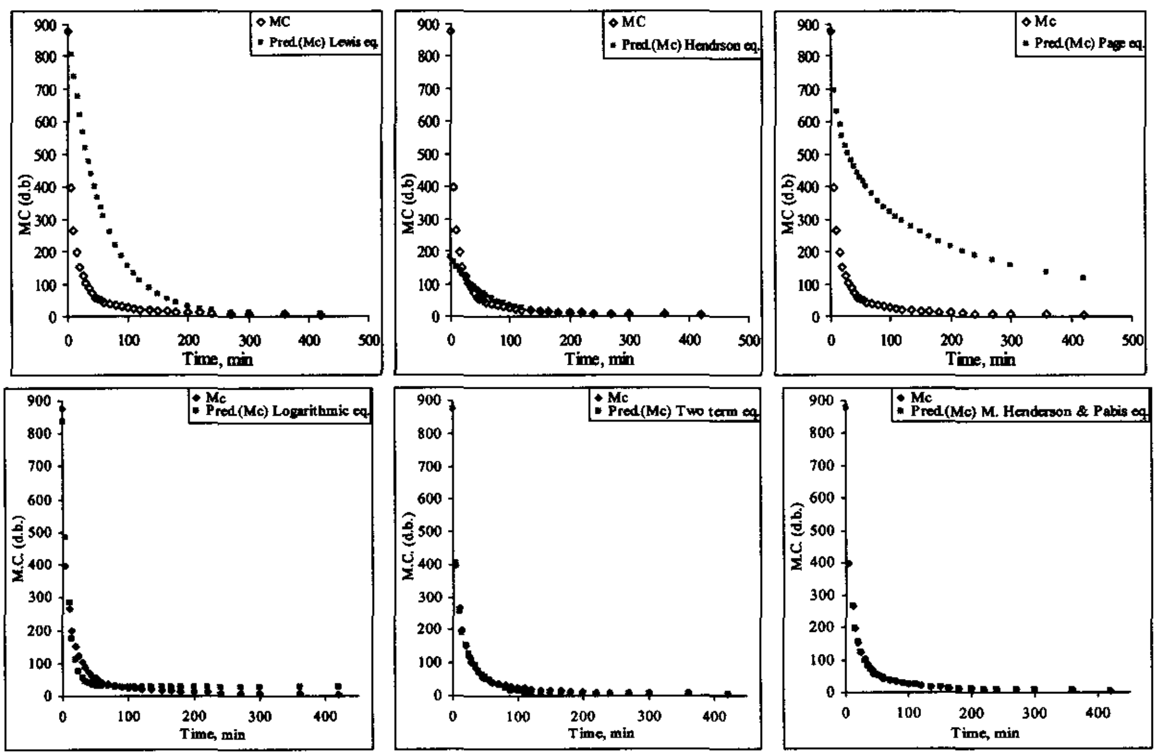

Fig. 15. Comparison between the observed and calculated moisture content which calculated from the tested models at 1.5 m/sec. drying air velocity and 5 mm slice thickness

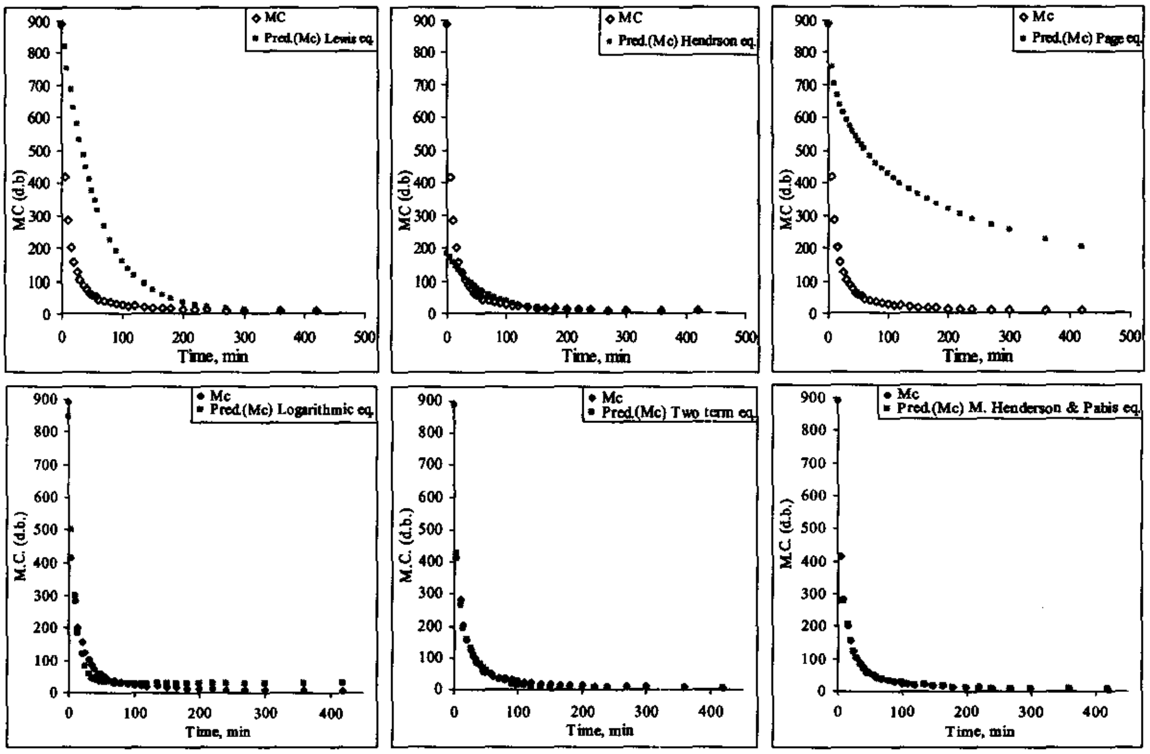

Fig. 16. Comparison between the observed and calculated moisture content which calculated from the tested models at 2 m/sec. drying air velocity and 5 mm slice thickness

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معادلات رياضية لتجفيف الطماطم في طبقات رقيقة باستخدام الطاقة الشمسية

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تهدف الدراسة إلى تصنيع وتقييم أداء مجفف شمسي لتجفيف شرائح الطماطم ومقارنة سلوك تجفيف الشرائح مع ستة نماذج رياضية تصف سلوك التجفيف لشرائح الطماطم فى طبقة رقيقة. وقد تمت الدراسة لمستويات مختلفة من سرعة الهواء (٠,٥، ١,٠، ١,٥، ٢,٠ متر / ثانية)، وثلاثة شرائح مختلفة السمك (٣، ٤، ٥ مم). ودراسة تأثيرهم على كل من تغير درجة حرارة الهواء أثناء وبعد عملية التجفيف. أظهرت النتائج أن الانخفاض في المحتوى الرطوبي للطماطم يختلف مع زيادة سرعة الهواء، وسمك الشرائح في حين انخفض مع زيادة سرعة الهواء، وسمك الشرائح. معدل التجفيف ينخفض بشكل مستمر مع تناقص المحتوى الرطوبي، وكان أقل معدل تجفيف عند ٠,٥ م/ث سرعة الهواء و ٣ مم سمك شرائح. كما كانت درجة الحرارة العظمى المسجلة داخل غرفة المجفف ٥٦ درجة مئوية عندما كانت درجة الحرارة البيئية والرطوبة النسبية المقابلة ٣٤ درجة مئوية و ٣٠,٨% على التوالي مع سمك ٣ مم و ٠,٥ م/ث سرعة الهواء. ولوحظ أن جميع المعادلات أمكنها وصف سلوك التجفيف لشرائح الطماطم بشكل مرضي تحت الظروف التي تم اختبارها من سرعة هواء التجفيف وسمك الشرائح ولون الغطاء كما أمكن لجميع معادلات التجفيف التنبؤ بالمحتوى الرطوبي بصورة مرضيه وكان ذلك مصحوبا بقيم عاليه لمعامل الارتباط (R^2) تراوحت بين (٠,٩٤٨٥٢٢ ، ٠,٩٩٩٩٠٦) حيث تنبأت معادلة هندرسون المعدلة بالتغير في المحتوي الرطوبي بشكل أكثر ملائمة بالمقارنة بالمعادلات الأخرى.

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