New Method For The Mathematical Determination Of Drying Rates Of Fig Fruits Depending On Empirical Data Under Conditions Suiting Solar Drying

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Thin-layer drying rates of fig fruits were determined experimentally under different conditions of the drying air temperature, relative humidity and velocity, and under different initial moisture content of the fruits. Twenty-four drying tests were run by an experimental dryer, locally designed and fabricated for thin-layer drying.
The results showed that the drying air temperature, the fig fruits initial and final moisture content had the greatest effect on the drying rate of fig fruits, followed by the drying air relative humidity. Air velocity had the least effect.

The objectives of this research work could be summarized as: expressing the loss of moisture during the drying process of the fruit or the vegetable, as a function of the affecting factors of the drying process, the determination of the fruit or the vegetable drying rate as a function of all the affecting factors, the determination of the needed time through each stage of the drying process, and how to benefit from the findings of this research work in conducting productive drying operation of fruits on large scale.

This work was planned for mathematically expressing the loss in fig fruits moisture throughout the drying process as a function of the affecting factors using multiple linear regression analysis. The derived mathematical expressions which relate the results of the drying process with the affecting factors could be used in the determination of the instantaneous moisture content of the fruits at successive time intervals. These equations are especially useful for solar drying under which the drying air properties are under continuous changes along the time of the day and along the days of the year.
The derived mathematical equations covered all the stages of the drying process, i.e, the stage of the primary increasing drying rate, the stage of the constant drying rate and the stage of the falling drying rate.
Key word: Drying, Drying rate, thin layer, fig fruit & mathematical.

1- Introduction:

Food drying is an ancient process which man copied from nature. The yearly amounts and the values of the dried agricultural products in Egypt from 1985 to 1995 ranged between 4500 and 7000 tons and between 16 million and 50 million L.E. respectively, **CAPMS (1995)**. Egypt is one of the countries which has favorable solar energy conditions suiting solar drying. It has a clear sky all year around except very few days during winter and spring equinox.
Determination of the time needed for accomplishing the drying process is difficult to achieve, especially in solar drying, due to the continuous variation in solar drying air temperature & humidity, the continuous changes in the moisture content of the drying fruit & vegetable and its tissue properties in conveying moisture. However, this can be simplified if the drying rate is expressed as a function of these continuously changing affecting factors.

So, the problem of the present research work is the continuous changing conditions along the period of the drying process. These conditions are also under continuous change through the different locations along the dryers. Besides, the drying rate does not have a constant value, rather it starts with a rising value, then it stays constant for a period of time, then it has a falling value. All these facts make it difficult to determine the volume of air needed for any drying process, the energy requirement for the process, the time duration of the process, and the most suitable values for the affecting factors to accomplish a successful drying process.

It was found that it is better to utilize a locally designed and fabricated special apparatus in the Agricultural Engineering Department, Faculty of Agriculture, Cairo University, which can be used as an experimental apparatus to determine the impact of the affecting factors on the drying process of fruits and vegetables. Using this experimental apparatus, the affecting factors may be controlled to give all the expected variations during the solar drying process, which followed thin-layer drying.

Hence, the objectives of this research work is:

Expressing the loss of moisture during the drying process and the duration of the drying process of the fruit or the vegetable, as a function of the affecting factors of the drying process.

According to **Bolin et al. (1975), Eissen et al. (1985a), Eissen et al. (1985b), Bains et al. (1989), Fohr & Arnaud (1992) and Ibrahim (1994)** there are many factors affecting the drying rate of the agricultural products. The most affecting factors related to the drying air are the drying air temperature, the drying air relative humidity and the drying air velocity as well as the product initial moisture content.

The majority of investigators recommended that the best range to be used for the drying air temperature for figs is between 55 to 75°C, according to **Hassan, (1995)**, and the best drying air velocity for fruits is ranged between 6 to 72 (m/min), according to **Eissen et al. (1985a)**. It is preferred to have the drying air relative humidity at its lowest values from 10 to 20%, according to **Bains et al. (1989).** On the other hand, the initial moisture content of the tested fig fruit variety Sultani was found to be between 70 to 85% (wet basis).

There are many equations, derived and applied to determine the drying rate as a function of time and the drying conditions. **Page's equation,** equation (1-1), is an important equation for the determination of the moisture ratio (MR) as a function of the affecting factors.

$$MR = \frac{Md_i - Mde}{Md_\circ - Mde} = \exp\left(-K\, t_i^{N}\right) \qquad \textbf{(1-1).}$$

Where:

Md_o , Md_e and Md_i = original (initial) moisture content (dry basis) of the fruit, fruit moisture content (dry basis) at equilibrium, and fruit moisture content (dry basis) during the drying process at any time "t_i", respectively.

This equation uses two parameters, which are the drying constant "K", and the drying parameter "N". Both parameters are empirical functions of the affecting factors.

This mean that the moisture ratio while it is a linear function at the constant drying rate period, but it is an exponential function at the falling drying rate period. So, the determination of "MR" needs the empirical determinations of both "K" and "N" at previous steps as functions of the affecting factors.

The literature review revealed that there are many investigators studied the moisture ratio of grains as a function of the affecting factors, but there are just very few investigators studied the moisture ratio or the drying rate of fruits and vegetables as a function of the affecting factors.
Therefore, this research plan carried out an attempt to derive the mathematical equations which could directly determine the instantaneous drying fruit moisture content, the moisture loss, the instantaneous drying rate, the final fruit moisture content and the time needed for the drying process. This was completely based on empirical data, and was done by applying the multiple linear regression analysis on all the data collected from the whole experimental work of this research, in order to express the required information as functions of all the affecting factors on the drying process of fruits.

2- Materials and Methods:

The selected fruit for the experimental work was "fig", variety **"Sultani"** and its scientific name is **"Ficus carica"** for its great economical importance in Egypt, according to **Grace (1957), Gouda et al. (1975) and CAPMS (1995).**
An experimental apparatus was designed and was locally built in Egypt for the determination of the effect of the different factors on the drying process. This apparatus was designed as a thin-layer dryer for fruits and vegetables.

Determination of fruit moisture loss and hence the determination of both fruit moisture content and fruit drying rate could be done by weighing the drying tray of the designed apparatus with its load of fruits at successive periods of time, which are expected to be short periods at the beginning of the test and longer periods as the fruits lose more of its moisture.

2-1- The tested affecting factors are:

A- The temperature of the drying air:

Many levels of drying air temperature: between 56 and 76 °C were tested, according to **Hassan (1995)**. The dry temperature of the air was measured by a thermocouple transducer probe connected with a temperature recorder with accuracy ± o.1°C. The thermocouple was firstly used to measure the dry temperature of the ambient air. After heating the ambient air, the thermocouple was also used for measuring the drying air temperature just before entering the drying tray in which the fruits were placed for drying. Another two digital instruments were also used for measuring air temperature which were a "Hygrometer" and a "digital thermohygrometer" after connecting it with the temperature probe.

B- The relative humidity of the drying air:

Many levels of the drying air relative humidity between 10% to 20% were tested, according to **Bains et al. (1989)**. The typical method for the determination of air humidity was applied by measuring both the dry bulb and the wet bulb temperatures. The wet-bulb temperature was measured by placing a thermocouple in the stream of air after wrapping its end by a wet cotton web.
Another instrument was also applied for measuring the relative humidity of air, which was the "digital thermohygometer" with accuracy ± 1.5%.

C- The air velocity of the drying air stream:

Many different levels of drying air velocity were tested; which were between 0.2 and 1.0 m/s (between 12 and 60 m/min), according to **Eissen et al. (1985a)**. The velocity of the drying air

stream was measured by using a digital instrument "Tri-Sence" after connecting it with the velocity probe with accuracy ± o.1 m/s.
The velocity of the drying air was measured just before entering the drying tray. The actual air velocity in the interspaces between the fruit was then determined according to the actual cross section area of air paths around the fruits.

D- The moisture content of the fruit:

The moisture content, dry basis, of the fresh fig fruit used in the experimental work was ranging between 245% and 400% (equal 71% and 80% moisture content at wet basis respectively).
The original "initial" moisture content, dry basis, "Md_o" of the fresh fruits was determined by the vacuum oven drying method. Samples of the fresh fruit of weight "Wo" were dried in a vacuum oven at 70°C until the weight "Wd" of the dried sample became stable, according to **A.O.A.C. (1984)**. The moisture content, dry basis, "Md_o" of the fresh fruit was expressed as:

$$Md_o = \frac{W_o - Wd}{Wd} \times 100 \qquad (\%) \qquad \textbf{(2-1).}$$

For the determination of the moisture content, dry basis, "Md_i" of the fruit at any time "t_i" during the drying process, the following equation could be used:

$$Md_i = \frac{W_i - Wd}{Wd} \times 100 \qquad (\%) \qquad \textbf{(2-1a).}$$

Where:

W_i is the weight of the fruit at time t_i

The determination of the fruit weight was done by weighing the drying tray with its load of fruits at any time during the drying process.

2-2- Experimental work tested treatments:

the experimental work included 24 drying experiments. For all treatments, the whole weight of the drying tray was recorded periodically at time intervals of 5 minutes at the first part of the drying process, where the drying rate is expected to be constant. At the next part of the drying process when the differences of the successive readings of drying tray weight showed decreasing values, the time intervals for measuring and recording the readings were increased to be 15 minutes.

During all the periods of the drying process, the values of the drying air affecting factors were periodically checked to be very close to the same values chosen for the executed experiment. Whenever any slight deviation occurred in any value, the suitable adjustments were immediately done to maintain their values exactly as the assigned ones.

For the determination of the instantaneous drying rate "RDd_i" (dry basis), equation (2-2) was applied:

$$RDd_i = \frac{\Delta W_i}{Wd * \Delta t} = \frac{W_{i-1} - W_i}{Wd * (t_{i-1} - t_i)} \qquad (kg_w / kg_d.min) \qquad \textbf{(2-2).}$$

Another equation can be used for the determination of the drying rate, (dry basis):

$$RDd_i = \frac{Md_{i-1} - Md_i}{100 * \Delta t} = \frac{Md_{i-1} - Md_i}{100 * (t_{i-1} - t_i)} \qquad (kg_w / kg_d.min) \qquad \textbf{(2-2a).}$$

3- Results and Discussion:

3-1- The characteristics of fig fruits:

For the determination of the characteristics of the selected fig fruits, 50 fruits of the selected size were taken. Table (3-1) shows the results of this determination as averages of the selected 50 fruits. These characteristics of fig fruits will surely affect the rate of moisture loss during the drying process. Since the selected fruits for conducting the experiments had almost the same size, weight and some other characteristics, the characteristics shown in Table (3-1) were manifested just for record. However, some of these characteristics were used in some of the calculations. As an example, the diameter of the fruits was used in calculating the actual velocity of the drying air passing through the inter spaces between fig fruits from the average air velocity just beneath the drying tray.

Also, in each conducted drying experiment, only three fruits were taken for the determination of the initial moisture contents of the fresh fruits. After the determination of the dried material of these three fruits, the moisture content (dry basis) and the moisture content (wet basis) were determined and the results are shown too in table (3-1).

Table (3-1). Characteristics of fresh fig fruits "Sultani"

Characteristics	Average Values
Fruit shape	conic
Fruit weight, (gram)	40
Number of fruits per kilogram	25
Fruit diameter, (cm)	4.5
Fruit thickness, (cm)	4.1
Fruit size, (cm^3)	33
Fruit density, ($gram/cm^3$)	1.12
Moisture content, wet basis, ($g_{water}/ g_{fresh\ material}$)	71 - 80%
Moisture content, dry basis, ($g_{water}/ g_{dry\ material}$)	245 – 400%
Dried material of the fruit, ($g_{dry\ material}/ g_{fresh\ material}$)	20 – 29%

3-2- Experimental work for drying fig fruits:

It was proposed that the readings for the decreasing weight of the drying fruit correspondent to the passing time through the drying process are the main important data in the 24 experiments which were carried, as shown in Table (3-2). From these data, the results dealing with the loss of moisture, the new moisture content of the drying fruit, and the instantaneous drying rate could be all calculated and related to the time. Also, the starting time, the time period and the range of fruit moisture content through which each of the rising drying rate, the constant drying rate and the falling drying rate occurred could be determined.

3-3- Determination of the effects of the affecting factors on the drying process of fig:

In general the results of the experimental work showed that the drying process could be divided into three periods that are: a short primary increasing, a constant and a falling drying rate periods as shown in Fig.(3-1).

Figures (3-2) through (3-7) graphically show some of the obtained results of the carried 24 experiments. It was found that the original "initial" moisture content "Md_o" of the fresh fruit had considerable effect on the results. Also, it is expected that any location in any commercial dryer in the actual drying processes at any time along the drying process will have unique drying conditions. Therefore, it was found that the effect of the affecting factors could be better expressed by using a multiple linear regression analysis.

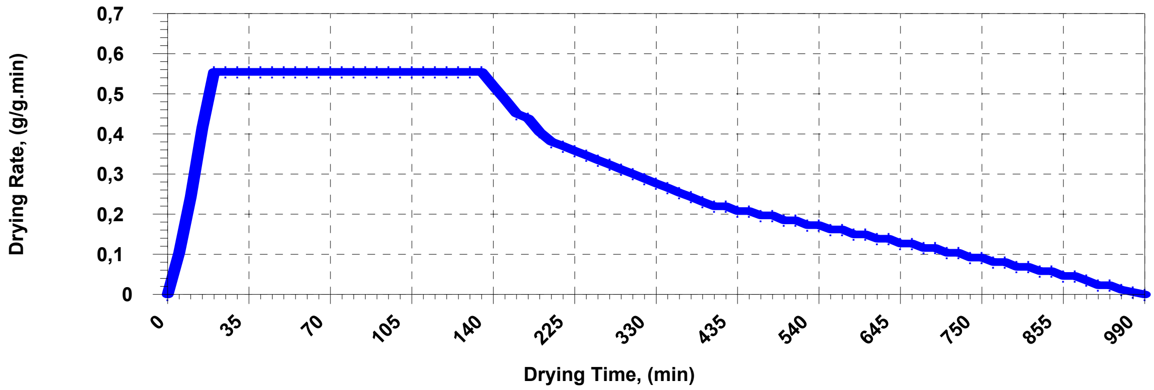

Fig. (3-1), Drying Rate expressed directly from experiments vs. time

The drying process starts with a certain original or initial moisture content value "Md_o" of the fresh fruit, and ends with an acceptable final moisture content value "Md_F" of the dried fruit at the end of the drying process.

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Table (3-2). Tested treatments of the drying air conditions for studying their effects on the drying process of fig fruits.

Treatment No.	Values of the affecting factors		
	Drying air velocity (m/min)	Drying air relative humidity (%)	Drying air temperature (°C)
1	12	10	74
2	12	12	65
3	12	15	56
4	12	12	74
5	12	15	65
6	12	18	56
7	12	15	74
8	12	18	65
9	12	20	56
10	24	10	74
11	24	12	65
12	24	15	56
13	24	12	74
14	24	15	65
15	24	18	56
16	24	15	74
17	24	18	65
18	24	20	56
19	42	12	72
20	42	16	65
21	42	19	58
22	60	11	76
23	60	14	69
24	60	17	62

By applying the multiple linear regression analysis technique to the whole data of the 24 experiments of the experimental work, a series of mathematical equations were derived with "R^2" values ranged between 0.87 and 0.98. These series of equations gave the values of:

* Md_P, Md_C and Md_F which are the fruit moisture content at the end of the primary rising, the constant and the falling drying rate periods, respectively.
* t_P , t_C and t_F which are the time period for the primary rising, the constant and the falling drying rate periods, respectively.
* RDd_C which is the drying rate value at the constant drying rate period, and the value of RDd_F which is the average value of the drying rate during the falling drying rate period.
* Md_{Pi} , Md_{Ci} and Md_{Fi} which are the instantaneous fruit moisture content at any time t_i during the drying process.

In all these series of equations, the values of each affecting factors appear in the equation with its corresponding value of the coefficients "C". The six following equations show some examples of the forms of the derived mathematical equations:

$Md_P = C1 + C2\ (T) + C3\ (RH) + C4\ (v) + C5\ (Md_O)$ **(3-1).**

$Md_C = C1 + C2\ (T) + C3\ (RH) + C4\ (v) + C6\ (Md_P)$ **(3-2).**

$t_F = C1 + C2\ (T) + C3\ (RH) + C4\ (v) + C8\ (Md_F)$ **(3-3).**

$Md_{Ci} = C1 + C2\ (T) + C3\ (RH) + C4\ (v) + C6\ (Md_P) + C7\ (Md_C) + C13\ (t_{Ci})$ **(3-4).**

$Md_{Fi} = C1 + C2\ (T) + C3\ (RH) + C4\ (v) + C7\ (Md_C) + C8\ (Md_F) + C14\ (t_{Fi})$ **(3-5).**

$RDd_{Ci} = C1 + C2\ (T) + C3\ (RH) + C4\ (v) + C6\ (Md_P) + C7\ (Md_C) + C10\ (Md_{Ci}) + C13\ (t_{Ci})$ **(3-6).**

Where:

1. The values of the affecting factors are those written between parentheses.
2. The values of the "C"s differ according to the different equations.
3. The complete set of the derived mathematical equations and the values of the "C"s for drying fig fruit variety "Sultani" could be found in **Amer (1999).**

3-4- Expected deviation through out the falling drying rate-period, and the necessary modifications:

The reason for dividing the falling drying rate-period into 4 intervals was because the drying rate curve through out this period has almost the same feature for all the carried 24 experiments. Applying this idea onto the falling drying rate curves of the 24 experiments, it was found by the carried out analysis that the steep slope part of the curve was representing time interval through which the drying fig fruit lost in average about 28% of its moisture content through out this period, i.e, 28% of the difference between "Md_C" and "Md_F". It was also found that the second time interval was representing time interval through which the drying fig fruit lost in average about 44% of its moisture content throughout this period, the third time interval was representing time interval through which the drying fig fruit lost in average about 24% of its moisture content throughout this period, while the last time interval was representing time interval through which the drying fig fruit lost in average about 4% of its moisture content throughout this period, Fig. (3-8). Fig. (3-8) shows how much these four linear segments are close to the experimentally obtained curve.

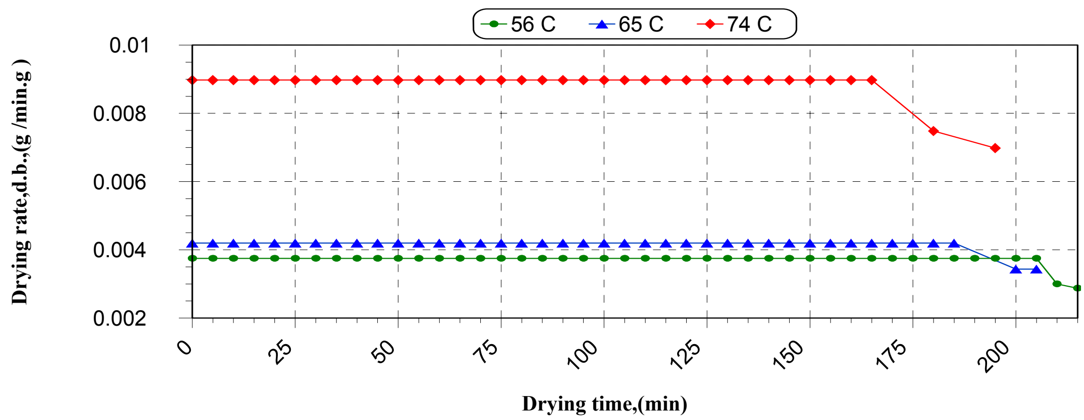

Fig. (3-2), Effect of air temperature at air velocity of (24 m/min) and air relative humidity of (15%)on the drying rate of figs at the constant rate period.

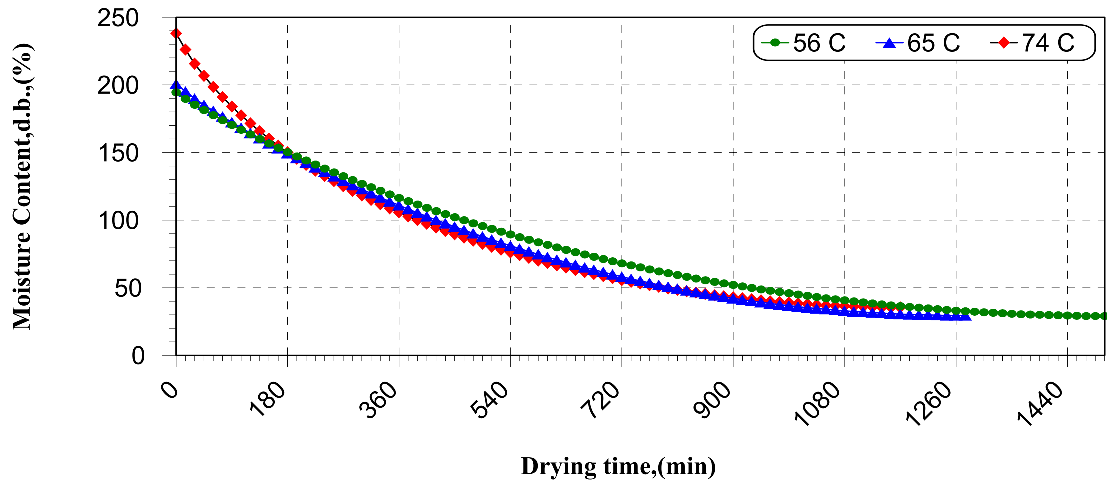

Fig. (3-3), Effect of air temperature at air velocity of (24 m/min) and air relative humidity of (15%) on the moisture content of figs at the falling rate period.

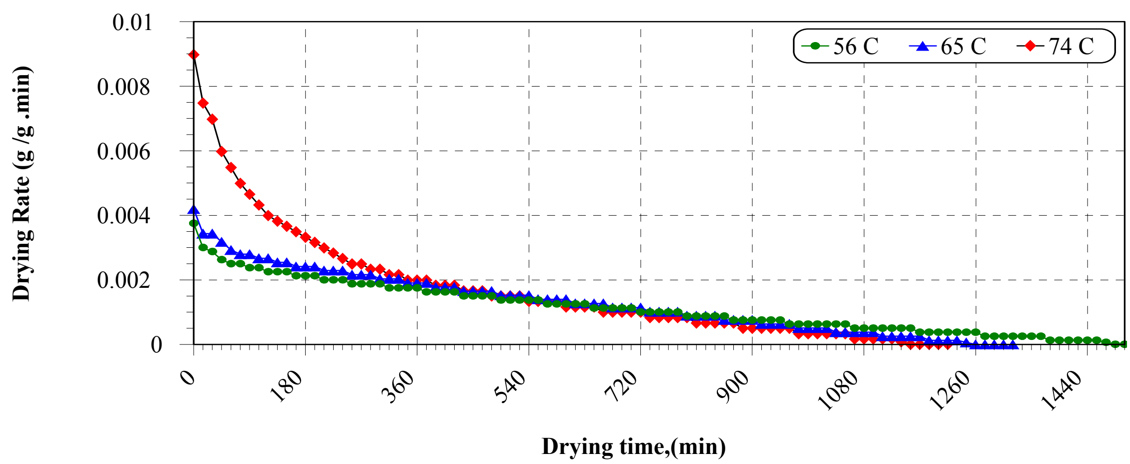

Fig. (3-4), Effect of air temperature at air velocity of (24 m/min) and air relative humidity of (15%)on the drying rate of figs at the constant rate period.

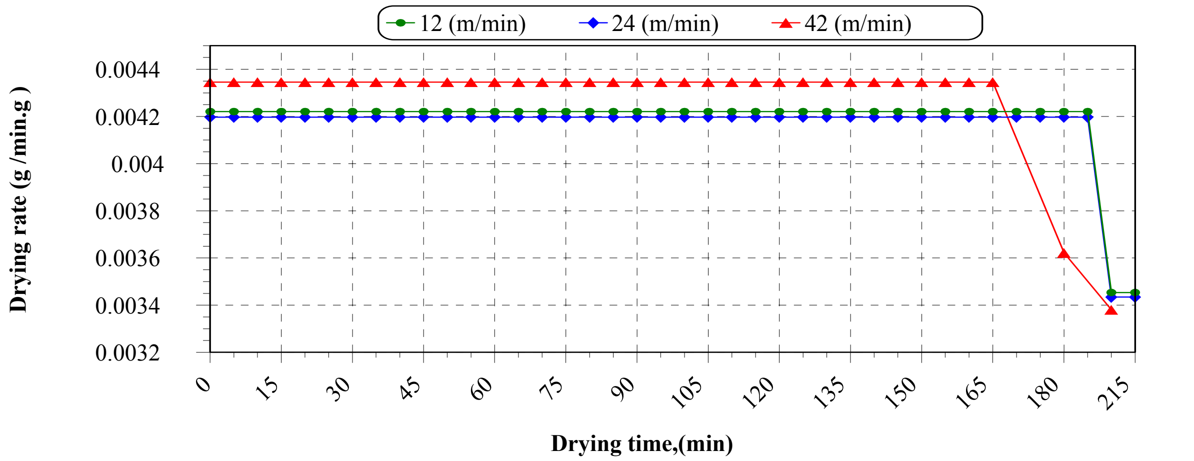

Fig. (3-5), Effect of air velocity at air temperature of (65 ⁰C) and air relative humidity of (15%) on the drying rate of figs at the constant rate period.

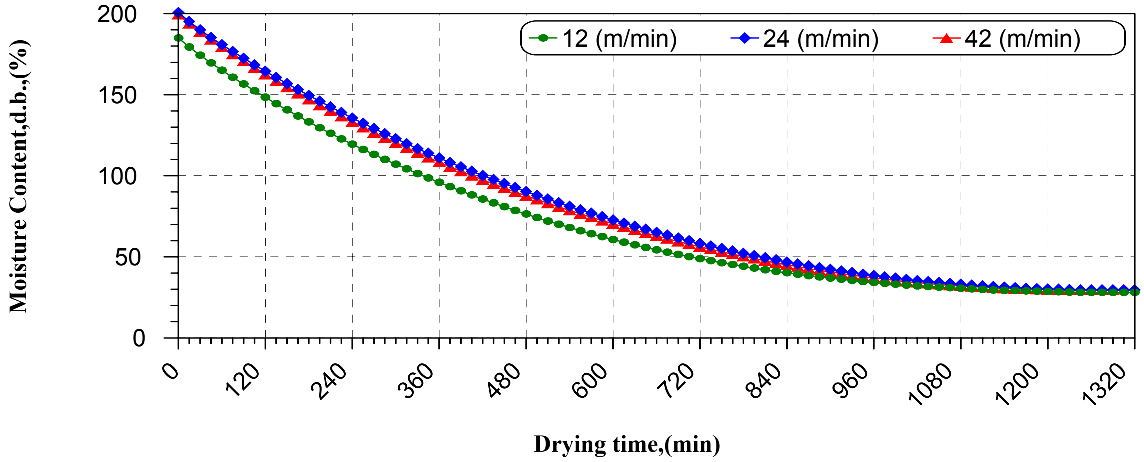

Fig. (3-6), Effect of air velocity at air temperature of (65 °C) and air humidity of (15%) on the moisture content of figs at the falling drying rate period

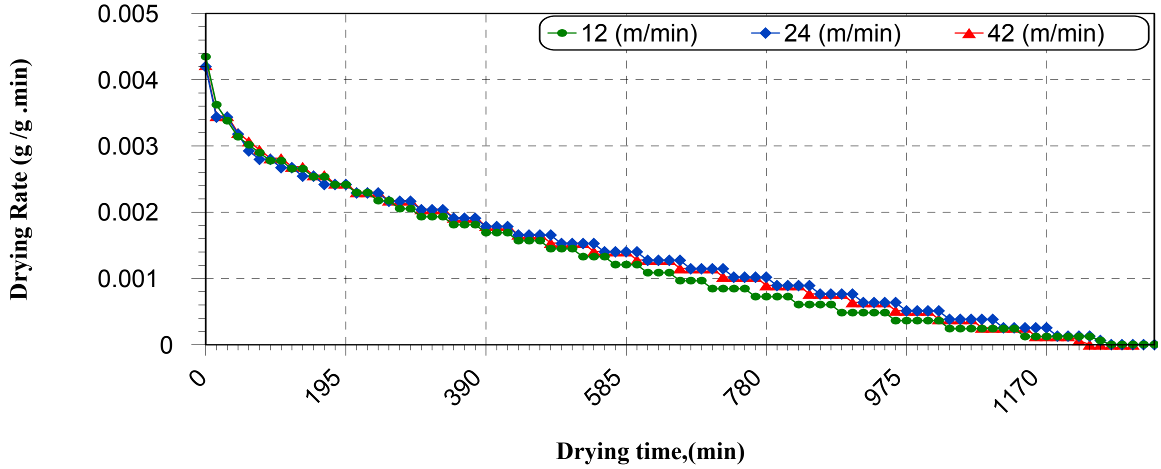

Fig. (3-7), Effect of air velocity at air temperature of (65 °C) and air humidity of (15%) on the moisture content of figs at the falling drying rate period.

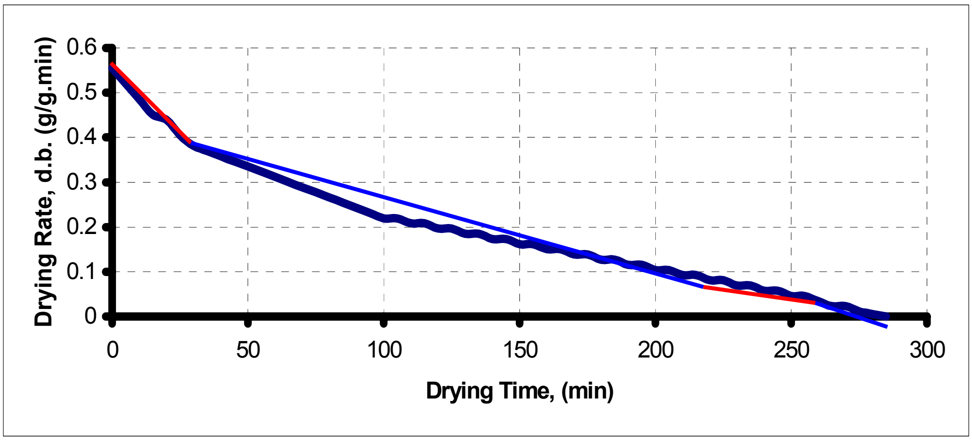

Fig. (3-8), Effect of the drying air temperature (74 °C) with air velocity of 0.1 m/s & air humidity 0f 10% on the drying rate of figs at the falling rate period and the method of divided the *falling drying rate-period.*

The difference in moisture content "Δ Md" between the critical moisture content "Md_C" at the beginning of the falling drying rate-period and that at the end of this period "Md_F", could be expressed as the following equation:

$$\Delta Md = Md_C - Md_F \qquad \textbf{(3-7).}$$

The value of the percentage of the moisture content "Md_{1F}" of the drying fig fruits at the end of the first interval of the falling drying rate-period could be computed as:

$$Md_{1F} = Md_C - 0.28\,(Md_C - Md_F)$$

$$\therefore Md_{1F} = 0.72\ Md_C + 0.28\ Md_F \qquad \text{(percentage)} \qquad \textbf{(3-8).}$$

The value of the percentage of the moisture content "Md_{2F}" of the drying fig fruits at the end of the second interval of the falling drying rate-period could be computed as:

$$\therefore Md_{2F} = 0.28\ Md_C + 0.72\ Md_F \qquad \text{(percentage)} \qquad \textbf{(3-9).}$$

The value of the percentage of the moisture content "Md_{3F}" of the drying fig fruits at the end of the third interval of the falling drying rate-period could be computed as:

$$Md_{3F} = Md_C - (0.28 + 0.44)\,(Md_C - Md_F)$$

$$\therefore Md_{3F} = 0.04\ Md_C + 0.96\ Md_F \qquad \text{(percentage)} \qquad \textbf{(3-10).}$$

The value of the final moisture content "Md_{4F}" of the drying fig fruits at the end of the fourth interval of the falling drying rate-period will be exactly equal to the final moisture content "Md_F" at the end of this period.

The reason of applying this multiple linear regression technique instead of using an exponential equations in the form like that of Page's equation, is that in the actual drying process, especially in solar drying processes, the fruits in each location in the dryer and at different times along the whole drying time will have unique drying conditions from the very beginning to the very end of the drying process. Therefore, the drying constant "K" and the drying parameter "N" in any derived exponential equation have to have numerous values for the numerous locations of the dryer and not just one value for each. So, in the actual drying processes, it is better to use a finite differences technique since the drying air at each location will have its specific temperature and relative humidity which are determined by the previous location. Also, at any location, the drying air temperature and relative humidity will change with the passing of time due to the continuous decrease in the drying rate of the fruits in the previous locations.

So, at each location in the dryer, and at each time of the drying process, the drying conditions have to be applied to determine the drop of fruit moisture content in this location. It is expected that the fruits in the first locations in the dryer will reach the desired moisture content "Md_F" at shorter periods of time than those at the end of the dryer.

4- Conclusion:

1. Fig fruits, variety "Sultani" could be dried with an accepted quality using an air temperature ranges from 56 to 76°C, relative humidity ranges from 10 to 20% and air velocity ranges from 12 to 60 m/min.
2. The initial moisture content of the local fresh fig fruits "Sultani" is ranging from 71% to 80% (w.b.), and from 245% to 400% (d.b.). The final accepted moisture content of the dried fruits is ranging from 21% to 26% (w.b.), and from 27% to 36% (d.b.).
3. Total moisture loss percentage for all the tested treatments ranged from 63% to 73% of the original total weight of the fresh fruit. Total moisture loss percentage for all the tested treatments ranged from 89% to 91% of the original water weight in the fresh fruit.
4. Generally speaking, each one percent of the dried material of the fresh fig fruits "Sultani" kept 0.43 (±) 0.12 percent moisture content in the final dried fig fruits at the end of the drying process, depending on the original moisture content of the fresh fig fruits. On the large scale of the experiments tested, the percentage of the dried material in the fresh figs fruits ranged from 20 to 29%, and they kept at the end of the drying process from 9% to 11% moisture content in the dried fig fruits. A big decrease in the percentage of the dried material of the fresh fruits increased the drying rate. But the increase in the percentage of the dried material in the fresh fig fruits had the tendency to decrease the constant drying rate but not all the times.
5. The results assured that the drying rate of fig fruits is consisting of three distinct periods, which are: the increasing drying rate-period (a primary short period), the constant drying rate-period and the falling drying rate-period. The falling drying rate-period could be divided into 4 intervals, to make the predicted results by the derived equations very close to the experimental ones.
6. The total drying time of fig fruits "Sultani" for the total treatments ranged from 19.5 to 32 h. The increasing drying rate-period for drying fig fruits extended only for about 15 to 25 minutes. This period for the increasing drying rate is a very small period since it consumed only 1.3% of the total time of the drying process. The constant drying rate-period of drying fig fruits extended only for about 115 to 255 minutes (between 10% to 13% of the total time of the drying process). The falling drying rate-period for drying fig fruits have extended for about 16.5 to 27.5 h. (between 84.6% to 86% of the total time of the drying process).
7. The smallest value of the drying air velocity at the constant drying rate-period could be used without any remarkable decrease in the percentage of the water loss from the original water of the fresh fig fruits (ranged from 34.8% to 35.2%) at the end of this period, and the time of drying through this period ranged from 134.5 to 142.5 min only by decreasing drying air velocity from 60 to 12 m/min, with drying air temperature of 76°C. But increasing the drying air temperature from 55 to 75°C (with drying air velocity from 12 to 60 m/min) at the same period had a very remarkable effect since it decreased the time of this period from 243.3 to

147.5 min, while the amount of moisture loss to the end of the constant drying rate-period was very limited (from 33.8% to 35.1%).

8. The drying air temperature had the greatest effect on the whole drying process, and on the drying time of fig fruits within its increasing rate-period, constant rate-period and falling rate-period. The relative humidity of the drying air had the next remarkable effect, followed by the effect of the initial moisture content of the fruit. Air velocity had the smallest effect.
9. The derived mathematical equations in this work are very useful in the actual drying processes for fruits and vegetables (especially for solar drying). A sensitivity analysis could be conducted to assure what are the best values of all the affecting factors for drying fruits, vegetables or any agricultural product. According to these selected values, similar derived mathematical equations for a particular agricultural product could be utilized for predicting the progress of the drying process at different stations of the dryer and along the whole time of the drying process. Of coarse, at each station and at each time, the values of the affecting factors are expected to change, and the derived mathematical equations have to apply the new values of the affecting factors to achieve the maximum production at the higher achievable quality values at the minimum energy costs.

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