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Drying of ear corn

Part I: Determination of drying parameters

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ABSTRACT

This study was carried out to determine the drying parameters of ear corn (T. W. C. 310). Experimental dryer was designed and constructed at the department of Agricultural Engineering, Faculty of Agriculture, Mansoura University to dry ear corn in thin layer under controlled conditions of air temperature and air relative humidity.

Mathematical procedures were also developed to determine the drying parameters (drying rate constant and equilibrium moisture content) from the actual data of moisture content – time curve.

The obtained results confirmed the dependence of the determined drying parameters on air temperature and air relative humidity. A set of empirical equations was developed to describe this dependence.

A multiple regression analysis was also used to account for the interaction effect of the air temperature in the range of 45 to 60°C and air relative humidity in the range of 32 to 56% on the determined drying parameters.

The developed equations could be used within any computer program concerning thin layer drying of ear corn since they account for both the change of air temperature and air relative humidity.

INTRODUCTION

Corn like wheat may be considered as one of the most important grain crop in Egypt. However the planted area of corn decreased from (1,900,000 feddan in 1980 to 1,697,000 feddan in 1998, the production increased from 2,865,000 tons to 5,431,000 tons (M. O. A., 1998)). In spite of this increase in the production it still cannot cope with the increasing demand and hence, an increase in the planted area would be expected in the coming few years.

Ear corn is usually harvested at relatively high moisture content, so some treatments on the crop after harvesting and before they may safely be stored may be required. In spite of recent development in chemical treatment, the most usual treatment is to dry the corn to safe moisture content.

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The value of the moisture content of a solid after drying time, T, predicted by any drying equation depends mainly on the parameters of the equation such as drying coefficient and equilibrium moisture content. An accurate knowledge of these parameters in terms of the variables affecting them is necessary for a better prediction.

A great deal of work has been devoted to study the effect of air temperature and relative humidity on the drying parameters of various grains (Greig, 1970, Matouk, 1976, Syrief et al., 1984, Jayas and Sokhansanj, 1988, Radajewski et al., 1992, Tang and Sokhansanj, 1993, Morita et al., 1994, Tagawa et al., 1996 Chen Yi Luen, 1999 and Tanaka et al., 2000). On the other hand the authors noticed that there is a great dearth on basic information pertaining to drying process in which ear corn is dried under controlled conditions.

The objective of this work was an attempt to study the effect of air temperature and relative humidity on drying parameters of ear corn. Developing a proper mathematical model which may be used to describe the loss of moisture during thin layer drying of ear corn was not the target of this work, but it will be presented in the second part.

MATERIALS, APPARATUS AND EXPERIMENTAL PROCEDURE

1. Material:

Ear corn used in this study was freshly harvested ear corn (three way cross (T.W.C. 310). It was obtained from agricultural crops developing center in Sakha. It had nearly constant initial moisture content ranged from (38 to 41% d.b.). The ear corn lot had been cleaned and were kept in refrigerated room.

2. Apparatus:

The experimental drying equipment was designed and constructed at the department of agricultural engineering, faculty of agriculture, Mansoura University. It was designed to allow the control of air humidity and temperature and reduce turbulence of the air inside the drying chamber and ensure even distribution of the air around the sample tray. The drying chamber was also designed to provide an easy handling of the sample tray and ensure a minimal temperature gradient a cross the bed of material.

2.1. General description of the apparatus:

Figure (1) shows the drying setup. Atmospheric air was supplied by 1.3 kW centrifugal fan with straight impeller blades, which was fitted with a flow regulator. The air at controlled rate was then delivered to the bottom of vertical PVC tower. Water at controlled temperature was then delivered from an electrically driven centrifugal pump (0.59 kW) to the top of the tower and then to the water tank to allow water circulation. The mixture of air and saturated water vapour passes from the top of the tower to the air heating unit and then to the drying chamber via a 203.2 mm (8 in.) diameter insulated steel pipe.

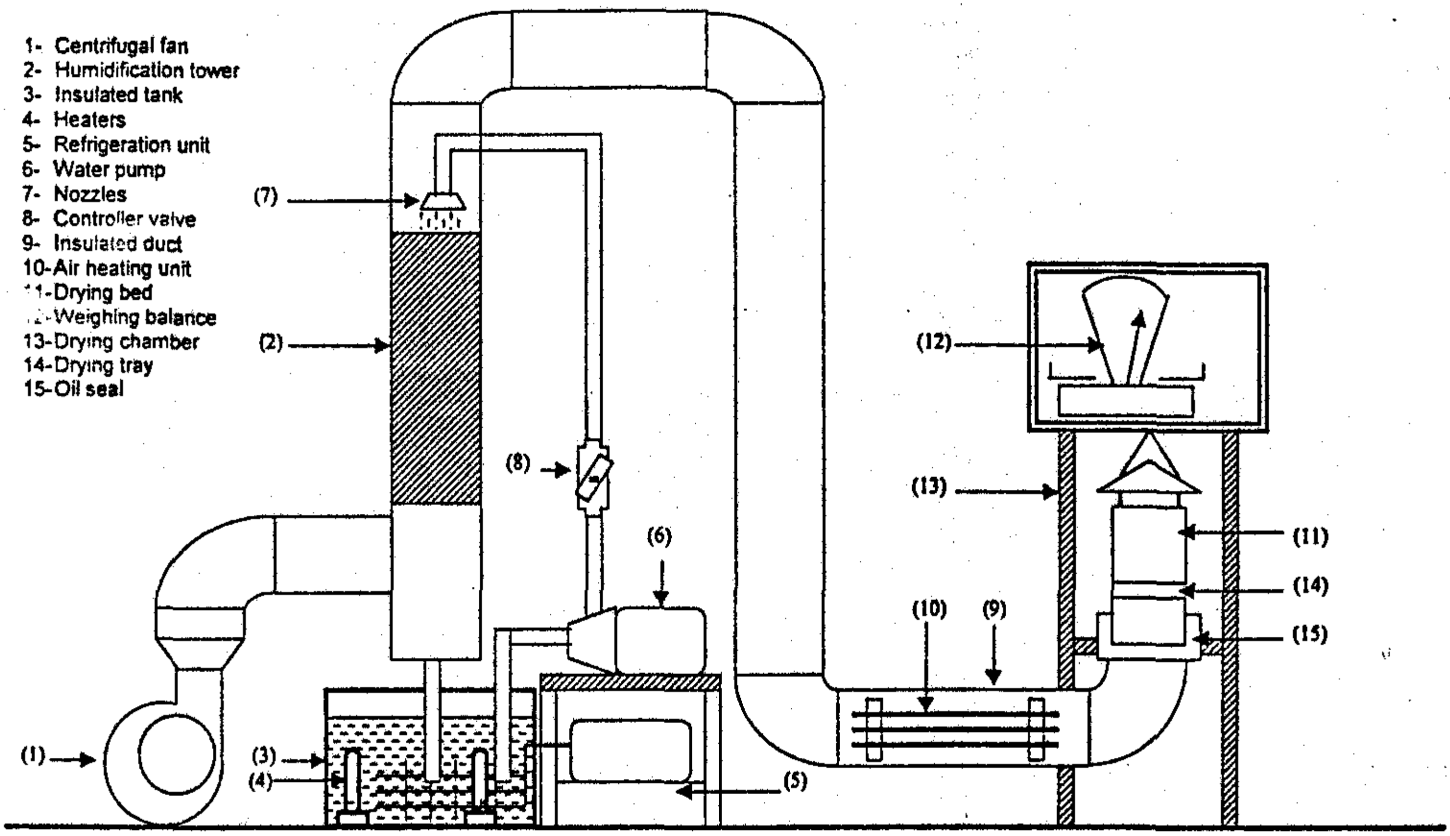

Figure (1):Schematic diagram of the experimental drier.

2.2. Humidity control system:

Indirect method was used to control and measure the humidity of the drying air. This method was based on the assumption that the mixture of air water vapor behaves as an ideal gas. Then from the basic principles of thermodynamics, the humidity of the air can be evaluated if at least two other parameters defining its thermodynamic state are known. So if the pressure is maintained nearly constant, the humidity could be evaluated by measuring the dew point and dry bulb temperatures of the air. To get air at certain dew point temperature the ambient air was passed upward (as mentioned above) through the vertical PVC tower which was packed with broken glass to provide a large liquid surface area to the air stream so that the air was humidified. The water was circulated to the tower from a 150 litters insulated tank. Dew point temperature below ambient temperature is obtained by the continuous operation of a small refrigeration unit where evaporator section is located in the water tank. On the other hand dew point temperatures above ambient temperature were obtained by four coils (2.5 k Watt) which were also located inside the water tank.

This system provided set of dew point temperatures ranging from 10 to 50 °C which could be maintained for a period of 24 hr.

2.3. Air temperature control system:

The dry bulb temperature of the air was raised to the required value as it passed through a bank of mineral insulated electrical heating elements, which were fitted inside the steel pipe. Heating elements were energized through a power regulator and sensor. The sensor was placed at the outlet of the pipe facing the air stream just below the drying tray. The action of the control may be described as: if the air temperature decreased than the pre-set value the sensor sends a signal to the thermostat, which switchs the heaters on. During this heating process the dew point temperature of the air remained constant at the temperature of the water in the tower.

2.4. Drying bed and chamber:

The moistened hot air was then passed from the heating unit to the drying bed via the insulated steel pipe. The drying bed consisted of galvanized steel cylinder (27 cm diameter and 70 cm length). It was suspended from the under hook of a balance stood in a rigid wood shelf above the chamber. The drying tray, which contained the ear corn sample, was placed inside the cylinder. The drying chamber was made of wood (70x70x100 cm) with a roof on top, to constrain the air leaving the sample to flow down the outside of the drying bed and leave the drying chamber at its base. This ensured a minimal temperature gradient across the bed of ear corn.

An oil seal was also placed at the base of inner cylinder to ensure that all of the drying air passed through the drying bed. Access to the inner cylinder to load or remove the sample was provided by a hinged door on the drying chamber, which could be closed by a latch.

2.5. Weighing equipment:

As was mentioned above, drying bed was suspended from the under hook of a balance, which was placed on a rigid wood shelf above the drying chamber. This balance was used to determine the change in weight of the ear corn sample due to moisture transfer. Weight changes indicated on a reading meter in the panel of the balance were accurate to ± 1 gm.

3. Measurements:

During the course of the experiments several parameters were measured as follows:

Moisture content:

The moisture content of ear corn was determined using a hot air drying oven set at 130 °C for 16 hr (Matouk, 1976).

The moisture content of ear corn was measured by dividing each ear into two halves and taking equal pieces from the two sides of each half. The ear corn pieces were then distributed into three aluminum tins, which were weighed before, the tins were then covered with its lid and weighed again and used to determine moisture content. Weights were measured with a static electrical balance accurate to ±0.01 gm. Detailed description of this procedure was given by Tharwat, (2000).

It should be mentioned here that all moisture contents were expressed in dry basis unless other wise specified.

Air velocity:

Air velocity was measured using Tri-sense meter model No. (370000) It should be mentioned that air velocity was kept constant through our all experiments at 2.5 m / sec.

Air temperature:

Drying air temperature was controlled by means of thermostat accurate to ± 1 °C. The sensor of the thermostat was placed under the sample tray.

Air relative humidity:

Air relative humidity was calculated from the measurement of the dry bulb and dew point temperatures of the heated air by using a software program (Plus) and checked by a mathematical model of the psychometric chart presented by Brooker (1967). The dew point temperature was measured using a thermocouple placed at the top of the humidification tower.

Initial and final weight:

The weight of samples at the beginning and end of the experiments were obtained by using a weighing balance accurate to 1 gm.

Experimental Procedures:

1. Thin layer experimentaation of ear corn:

In conducting the thin layer experiment, the air temperature was set at approximately 45, 50, 55 and 60 °C, and the air relative humidity at about 30%, 40%, 50% and 60%. The experiments were kept running until the weight loss had almost ceased, which indicated that the moisture content of the ear corn had approached equilibrium with the drying air. At the completion of each drying test the final weight of ear corn was measured and then the ear corn were used to determine the final moisture content as explained before. Detailed description of thin layer drying procedure will be presented on the second part.

DATA PROCESSING AND ANALYSIS

1. Determination of the Drying Coefficient (K):

In this part of study the rate of moisture removal from wet ear corn is assumed to be related to the moisture content of the ear corn by the following relationship:-

$$-\frac{dM}{dT} = K(M - M_e) \qquad (1)$$

where:

M: the moisture content at any time t (% d.b).

K: drying coefficient.

M_e: equilibrium moisture content (% d.b).

In fact equation 1 may be considered as another form of the simple exponential equation:

$$\frac{M - M_e}{M_o - M_e} = \exp[-Kt] \qquad (2)$$

which is known as Page's equation (Page, 1949). In order to evaluate the value of the constant (K), the procedure which was established by O'callaghan *et al.*, (1971) and used by Matouk (1976) and Tharwat (2000) was adopted as follow:

Upon separation of variables of equation (1)

$$\therefore \frac{dM}{(M - M_e)} = -K\, dT \qquad (3)$$

The integrated form of equation (3) is given by:

$$\ln(M - M_e) = -KT + C \qquad (4)$$

or

$$(M_1 - M_e) = C_1 e^{-KT_1} \qquad (5)$$

at time (T_1+X) where X is a constant:

$$(M_2 - M_e) = C_1 e^{-K(T_1+X)} \quad \text{.........(6)}$$

subtracting equation (6) from equation (4), then

$$(M_1 - M_2) = C_1 e^{-KT_1}(1 - e^{-KX}) \quad \text{.........(7)}$$

But $(1 - e^{-KT_1}) = \text{constant}$

So :

$$(M_1 - M_2) = C_2 e^{-KT_1} \quad \text{.........(8)}$$

or

$$\ln(M_1 - M_2) = -KT_1 + \ln C_2 \quad \text{.........(9)}$$

If ordinates of the drying curve are subtracted at constant time intervals, and logarithm of the difference plotted against time on a uniform abscissa, the slope of the resulting line may be considered as the drying coefficient, K.

2. Determination of Equilibrium Moisture Content:

Two values of dynamic equilibrium moisture content were determined for each run. The determination procedures were as follow:

1- The first value was the final moisture content of each run which was considered as an approximate value for dynamic equilibrium moisture content taking into account that the drying run was turned off when the decrease in the sample weight was almost ceased. This value was denoted as M_f.

2- The second value was developed by taking into consideration that thermodynamically, the equilibrium occurs when the net exchange of moisture between the ear corn sample and air is zero, i,e the rate of drying equal to zero. It was desirable, therefore, as a first step of the analysis to calculate the drying rate at various points on the moisture content- time curve. The procedure of developing such equilibrium value may be summarized as follow:

a) The drying rates and the corresponding moisture contents and time for the mid points were calculated.

b) A straight line was fitted by the least square method to the calculated values of the drying rates (dM/dT) and the corresponding moisture contents.

c) The best fitted straight line was then extrapolated to read the value of the moisture content at drying rate equal zero, i.e. the x-intercept of the straight line. This value of moisture content was considered as the dynamic equilibrium moisture content and denoted as (Me).

RESULTS AND DISCUSSIONS

1. Drying coefficient (K):

Values of the drying coefficient (K) and the corresponding values of air temperature and relative humidity for each drying run and average values of the drying coefficient, drying air temperature and air relative humidity at each temperature and relative humidity are shown in table (1). Inspection of these data show that the drying coefficient is influenced by both drying air temperature and air relative humidity. The effect of drying air temperature on the drying coefficient (K) at constant relative humidity was analyzed using simple regression analysis, which showed that the nature of dependence may be described by the following empirical relation:

$$K = A \exp(B(T_a)) \qquad (10)$$

where

T_a: drying air temperature °C.

A and B: are constants.

Table (2) shows the values of the constants A and B at each air relative humidity. Figure (2) also shows the relation between drying coefficient and air temperature at different air relative humidities.

Similar analysis was also proceeded to estimate the nature of dependence of the drying constant (K) on air relative humidity at constant air temperatures. The analysis showed that the relationship between drying coefficient (K) and air relative humidity (RH) may be approximated by:

$$K = C \exp(D(RH)) \qquad (11)$$

Where:

RH: the air relative humidity (%).

C and D: are constants.

The values of the constants C and D at all air temperatures are presented in table (3). Figure (3) also shows the relation between drying coefficient (K) and air relative humidity (RH) at different air temperatures.

A multiple regression analysis was also employed to determine the inter action effect of both drying air temperature and air relative humidity on the drying coefficient (K). The multiple regression equation for the best fit was:-

$$K = 0.001232 + 0.0000622\, T_a - 0.000025\, RH \qquad (12)$$

(S.E. = 0.000116 R^2 = 0.950046)

These results which confirmed the dependence of drying coefficient (K) of ear corn on both air relative humidity and temperature are in agreement with similar results obtained for barley by Jayas and Sokhansanj, 1988 and for peanut by Mustafa and Abdalla, 1989 and for rough rice by Chen Yi Luen, 1999 and by Tanaka *et al.*, 2000.

Table (1): Air temperature, average of air relative humidity, and average of drying coefficient (K) for each experimental run.

Run no.	Air temp. (°C) ±1 °C	Air relative humidity (%)	Drying coefficient (K)	Av. air temperature (°C)	Av. air relative humidity (%)	Av. (K)
1	45	32.6	0.0032	45	32.3	0.0031
2	45	32.4	0.0029			
3	45	31.9	0.0032			
4	45	41.4	0.003	45	41.4	0.003
5	45	41.4	0.003			
6	45	41.4	0.003			
7	45	49.6	0.0029	45	50.07	0.00287
8	45	50.2	0.0028			
9	45	50.4	0.0029			
10	45	59.5	0.0031	45	59.65	0.00275
11	45	59.8	0.0024			
12	50	29.9	0.0036	50	30.1	0.0035
13	50	30.2	0.0035			
14	50	30.2	0.0034			
15	50	40.1	0.0031	50	40	0.0033
16	50	40.5	0.0036			
17	50	39.4	0.0032			
18	50	49.6	0.0033	50	49.85	0.0030
19	50	50.1	0.0027			
20	50	60.6	0.0027	50	60.55	0.0028
21	50	60.5	0.0029			
22	55	29.9	0.004	55	29.93	0.0039
23	55	30	0.004			
24	55	29.9	0.0037			
25	55	40	0.0034	55	40.15	0.0036
26	55	40.3	0.0038			
27	55	48.9	0.0032	55	49.25	0.00335
28	55	49.6	0.0035			
29	55	59.8	0.0031	55	60.1	0.00305
30	55	60.4	0.0030			
31	60	29.9	0.0042	60	30.17	0.0044
32	60	30.2	0.0047			
33	60	30.4	0.0043			
34	60	40.2	0.0036	60	40.3	0.0041
35	60	40.3	0.0044			
36	60	40.4	0.0043			
37	60	46.9	0.0036	60	47.05	0.0037
38	60	47.2	0.0038			
39	60	55.3	0.0033	60	55.6	0.0035
40	60	55.9	0.0037			

Table (2): Values of constants (A and B) of equation (10) at constant levels air relative humidity.

RH (%)	A	B	R^2
30	0.0010941	0.023176	0.9995
40	0.0011862	0.020483	0.9918
50	0.0012860	0.017448	0.9730
60	0.0008126	0.024348	0.9894

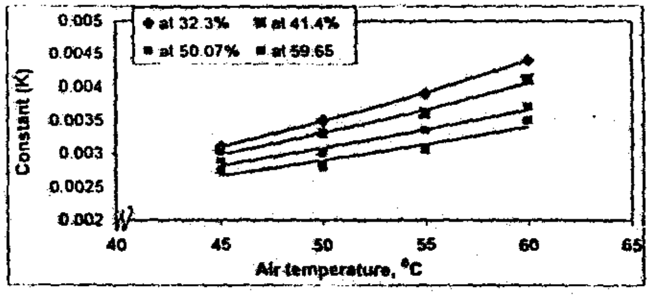

Figure (2): Relation between (K) and (T_a) at each level of relative humidity.

Table (3): Values of constants (C and D) of equation (11) at constant levels air temperature.

Ta (°C)	C	D	R2
45	0.003446	- 0.000924506	0.9973
50	0.004123	- 0.001574105	0.9918
55	0.0046345	- 0.001697586	0.9999
60	0.0054138	- 0.001983832	0.9741

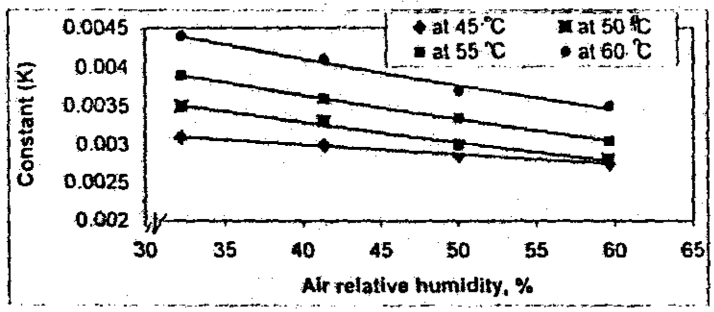

Figure (3): Relation between (K) and (RH) at different air temperatures.

2. Equilibrium moisture content:

Table (4) shows the values of final and equilibrium moisture contents for all drying runs. The average values of final and equilibrium moisture contents at different air temperatures and air relative humidities are also shown in the same table.

Table (4): Values of (M_e) and (M_f) for each run:

Run no.	Ta (°C)	RH (%)	M_e (% d.b.)	av. of M_e	M_f (% d.b.)	av. of M_f	Run no.	Ta (°C)	RH (%)	M_e (% d.b.)	av. of M_e	M_f (% d.b.)	av. of M_f
1	45	32.6	8.63		12.21		21	50	60.5	11.167	11.445	14.33	14.45
2	45	32.4	9.71	9.367	12.34	12.287	22	55	29.9	7.692		10.2	
3	45	31.9	9.762		12.31		23	55	30	7.4	7.478	10.0	10.173
4	45	41.4	10.95		13.58		24	55	29.9	7.556		10.32	
5	45	41.4	10.2	10.613	13.21	13.293	25	55	40.0	8.583	8.019	11.01	11.09
6	45	41.4	10.69		13.09		26	55	40.3	7.455		11.17	
7	45	49.6	11.05		14.52		27	55	49.6	9.25	9.396	13.19	12.83
8	45	50.2	11.39	11.217	14.51	14.49	28	55	48.9	9.542		12.47	
9	45	50.4	11.21		14.44		29	55	60.4	10.308	10.25	13.52	13.405
10	45	59.5	13.25	13.475	16.98	15.76	30	55	59.8	10.192		13.29	
11	45	59.8	13.7		15.54		31	60	29.9	6.047		9.86	
12	50	29.9	8.59		11.49		32	60	30.2	6.449	6.988	9.49	9.757
13	50	30.2	8.1875	8.698	11.55	11.55	33	60	30.4	6.487		9.92	
14	50	30.2	8.208		11.61		34	60	40.3	7.444		10.13	
15	50	40.1	9.667		12.28		35	60	40.2	9.877	7.3545	10.05	10.143
16	50	40.5	9.667	9.645	12.41	12.287	36	60	40.4	7.265		10.25	
17	50	39.4	9.6		12.17		37	60	46.9	8.875	8.264	11.42	11.475
18	50	49.6	9.556	10.142	13.16	13.37	38	60	47.2	7.6538		11.53	
19	50	50.1	10.727		13.58		39	60	55.3	9.591	9.646	12.03	12.4
20	50	60.6	11.7222		14.63		40	60	55.9	9.7		12.77	

Inspection of the data tabulated in table (4) showed that equilibrium moisture content (M_e) (based on thermodynamic basis) was affected by both air temperature and air relative humidity. Regression analysis revealed a highly significant between these parameters.

The regression equations obtained were:-

M_e = E exp(F(*Ta*)) at const. RH ....(13)

M_e = G exp(H(*RH*)) at const. T_a ....(14)

Where:

Ta: drying air temperature °C.

RH: the air relative humidity (%).

E, F, G and H: are constants.

Values of the constants E, F, G, and H are tabulated in tables 5 and 6. Figures 4 and 5 also show the effect of air temperature on M_e at different air relative humidities and the effect of air relative humidity on M_e at different air temperatures respectively.

A multiple regression analysis was also employed to determine the inter action effect of both drying air temperature and relative humidity on M_e. The following multiple regression equation was obtained:

M_e = 14.90589 - 0.19329 T_a + 0.105894 RH...............................(15)

(R^2 = 0.949)

These results were in line with those obtained for shelled corn by Matouk, 1976, for peanut by Mostafa and Abdalla, 1989, for long and medium grain rice varieties by Fan Jin Tain *et al.*, 1998, for tomato by Unadi *et al.*, 1998 and for Prunes by Stencl *et al.*, 1999.

Similar analysis was also applied to study the effect of air temperature and air relative humidity on the final moisture content (M_f) as an equilibrium value. Similar regression equations were also obtained to describe the effect of each factor and the inter action of both variables on the final moisture content (M_f) as an equilibrium value:

M_f = I exp(J(*Ta*))..(16)

M_f = R exp(V(*RH*))..(17)

I, J, R and V: are constants.

M_f = 17.09168 - 0.18396 T_a + 0.111444 RH...............................(18)

(R^2 = 0.978154)

Values of the constants I, J, R and V at different air temperatures and air relative humidities are tabulated in tables (7) and (8) Figures (6) and (7) also show the effect of air temperature on M_f at different air relative humidities and the effect of air relative humidity on M_f at different air temperatures respectively.

Table (5): Values of constants (E, F) of equation (13) at constant relative humidities.

RH	E	F	R2
30%	23.825	- 0.020602464	0.9762
40%	33.974	- 0.025698556	0.979
50%	27.498	- 0.019858342	0.9903
60%	34.761	- 0.022263073	0.9593

Table (6): Values of constants (G, H) of equation (14) at constant air temperatures.

Ta (°C)	G	H	R2
45	6.1900	0.01268	0.9662
50	6.7245	0.0086465	0.9820
55	4.3139	0.011035	0.9701
60	4.5901	0.012837	0.9302

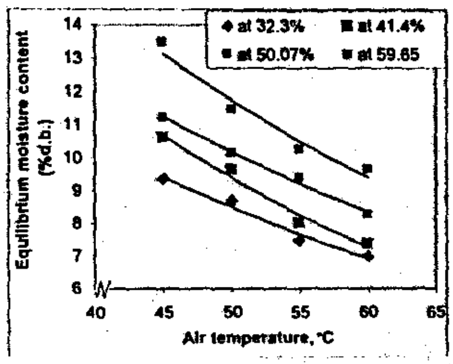

Figure (4): Relation between (M_e) and (T_a) at different relative humidities.

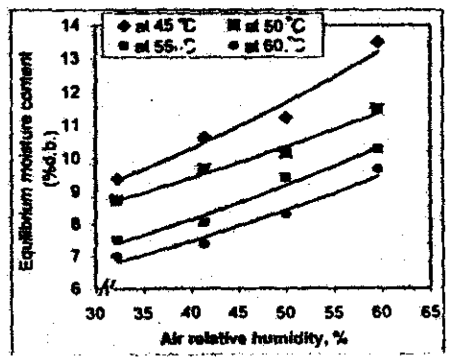

Figure (5): Relation between (Me) and (RH) at different air temperatures.

These results were based on considering final moisture content, M_f, as an equilibrium moisture content are also in line with those obtained for onion by Matouk *et al.*, 1985, for barley by Sun and Woods, 1994 and for rice by Chen Chia Chung, 1997 and Basunia and Abe, 2001.

Table (7): Values of constants (I, J) of equation (16) at constant relative humidities.

RH	I	J	R2
30%	24.733	- 0.01637237	0.9646
40%	30.333	- 0.01827719	0.9977
50%	28.297	- 0.01482182	0.9702
60%	27.244	- 0.00321232	0.9991

Table (8): Values of constants (R, V) of equation (17) at constant air temperatures.

Ta (°C)	R	V	R2
45	9.1228	0.009179	0.9993
50	9.1622	0.0075384	0.9968
55	7.6376	0.0097021	0.9515
60	7.0827	0.0099469	0.9344

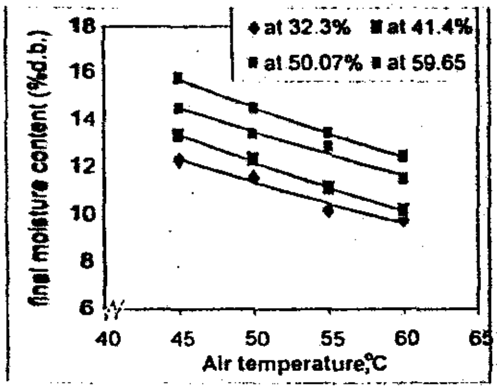

Figure (6): Relation between (M_e) and (T_a) at relative humidities.

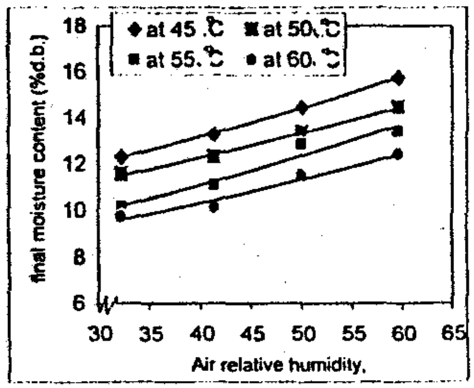

Figure (7): Relation between (M_e) and (RH) at different air temperatures.

5. CONCLUSION

The obtained results may lead to the following conclusions:-

1- Procedures to determine the drying parameters of ear corn (drying constant and equilibrium moisture content) were developed.

2- Results obtained confirmed the dependence of the drying parameters of ear corn on both air temperature and air relative humidity.

3- A new approach was presented were uses the final moisture content of ear corn as an equilibrium moisture content at the specific condition of each run. These values of final moisture contents were also found to be dependent on both air temperature and air relative humidity.

4- The results obtained may help in providing rational basis for developing mathematical model to simulate the simultaneous heat and mass transfer during drying of ear corn.

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الملخص العربى

تجفيف كيزان الذرة

الجزء الأول: تقدير معاملات التجفيف

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أجريت هذه الدراسة لتقدير معاملات التجفيف لكيزان الذرة. تم تصميم وتنفيذ مجفف تجريبى فى قسم الهندسة الزراعية – كلية الزراعة – جامعة المنصورة لتجفيف كيزان الذرة فى طبقات رقيقة تحت ظروف ثابتة من درجة الحرارة والرطوبة النسبية لهواء التجفيف.

تم تطوير نموذج رياضى لتقدير معاملات التجفيف لكل من ثابت التجفيف (k) ، المحتوى الرطوبى المتوازن (M_e) ° من منحنى المحتوى الرطوبى والزمن والمستنتج من القياسات الفعلية لتجارب التجفيف.

ولقد أكدت النتائج المتحصل عليها من التحليل الرياضى إعتماد معاملات التجفيف على كل من درجة الحرارة فى المدى من ٤٥ إلى ٦٠ °م والرطوبة النسبية لهواء التجفيف فى المدى من ٣٠ إلى ٦٥ % ولقد تم إستنتاج معادلات لتصف هذا الإعتماد.

ولقد تم إجراء تحليل إحصائى متعدد لإستنتاج معادلات تربط بين معاملات التجفيف وعلاقتها بدرجة الحرارة والرطوبة النسبية لهواء التجفيف المستخدم.

يمكن إستخدام المعادلات المستنتجة من خلال برنامج حاسب آلى للتجفيف فى طبقات رقيقة لكيزان الذرة إعتماداً على تغير كل من درجة الحرارة والرطوبة النسبية لهواء التجفيف.