MATHEMATICAL MODELING OF SOLAR DRYING OF TOMATO SLICES

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DEDICATION

To the soul of my late father …
By his spritual guidance,support and wisdom
I was driven to this stage.

ACKNOWLEDGEMENT

Thanks are first to Allah, who enabled me and donated me strength and patience to conduct this study by his grace.

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ABSTRACT

Solar drying experiments in thin-layer of tomato slices were conducted at Shambat, Faculty of Agriculture, University of Khartoum. The study was conducted to develop a mathematical model for tomato slices solar drying. Then the mathematical model was written into Pascal programming language.

An indirect forced convective solar dryer was constructed and used in the experiments. Air was forced into the solar air heater or collector by a suction fan and the resulting hot air was then passed to the drying chamber where the tomato slices were placed in a thin-layer. The change in mass of tomato slices and the drying air parameters were recorded continuously at specified intervals during the experiment. Drying curves obtained from the data were examined to fit into two semi-theoretical mathematical models, Lewis and Page models.

The results illustrate that in spite of the high initial moisture content of the tomato slices, the drying takes place only in the falling rate period.

The consistency of the two selected models was tested by using statistical parameters, namely reduced chi-square (χ^2), root mean square error (RMSE) and modeling efficiency (EF). The results of these measures have confirmed the consistency of the developed model to describe satisfactorily the thin-layer solar drying characteristics of tomato slices.

خلاصة الأطروحة

أجريتْ تجارب التَجفيف الشمسي في الطبقاتِ الرقيقةِ لشرائح الطماطمِ في شمبات، كليّة الزراعة، جامعة الخرطوم.أستهدفت الدراسة تطوير أنموذج رياضي للتجفيف الشمسي لشرائح الطماطم. ثم تمت كتابة هذا الأنموذج الرياضي في الحاسوبِ باستخدام لغة البرمجة باسكال.

تم تصميم مجفف شمسي غير مباشر وقسري لإجراء التجارب. استخدمت مروحة شفط لدفع الهواءِ الذي تم تسخينه في المجمع الشمسي إلى غرفةِ التَجفيف حيث وضعت شرائحَ الطماطمَ في طبقة رقيقة. تم رصد عدة قياسات وهى: التغيير في كتلة الطماطم، درجة الحرارة والرطوبة النسبية داخل وخارج المجفف الشمسي وسُجّلتْ بشكل مستمر في فترات محدّده خلال مدة كُلّ تجربةِ. تمت مُلاءمة منحنيات التَجفيف، والمتحصل عليها مِنْ البياناتِ التي رصدت إلى نموذجين رياضيين لتجفيف الشرائح الرقيقة. هذان النموذجان هما: نموذج لويس (Lewis model) ونموذج بيج (Page model).

بالرغم من ارتفاع المحتوى الرطوبي الأولي لشرائح الطماطم إلا ان النتائج أظهرت ان التَجفيف قد تم فقط في فترة المعدل الهابط أو المنحدر.

لدِراسَة اتساق كُلّ من النموذجين المختارين استخدمت بعض المقاييس الإحصائية، مثل χ^2 والجذر ألتربيعي لمتوسط الخطأ (RSME) وكفاءة النموذج (EF). أكّدتْ نَتائِج هذه المقاييس اتساق النموذجِ المطوّر لوَصْف خصائص التَجفيف الشمسي لِشرائح الطماطمِ.

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CHAPTER ONE

INTRODUCTION

Economical growing of fruits and vegetables is limited in many countries to certain seasons and localities. To meet the demand during the entire year in all areas these products should be preserved using different techniques. Drying technology as a process for food conservation seems to be an adequate method under most conditions specially in developing economies.

Among the vegetable products, tomato is one of the most important and popular produce. It is used fresh, juice or dried in most meals. It’s an important source of vitamin C, and also plays an important role in the protection from cancer because it contains a considerable amount of lycopene. In Sudan, there is a large quantity of tomatoes produced, which is grown as a winter – crop produce. Unfortunately most of the produce is lost due to improper preservation. Hence, drying technique could be one of the promising solutions to face such problem.

Drying is one of the conservation methods of agricultural products, which is most often used and is the most energy consuming process in industry (Dincer, 1998). Drying is one of the oldest methods of food preservation and is a difficult food processing operation mainly because of the undesirable changes in the quality of the dried product. Longer shelf-life, product diversity and substantial volume reduction are the reasons for popularity of dried fruits and vegetables, and this could be expanded further with improvements in product quality and process applications. These improvements increased the current degree of acceptance of dehydrated foods in market (Maskan, 2001).

Solar drying of crops, fruits and vegetables has been practiced all over the world for centuries. Open-air sun drying has been used since the beginning of human life in the world to dry grains, plants and other agricultural products as a means of preservation. A large portion of the world's supply of dried fruits and vegetables continues to be sun dried in the open air without technical aids (Szulmayer, 1971).

However, large-scale production limits the use of the open-air natural sun drying. Among these are lacks of ability to control the drying process properly due to weather uncertainties, high labor costs, large area requirements, insect infestation, mixing with dust and other foreign materials and so on. The solution involving solar energy collection devices or solar dryers have been proposed to utilize free, renewable and non-polluting energy source provided by the sun. The introduction of solar dryers in developing countries can reduce crop losses and improve the quality of dried product significantly compared to traditional drying methods (Muhlbauer, 1986). In recent years, numerous attempts have been made to develop solar drying mainly for preserving agricultural and forest product (Toğrul and Pehlivan, 2002).

In Sudan and most developing countries, the price of the fossil fuels and electricity, which provide the heat energy for drying, is comparatively high. As known, Sudan has been blessed with plenty of sunshine hours, therefore many attempts have been directed towards the use of the solar energy as a heat source for crop drying.

Solar drying systems must be properly designed in order to meet particular drying requirements of specific crops and to give satisfactory performance with respect to energy requirements (Steinfeld and Segal, 1986). Drying characteristics of the particular materials being dried and simulation models are needed in the design, construction and operation of drying systems. Recently, there have been many studies on the drying behavior of various vegetables and fruits. Therefore the objectives of the present study are:

1- To develop a mathematical model to simulate convective solar drying of a thin-layer of tomatoes slices.
2- To validate the developed model by comparing the predicted results with the experimental ones.

CHAPTER TWO
LITERATURE REVIEW

2.1 Drying concept

2.1.1 Definition

Drying by convention is the process of removing excess moisture from a product. Removal of all or most of the moisture is termed dehydration (Andales, 1982).

Drying of foods implies the removal of water from the foodstuff. In most cases, drying is accomplished by vaporization of the water that is contained in the foods. To do this the latent heat of vaporization must be supplied. There are, thus two important process – controlling factors, which are encountered in the unit operation of drying:

a) The transfer of heat to provide the necessary latent heat of vaporization.
b) The movement of water or water vapor through the food material and then away from it to affect the separation of water from food-stuff (Earle, 1983).

Brooker *et al*. (1992) and Gögüs (1994) stated that, drying is a process of simultaneous heat and moisture transfer. The heat is required to evaporate the moisture that flows from the product surface into an external drying medium, usually air.

Henderson and Perry (1976) stated that, the removal of moisture from a product is known as drying or dehydration, which are used interchangeably. Drying is the removal of moisture to a moisture content in equilibrium with normal atmospheric air or to such a moisture content that decreases in quality from molds, enzymatic action and insects will be negligible (12% to 14% w.b for most materials). Dehydration is the removal of moisture to a very low moisture content, nearly bone-dry condition. Bone-dry material is the material from which all the moisture has been removed i.e. the moisture content is zero.

2.1.2 Importance of the drying

Drying is one of the oldest methods for preservation of foodstuffs. Several new methods of food dehydration have been proposed during the last few years. The primary objective of development in this field is to produce high quality dehydrated foods, which should reconstitute readily upon rehydration to produce a material closely resembling the fresh material (Husain *et al*., 1972).

The biological forces acting upon the food supply are controlled by reducing the free water content by heating. To be a suitable substrate to support growth of microorganisms, food must be having free water available for the microorganisms. By reducing the free water content, thereby increasing osmotic pressures, microbial growth can be controlled (Norman and James, 1977).

Dried and dehydrated foods are more concentrated than any other preserved form of foodstuffs. They are less costly to produce where there is a minimum of labor required and limited processing equipment. Dried food storage requirements are at a minimum, and distribution costs are reduced (one car load of dried, compressed food may equal ten car loads of the fresh commodity), Table 2.1.

Table 2.1 Relative space requirements per unit (fresh basis) of food

Product	**Fresh**	**Dehydrated**	**Canned or frozen**
Fruits	50 – 55	3 – 7	50 – 60
Vegetables	50 – 85	5 – 25	50 – 85
Meats	50 – 85	15 – 20	50 – 60
Fish	50 – 75	20 – 40	30 – 75

Source: Norman and James (1977).

Henderson and Perry (1976) stated that, the importance of drying farm products is increasing. Drying permits the farmer to secure a greater economic return for the following reasons:-

1- Early harvest (at high moisture content) minimizes field damage and shatters loss and facilitates tillage operations for such products as corn, small grains and grass seeds.
2- Long-period storage without product deterioration is possible.
3- Viability of seeds is maintained over long-periods.
4- Production operations are facilitated for such products as cotton and corn.
5- Products with greater economic values are produced, for example tobacco, dried fruits and vegetables.
6- Waste products can be converted to useful products, for example livestock feed, from fruit bulb and almond hulls.

Parti (1993) concluded that, proper drying is precondition for safe storage and delivery. Greater yields and the need for storage over long periods of time demand a high degree of control over various properties of the final product (Parry, 1985). Drying is a classical method of food preservation, which provides longer shelf life, a lighter weight for transportation and smaller space for storage (Ertekin and Yaldiz, 2004).

2.2 Drying theory

Because of the basic differences in drying characteristics in thin-layer and deep bed, the whole drying processes are divided into thin-layer and deep bed drying.

2.2.1 Thin-layer drying

Thin-layer drying refers to the grain (product) drying process in which all grain are fully exposed to the drying air under constant drying conditions i.e. at constant air temperature and humidity (Chakraverty and De, 1981). Also, thin-layer drying characteristically limits the depth of the product in the direction of the airflow (Abdel Aziz, 1989). The thin-layer drying process divided according to Henderson and Parry (1976) into two periods:

1- The constant drying – rate period

2- The falling drying – rate period.

2.2.1.1 Constant drying-rate period

In this period, a material or mass of material containing so much water will dry in a manner comparable to an open-faced body of water. The water of its surroundings, not the solid, will determine the rate of drying (Henderson and Perry, 1976).

Norman and James (1977) added that, during this period the rate of drying is governed by how rapidly the air can supply heat to the water in the food particle, and remove the water vapor produced. During this period the water is diffusing to the surface of the particle as fast as it can be evaporated.

Brooker *et al*. (1992) concluded that, the initial rate of drying of biological products with m.c. above 70-75% (w.b) is a function of three external drying parameters: air velocity, air temperature and air humidity. Constant-rate drying is observed in products for which the internal resistance to moisture transport is much less than the external resistance to water vapor removal from the product surface.

The drying rate ($^{\mathbf{dm}}/_{\mathbf{dt}}$) of the constant period of a biological product can be approximated by use of the wet-bulb thermometer equation, which results in the following expression for the rate of moisture loss of a biological product during the constant-rate drying period:

$$\frac{d\overline{M}}{dt} = \frac{\overline{h}_D A}{R_v T_{abs}} \left(P_{vwb} - P_{vx} \right) = \frac{\overline{h} A}{hfg} \left(T_x - T_{wb} \right)$$

Where:

T_x and T_{wb}, P_{vwb} and P_{vx} = represent the drying-air, dry-bulb and wet-bulb temperatures, respectively, and P_{vwb} and P_{vx} are the associated vapor pressures.

$\overline{h}_D$ = convective mass transfer coefficient, kg/ m^{2}hr.

A = specific surface area.

R_v= gas constant for water vapor, 461.91 kJ /mole k.

$T_{abs.}$= Absolute dry-bulb temperature, K

$\frac{d\overline{M}}{dt}$ = drying rate, kg/hr.

$\overline{h}$ = convective heat transfer coefficient, w/m^2.^{o}C.

$h_{fg} = h_f - h_g$ = heat of vaporization at saturation, J/kg .

h_f = specific enthalpy of saturated liquid water, J/kg.

h_g = specific enthalpy of saturated water vapor, J/kg .

As stated by Norman and James (1977) the rate of drying during this period is primarily governed by the properties of the drying air.

Andales (1982) stated that the constant rate period ends when the critical moisture content is reached, the critical moisture content is a function of the product and its thickness.

2.2.1.2 Falling-rate drying period

It's the point where the water can no longer diffuse to the surface as rapidly as it's evaporated. Then the rate of drying is controlled by the rate of diffusion. As the moisture content decreases, the rate of diffusion drops and the rate of drying slows. The solid material of the particle begins to adsorb heat from the air, and the temperature begins to approach the dry bulb temperature of the drying air (Norman and James, 1977).

Andales (1982), furthermore divided this period into two divisions, first falling rate period and second falling rate period. These two periods are separated by that, the fraction of wet surface decrease to zero where the subsurface evaporation begins and under prolonged operation this last period continues until the equilibrium moisture content is reached, Figures 2.1 and 2.2.

Brooker *et al*. (1992) defined this period as the moisture content of the product falls below the critical point, driving potential of the drying process, ΔP_v, decreases because the vapor pressure at the product surface, P_v, falls below P_{vwb}. This results in lowering of the drying rate, also, a moisture content gradient appears within the drying product and the product temperature rises above the wet bulb temperature.

Parry (1985) further explained this period and stated that, after the first critical moisture content has been reached the drying rate begins to fall. Initially this rate is proportional to the remaining area normally wetted surface. When all of this free moisture has been removed the hygroscopic limit is attained. Chen and Johnson (1969) call this tertiary moisture content. At this point the capillary theory tells us that, in capillary – porous bodies, the vapor pressure lowering effect becomes significant and a second falling rate period begins. In this and any subsequent periods, the drying rate is dependent on the rate at which moisture in both liquid and vapor form is transported from the interior to the surface of the grain. Many theories have been proposed to explain the transport of moisture from biological materials. The suggested mechanisms include:

1- Liquid transport due to capillary forces (in capillary-porous bodies), i.e. molar `transport, and moisture concentration gradients, i.e. molecular transport or diffusion.

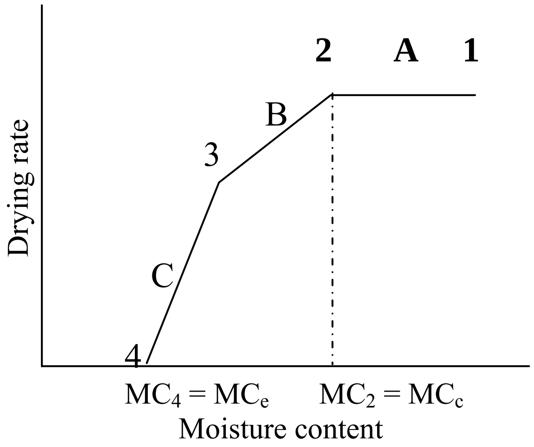

Fig 2.1 Drying rate for a wet product

A = constant period, B = 1st falling rate period, C = 2nd falling rate period

Source: Andales (1981).

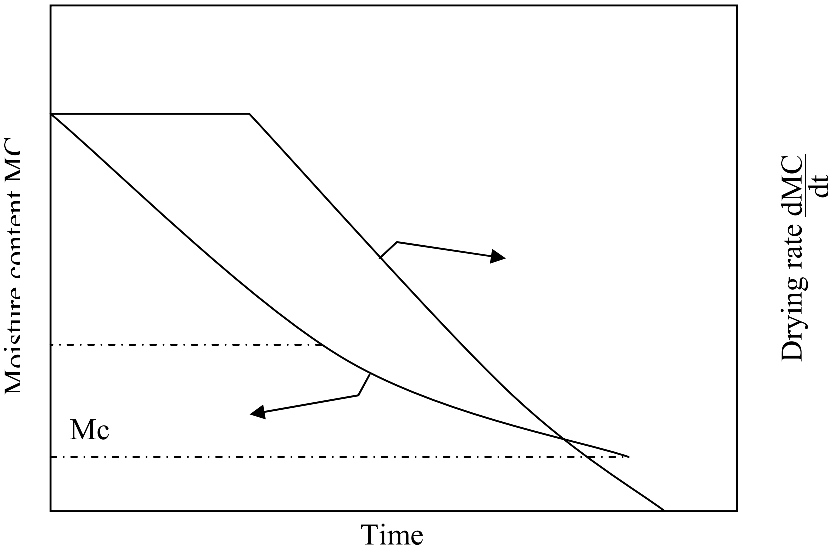

Fig 2.2 Biological product drying during constant and falling-rate periods

Source: Brooker *et al*. (1992).

2- Vapor transport due to moisture concentration and temperature gradients, i.e. mass and thermal diffusion, respectively.
3- Liquid and vapor transport due to total pressure difference.

2.2.2 Deep-bed drying

In deep-bed drying, all the grains (product) in the dryer are not fully exposed to the same condition of drying air, which at any point in the grain (product) mass changes with time and with the depth of product bed (Chakraverty and De, 1981). The condition of drying in deep-bed is shown in Fig 2.3.

Abdel Aziz (1989) stated that, drying is performed in a drying zone, which moves through the grains in the direction of air movement. Drying of food products can be thought of as the drying of several thin-layers, in which the humidity and temperature of air entering and leaving each layer vary depending upon the stage of drying. Usually the moisture removed from the lower layer is added to the next layer, which remains wet until the drying zone reaches it.

Andales (1982) stated that, in deep bed drying the drying air moves from the bottom to top of the bed. Exchange of moisture, from grain to air, takes place in a finite depth or zone of grains. At the start of the drying process the drying zone exists at the bottom of the bed. As drying continues the zone moves upwards, and when the zone passes entirely through the grain, the entire mass is dried to equilibrium with the drying air. Hot air of a very low relative humidity is not suitable to be used in this method of drying because it will cause an over-drying of grain at the bottom at the time when the top grains

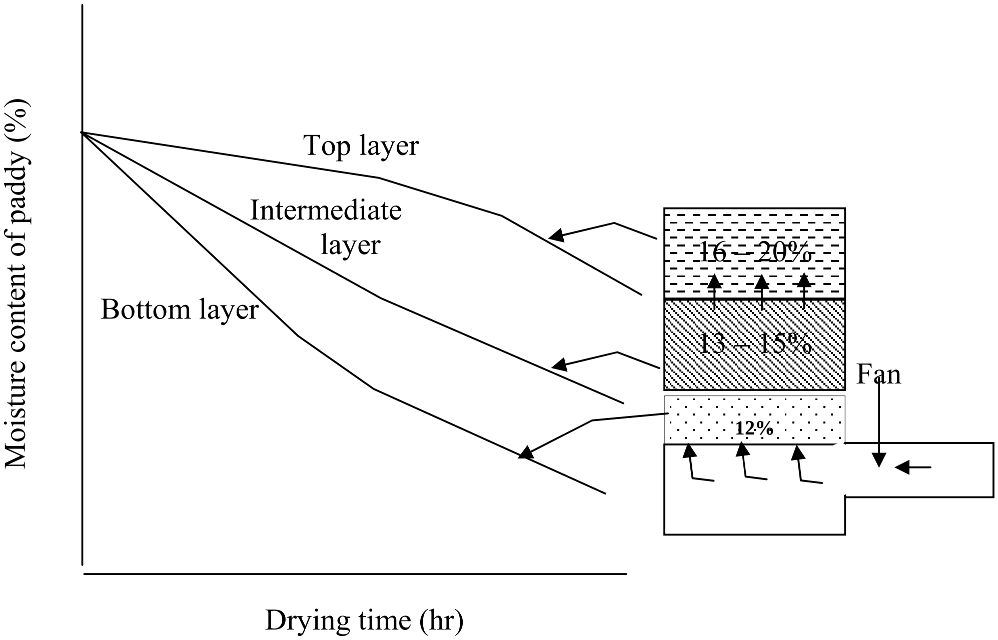

Fig 2.3 Deep-bed drying characteristics at different depths

are dried to the desired moisture content. However, if the air has a high relative humidity, the drying zone may take undesirable long time to reach the top of bed allowing the top weight grain to be destroyed by mold.

2.3 Drying of vegetables and fruits

Gomez (1982) concluded that, the absence of an adequate animal protein intake, vegetables and fruits are the cheapest and most available sources of vitamin A and C, riboflavin, folic acid, calcium and iron. However, the availability of fruits and vegetables is seasonal, and they are particularly scarce during the long periods of drought. The application of simple solar dehydration technologies at the rural level would not only ensure a year-round supply of these foods but would reduce waste of these highly perishable foods during the seasonal overabundance.

Ali and Sakr (1982) stated that, in their studies of vegetables drying, once a decision is taken by policymakers to reduce post harvest losses of food commodities, drying should be given serious consideration as this can save about 20% of the losses experienced in production. Early harvesting of crops reduces losses in the field and increases the land available for other crops and better production due to the early planting of the next crop. The post harvest losses of vegetables due to the long distance from production sites to the market can be reduced together with the cost of transportation. The economic benefits are so great that drying should be considered as standard practice in reducing post harvest losses.

Sarvacos (1962) showed that, most high moisture foods such as fruits and vegetables may undergo three phases of drying: (a) constant rate, (b) first falling rate, and (c) second falling rates. A hypothetical picture of the various phases of drying is shown in Fig 2.4. Although, in his study of the drying of potatoes slices he found that, the entire drying process took place only during the falling rate with no constant rate period observed. It has also been observed by many researchers that during the early phases of drying such as constant and first falling rates, the mechanism of moisture transfer is mainly liquid diffusion. The diffusivity is constant for moisture contents above the maximum hygroscopic moisture (Gorling, 1958; Chen, 1969; Sarvacos, 1962 and Van Arsdel, 1963).

Henderson and Perry (1976) stated that, fruits and vegetables must be dried in thin-layers, because they are materials that crushed or deformed under pressure (compression force).

Recently, there have been many studies on the drying behavior of various vegetables and fruits such as potato (Diamante and Munro, 1991; Gögüs, 1994), onion (Sarsavadia *et al.,* 1999), green pepper, green bean and pumpkin (Yaldiz and Ertekin, 2001), grape (Dincer, 1996; Yaldiz *et al.*, 2001).

2.3.1 Solar drying of vegetables and fruits

The use of solar technology has often been suggested for the dried fruits industry both to reduce energy costs and economically speed up drying, which would be beneficial to final quality (Lambert *et al.*, 1980; Szulmayer, 1973).

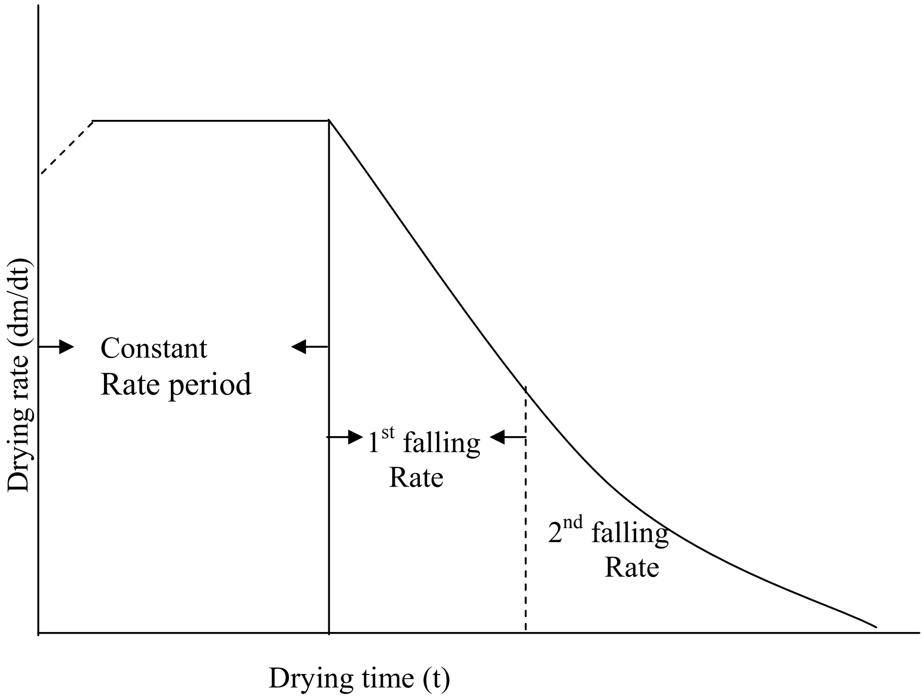

Fig 2.4 Various phases of drying

El-Shiatry *et al.* (1991) dried grapes, okra, tomatoes and onion using solar energy. The drying time was reduced significantly resulting in a higher product quality in terms of color and reconstitution properties. As compared to oil, or gas-heated dryers, solar drying facilities are economical for small holders, especially under favorable meteorological conditions. Muller *et al.* (1987) used solar energy for drying mint, sage and hops. High quality crude drugs in terms of color and content of active ingredients were obtained.

2.3.2 Tomato vegetable

Tomato (*Lycopersicon esculentum* Mill.) is the world's most commercially produced vegetable (Ensminger *et al.*, 1994). It belongs to the family *Solanaceae*. Jenkins (1948) and Rick (1956) considered that tomato was originally confined to the Peru – Ecuador area in South America. The economic importance of the fruit is considerable and it has become one of the most popular vegetables throughout the world. Its versatility in fresh and processed forms has played a major role in its rapid and widespread adoption as an important foods commodity. It is the leading fresh market vegetable, coming first in a group of ten major vitamins and minerals source contributing to human diet (Wills *et al.*, 1998).

The world production of tomato increased from 67.6 million metric tons (MMT) in 2000 to 98.6 (MMT) in 2001 (FAO, 2001). In Sudan, tomato is grown successfully in every state as a winter crop. The total production in 2001 was 243 thousand tons (FAO, 2001).

In spite that, tomato vegetable is not the richest vegetable in vitamin A and C, but it is consumed in large quantities, which makes it an essential and main source for these vitamins. In a study in USA for the most important vegetables, tomato ranked the 13th for its content of vitamin C and 16th for its content of vitamin A. It ranked the 3rd as a main source for vitamin A and C for its high consumption in comparison with other vegetables. In the same study it ranked the 1st as a main source for vitamins and minerals collectively (Ahmed, 1998). Table 2.2 shows the approximate composition of dried tomato.

Table 2.2 Approximate composition of dried tomatoes flakes per 100 g

Ingredient	**Mass (g)**
Water	3.0
Protein	10.8
Carbohydrate	76.7
Fat	1.0
Ash	6.2
Others	2.3

Source: Norman and James (1977).

Recently epidemiological studies have shown that some pathologies are associated with low lycopene content in plasma due to low intake of tomato, which is the main source of lycopene (Franceschi *et al*. 1994).

Dried tomato products are used as a component for pizza and various vegetable and spicy dishes. Fresh tomato can be dried in different shapes such as halves, slices and quarters (Zanoni *et al*., 1999).

During the process of drying the M.C of tomato is reduced to ≤ 15%. Usual operating conditions are as follows: Drying times 2 to 10 hours; air temperature 60°C to 110°C; air flow rate 0.5 to 2.0 m/s through-flow or cross flow (Hawlader *et al*., 1991).

Charles *et al*. (2005) investigated the drying behavior of tomato slices. Kamil *et al*. (2005) in his study of drying tomato stated that, recently, there has been increasing demand for organic fruits and vegetables due to human health benefits. Organic and dehydrated agricultural products are of growing importance in the world. However, no published work seems to have been done in the solar drying behavior of organic tomato.

2.4 Drying methods

Chakraverty and De (1981) stated that, so far drying systems have not been classified systematically. However, drying methods can be broadly classified on the basis of either the mode of heat transfer to the wet solid or the handling characteristics and physical properties of the wet material. The first method of classifications reveals differences in dryer design and operation, while the second method is most useful in the selections of group of dryers for preliminary consideration in a given drying problem. According to the mode of heat transfer, drying methods can be divided into; (a) conduction drying, (b) convection drying, (c) radiation drying. There are other methods of drying, namely, dielectric drying, chemical or sorption drying, vacuum drying, freeze-drying …etc.

Earle (1983) divided the drying process into three categories:

1- Air and contact drying under atmospheric pressure.

2- Vacuum drying.

3- Freeze-drying.

Food stuffs may be dried in air, superheated steam, in vacuum, in inert gases and by direct application of heat. Air is generally used as a drying medium because it is plentiful convenient and overheating of food can be controlled (Norman and James, 1977).

According to Andales (1982), there are several ways of creating the vapor pressure differentials between the vapor in the grain (product) and the vapor in the air to affect drying. One can either increase the vapor pressure in the grain (product) or decrease the vapor pressure in the air or do both simultaneously. Techniques of increasing the vapor pressure are: sun drying, infrared drying and conduction drying. Technique of lowering the vapor pressure in the air, which is not fully saturated are: desiccated air-drying, refrigerated air-drying and heated air-drying.

In air-drying, which is the most popular method of drying, the air can be either unheated or heated by direct or indirect heat source (combustion of fuel, electrical heater or collected solar energy).

2.4.1 Unheated (natural) air drying

Andales (1982) concluded that, in locations where the ambient air condition is already suitable for drying, artificial means of creating vapor pressure differential between the grain (product) and air to effect drying might not be required (hence, the name natural air drying).

Brooker *et al*. (1992) stated that, low temperature dryers are those that use air, which is either unheated or heated to raise its temperature 6°C or less to dry grains in bins commonly used for grain storage.

Chakraverty and De (1981) reported that, unheated or natural air drying is usually performed in the grain storage bin, that is why unheated air drying is also known as in-bin or in-storage drying. The period of drying may be as long as several weeks depending on the weather. Natural air-drying cannot be used if the ambient relative humidity exceeds 70%, also if grain-containing moisture higher than 20% should not be dried with natural air.

2.4.2 Heated air drying

The drying air can be heated using different technologies.

2.4.2.1 Fossil dryer

An example of this type of dryers is Louisiana State University Dryer. Burning gaseous fuels such as natural gas, butane gas, etc, or liquid fuel such as kerosene furnace oil, fuel oil, …etc, or solid fuels like coal, husk, …etc heats the air. Heat can be supplied directly by the use of gas burner or oil burner or husk-fired furnace and indirectly by the use of heat exchangers. The disadvantages of this type of dryer are; high capital investment and cost of drying is very high if oil is used as fuel (Chakraverty and De, 1981).

2.4.2.2 Electrical drying

The dryers were equipped with an electrical heater (coils). The air was blown through these heaters.

2.4.3 Solar drying

Merkel (1983) stated that, the source of all energy in the universe is the sun. It radiates continuously and supports our daily life processes by providing energy for photosynthesis and hydrologic cycle. It’s also responsible for vast stores of fossil fuels buried beneath the earth’s surface.

N.S.F (1972) presented that, solar energy is an essentially inexhaustible source potentially capable of meeting a significant portion of the nation’s future energy needs with a minimum adverse environmental consequences. The indications are that solar energy is the most promising of the unconventional energy sources.

The solar radiation available at the earth’s surface consists primarily of wavelengths ranging from 0.3 to 2.4 μm. Most practical applications use solar radiation between 0.38 and 2.0 μm, which covers the visible range (0.38 – 0.78 μm) and the near infrared (0.78 – 2.0 μm), as stated by Bassey (1982).

Frank and Jan (1978) divided the radiation into:

- Beam radiation, which is the solar radiation intercepted by a surface with negligible direction change and scattering in the atmosphere. It’s also referred to as direct radiation.

- Diffuse radiation: it’s the solar radiation, which is scattered by aerosols, dust, and by the Raleigh mechanisms. It doesn’t have a unique direction.
- Total radiation: it’s the total of diffuse and beam radiation, it’s sometimes referred to as global radiation.

Fig 2.5 shows an overview of the principal methods currently under consideration for solar energy conversions.

2.4.3.1 Sun drying

It’s the most traditional method of drying. The grain or the product is spread over a floor area directly exposed to solar radiation.

Solar radiation heats the grain kernels and increases the vapor pressure of moisture in the grain. Ambient air (wind breeze) with low relative humidity picks up moisture from the grain, Fig 2.6.

2.4.3.2 Solar drying techniques

Thermal conversion is a technological scheme that utilizes a familiar phenomenon. When a dark surface is placed in sunshine, it absorbs solar energy and heats up. Solar energy collectors working on this principle consist of a surface facing the sun, which transfers part of the energy it absorbs to a working fluid in contact with it. To reduce heat losses to atmosphere, one or two sheets of glass usually placed over the absorber surface to improve its efficiency. These simple thermal conversion devices are called flat-plate collectors dryers (Frank and Jan, 1978).

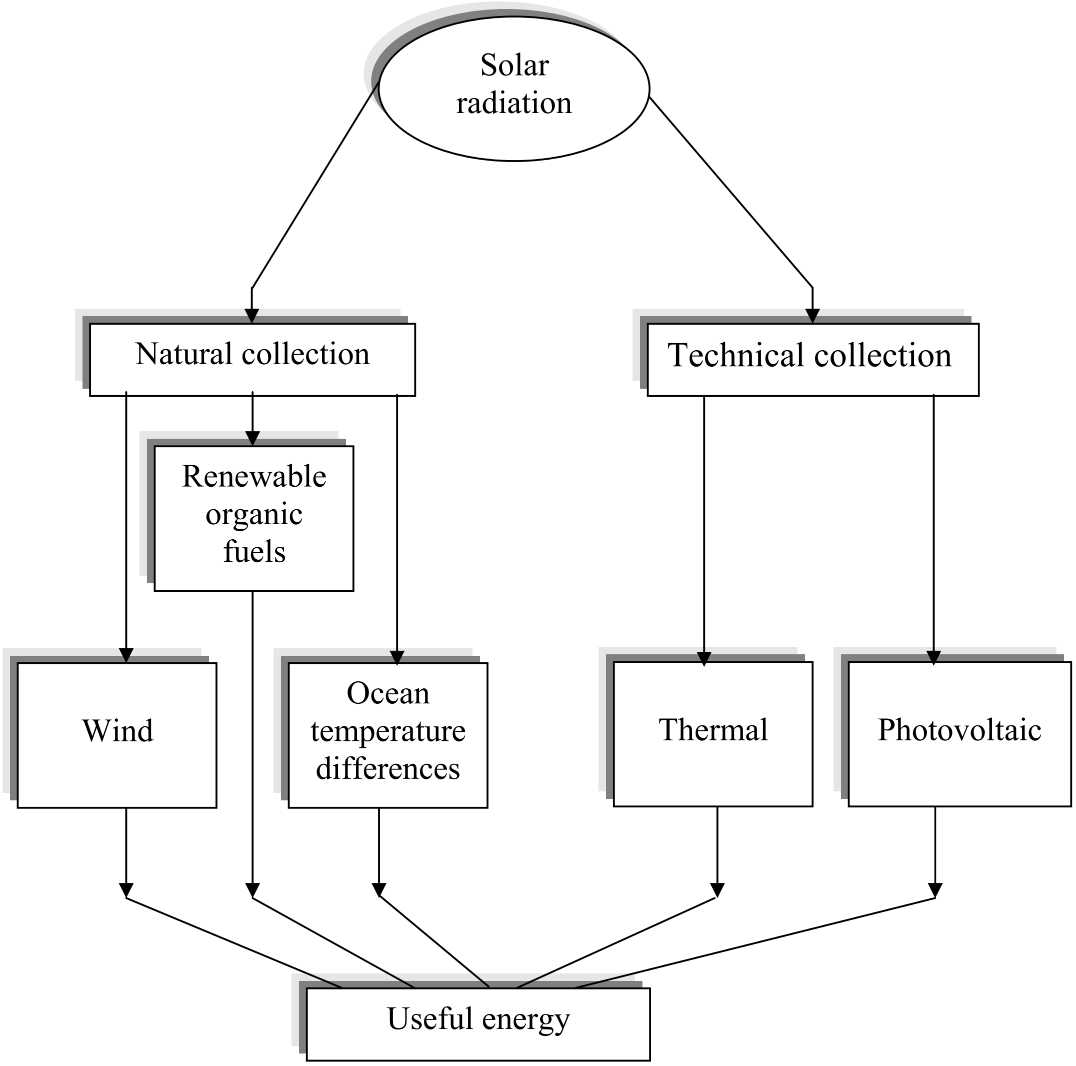

Fig 2.5 A summary of schemes for solar energy conversion

Source : NSF/ASA (1972).

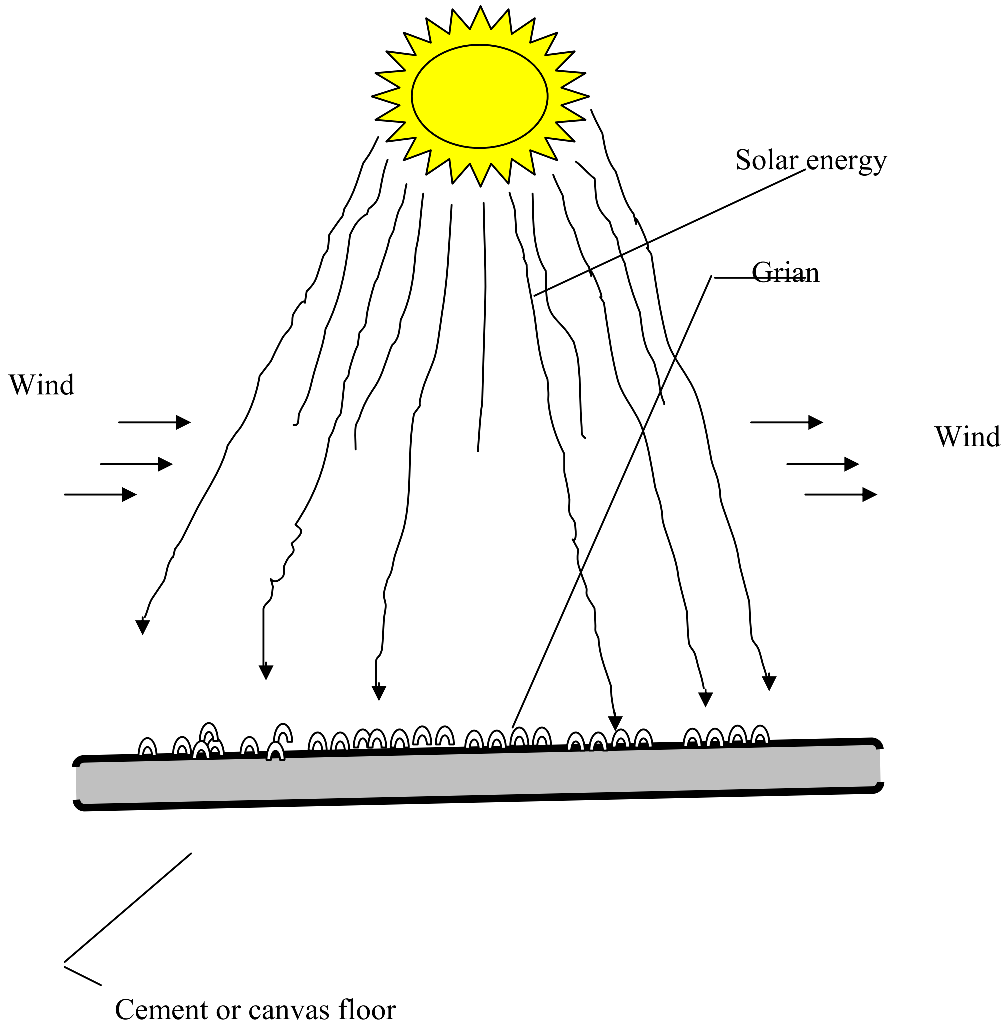

Fig 2.6 Increasing the vapor pressure in the grain

Source: Bassey (1982).

They reported that, flat-plate collectors are usually required for air-heating systems.

i- Types of solar dryers

Solar drying techniques can be divided according to the mechanism used to transfer heat energy of vaporization to the product into the following:

a) Direct or ambient dryers:

In this case, the product is placed in an enclosed cabinet that has a transparent cover besides protecting it from birds or insect attack, it also acts as a protection against the weather. Small apertures in the bottom and sides of the cabinet improve the removal of moist drying air.

b) Indirect solar dryers:

The product is placed in a package-drying chamber to which solar heated air is conveyed by natural or forced convection. This type of dryers has been studied and reported in the literature (Akyurt and Selçuk, 1973; Headly and Springer, 1973; Satcunanathan, 1973; Selçuk *et al.*, 1974; BRI, 1979 and Bassey, 1980a).

Bassey (1982) stated that, the solar energy as collected in the air heaters by means of greenhouse effect using transparent cover and absorber. Because of the buoyancy effects the warm air rises through the sloped collector and into the drying chamber where the crops are placed. Many designs are possible depending on the mode of circulating the air. The agent for moving the air in most available designs is mechanical such as the fan (forced indirect dryers). The effect of buoyancy can be enhanced by using a chimney, which creates a draft that can cause an adequate mass flow of air to pass through the collector and then through the crops. There is not a great deal of interest in this method.

c) Mixed type solar dryers:

This type usually has a solar air pre-heater and a closed drying chamber with transparent cover. Air circulation can be natural or forced.

d) Hybrid drying system:

In this type of dryers, another form of energy such as fuel or electricity is used to supplement solar energy for heating.

There are also other solar drying systems based on freeze-drying and dehydration.

Bassey (1982) also classified solar dryers into two main types, active dryers and passive dryers. Active dryers use an external device (fan) to circulate the air, while passive dryers do not.

ii- Importance of solar drying

Sun drying is the most common method used to preserve agricultural products in most tropical countries. However, this technique is weather dependent, and has the problems of contamination with dust, soil, sand particles and insects. Also, the required drying time can be quite long, therefore, using solar and hot – air dryer, which are far more rapid, providing uniformity and hygiene are inevitable for industrial food drying processes (Diamante and Munro, 1993; Ratti and Mujumdar, 1997).

The drying processing should be undertaken in closed equipment to improve the quality of the final product (Ertekin and Yaldiz, 2004).

Munir and Abdul Shakoor (1997) stated that, drying with direct sun light affects the germination ability of the seeds. They stated also, poor quality due to contamination with partly pathogenic microorganisms and high losses caused by uneven or incomplete drying are the characteristic of natural sun drying. To overcome these problems a solar drying system was designed and developed.

Morey and Cloud (1977) found that, energy requirements were reduced appropriately 25% by using supplemental solar heat in low-temperature phase of combination drying compared to ambient air in the low-temperature phase.

In developing countries, the uses of solar energy technologies in agriculture are most economically vital compared to industrialized countries. The introduction of solar drying systems seems to be the most promising alternative in reducing post harvest losses and could have significant contribution to warrant continuous food supply (Muhlbauer *et al*., 1993).

Morey *et al*. (1979) reported that, considerable research is currently underway to investigate the use of solar energy as a replacement for fossil fuel in grain drying. Solar energy is then one potential source of supplemental heat for low-temperature-drying systems.

Abdel Aziz (1989) stated that, solar drying might effectively be used particularly where the cost of fuel for conventional drying methods is high. Compared with sun drying solar drying limits the risk of spoilage during the drying process and subsequent storage.

2.5 Mathematical modeling of thin-layer drying

Clearly suitable constructed models can be used to help with the design of new dryers and to promote the more efficient use of existing dryers. Models are tools to assist in learning solving problems and communicating. In the seventeenth century, coordinate in turn led to mathematical functions, which are the basic for modern science and technology. Mathematical modeling is a calculation approach, by which mathematical representation of individual component are integrated into a dynamic numerical system. Thus, systems of algebraic, differential and integral equation can be used to calculate the response of physical systems to arbitrary forcing function (Frank and Jan, 1978).

Henderson and Perry (1976) stated that, practically all agricultural drying takes place in the falling-rate period. Products that are moved into a dryer from a washer may experience a short initial constant drying rate period. This period is usually minor when compared to the complete drying process and can be neglected in the calculations.

Thin-layer drying models are used in bulk drying model to characterize the changes of moisture content and temperature of an individual kernel under constant drying air conditions (Parti, 1993). It has been accepted that the drying phenomenon of biological products during the falling rate period is controlled by the mechanism of liquid and/or vapor diffusion.

The thin-layer drying models can be divided with some overlapping, namely, distributed parameter models, lumped parameter models, and thin-layer drying equations. The distributed and the lumped parameters models take into account the simultaneous heat and mass transfer during the drying process. Lumped parameters models ignore the internal heat and mass transfer resistance but distributed parameter models take into account both the internal and the external resistance. Most lumped models are derived by simplifying the distributed models. Frequently temperature equilibrium is assumed between the kernel and its surroundings when only one equation is required to describe the moisture loss of a kernel fully exposed to given drying conditions and this is called the thin-layer drying equation. It follows that thin-layer drying equations neglect the effect of temperature change on the drying process since they assume that the kernel temperature reaches the bulk air temperature immediately at the beginning of the process.

Thin-layer drying models mainly fall into three categories namely; theoretical, semi-theoretical and empirical. The first takes into account only internal resistance to moisture transfer, while the other two consider only external resistance to moisture transfer between the product and the air (Fortes and Okos, 1981; Henderson, 1974; Whitakers *et al.*, 1969).

The drying process of agricultural products may be predicted by empirical, theoretical or semi-theoretical equations (Claser, 1995; Correa *et al.*, 1992 and Misra and Brooker, 1980). The empirical method is based on experimental data and dimensional analysis. This method does not lead to a general systematic approach for drying studies, although designers prefer it because it furnishes practical information for project elaboration (Luiz, 1982). The theoretical method takes into account not only the internal conditions, but also the mechanism of internal movement of moisture and their consequent effects.

Afzal and Abe (2000) furthermore differentiate among the above three categories; the theoretical approach concerns with either the diffusion equation or simulation heat and mass transfer equations. The semi-theoretical approach concerns with approximated theoretical equations. The use of empirical equations to the drying simulation is easy to apply and has been widely used. The main justification of the empirical approach is the satisfactory fit to the experimental data.

The theoratical model is the analytical solution of the diffusion equation:

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-n^2\pi^2 Dt}{a^2}\right)$$

Where:

MR = moisture ratio, dimentionless.

D = effective diffusivity, m^2/sec.

t = time.

a = half slab thickness, m.

Sharp (1982) concluded that, introducing a diffusion equation to represent the drying rate rather than using emperical equations from thin-layer experiments, increases the complexity of solving the equations.

The thin-layer drying equation has been used for estimation and prediction of drying time for several products and for generalization of the drying curves. The drying constant is a suitable quantity for the purposes of process design, optimization and in cases where a large number of iterative model calculations are needed. This is due to the fact that the drying constant embodies all the transport properties into a simple exponential function. There are four prevailing transport phenomena during drying (internal heat transfer, internal mass transfer, external heat transfer, external mass transfer), which may describe the drying process analytically (Jayas *et al.*, 1991). These four classical partial differential equations demand considerable computing time for their numerical solution so that they are less attractive for iterative calculations (Marinos and Maroulis, 1995).

Several thin-layer equations, which describe the drying in the falling rate period are available in the literature. The drying curves were processed to find the most convenient one among different expressions defying drying rates given in Table 2.3. These equation vary widely in nature. Azal and Abe (2000) stated that, thin-layer drying equations contribute to understanding of drying characteristics agricultural materials. Many investigations have successfully used thin- layer equations to explain drying of several agricultural products, for example, apricot (Toğrul and Pehlivan, 2002, 2003), grape (Doymaz and Pala, 2002; Pangavhance *et al.*, 2002), potato (Kavak Akpinar *et al.*, 2003), eggplant (Ertekin and Yaldiz, 2004) and carrot (Doymaz, 2004).

Table 2.3 Mathematical models applied to drying curves

Model name	**Model**	**Reference**
Newton	$MR = \exp(-kt)$	Ayensu (1997); Hummedia and Sheikh (1989); Kassem (1998); Liu and Bakker Arkema (1997); Nellist (1987); O'Callaghan, Menzies and Bailey (1971); Sarsavdia, Sawhney, Pangavhane and Singh (1999); Tiris, Ozbalta, Tiris and Dincer (1994); Westerman, White and Ross (1973).
Page	$MR = \exp(-kt^n)$	Agrawal and Singh (1977); Bruce (1985); Chhinnan (1984); Diamente and Munro (1993); Guarte (1996); Hutchinson and Otten (1982); Pathak, Agrawal and Singh (1991); Sun and Woods (1994); Zhang and Litchfield (1991).
Modified page	$MR = \exp[-(kt)^n]$	Overthults, White, Hamilton and Ross (1973); White, Bridges, Loewer and Ross (1978); White, Ross and Ponelert (1981); Yaldiz *et al*. (2001).
Modified page	$MR = \exp[(-kt)^n]$	Overthults *et al.* (1973); Ozdemir and Devies (1999); Yaldiz and Ertekin (2001).
Henderson and Pabis	$MR = a \exp(-kt)$	Bengtsson, Rahman, Stanley and Perera (1998); Bhuyan and Prasad (1990); Chhinnan (1984); Guarte (1996); Pal and Chakrverty (1997); Rahman and Perera (1996); Rahman, Perera and Thebaud (1998); Westerman *et al*. (1973); Yagcioglu *et al*. (1999).
Logarithmic	$MR = a \exp(-kt) + c$	Yagcioglu *et al*. (1999); Yaldiz and Ertekin (2001).
Two term	$MR = a \exp(-k_o t) + b \exp(-k_1 t)$	Henderson (1974); Madamba, Driscoll and Buckle (1996); Rahman and Perera (1996); Rahman *et al*. (1998); Verma, Bucklin, Endan and Wratten (1985).
Two term exponential	$MR = a \exp(-kt) + (1-a)\exp(-k_a t)$	Sharaf Eldeen, Blaisdell and Spagna (1980); Yaldiz *et al*. (2001); Yaldiz and Ertekin (2001).
Wang and Singh	$MR = 1 + at + bt^2$	Ozdemir and Devres (1999); Wang and Singh (1978)
Thompson	$t = a \ln(MR) + b [\ln(MR)]^2$	Paulsen and Thompson (1973); Thompson, Peart and Foster (1968); Yaldiz and Ertekin (2001)
Diffusion approximation	$MR = a \exp(-kt) + (1-a)\exp(-kbt)$	Kassem (1998); Yaldiz and Ertekin (2001).
Verma *et al*.	$MR = a \exp(-kt) + (1-a)\exp(-gt)$	Verma *et al*. (1985); Yaldiz and Ertekin (2001)
Modified Henderson and Pabis	$MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$	Karathanos (1999).
Midilli *et al.*	$MR = a \exp(-kt^n) + bt$	Midilli, Kucuk and Yapar (2002).

Source: Ertekin and Yaldiz (2004).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Mathematical model development

It’s exceedingly difficult to obtain an exact mathematical solution, but approximate solutions can be reached by making suitable assumptions. The following assumptions were made so as to develop a suitable mathematical model for thin-layer drying of tomato slices:

3.1.1 Assumptions

1- The drying process takes place under constant air conditions.
2- Heat and mass transfer occur in one direction (vertically) and tomato slices are homogenous.
3- The drying process is solely a convection heat transfer.
4- There is no temperature gradient within the tomato slices, i.e. all slices dried uniformly and thermal diffusion is assumed negligible.
5- The whole drying process takes place in the falling-rate period.
6- The tomato slices thermo-physical properties are constant during the drying process.
7- All evaporation takes place at the surface of the slices.
8- There is a thermal equilibrium between the tomato slices and the drying air.

3.1.2 Thin-layer drying models

In the following sections, the models concerning thin-layer drying will be described.

3.1.2.1 Introduction

Toğrul and Pehlivan (2004) stated that, the materials drying kinetics might be described completely using their transport properties (thermal conductivity, thermal diffusivity, and interface heat and mass transfer coefficients) together with those of the drying medium (Sokhansanj, 1984 and Vagenas and Karathanos, 1993). In the case of food drying, the drying constant (k) is used instead of transport properties. The drying constant combines all the transport properties and may be defined by the thin-layer equations.

Thin-layer equations describe the drying phenomena in a unified way, regardless of the controlling mechanisms. They have been used to estimate drying times of several products and to generalize drying curves, Table 2.3. In the development of thin-layer drying models for agricultural products generally the moisture content of the material at any time after it has been subjected to a constant relative humidity and temperature conditions is measured and correlated to the drying parameters (Midilli *et al.*, 2002).

Thin-layer drying equations can be divided broadly into three groups, namely: empirical equations, semi-empirical equations and theoretical equation.

Emphasis has been given on the development of semi-theoretical models, which permit harmony between the theory and ease of use. Semi-empirical models were generally derived by simplification of the general series of Fick second law of diffusion. These models were valid only within the temperature, relative humidity, air velocity and moisture content range for which they were developed (Fortes and Okos, 1981). These models are based, in general, on the Newton's law for cooling or heating of bodies, which applied to mass transfer. Among these equations two mathematical models, the Lewis and the Page model were used in this study to describe the drying curves of tomato slices in thin-layer.

3.1.2.2 Lewis model

Lewis model represents the movement of moisture during the falling rate period of drying. It is based on Newton's law of cooling or heating of solids, so sometimes referred to as Newton model. This law states that "the rate of change in temperature of a body surrounded by a medium at constant temperature is proportional to the difference in temperature between the body and the surrounding medium when the temperature difference is small". The law can be expressed by the following equation:

$$\frac{dT}{dt} = -k(T - T_e) \qquad \text{…… (3.1)}$$

Where:

$\frac{dT}{dt}$ = Rate of change in temperature, ^{o}C/s.

k = Cooling or heating constant, ^{1}/s.

T = Body temperature at any time, ^{o}C.

T_e = Surrounding medium temperature, ^{o}C.

Equation 3.1 is a differential one because it expressed a relation between a function and its derivative. This law applied to the drying process at constant temperature by assuming that the resistance to the moisture movement is restricted to the product surface (Brooker *et al.*, 1992). By substituting moisture content instead of the temperature in equation 3.1 this will give the following equation:

$$\frac{dM}{dt} = -k(M - M_e) \qquad \text{….. (3.2)}$$

Where:

$\frac{dM}{dt}$ = drying rate.

k = drying constant.

M = moisture content, dry basis

M_e = equilibrium moisture content, dry basis

To solve equation 3.2, the separation of variable method of integration will be employed. First put those containing moisture on the left hand side and those containing time on the right hand side of the equation. This will give the following equation:

$$\frac{dM}{M - M_e} = -kdt \qquad \text{…… (3.3)}$$

The next step is to find the integral of each side of equation 3.3.

$$\int_{M_o}^{M} \frac{dM}{M - Me} = \int_{M_o}^{M} \frac{1}{M - M_e} dM = \ln\left[M - M_e\right]_{M_o}^{M}$$

Left hand side integral:

$$= \ln[M - M_e] - \ln[M_o - M_e] = \ln\frac{M - M_e}{M_o - M_e}$$

Right hand side integral:

$$\int_{t_o}^{t} -kdt = -k\int_{t_o}^{t} dt = -k\left[t\right]_{t_o}^{t}$$

$= -k\,(t - t_o)$ (but t_o = zero) $= -kt$

Equate the two sides of the integrated equations to have the following equation:

$$\ln\frac{M - M_e}{M_o - M_e} = -kt \qquad \text{..... (3.4)}$$

To get rid of the logarithmic form of equation 3.4 the antilog of both sides will be obtained and this will give:

$$MR = \frac{M - M_e}{M_o - M_e} = e^{-kt} \qquad \text{....... (3.5)}$$

Where:

M = Moisture content at any time, d.b percent.

M_e = Equilibrium moisture content (EMC), d.b percent.

M_o = Initial moisture content, d.b percent.

k = Drying constant, $^1/s$ or $^1/hr$.

t = Drying time, s or hr.

MR $= \frac{M - M_e}{M_o - M_e}$ = Moisture ratio, dimensionless.

Bruce (1985) used this model to study the drying behavior of barely. Doymaz (2004) stated that, the values of the equilibrium moisture content, M_e, are relatively small compared to M and M_o, then the moisture ratio is calculated as follows:

$$MR = {}^{M}/_{M_o} \qquad \text{....... (3.6)}$$

3.1.2.3 Page model

The limitation of Lewis model in the prediction of the drying curve has necessitated the introduced of a second drying parameter, the product constant n, (Morey and Li, 1984).

Page (1949) modified equation 3.5 by introducing an empirical parameter n (Brooker *et al.*, 1992). The resulting equation is known as the Page equation.

$$MR = e^{-kt^{n}} \qquad \ldots. (3.7)$$

The parameters k and n depend on the product type, temperature and drying conditions (Martins, 1988; Shatadal *et al.*, 1990 and Sokhansanj *et al.*, 1986). Page model has been widely advocated for thin-layer drying of solids under constant drying conditions. This model has produced good fits in predicting drying of sweet potato (Diamante and Munro, 1993), garlic (Madamba *et al.*, 1996), apricot (Pala *et al.*, 1996), seedless grapes (Doymaz and Pala, 2002), and mint leaves (Park *et al.*, 2002).

Panchariy *et al.* (2002) stated that, the Page model is a modification of the Lewis model to overcome its shortcoming.

Brooker *et al.* (1992) concluded that, theoretical model and Lewis model often predict the shape of the drying curves of grains poorly, the initial drying rates are too low, and approach to the equilibrium moisture content is too rapid. He also added that, Page model usually predicts the drying of grain more closely than the theoretical and Lewis model, the drying rate is, however, too high initially.

The modified exponential model (Page model) has been extensively used to describe thin-layer drying of cereals and other products (Wang and Singh, 1978; Chhinnan, 1984; Bruce, 1985; Pathak *et al.*, 1991).

3.1.3 Moisture contents determination

Sharp (1982) concluded that, the criteria for validation of the model depend on the intended application of the model and predictions of exhaust air conditions or simply the average grain moisture content may be attained.

Initial moisture content of tomato slices was determined as described in the next sections. The moisture contents of the tomatoes slices during the drying process was calculated by knowing the dry matter from the initial moisture content, and the weight losses, which were measured periodically as a function of drying time through out the experiment. Then moisture content at each time interval was calculated as follows:

$$M.C(t) = \frac{W(t) - d.m}{d.m} \qquad \text{..... (3.8)}$$

Where:

M.C(t) = Moisture content of the sample (d.b, decimal) at time t.

W(t) = Weight of the sample at time t, g.

d.m = Dry matter of the sample, g.

Then the moisture contents values were converted into (MR), which was simplified to $^{\mathbf{M}}/_{\mathbf{Mo}}$ (Doymaz, 2004; Diamante and Munro, 1993; Yaldiz and Ertekin, 2001; Yaldiz *et al.*, 2001 and Ertekin and Yaldiz, 2004).

3.1.4 Drying curves

The drying curves were determined by converting the moisture contents to the most useful expression moisture ratios (which was mentioned earlier). These moisture ratios were then plotted versus the drying time.

3.1.5 Drying constant determination

The following sections describe the procedure adopted for this determination.

3.1.5.1 Lewis model

Nellist (1969) examined methods of evaluating “k” by using Lewis model or its differential form to experimental data. It was concluded that the equation was best fitted in the un-differential form either by logarithmic, or direct least squares.

A linear relation is obtained by logarithmic transformation of the Lewis model as follows:

$$MR = e^{-kt}$$

A linear relation can be expressed as:

$$y = -ax$$

assuming that the intercept is zero.

Where:

y = ln MR
a = k
x = t

3.1.5.2 Page model

The Page model can be presented in a linearized form (Pathak *et al*., 1991; Byler *et al*., 1987) as follows:

$$ln(- ln MR) = ln k + nln t \qquad \text{…… (3.9)}$$

Where:

MR = Moisture ratio (dimensionless).

k = Drying constant, h^{-1}.

n = Page parameter (dimensionless).

t = Time, h

This equation has been applied to drying data of tomato slices dried in a thin-layer .The drying data were plotted in a ln(– ln MR) versus ln t diagram, the trend should be a straight line. The slope of the curve, as found by application of linear regression, resulted in the Page parameter n, while the intercept was equal to ln k (Vaios and Vasilios, 1999).

3.2 Experiments

The indirect forced convective solar dryer was used to dry tomato slices. The experiments were carried out during the period of May – June 2004. Each run was started at 7:30 and continued till 18:00 at the workshop of the Department of Agricultural Engineering, Faculty of Agriculture, University of Khartoum, Shambat. The area lies at latitude of $15^{o}40'$ N, longitude of $32^{o}32'$ E and altitude 381 m above mean sea level, with solar intensity of about 22.42 $MJ/m^2/day$ and sunshine hours of about 9.8 (Akoy, 2000).

3.2.1 Construction of the solar dryer

Materials

i- Metal sheets
ii- Timber
iii- Masonite
iv- Transparent glass
v- Fiber glass
vi- Angle irons, silicon rubber, bolts and nuts.

Plate 3.1 shows the front view of the solar dryer, which was used in this study. Fig 3.1 shows a schematic diagram of this solar dryer. It consists of the solar collector (absorber), drying chamber and fan.

3.2.1.1 Solar collector (the absorber)

It acts as a heat source for the solar dryer that absorbs the solar energy and converts it to heat energy. It consists of a metal plate (100 cm × 100 cm) painted in non-shine black paint so as to prevent the reflection of solar radiation. This plate was a base of a wooden side box (100 cm × 100 cm × 20 cm). All insides of the box were painted in non-shine black paint.

The solar collector or the absorber box was covered with a glass sheet (100 cm × 100 cm) with thickness of 0.3 cm, so as to minimize the loss of heat energy collected and to improve the solar dryer efficiency. This glass sheet was fixed tightly by a silicon rubber to the top of absorber box, which allows the glass sheet to expand and contract due to the temperature fluctuations.

In order to minimize the heat losses to the surroundings, another box was made of a masonite with the same shape of the absorber box but larger in dimensions (114 cm × 114 cm × 25 cm) and was used as a case of the absorber box and the gab between the two boxes was filled with fiber glass as insulating layer.

At the lowest side of the two boxes an opening was made to represent the inlet of the solar collector. A tube of 15 cm in diameter and 10 cm in length was fitted in this opening. A suction fan was then fixed inside another tube of 17 cm in diameter and the latter was welded to the inlet tube of the solar collector.

Plate 3.1. Forced convective solar dryer

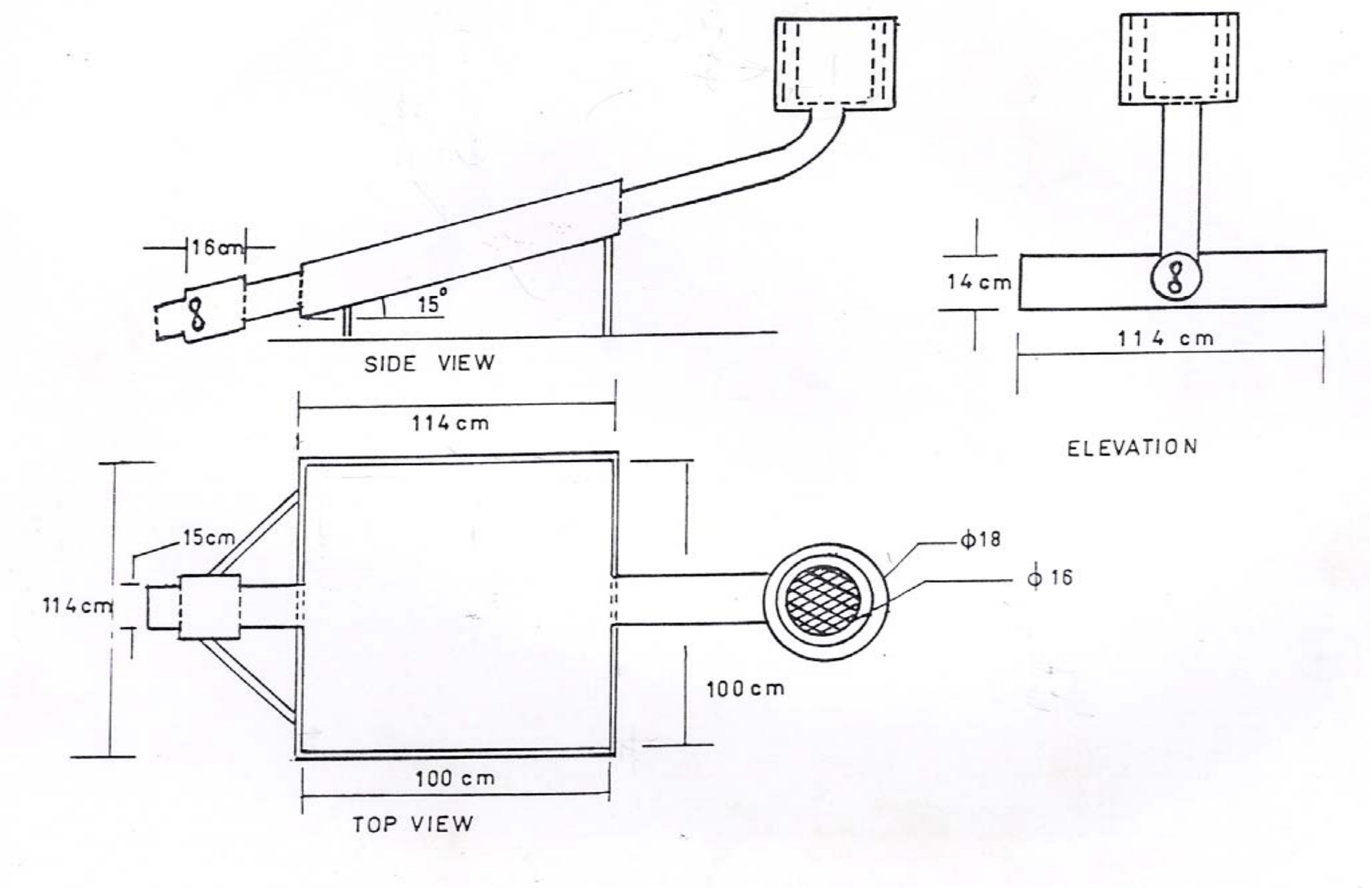

Fig 3.1 A schematic diagram of the solar dryer (Not to scale)

At the upper side of the two boxes another opening was made to represent the solar collector outlet. A detachable tube of 15 cm in diameter and about 56 cm in length was connected to this hole to convey the heated air to the drying chamber.

The solar collector was directed due to the south with 15^o tilt angle.

3.2.1.2 Drying chamber

It was used to dry the tomato slices. It was made of two coaxial cylinders made of a metal sheet. The outer cylinder (22 cm in diameter and 35 cm in height) was welded at the bottom to the tube of the absorber outlet.

The inner cylinder (15 cm in diameter and 25 cm in height) was the moveable one and it had a detachable perforated base for the ease of taking the measurements. The design of the two – coaxial cylinders allows a gap between the two bases of the cylinders so as to guarantee a uniform distribution of the hot air through the tomato slices.

Aluminum foil was used as a cover for the drying chamber with a small hole to act as a vent to allow the exhaust air to pass through to the surroundings. Also, this cover prevents the direct solar radiation to interfere in the drying process and also prevents rains from falling inside.

3.2.2 Equipment and instruments

i- Solar dryer

The indirect forced convective solar dryer was used for the drying of the tomato slices in a thin-layer.

ii- Suction fan

An electrical suction fan (15 cm in diameter), of sinar make made in Japan, was fixed in the solar collector inlet.

iii- Sensitive balance

Model Yss – 620 with 620 g capacity and 0.01 g accuracy. Yamato scale LTD, AKA Shi, Japan, was used for periodic weighing of tomato slices during the drying process and recording the weight loss, Plate 3.2.

iv- Delta T-logger

Delta T-logger DL 2e type and copper-constantan thermocouples, commercially marked by Delta-T Device Limited England, was used to record the temperatures change at different selected locations in the solar dryer during the trial, Plate 3.3.

v- Digital hygrometer

Testo GMbH type 6350, made in Germany, was used for relative humidity measurement, Plate 3.4.

vi- Anemometer

UNITEST-BEHA, CAT. No. 93515 digital anemometer with USB connector so as to be connected to a computer, was used for measuring air velocity during the trial, Plate 3.5.

Plate 3.2. Sensitive balance

Plate 3.3 Delta T-logger sensors located at different places in solar dryer

Plate 3.4. Digital hygrometer

Plate 3.5. Anemometer

vii- Vacuum oven

Elektroheilios KAT, oven type with a thermometer on the door to indicate the oven temperature, was used for the determination of the tomato slices initial moisture content.

viii- A personal computer

A personal computer (PC), PIII was used for running of the computer program, which simulate the thin-layer drying of the tomato slices.

3.2.3 Procedure of the experiment

Newly harvested tomato fruits of a variety locally known as “Siko”, were brought from the Central Market, Khartoum North. They were sorted out to separate the perishable ones and then washed and wiped out from excess water, Plate 3.6. Then fruits samples were selected randomly and further sliced with a sharp knife. The slices were cut to a thickness of approximately 0.01 m by using a vernier. From these sliced tomatoes a random sample was selected, and placed gently onto the movable perforated base of the drying chamber in one-slice depth as shown in Plate 3.7, in order to represent the thin-layer drying process. Then this perforated base was placed inside the drying chamber.

Before connecting the solar collector box to the detachable tube of drying chamber, thermocouples were placed at three different locations:

Fig 3.6 Tomato fruit

Plate 3.7 Tomato slices in a thin layer

At the base of the solar collector plate,

- i- At the middle position by suspending the thermocouple to measure the temperature of the working fluid (heated air),
- ii- Beneath the glass cover, Plate 3.3

Then the detachable tube was connected firmly to the absorber or solar collector box. A small hole covered with aluminum foil was left to insert the hygrometer probe periodically during the experiment so as to record the working fluid (heated air) relative humidity change.

The remaining thermocouples of the data logger were located to measure the temperature periodically at:

- i- The drying chamber plenum.
- ii- The lower surface of the tomato slices (at the centers and the peripheries of different slices).
- iii- The upper surface of the tomato slices.
- iv- The outlet of the drying chamber in order to measure the temperature of the exhaust air.
- v- The surrounding to measure the ambient temperature.

The relative humidity was recorded at the following locations:

- a) The surrounding to measure the ambient relative humidity.
- b) Drying chamber outlet (exhaust air).
- c) Solar collector (inlet).

The data logger was configured to record the temperatures at the desired locations at an interval of half an hour before commencing the experiment.

The digital anemometer measured air velocity of the ambient and the drying air in the drying chamber.

The measurements were taken periodically at the same interval. The starting time of the experiment was at 7:30 and continued till near sunset i.e. 18:00.

Before the experiment began a sample of the tomato slices were taken so as to measure its initial moisture content. A scoop with a long handle of one tomato slice capacity was placed in the removable base in the drying chamber to facilitate the measuring of the weight loss periodically.

The mean sunshine hours and the solar intensity (radiation) data were obtained from the Shambat Meteorological Station for the period 1990-1999, Appendix A Tables 1, 2 and 3. The reason for this was due to the malfunction of the instruments, which measure these data or parameters at the station.

3.2.4 Initial moisture content determination

It was determined according to the method approved by the AOAC (1980).

A representative sample of the sliced fresh tomato was chosen. Three different aluminum dishes were cleaned and placed into the oven to dry up, and then transferred into a desiccator to cool down without gaining any moisture from the atmosphere. These dishes were weighed using a sensitive balance, and then the samples of tomato slices were put into these dishes and weighed again. Immediately they were placed into the oven at 70^{o}C and left 24 hours. After this period the samples were taken and placed into the desiccator to avoid gaining moisture from the atmosphere, and left after cooling down, they were weighed again. The moisture contents of the samples were then calculated using the following equations:

1- Moisture content (wet basis):

$$m = \frac{W_1 - W_2}{W_1} \times 100 \qquad \text{….. (3.10)}$$

2- Moisture content (dry basis):

$$M = \frac{W_1 - W_2}{W_2} \times 100 \qquad \text{….. (3.11)}$$

Where:

m = Moisture content, wet basis (percentage).

M = Moisture content, dry basis, (percentage).

W_1 = Weight of fresh sample, g.

W_2 = Weight of dried sample, g.

The average of the 3 samples represents the initial moisture content of the tomato slices.

3.2.5 Drying rate calculation

The drying rate was calculated by using the following equation (Kavak Akpinar, 2002):

$$\text{DR} = \frac{M_{t+dt} - M_t}{dt} \qquad \text{……. (3.12)}$$

Where:

M_t = Moisture content at the time t, dry basis, (percentage).

M_{t+dt} = Moisture content at the time t+dt, dry basis, (percentage).

dt = the time interval, hr.

3.3 Model validation

The tomato slices drying curves obtained were processed to find the most convenient model between the two different pre-selected expressions of moisture ratio.

Regression analysis was done using Microsoft Excel program. The best-fitted model was selected by comparing the coefficient of correlation (R^2), the root mean square error (RMSE), the reduced chi-square (χ^2) and the model efficiency (EF), (Ertekin and Yaldiz, 2004; Kavak Akpinar *et al.*, 2003, Midilli and Kucuk, 2003; Loague and Green, 1991).

The expressions for each of these statistical parameters are as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp.,mean} - MR_{pre.,i}\right)^2}{N-n} \qquad \text{........ (3.13)}$$

$$RMSE = \frac{\sum_{i=1}^{N}\left(MR_{i,pre} - MR_{i,\exp}\right)^2}{N} \qquad \text{........ (3.14)}$$

$$EF = \frac{\sum_{i=1}^{N}\left(MR_{i,\exp} - MR_{i,\exp_{mean}}\right)^2 - \sum_{i=1}^{N}\left(MR_{i,pre} - MR_{i,\exp}\right)^2}{\sum_{i=1}^{N}\left(MR_{i,\exp} - MR_{i,\exp_{mean}}\right)^2} \qquad \text{........ (3.15)}$$

Where:

$MR_{exp.,i}$ = the i^{th} experimental moisture ratio.
$MR_{exp., mean}$ = the mean experimental moisture ratio
$MR_{pred.i}$ = the i^{th} predicted moisture ratio.
N = number of observation
n = number of constants in the drying model.

Another procedure adopted for the validation of the established model was made by comparing the computed moisture contents with the measured moisture contents graphically. When the straight line is obtained this indicates the suitability of the model to describe drying behavior of the tomato slices.

3.4 Simulation of thin-layer drying of tomato slices

The developed mathematical model was written in Turbo Pascal for Windows, Version 1.5 Copyright 1991-1992 Borland International, Inc. and run using a P.C, the flowchart, of the computer program is presented in Fig 3.2.

The main program has three choices to opt for a subroutine. The first subroutine calculates the measured moisture contents in dry basis (CMMC) of the tomato slices at each time interval of 30 min. during the drying process. This calculation is done by entering data concerning weight loss (g) at each time interval (WTi) and the dry matter (g). Consequently, this subroutine calculates the measured moisture ratio (CMMR), which has a formula as follows:

$$MR = \frac{M}{M_o}$$

The second subroutine calculates the predicted moisture contents (CPMC) at different time intervals after calculation the predicted moisture ratio (CPMR) using the most appropriate thin-layer drying model, (which is to be selected from the above mentioned two models).

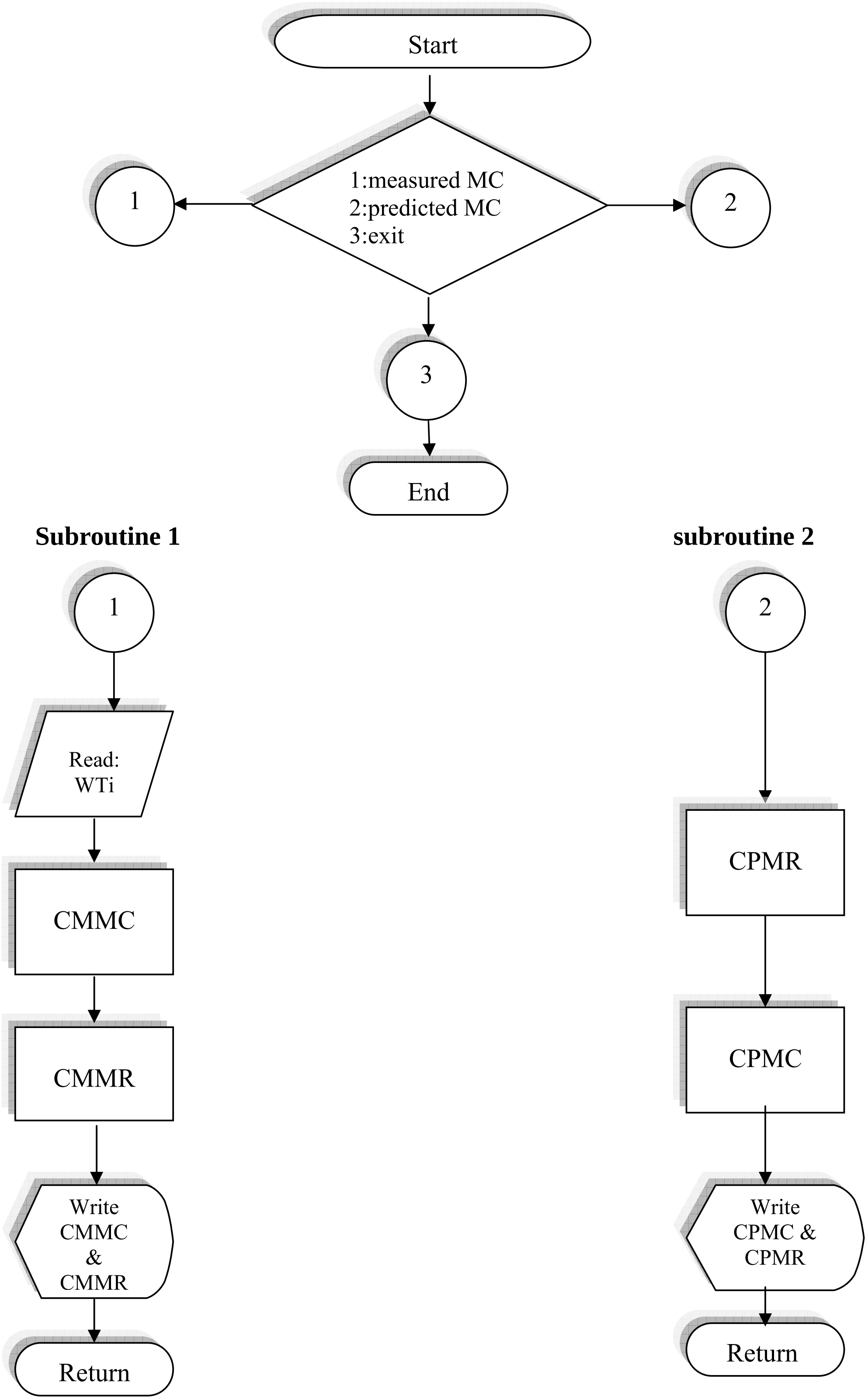

Fig 3.2 The program main flow chart

The selected model was Page model, which can be expressed as follows:

$$MR = e^{-kt^{n}}$$

Where:

MR = calculated moisture ratio (dimensionless) = $^{M(t)}/_{Mo}$

M(t) = moisture content, d.b, decimal, at different time.

M_o = initial moisture content, d.b, decimal.

k = drying rate constant, h^{-1}.

n = coefficient.

t = time, hr.

Then this subroutine calculates the predicted moisture contents of tomato slices at different time intervals using the following expression:

$$M(t) = MR_{cal} \times M_o$$

The third subroutine exits the user from the whole program.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Solar collector temperature and R.H

The climatic conditions during the experimental days were presented in Appendix A Tables 1-3. The drying conditions within the experimental days were presented in Appendix B Tables 1 and 2.

Figures 4.1 and 4.2 show the ambient and the solar collector air temperature for the two days of the experiment (24/5/2004 and 9/6/2004). The heated air temperature increased as the time proceed till noon then decreased towards evening. This is in conformity with the findings of Duffie and Beckman (1980) and Akoy (2000). The temperatures obtained by the solar collector air are higher than the ambient temperature by approximately 20^oC. This indicates the effectiveness of using the solar collector as a heat source for drying purposes.

Figures 4.3 and 4.4 show the ambient and the solar collector air relative humidity for the two days of the experiment (24/5/2004 and 9/6/2004). The figures clearly indicate that the solar collector air relative humidity values were lower than those for the ambient air relative humidity; they both decreased specially at noon. The solar heated air becomes efficient for drying technique. It is well known that air at a given temperature and R.H when heated experiences a decrease in R.H. Thus, heated air takes away more moisture from the product than unheated air. This fact has been used in various solar crops dryers that use direct and indirect methods of heating the

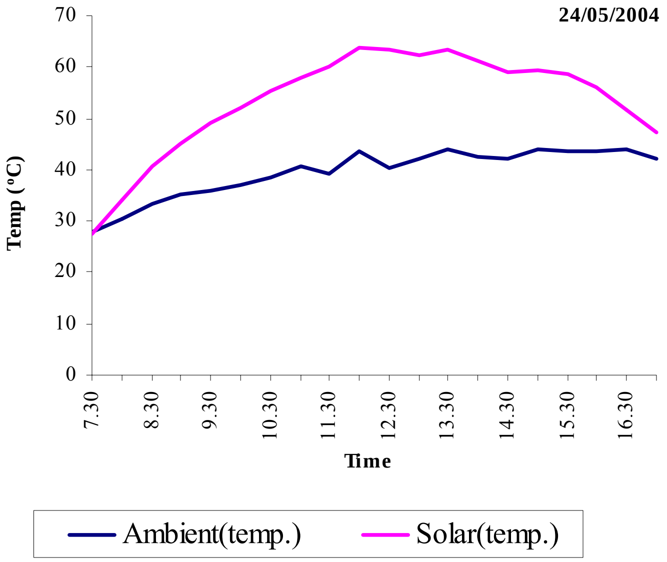

Fig. 4.1. The ambient and solar heated air temperatures

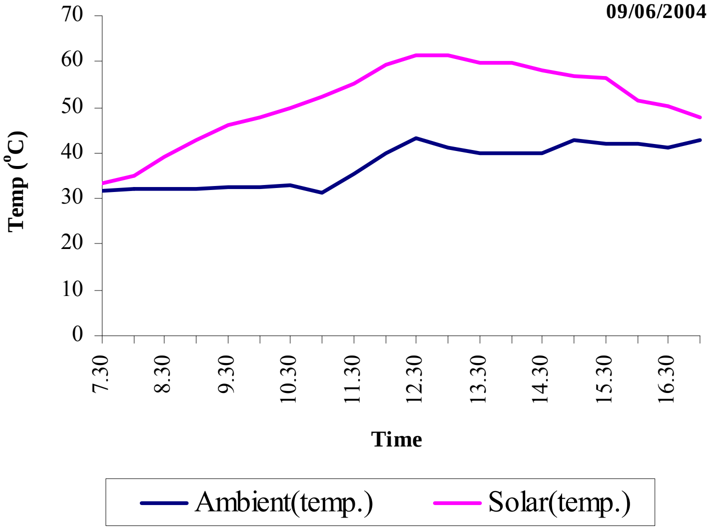

Fig. 4.2. The ambient and solar heated air temperatures

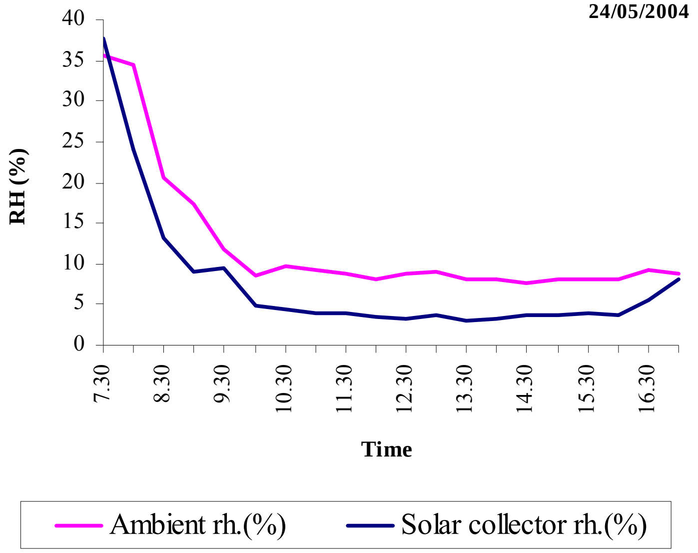

Fig. 4.3. The ambient and solar heated air relative humidity measurments

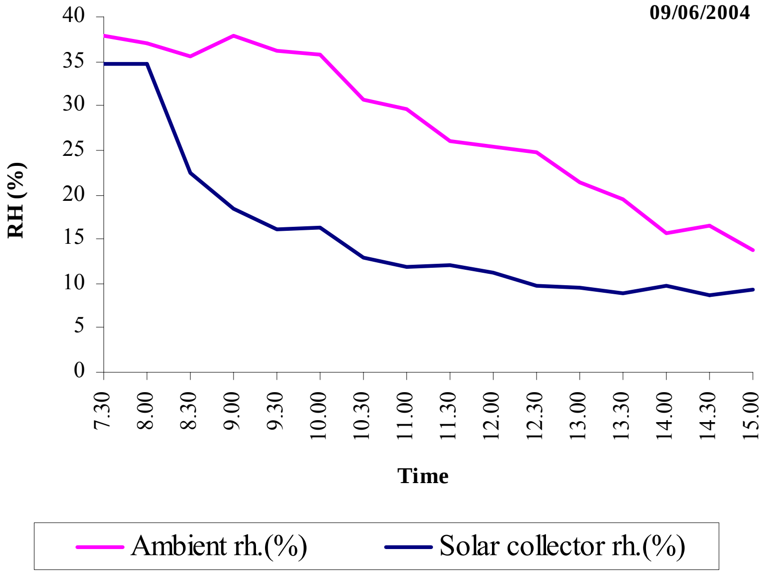

Fig. 4.4. The ambient and solar heated air relative humidity measurments

ambient air. This implies that the solar collector is a suitable device for drying applications, as the air used for drying should be at high temperature and low relative humidity.

The monthly mean value of the ambient relative humidity values at June was 28 % , while it was only 19 % at May (Appendix A Table 3) which shifted the relative humidity values curves slightly upwards of the experiment held in June.

Fig 4.5 shows the difference in temperature between periphery and the centre of the tomato slices. Figures 4.6 and 4.7 show the upper and lower surfaces temperature of the tomato slices. The statistical analysis, Appendix C Table 1 and 2 and the above-mentioned graphical presentations, reveal that the temperature differences were not significant. These results indicate that the heat transfer by conduction mode can be neglected and the whole drying process was a convective heat transfer. When air was used in the drying process, the whole process can be considered as a convective mode of heat transfer.

Figures 4.8 and 4.9 show the inlet and exhaust air relative humidity's measurements entering and leaving the drying chamber for the two days of the experiment (24/5/2004 and 9/6/2004). The exhaust air relative humidity was higher than the inlet one, this is true because drying air when comes in contact with the tomato slices heat up the product and evaporates its water content. It picks up this vaporized water within and consequently rising up water vapor within the exhaust air.

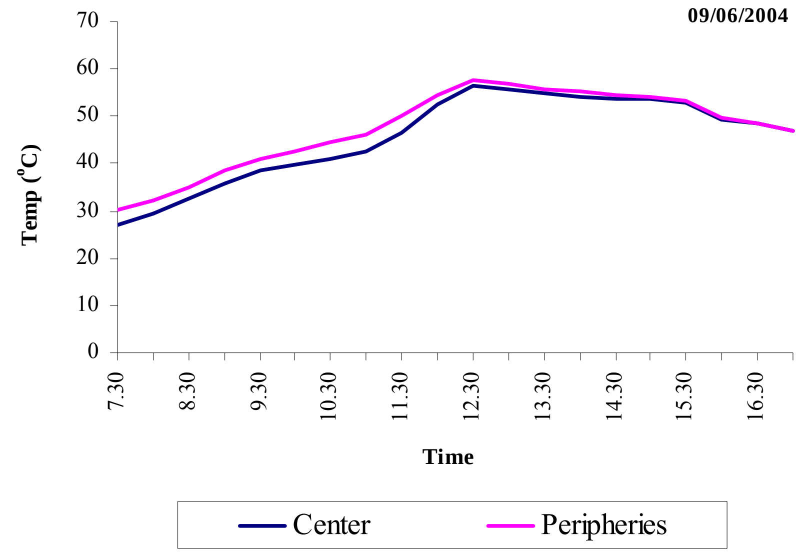

Fig. 4.5. The temperature difference between the center of tomato slices and their peripheries

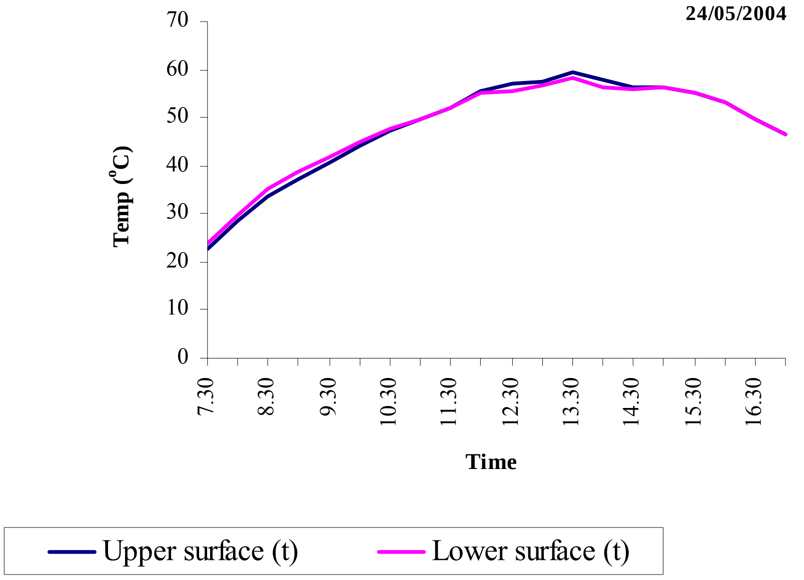

Fig. 4.6. The temperature difference between the upper and lower surfaces of tomato slices

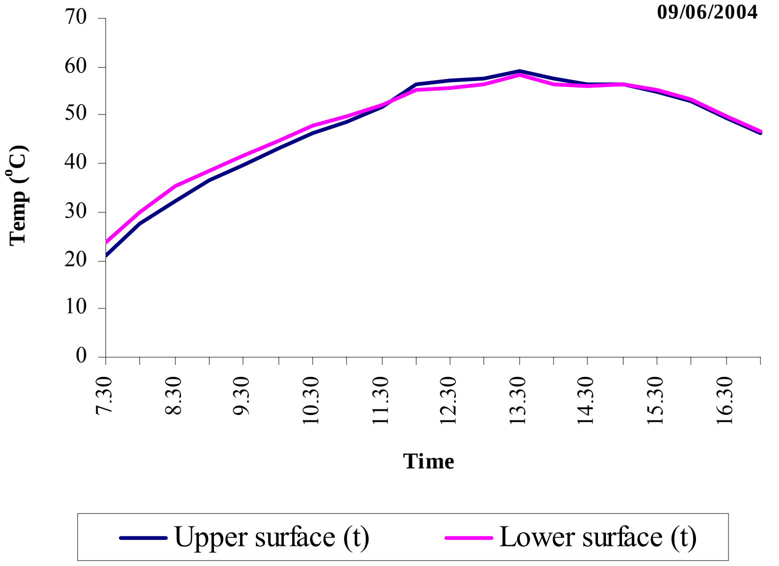

Fig. 4.7. The temperature difference between the upper and lower surfaces of tomato slices

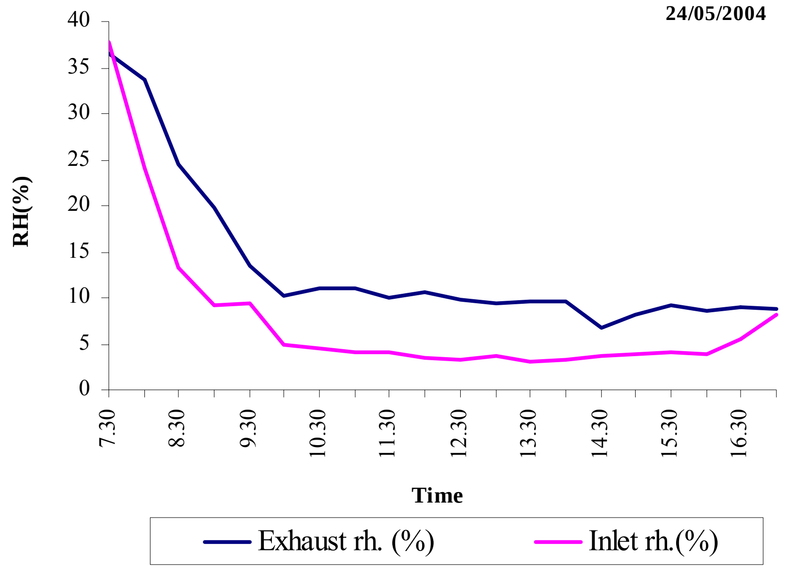
24/05/2004

Fig. 4.8. Inlet and exhaust air relative humidities after passing through tomato slices

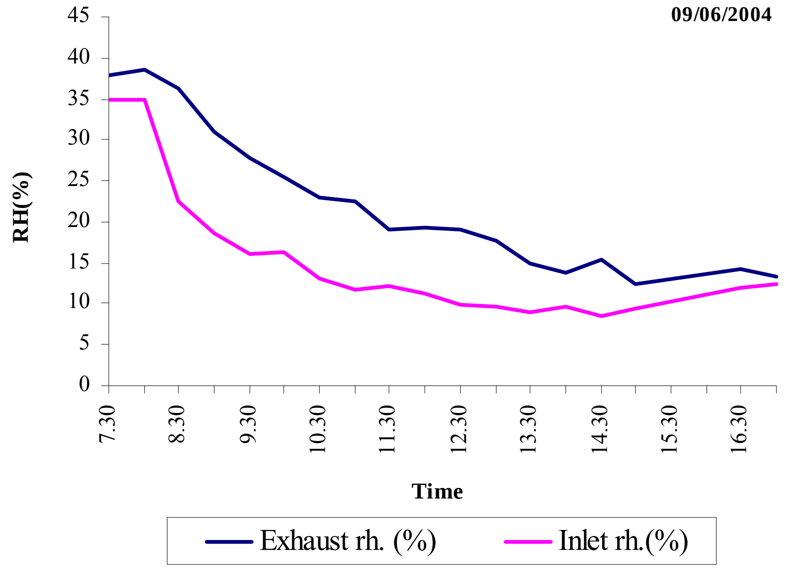
09/06/2004

Fig. 4.9. Inlet and exhaust air relative humidities after passing through tomato slices

Figures 4.10 and 4.11 show the inlet and exhaust air temperatures entering and leaving the drying chamber for the two days of the experiment (24/5/2004 and 9/6/2004). The exhaust air temperature was lower than the inlet one, Henderson and Perry (1976) reported that, drying with heated air is an adiabatic process the energy for moisture evaporation being supplied by a reduction in temperature of the drying air (exhaust air).

Earle (1983) stated that, the capacity of air for moisture removal depends on its humidity its temperature. Figures 4.12 and 4.13 show the temperature and the relative humidity of the solar collector for the two days of the experiment (24/5/2004 and 9/6/2004). As discussed earlier when air was heated its relative humidity decreased. The above-mentioned results clearly indicate the effectiveness of using the solar collector as a heat source for drying or for other purposes where the heat energy is needed.

The air velocity was constant in these tests (1.5 m/s). It is reported that air velocity during convective grain drying in thin layers has little influence (would normally increase the drying rate although may not be substantial) on the moisture removal rate (Pabis and Henderson, 1962; Misra and Brooker, 1980; Hutchinon and Olten, 1982; Syarief *et al.*, 1984; Jayas and Sokhansanj, 1989).

4.2 The tomato quality

Plate 4.1 shows the fresh and dried tomato slices. Plate 4.2 shows the difference in color and appearance between the solar and sun dried tomato slices. As known the color of the tomato indicates its lycopene content. The general appearance of the solar dried tomato

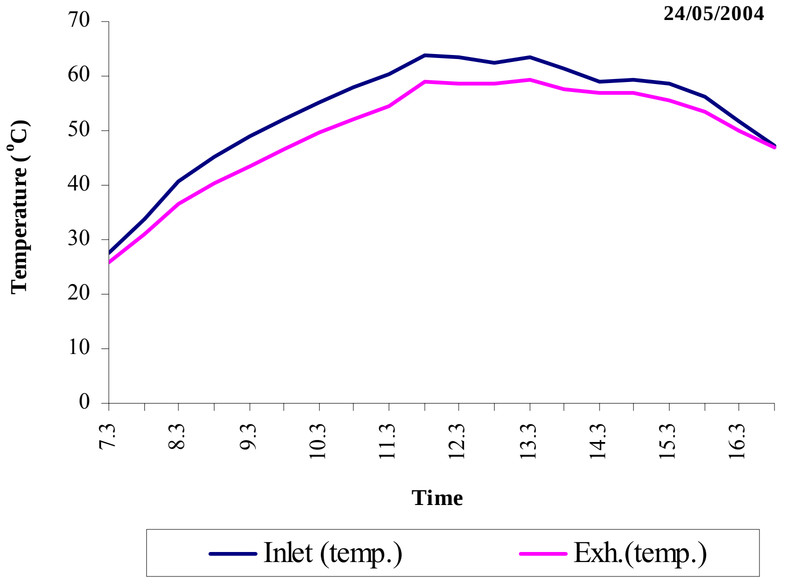

Fig. 4.10. Inlet and exhaust air temperature after passing through tomato slices

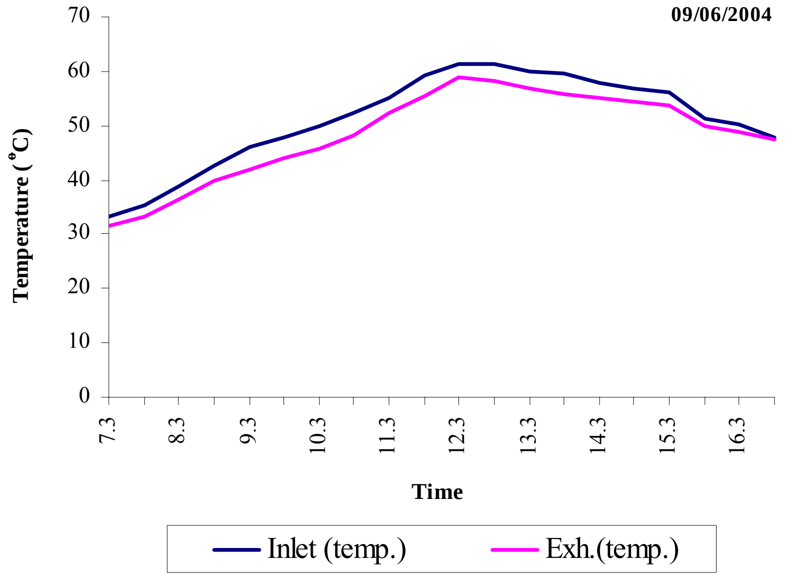

Fig. 4.11. Inlet and exhaust air temperature after passing through tomato slices

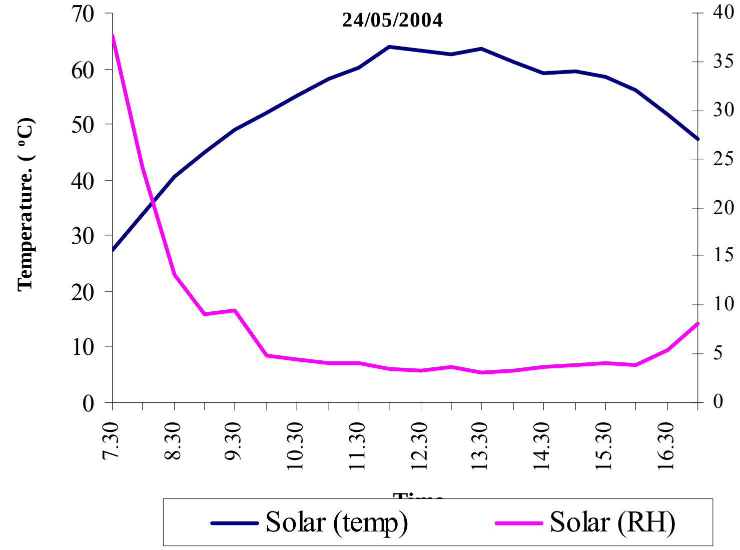

Fig. 4.12. The temperature and relative humidity of the solar collector

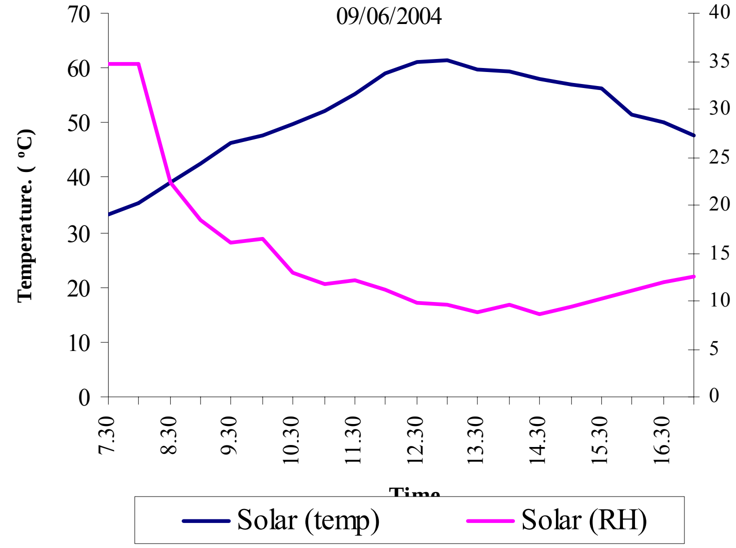

Fig. 4.13. The temperature and relative humidity of the solar collector

Plate 4.1 Comparison between fresh and solar dried tomato slices

Open-air dried **Solar dried** **Open-air dried**

Plate 4.2 Comparison between solar dried tomato slices and those dried by open air drying

slices seems more bright and clean and slices preserved their natural color during the drying. Ba *et al.* (1981) concluded that, when onion dried by direct sun drying the resulting product is often insect infested and sand covered.

4.3 The solar drying kinetics of tomato slices

The measured moisture content on wet basis (w.b.) for the solar dried tomato slices were tabulated in Table 4.1. The mean moisture content on dry basis (d.b.) were plotted versus drying time, Fig 4.14; Table 4.1. It shows the drying kinetic of tomato slices when dried using the solar collector. The experimental results illustrate the absence of the constant drying-rate period and the drying process took place only in the falling-rate period. This is in agreement with Doymaz (2006) findings. This indicates that diffusion is the most likely physical mechanism governing moisture movement in tomato slices (Panchariya *et al.*, 2002).

The drying rate of the solar dried tomato slices were presented in Table 4.2 and Fig 4.15. The general trend of drying rate decreases continuously with decreasing moisture content or improving drying time (Toğrul and Pehlivan, 2002; Yaldiz and Ertekin, 2001 and Yaldiz *et al.*, 2001).

Thinly sliced products dry faster due to the reduced distance the moisture travels and increased surface area exposed for a given volume of the product (Ertekin and Yaldiz, 2004). Since the migration to surface of moisture and evaporation rate from surface to air decreases with decrease of moisture in the product, the drying rate clearly decreases (Akpinar *et al.*, 2003).

Table 4.1 Measured moisture contents on wet basis and dry basis of tomato slices

Time	**Moisture contents**	
	Wet basis (%)	**Dry basis (g H_2O/g DM)**
7:30	94.48773	17.14134
8:00	93.90612	15.40989
8:30	93.3349	14.00353
9:00	92.50728	12.34629
9:30	91.5874	10.88693
10:00	90.07714	9.077739
10:30	88.01355	7.342756
11:00	85.04228	5.685512
11:30	81.32013	4.353357
12:00	76.17845	3.19788
12:30	66.90058	2.021201
13:00	49.9115	0.996466
13:30	38.87689	0.636042
14:00	14.75904	0.173145
14:30	8.414239	0.091873
15:00	3.082192	0.031802

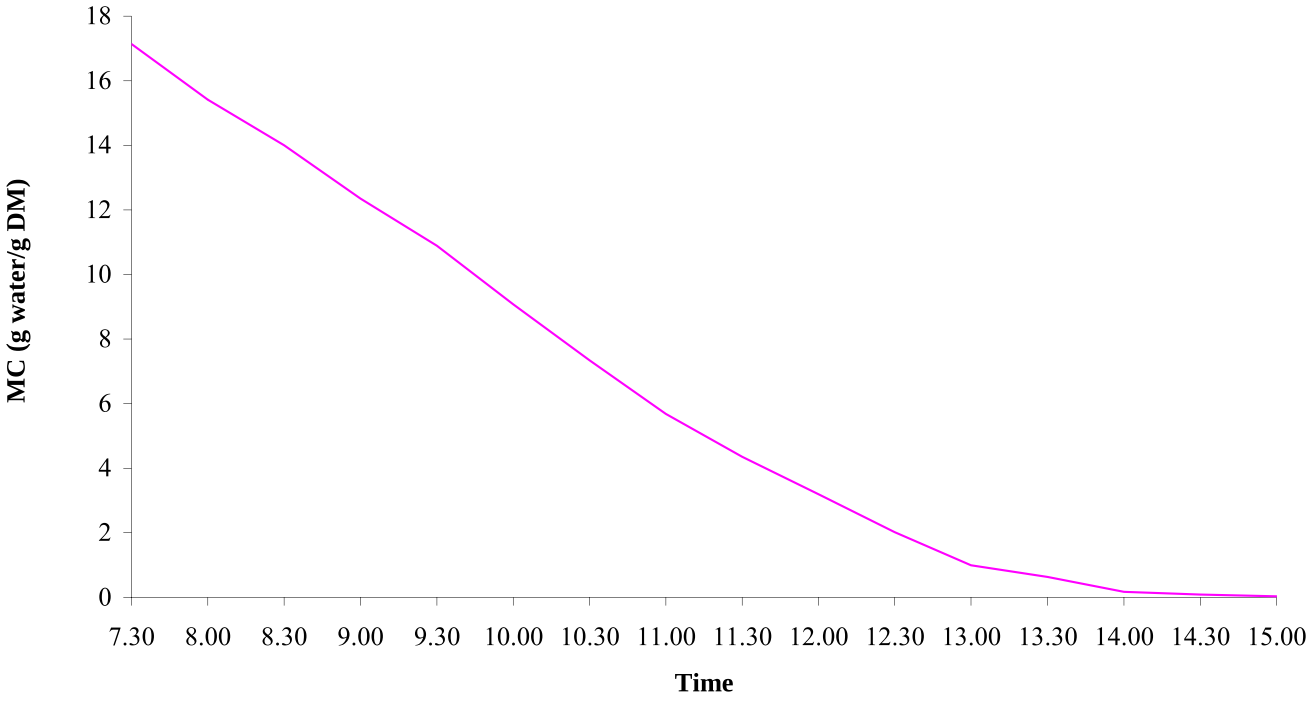

Fig. 4.14. Measured moisture contents on dry basis of tomato slices

Table 4.2 The drying rate of the solar dried tomato slice

Time	Drying rate (g water/g dry matter.min)
7:30	5.771496
8:00	4.687868
8:30	5.524146
9:00	4.864547
9:30	6.030624
10:00	5.783274
10:30	5.524146
11:00	4.440518
11:30	3.85159
12:00	3.922261
12:30	3.415783
13:00	1.201413
13:30	1.542992
14:00	0.270907
14:30	0.200236
15:00	0.106007

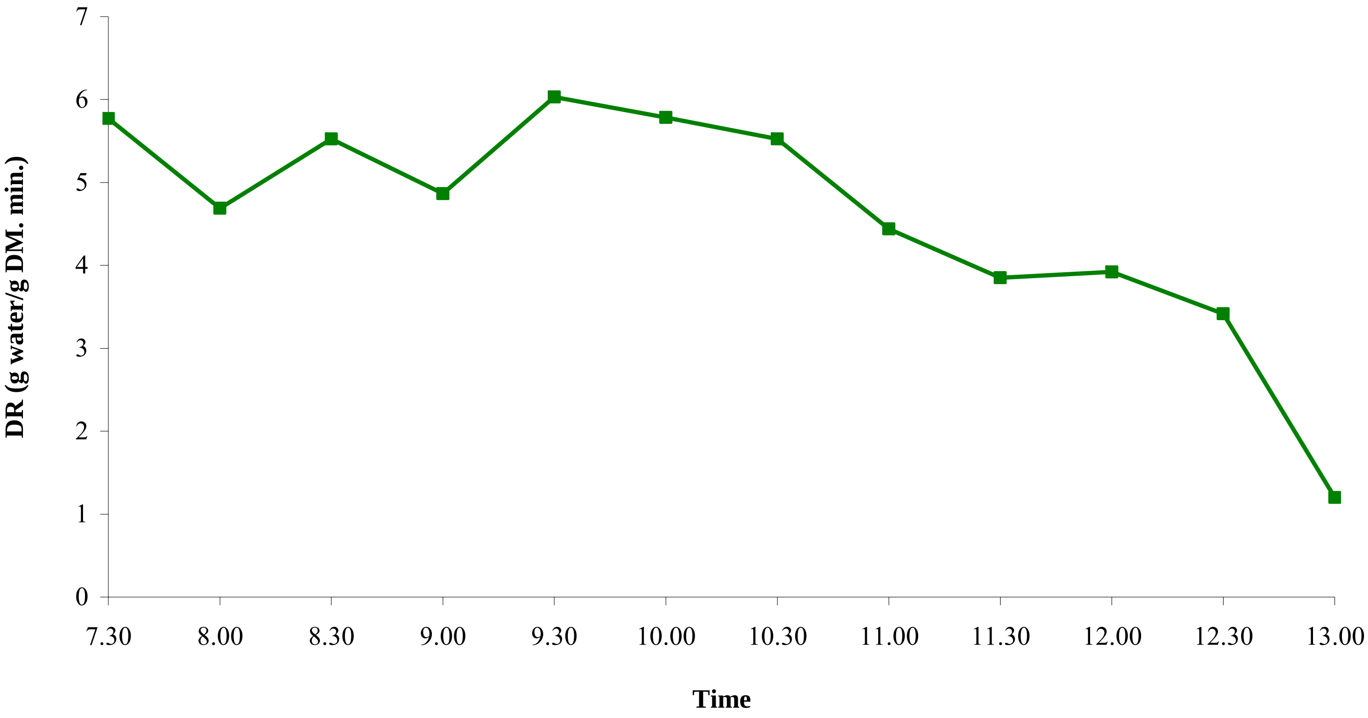

Fig. 4.15. Drying rate of tomato slices

4.4 Modeling of tomato slices solar drying

In order to normalize the drying curves, the data involving moisture content d.b. versus time was transformed to dimensionless parameter known as moisture ratio versus time Table 4.3.

Fig 4.16 shows the moisture ratio versus drying time, which represents the typical characteristic-drying curve of tomato slices during thin-layer drying operation when using solar dryer. The general trend of the curve in this figure is its similarity to typical drying curves.

The drying data was then fitted to two different semi-theoretical models, namely; Lewis and Page models, based on the ratios of the difference between the initial and final moisture contents. The application of Lewis and Page equations to the measured data resulted in the drying constants k and the product constant n for the tomato slices solar drying Figures 4.17 and 4.18. The models parameters were presented in Table 4.4. Then the predicted moisture ratios obtained from the two models were evaluated based on three statistics, namely; the reduced chi-square (χ^2), the root mean square error (RMSE) and the model efficiency (PE). The details of the statistical analysis were presented in Table 4.5.

The model efficiency (PE) of the Page model was higher than that obtained from Lewis model and tends to be one. The reduced chi-square (χ^2) and the root mean square error (RMSE) were lower for the Page model than that obtained from the Lewis model and tend to be zero.

Table 4.3 Measured moisture ratios of solar dried tomato slices

Time	Measured Moisture ratio (dimensionless)
7:30	1.0000
8:00	0.89899
8:30	0.816945
9:00	0.720264
9:30	0.635127
10:00	0.529582
10:30	0.428365
11:00	0.331684
11:30	0.253968
12:00	0.18656
12:30	0.117914
13:00	0.058132
13:30	0.037106
14:00	0.010101
14:30	0.00536
15:00	0.001855

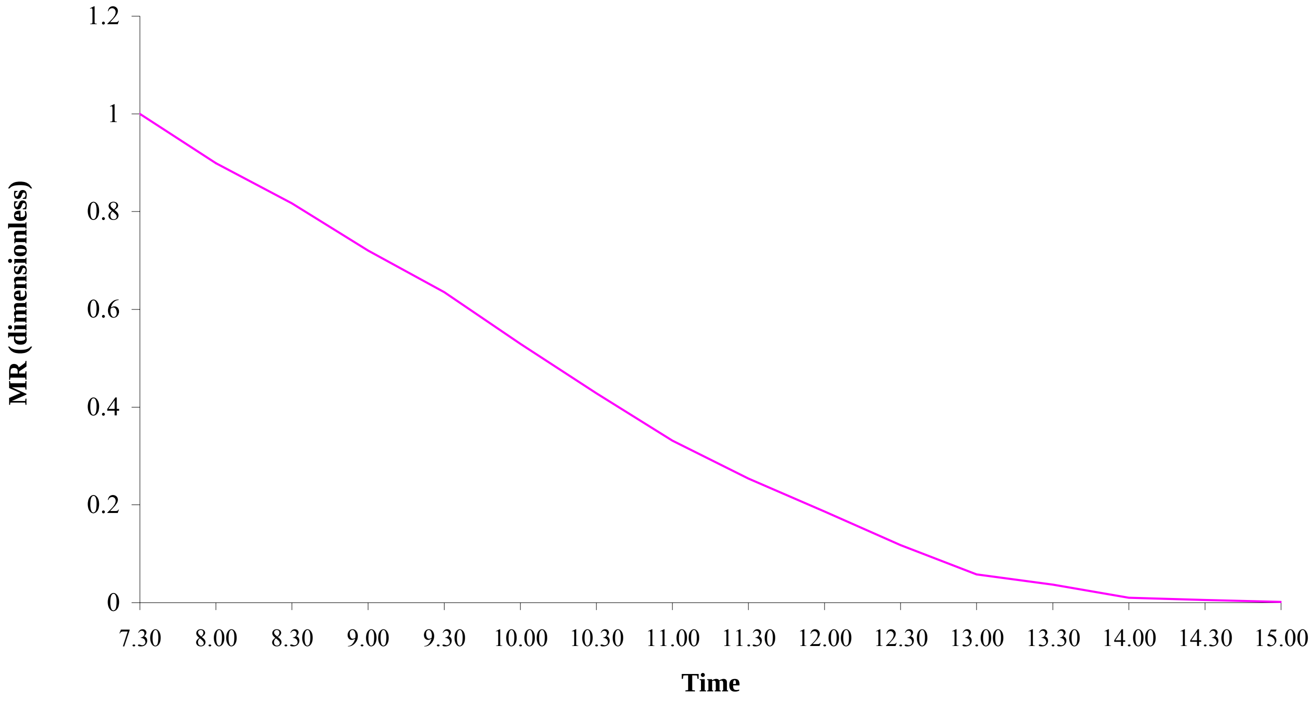

Fig. 4.16. Measured moisture ratio of tomato slices

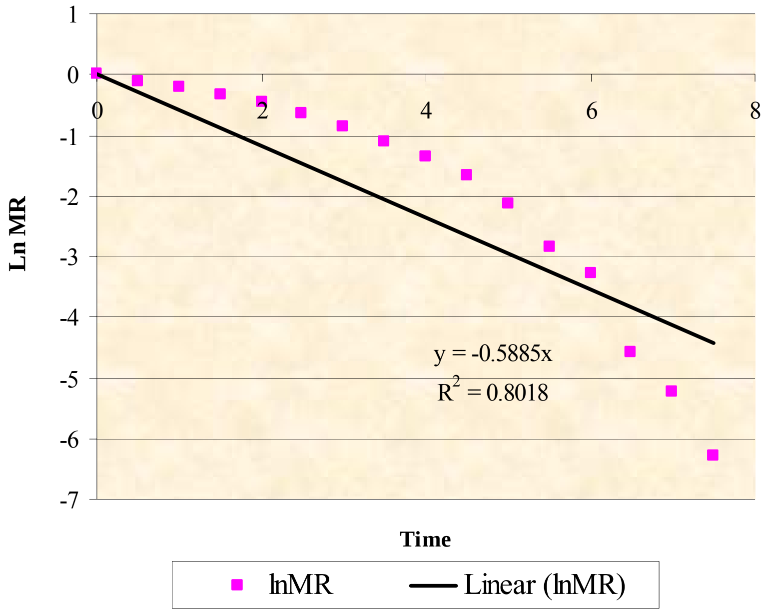

Fig. 4.17. Determination of the drying constant k of Lewis model

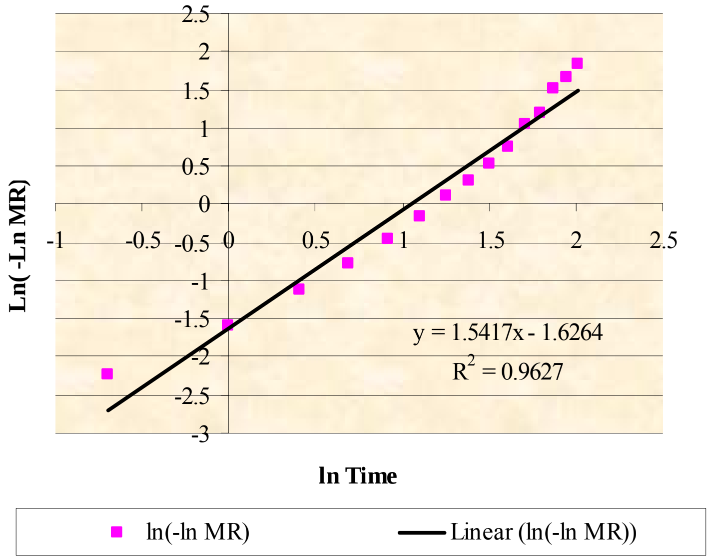

Fig. 4.18. Determination of the drying constant k and product constant n of PAGE model.

Table 4.4 Page and Lewis models parameters for solar dried tomato slices

Parameter / Model	K (h^{-1})	n
Lewis	0.5885	–
Page	0.1966	1.5417

Table 4.5 Statistical analysis for Page and Lewis models

Parameter / Model	χ^2	RMSE	EF
Lewis	0.03564	0.1828	0.7055
Page	0.0025	0.0467	0.9807

Hence, the Page model gave better predictions for the moisture ratio and moisture contents of the tomato slices than Lewis model did, Table 4.6, Figures 4.19 and 4.20. It's evident that the Page model could be used successfully to describe the solar drying behavior of tomato slices in thin-layer.

The Page model satisfactorily described the thin-layer solar drying characteristics of tomato slices. Nellist and O'Callaghan (1971) reported that, "it has been confirmed that Lewis model, which was commonly used to describe cereal drying curves, would not be adequate for seeds of such high initial moisture content".

Validation or the consistency of the established model was made also by plotting the predicted moisture ratio versus the measured moisture ratio, Fig 4.21. Also, the predicted moisture contents were plotted versus the measured moisture content, Fig 4.22. The measured data is generally scattered closely to the straight-line representing the predicted data with (R^2 = 0.99). This indicates the suitability of the Page mathematical model in describing drying behavior of tomato slices. Similar findings were reported by Doymaz (2004) for carrot cubes , Madamba *et al.* (1996) for garlic slices and by Doymaz and Pala (2002) for grape drying.

The significance of the developed model and therefore of the knowledge of the model's parameters is that the drying time and the moisture content at various drying times of the tomato slices can be predicted, which is important for design calculations of the dryers Therefore, knowing the initial moisture content and the weight of the dry matter, the required drying time or the required moisture content could be predicted.

Table 4.6 Measured and predicted moisture ratios and moisture contents of solar dried tomato slices

Time	Moisture ratio (dimensionless)			Moisture content (g H_2O/g DM)		
	Measured	Predicted (Lewis model)	Predicted (Page model)	Measured	Predicted (Lewis model)	Predicted (Page model)
7:30	1.0000	1.0000	1.0000	17.14134	17.14134	17.14134
8:00	0.89899	0.74509	0.93469	15.40989	12.77185	16.02184
8:30	0.816945	0.555159	0.82149	14.00353	9.516178	14.08143
9:00	0.720264	0.413644	0.69253	12.34629	7.090411	11.8709
9:30	0.635127	0.308202	0.564124	10.88693	5.282995	9.669846
10:00	0.529582	0.229638	0.445951	9.077739	3.936308	7.644202
10:30	0.428365	0.171101	0.343129	7.342756	2.932905	5.881697
11:00	0.331684	0.127486	0.257534	5.685512	2.185278	4.414481
11:30	0.253968	0.094988	0.188868	4.353357	1.62823	3.237455
12:00	0.18656	0.070775	0.135528	3.19788	1.213178	2.323133
12:30	0.117914	0.052734	0.095267	2.021201	0.903927	1.633011
13:00	0.058132	0.039291	0.065664	0.996466	0.673507	1.12557
13:30	0.037106	0.029276	0.044416	0.636042	0.501824	0.761358
14:00	0.010101	0.021813	0.029506	0.173145	0.373904	0.505777
14:30	0.00536	0.016253	0.019263	0.091873	0.278592	0.330191
15:00	0.001855	0.01211	0.012366	0.031802	0.207576	0.211963

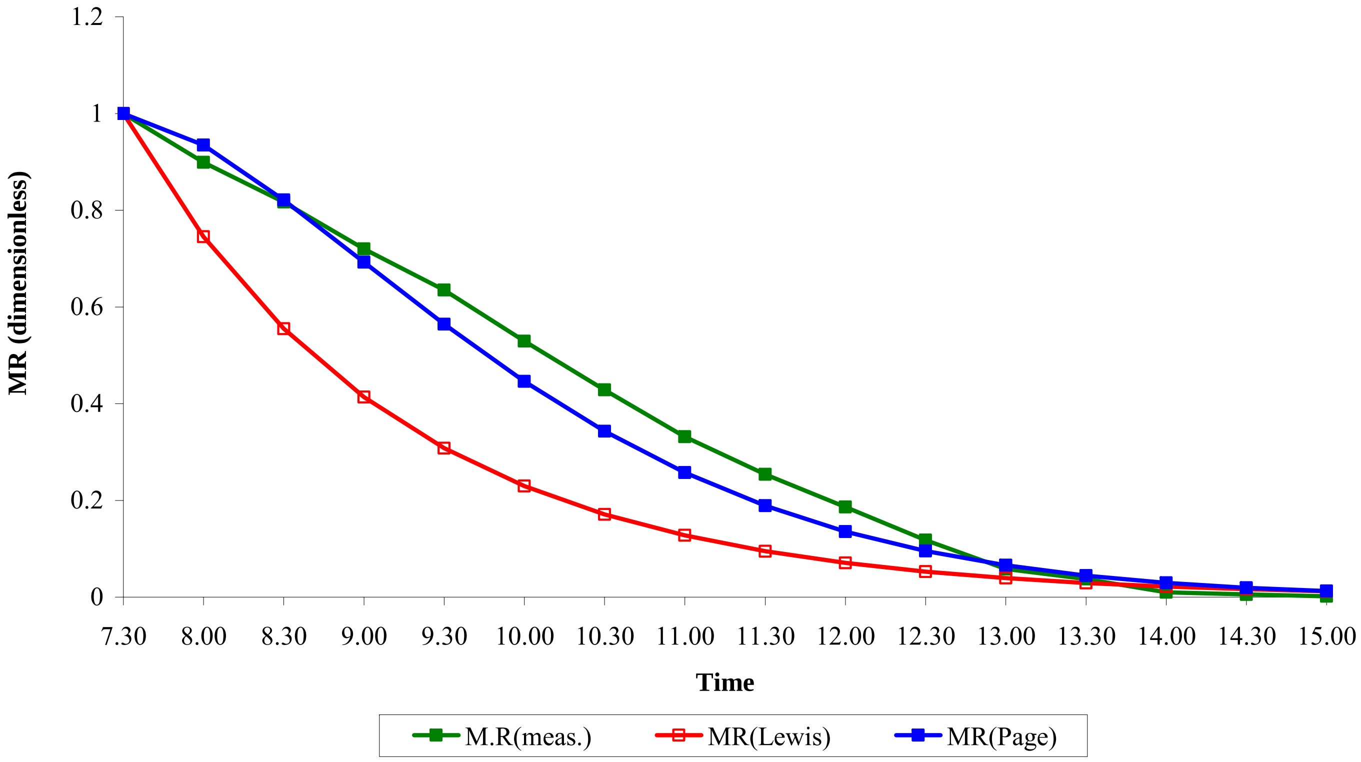

Fig. 4.19 Measured and predicted moisture ratio of tomato slices using Lewis and Page models

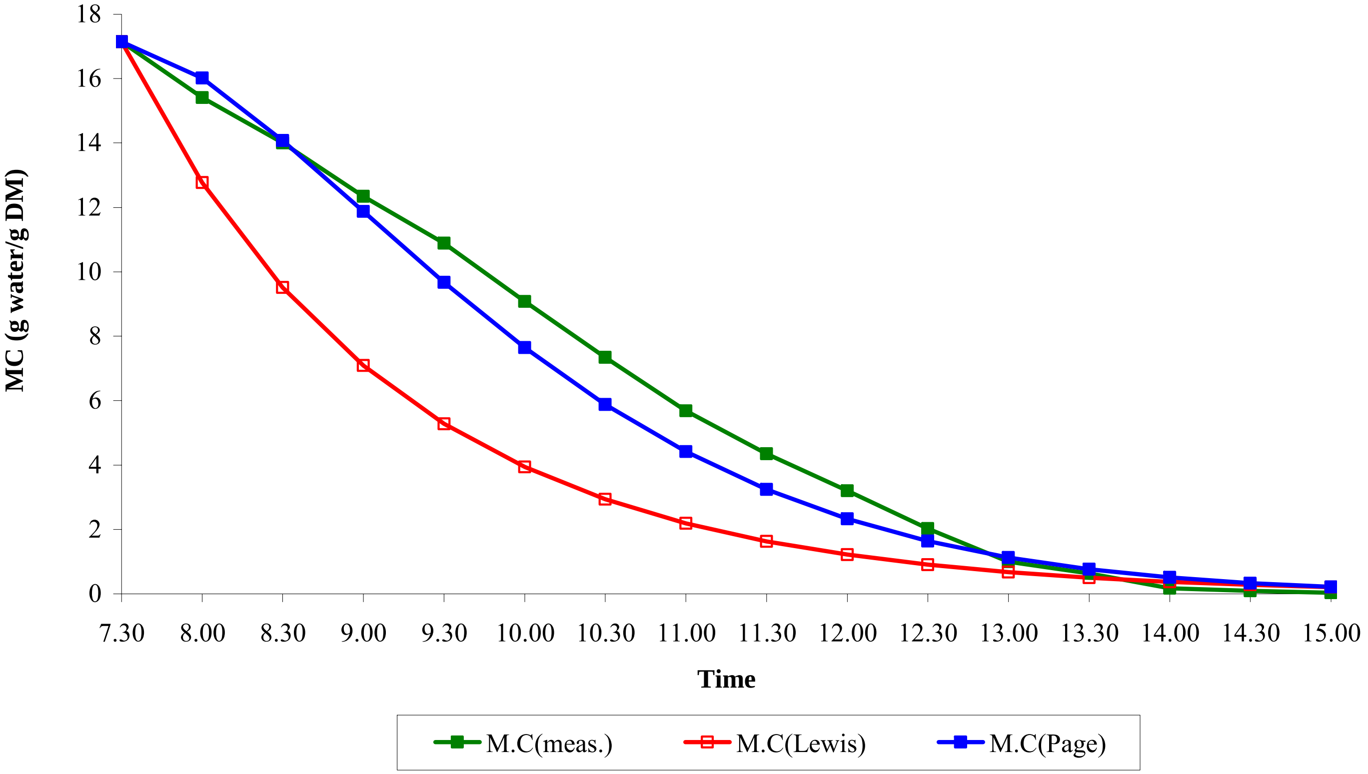

Fig. 4.20. Measured and predicted moisture contents of tomato slices using Lewis and Page models

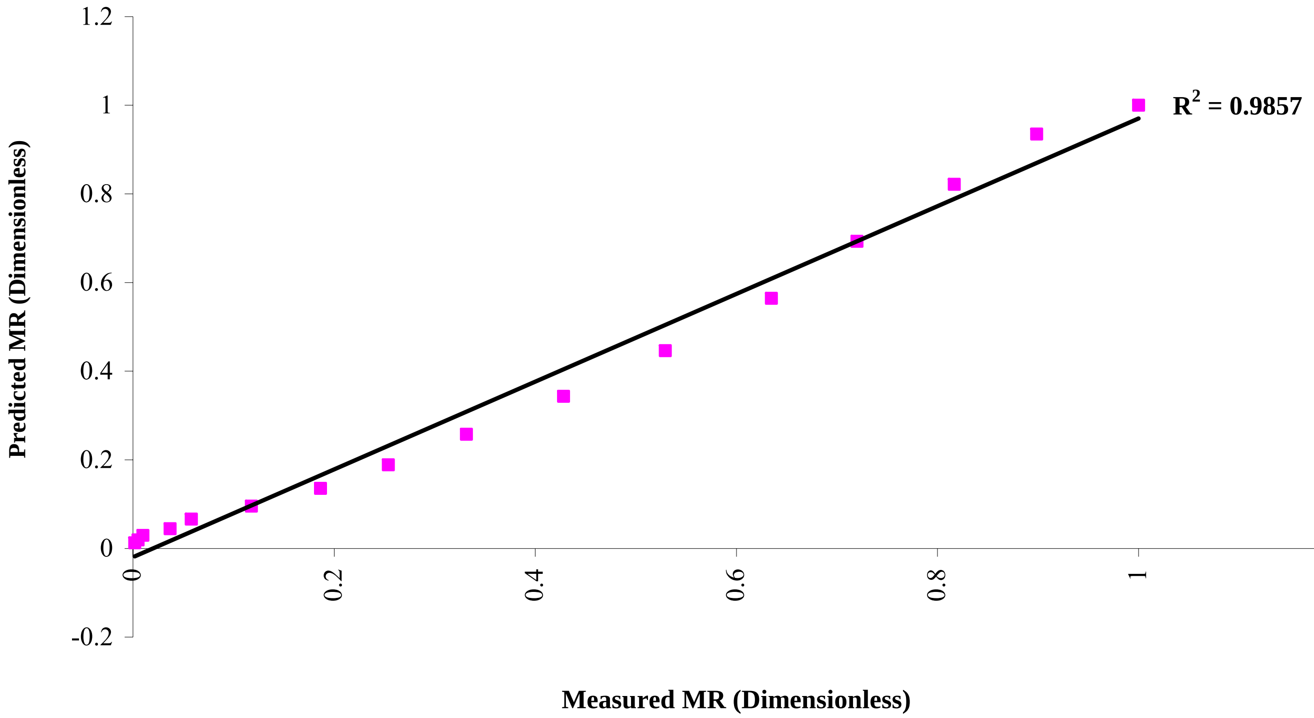

Fig. 4.21. Measured and predicted moisture ratio (Page model) of tomato slices

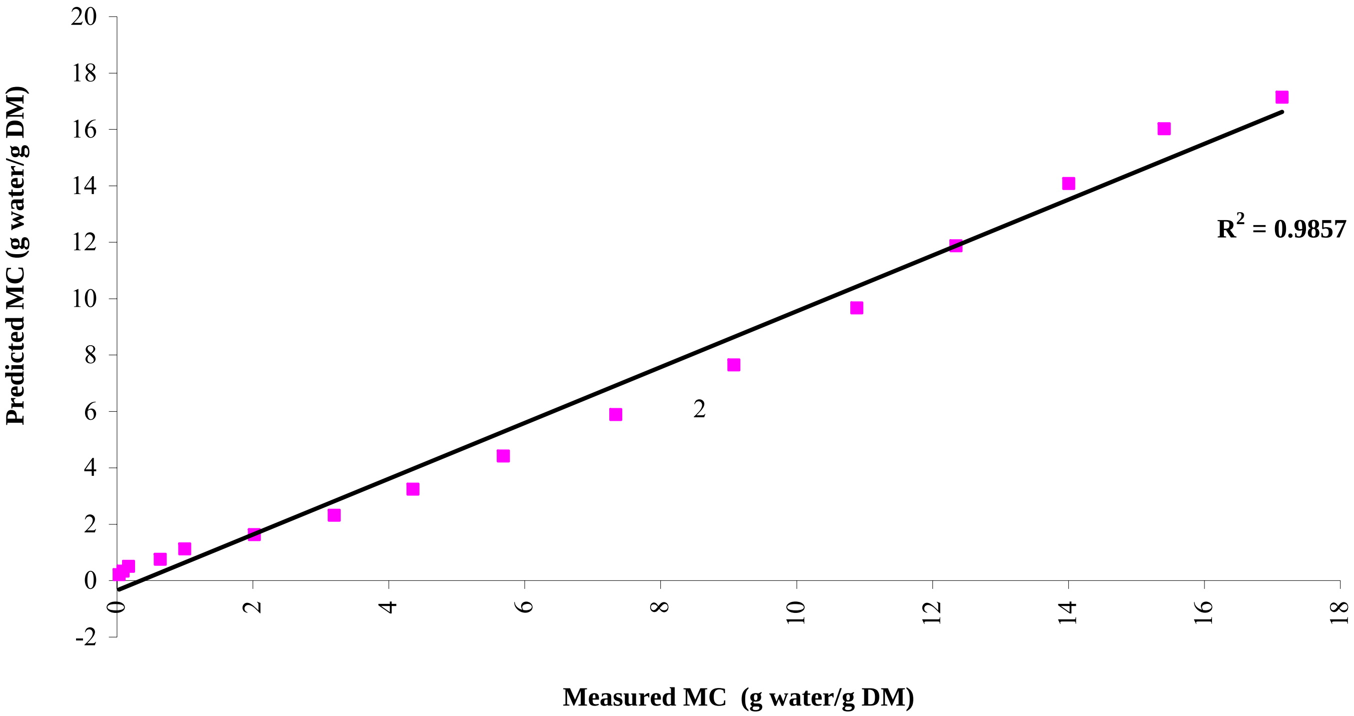

Fig. 4.22. Measured and predicted moisture contents (Page model) of tomato slices

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1- The solar dryer can be easily constructed from local materials using local labor.

2- Solar dried tomato slices had good appearance and clean shape compared to traditional sun dried slices.

3- Solar drying tomato slices took place during the falling-rate period. This implies that, the initial moisture content of the slices is less than their critical moisture content.

4- The developed model was found to describe the thin-layer solar drying of the tomato slices satisfactorily.

5- Mathematical modeling could be used as a tool in simulation of drying agricultural products accurately.

5.2 Recommendations

1- A lot of research work should be devoted to determine some physical and thermal properties of agricultural products due to their importance in heat and mass transfer problems.
2- Some modifications concerning the operation of the flat plate solar collector dryer should be considered. One suggestion is to test a movable mirror to reflect sun rays during early morning and late evening hours.
3- Deep-bed drying applications should be investigated by employing the simulation of thin-layer drying.
4- Constants should be calculated for the experimental data (drying air conditions).

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APPENDICES

Appendix (A)

Station: Shambat

Table 1. Mean monthly radiation on horizontal surface (MJ/m^2/day)

Month	**Jan.**	**Feb.**	**March**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Mean**
Radiation	20.3	23.1	24.5	25.9	24.7	23.6	23.0	22.8	22.9	21.9	21.0	20.0	22.82

Station: Shambat

Table 2. Mean monthly sunshine hours (hr)

Month	**Jan.**	**Feb.**	**March**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Mean**
Sunshine	10.2	10.5	10.2	10.6	10.0	9.3	8.7	8.9	9.2	10.2	10.6	10.5	9.92

Station: Shambat

Table 3. Type of data: monthly mean/totals

Element / Month	Mean temperature °C		Relative humidity	Total rainfall (mm)	Wind	
	Max.	Min.			Dir.	Speed Knots
January	31.4	14.0	29	TR	N	5
February	32.3	15.1	27	0	N	7
March	37.2	18.1	23	0	N	6
April	40.9	21.0	16	0	N	5
May	44.0	23.8	19	0	N	5
June	41.3	26.7	28	0.5	SW	6
July	40.3	26.2	34	5.4	S	6
August	38.7	25.7	42	44.0	S	5
September	38.7	26.6	37	1.0	S	5
October	39.5	23.9	36	15.2	N	4
November	36.1	19.9	32	0	N	5
December	.31.5	15.1	29	0	N	5
Total	-	-	-	66.1	-	-

Note:

Knots = 1.85 km/hr

= 0.5 m/s

= 1.15 mile/hr

= 1.69 feet/s

Vab = variable

TR = trace = rainfall less than 0.1 mm

Issued by: Met. Muth. (Sudan)

Appendix (B)

Table 1. Data sheet of drying test (24/5/2004)

Exhaust RH %	**Solar collector RH %**	**Ambient RH. %**	**Exhaust (º C)**	**Lower surface (ºC)**	**Upper surface (ºC)**	**Solar (temp.)**	**Ambient (temp.)**	**Drying tim.**
36.5	37.7	35.7	25.79	23.7	22.73	27.44	28	7.3
33.6	24.1	34.4	31.1	29.82	28.67	33.92	30.48	8
24.5	13.2	20.5	36.5	35.38	33.61	40.68	33.32	8.3
19.8	9.1	17.4	40.37	38.65	37.34	45.04	35.1	9
13.5	9.4	11.9	43.28	41.77	40.64	48.96	35.92	9.3
10.3	4.9	8.6	46.56	44.86	44	52.16	36.96	10
11	4.4	9.6	49.6	47.82	47.2	55.28	38.36	10.3
11	4	9.3	52	49.82	49.56	58	40.56	11
10	4	8.7	54.48	51.92	51.96	60.24	39.39	11.3
10.7	3.4	8	58.8	55.32	55.72	63.84	43.68	12
9.7	3.2	8.8	58.64	55.6	57.12	63.36	40.49	12.3
9.4	3.9	9	58.72	56.52	57.68	62.48	42.24	13
9.5	3.1	8	59.36	58.22	59.32	63.52	44	13.3
9.5	3.3	8	57.6	56.44	57.8	61.36	42.4	14
6.8	3.6	7.6	56.8	55.96	56.36	59.04	42	14.3
8.2	3.8	8	56.88	56.32	56.44	59.36	44.16	15
9.2	4	8.2	55.52	55.06	55.04	58.48	43.68	15.3
8.5	3.8	8.2	53.6	53.22	53.08	56.08	43.68	16
8.9	5.5	9.3	50.16	49.82	49.56	51.76	44.16	16.3
8.7	8.2	8.8	46.8	46.64	46.36	47.28	42.24	17

Table 2. Data sheet of drying test (09/06/2004)

Exhaust RH %	Solar collector RH %	Ambient RH. %	Exhaust (º C)	Solar collector (º C)	Ambient (º C)	Tomato				Time
						Peripheries (º C)	Center (º C)	Lower surface (º C)	Upper surface (º C)	
37.8	34.8	37.8	31.49	33.44	31.71	30.17	27.17	23.7	20.81	7.3
38.5	34.8	37	33.42	35.2	31.92	32.14	29.55	29.82	27.64	8
36.3	22.4	35.5	36.4	38.96	32.19	35.19	32.48	35.38	32.31	8.3
31.1	18.5	37.8	39.9	42.72	31.97	38.45	35.77	38.65	36.67	9
27.7	16	36.2	42	46.24	32.62	41.1	38.47	41.77	39.59	9.3
25.4	16.4	35.7	43.84	47.84	32.57	42.68	39.59	44.86	43.04	10
23	13	30.6	45.84	49.92	33.06	44.72	41.07	47.82	46.24	10.3
22.5	11.8	29.6	48	52.24	31.3	46.12	42.36	49.82	48.72	11
19	12.1	26.1	52.32	55.12	35.44	50.08	46.56	51.92	51.68	11.3
19.3	11.2	25.3	55.6	59.12	39.97	54.68	52.4	55.32	56.4	12
19.1	9.8	24.8	58.8	61.2	43.2	57.48	56.36	55.6	57.2	12.3
17.6	9.6	21.3	58.16	61.28	41.28	56.76	55.56	56.52	57.68	13
15	8.9	19.5	56.8	59.84	40	55.8	55	58.22	59.2	13.3
13.8	9.7	15.7	55.68	59.52	39.87	55.24	54.16	56.44	57.6	14
15.3	8.6	16.5	55.2	58	40.09	54.6	53.88	55.96	56.32	14.3
12.4	9.4	13.8	54.4	56.8	42.64	54	53.68	56.32	56.4	15
-	-	-	53.84	56.24	42	53.32	53.04	55.06	54.96	15.3
-	-	-	49.84	51.36	41.84	49.52	49.32	53.22	53.04	16
14.3	12	15.2	48.88	50.16	41.28	48.52	48.36	49.82	49.52	16.3
13.3	12.5	13.3	47.44	47.84	42.64	47	46.92	46.64	46.32	17

Appendix (C)

Table 1. Statistical analysis of the temperature difference between the center and the peripheries of the tomato slice during the drying process (9/6/2004)

Time 7:30

Cf = 3287.3022 $\bar{x}$ = 28.67

SOV	d.f.	SS	MS	F(cal)
Treatment	1	8.9701	8.9701	134.08**
Error	2	0.1338	0.0669	
Total	3	9.1039		

CV = 0.90% LSD = 1.11

Time 8:00

Cf = 3804.4224 $\bar{x}$ = 30.84

SOV	d.f.	SS	MS	F(cal)
Treatment	1	6.7081	6.7081	8.37ns
Error	2	1.6025	0.8013	
Total	3	8.3106		

CV = 2.90% LSD = 3.85

Time 8:30

Cf = 4577.8756 $\bar{x}$ = 33.83

SOV	d.f.	SS	MS	F(cal)
Treatment	1	7.3441	7.3441	5.72ns
Error	2	2.5657	1.2829	
Total	3	9.9093		

CV = 3.35% LSD = 4.87

Time 9:00

Cf = 5507.1241 $\bar{x}$ = 37.11

SOV	d.f.	SS	MS	F(cal)
Treatment	1	7.1824	7.1824	8.69ns
Error	2	1.6525	0.8263	
Total	3	8.8349		

CV = 2.45% LSD = 3.91

Time 9:30

Cf = 9329.7936 $\bar{x}$ = 39.78

SOV	d.f.	SS	MS	F(cal)
Treatment	1	6.9169	6.9169	13.74ns
Error	2	1.0069	0.5035	
Total	3	7.9238		

CV = 1.78% LSD = 3.05

Time 10:00

Cf = 6767.5302 $\bar{x}$ = 41.13

SOV	d.f.	SS	MS	F(cal)
Treatment	1	9.5791	9.5791	36.45*
Error	2	0.5256	0.2628	
Total	3	10.1047		

CV = 1.25% LSD = 2.21

Time 10:30

Cf = 7359.9241 $\bar{x}$ = 42.90

SOV	d.f.	SS	MS	F(cal)
Treatment	1	13.3225	13.3225	7.78ns
Error	2	2.7250	1.3625	
Total	3	16.0475		

CV = 2.72% LSD = 5.02

Time 11:00

Cf = 7828.7104 $\bar{x}$ = 44.24

SOV	d.f.	SS	MS	F(cal)
Treatment	1	14.1376	14.1276	8.11ns
Error	2	3.4880	1.7440	
Total	3	17.6256		

CV = 2.99% LSD = 5.68

Time 11:30

Cf = 9339.2896 $\bar{x}$ = 48.32

SOV	**d.f.**	**SS**	**MS**	**F(cal)**
Treatment	1	12.3904	12.3904	5.69ns
Error	2	4.3520	2.1760	
Total	3	16.7424		

CV = 3.05% LSD = 6.35

Time 12:00

Cf = 11466.1264 $\bar{x}$ = 53.54

SOV	**d.f.**	**SS**	**MS**	**F(cal)**
Treatment	1	5.1984	5.1984	1.10ns
Error	2	9.4880	4.7440	
Total	3	14.6864		

CV = 4.07% LSD = 9.37

Time 12:30

Cf = 12959.5456 $\bar{x}$ = 56.92

SOV	**d.f.**	**SS**	**MS**	**F(cal)**
Treatment	1	1.2544	1.2544	0.16ns
Error	2	15.5200	7.7600	
Total	3	16.7744		

CV = 4.89% LSD = 11.99

Time 13:00

Cf = 12615.7824 $\bar{x}$ = 56.16

SOV	**d.f.**	**SS**	**MS**	**F(cal)**
Treatment	1	1.4400	1.4400	0.30ns
Error	2	9.6832	4.6416	
Total	3	11.1232		

CV = 3.92% LSD = 9.47

Time 13:30

Cf = 12276.6400 $\bar{x}$ = 55.40

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.6400	0.6400	0.17ns
Error	2	7.6096	3.8048	
Total	3	8.2496		

CV = 3.52% LSD = 8.39

Time 14:00

Cf = 11968.3600 $\bar{x}$ = 59.70

SOV	d.f.	SS	MS	F(cal)
Treatment	1	1.1664	1.1664	0.66ns
Error	2	3.5360	1.7680	
Total	3	4.7024		

CV = 2.43% LSD = 5.72

Time 14:30

Cf = 11767.9104 $\bar{x}$ = 54.24

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.5184	0.5184	0.96ns
Error	2	1.0816	0.5408	
Total	3	1.6000		

CV = 1.36% LSD = 3.16

Time 15:00

Cf = 11594.9824 $\bar{x}$ = 53.84

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.1024	0.1024	0.39ns
Error	2	0.5248	0.2624	
Total	3	0.6272		

CV = 0.95% LSD = 2.20

Time 15:30

Cf = 11312.4496 $\bar{x}$ = 53.18

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.0784	0.0784	0.34ns
Error	2	0.4640	0.2320	
Total	3	0.5424		

CV = 0.91% LSD = 2.07

Time 16:00

Cf = 9769.3456 $\bar{x}$ = 49.42

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.0400	0.0400	0.17ns
Error	2	0.4768	0.2384	
Total	3	0.5168		

CV = 0.99% LSD = 2.10

Time 16:30

Cf = 9385.7344 $\bar{x}$ = 48.44

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.0256	0.0256	0.15ns
Error	2	0.3392	0.1696	
Total	3	0.3648		

CV = 0.85% LSD = 1.77

Time 17:00

Cf = 8820.9664 $\bar{x}$ = 46.96

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.0064	0.0064	0.12ns
Error	2	0.1088	0.0544	
Total	3	0.1152		

CV = 0.50% LSD = 1.00

Time	Temperature of the centre of tomato slice	Temperature of the pref of tomato slice	LSD	CV %
07:30	27.17	30.17	1.11^{**}	0.90
08:00	29.55	32.14	3.85^{ns}	2.90
08:30	32.48	35.19	4.87^{ns}	3.35
09:00	35.77	38.45	3.91^{ns}	2.45
09:30	38.47	41.10	3.05^{ns}	1.78
10:00	39.59	42.68	2.21^{ns}	1.25
10:30	41.07	44.72	5.02^{ns}	2.72
11:00	42.36	46.12	5.68^{ns}	2.99
11:30	46.56	50.00	6.35^{ns}	3.05
12:00	52.40	54.68	9.37^{ns}	4.07
12:30	56.36	57.48	11.99^{ns}	4.89
13:00	55.56	56.76	9.47^{ns}	3.92
13:30	55.00	55.80	8.39^{ns}	3.52
14:00	54.16	55.29	5.72^{ns}	2.43
14:30	53.88	54.60	3.16^{ns}	1.36
15:00	53.68	54.00	2.20^{ns}	0.95
15:30	53.04	53.32	2.07^{ns}	0.91
16:00	49.32	49.52	2.10^{ns}	0.99
16:30	48.36	48.52	1.77^{ns}	0.85
17:00	46.92	47.00	1.00^{ns}	0.50

Table 2. Statistical analysis of the temperature difference between the upper surface and lower surface the tomato slices during the drying process (9/6/2004)

time 7:30

Cf = 3287.3022 $\bar{x}$ = 28.67

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.0009	0.0009	0.0005ns
Error	2	3.8365	1.91825	
Total	3	3.8374		

C.V. = 4.83% LSD = 5.96

time 8:00

Cf = 3733.8210 $\bar{x}$ = 30.55

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.00725	0.00725	0.1ns
Error	2	1.38185	0.690925	
Total	3	1.3891		

C.V. = 2.72% LSD = 5.19

time 8:30

Cf = 4522.5625 $\bar{x}$ = 33.63

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.1681	0.1681	0.12ns
Error	2	2.7530	1.3765	
Total	3	2.9211		

C.V. = 3.49% LSD = 5.05

time.9:00

Cf = 5541.3136 $\bar{x}$ = 37.22

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.0484	0.0484	0.05ns
Error	2	1.8850	0.9425	
Total	3	1.9334		

C.V. = 2.61% LSD = 3.41

time 9:30

Cf = 6412.80.64 $\bar{x}$ = 40.04

SOV	**d.f.**	**SS**	**MS**	**F(cal)**
Treatment	1	0.2704	0.27704	4.33ns
Error	2	0.1250	0.0625	
Total	3	0.3945		

C.V. = 0.62% LSD = 1.08

time 10:00

Cf = 3287.3022 $\bar{x}$ = 28.67

SOV	**d.f.**	**SS**	**MS**	**F(cal)**
Treatment	1	1.221050	1.221050	21.19*
Error	2	0.115250	0.057623	
Total	3	1.336300		

C.V. = 0.58% LSD = 1.03

time 10:30

Cf = 7585.53 $\bar{x}$ = 43.55

SOV	d.f.	SS	MS	F(cal)
Treatment	1	1.703050	1.703050	11.87ns
Error	2	0.286850	0.143425	
Total	3	1.989900		

C.V. = 0.87% LSD = 1.63

time 11:00

Cf = 8006.6704 $\bar{x}$ = 44.74

SOV	**d.f.**	**SS**	**MS**	**F(cal)**
Treatment	1	1.0000	1.0000	1.30ns
Error	2	1.5392	0.7696	
Total	3	2.53920		

C.V. = 1.96% LSD = 3.77

time 11:30

Cf = 9549.1984 $\bar{x}$ = 48.86

SOV	d.f.	SS	MS	F(cal)
Treatment	1	1.1664	1.1664	1.03ns
Error	2	2.2688	1.1344	
Total	3	3.4352		

C.V. = 2.18% LSD = 4.58

time 12:00

Cf = 11659.6804 $\bar{x}$ = 53.99

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.81000	0.81000	0.32ns
Error	2	5.13040	2.5652	
Total	3	5.9404		

C.V. = 2.97% LSD = 6.89

time 12:30

Cf = 13150.35563 $\bar{x}$ = 57.34

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.69723	0.69723	0.19ns
Error	2	7.38725	3.69363	
Total	3	8.08448		

C.V. = 3.35% LSD = 8.27

time 13:00

Cf = 12678.7600 $\bar{x}$ = 56.3

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.0784	0.0784	0.03ns
Error	2	4.6400	2.3200	
Total	3	4.71840		

C.V. = 2.71% LSD = 6.55

time 13:30

Cf = 12299.9190 $\bar{x}$ = 55.45

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.0031	0.0031	0.002ns
Error	2	3.7748	1.8874	
Total	3	3.7779		

C.V. = 2.48% LSD = 5.91

time 14:00

Cf = 11850.4996 $\bar{x}$ = 54.43

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.2916	0.2916	0.38ns
Error	2	1.5496	0.7748	
Total	3	1.8412		

C.V. = 1.62% LSD = 3.79

time 14:30

Cf = 11603.5984 $\bar{x}$ = 53.86

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.5776	0.5776	1.60ns
Error	2	0.7200	0.3600	
Total	3	1.2976		

C.V. = 1.11% LSD = 2.58

time 15:00

Cf = 11389.1584 $\bar{x}$ = 53.36

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.9216	0.9216	3.97ns
Error	2	0.4640	0.232	
Total	3	1.3856		

C.V. = 0.90% LSD = 2.07

time 15:30

Cf = 11155.5844 $\bar{x}$ = 52.81

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.5476	0.5476	2.82ns
Error	2	0.3880	0.1940	
Total	3	0.9356		

C.V. = 0.83% LSD = 1.90

time 16:00

Cf = 9702.25 $\bar{x}$ = 44.25

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.1156	0.1156	0.89ns
Error	2	0.2600	0.1300	
Total	3	0.3756		

C.V. = 0.73% LSD = 1.55

time 16:30

Cf = 9323.8336 $\bar{x}$ = 48.28

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.1024	0.1024	1.10ns
Error	2	0.1856	0.0928	
Total	3	0.2880		

C.V. = 0.63 LSD = 1.31

time 17:00

Cf = 8813.4544 $\bar{x}$ = 46.94

SOV	d.f.	SS	MS	F(cal)
Treatment	1	0.0016	0.0016	0.06ns
Error	2	0.0544	0.0272	
Total	3	0.0560		

C.V. = 0.35% LSD = 0.71

Time	Temperature of the under tomato slice	Temperature of the above tomato slice	LSD	CV %
07:30	28.69	28.66	5.96^{ns}	4.83
08:00	30.60	30.51	0.19^{ns}	2.72
08:30	33.83	33.42	5.05^{ns}	3.48
09:00	37.11	37.33	3.41^{ns}	2.61
09:30	39.78	40.30	1.08^{ns}	0.62
10:00	41.14	42.24	1.03^{ns}	0. 58
10:30	42.90	44.20	1.63^{ns}	0.87
11:00	44.24	45.24	3.77^{ns}	1.96
11:30	48.32	49.40	4.58^{ns}	2.18
12:00	53.54	54.44	6.89^{ns}	2.97
12:30	56.92	57.76	8.27^{ns}	3.35
13:00	56.16	56.44	6.55^{ns}	2.71
13:30	55.43	55.48	5.91^{ns}	2.48
14:00	54.70	54.16	3.75^{ns}	1.62
14:30	54.24	53.48	2.58^{ns}	1.11
15:00	53.84	52.88	2.07^{ns}	0.90
15:30	53.18	52.44	1.90^{ns}	0.83
16:00	48.42	49.08	1.55^{ns}	0.73
16:30	48.44	48.12	1.31^{ns}	0.63
17:00	46.96	46.92	0.71^{ns}	0.35

Program menu

```
program mo_c;
uses  moisture,wincrt;
var choic:integer;  MC,Time:real;
procedure minu;
begin
writeln('            menues        ');
writeln('   ' ,'1......... .calculate Measured motisure content in dry basis   );
 writeln('   ',' 2...........calculate moisture content using Page model');
writeln('    ','3...........exit');
Writeln('           input your choice');
end;
begin
repeat
minu;
 readln(choic);
case choic of
 1: begin
   MC_IN_db;
    end;
2:
    begin
    Page_Model;
    end;
3:
   exit;
end;
writeln('are you want to excute this program again');
readln(choic);
until choic=3
end.
```

Program sub-routines

```
unit mo_co;
 interface
uses wincrt,winprocs;
 const n1=1; PageConst_KP=0.1966; NP=1.5417;
var Wt:array[0..100] of real;Time:array[0..100] of real; time1:real;
 M_C:array[0..100] of real;
 MR_cal,MC_cal,MR:array[0..100] of real;
  MR_Cal_P,MC_cal_P:array[0..100] of real;
 n,count:integer;   Db:real;
y1:array[0..100] of real; fac:real;
 procedure MC_IN_db;
 procedure Page_Model(MC:real);
 implementation
{**********************************************************************}
{procedure MC_IN_db}
begin
 enter time in hours;
time1:=0;
write('enter the number of observation'    ) ;
readln(n)  ;
for count :=0 to n do;
begin
Time[count]:=time1;
time1:=time1+0.5;
end;
{**********************************************************************}
{enter weight in time in hours}
for count:=0 to n do;
begin
write('enter weight in Time  ',Time[count],'h('  ',');
read(Wt[count]);
writeln;
end;
{**********************************************************************}
{calculate moiture content for any weight}
 writeln(' enter dry bone ') ;
```

```
readln(Db);
  for count:=0 to n do
     begin
        M_C[count]:=((Wt[count]-Db) /Db);
        writeln('the moiture content at time', Time[count],'=',M_C[count]);
     end;
{********************************************************************************}
{calculate moiture ratio}
for count:=0 to n do
  begin
     MR[count]:=M_C[count]/M_C[0];
     writeln('the moiture ratio  at time', Time[count]  ,'=',MR[count]);
end;
{******************************************************************************}
{calculate moiture content using Page Model MR=exp(-kt}
 procedure Page_Model(MC:real);
 var value1:real;
  begin
     for count:= 1 to n do
       begin
         value1:=exp(ln(dryConst_KP)+NP*ln(Time[count]));
        MR_Cal_P[count]:=(exp(-value1));
       MC_Cal_P[count]:=   MR_Cal_P[count]* MC;
      writeln('the moisture ratio calculated at time ', '  ' ,Time[count] ,'=' ,'  ' , MR_Cal_P[count]);
      writeln('the moisture content calculated at time ', '  ' ,Time[count] ,'=' ,'  ' , MR_Cal_P[count]);
       end;
 end;
{******************************************************************************}
 end.
```

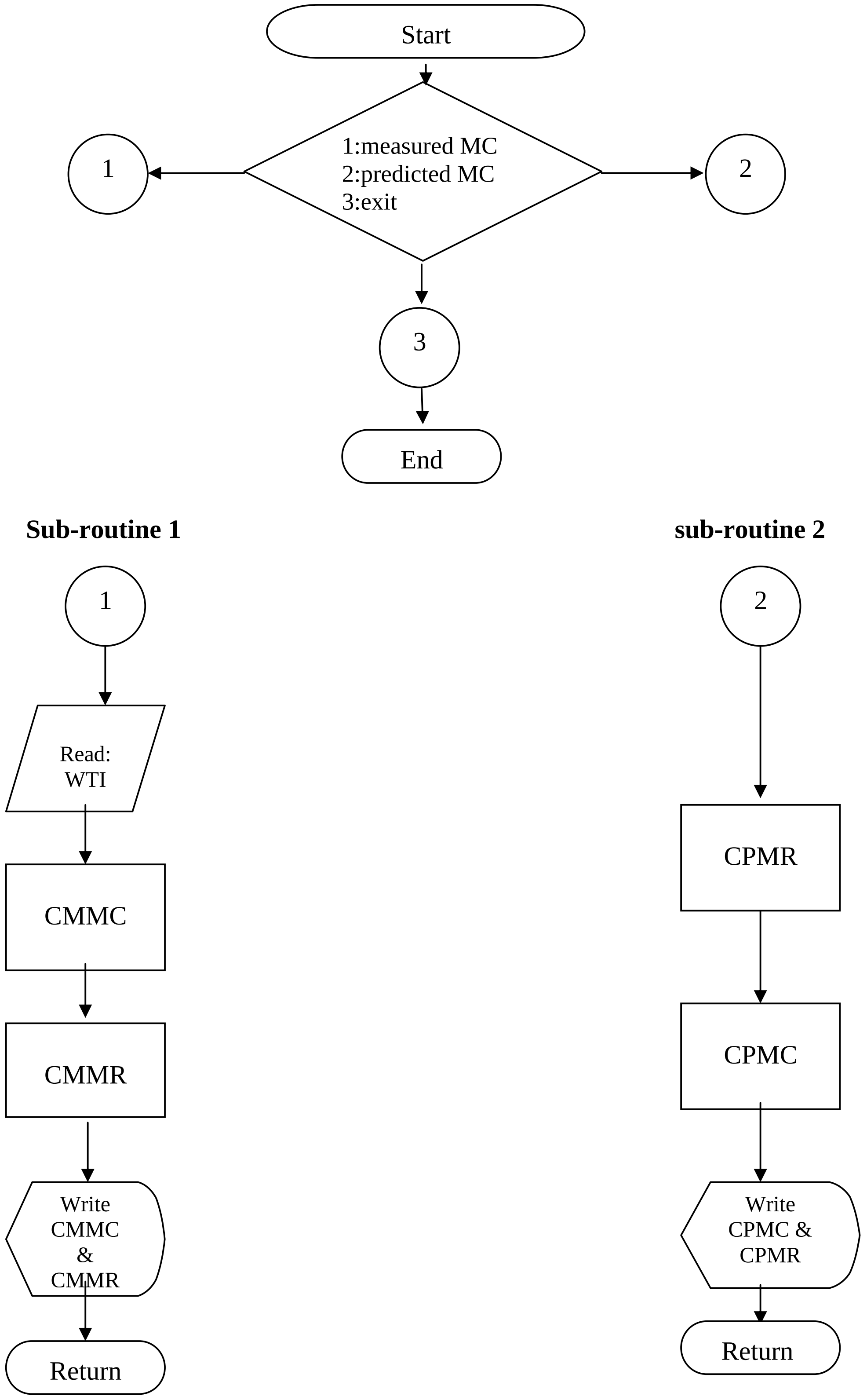

Fig 3.2 The programme main flow chart