



Experimental Studies and Mathematical Modelling of Solar Drying System for Production of High Quality Dried Tomato



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Dr. Md. Ayub Hossain

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PREFACE

Dried tomatoes are a well known food in the Mediterranean area and becoming popular also in the northern hemisphere of Europe where there is remarkable increase in the demands for that type of food. There, dried tomatoes have got a status of an additional food for snacks or for preparing salsa for pasta or gravy etc. Also, these food products with high quality standard are becoming gradually important in other regions of the world, such as Africa and Asia.

Drying is one of the oldest forms for preservation of food. For the natural method of drying, the fruits are simply placed in the sun, to remove slowly the moisture from the fresh fruit down to the final moisture content which makes the fruit suitable for preservation and long term storage. The moisture content of the fruit should be below 20% (w.b.) for save preservation. But good quality results for natural sun dried fruits can only be achieved under warm and sunny climate with windy and dry air conditions. Thus, the simple method of open air sun drying may be suitable for countries with a stable hot and dry climate to secure a high quality of the final dried product.

However, the problem of achieving the desired high quality of dried product make the natural air-drying method unsuitable in the tropical or sub-tropical countries. Risk of infection of pests (insects) and development of mould during drying is a big problem in these countries. In countries of moderate climate as in Middle and Northern Europe the natural sun drying method is not suitable due to unstable weather conditions with fluctuations between warm and cold and, dry and humid days. Besides, natural drying is not the adequate method for high level industrial production of dried fruits with desired high uniform quality standard. In both the Mid-European and (sub-) tropical areas, usage of forced convection drying systems with external heating is more appropriate but energy consuming and thus impacting the environment.

Natural sun drying is mostly not recommendable for tropical or sub-tropical countries with hot but humid air conditions. For these countries a hybrid solar dryer system will be more appropriate to produce high quality dried products especially from fresh high moisture fruits like tomatoes.

To test the performance of a solar drying system, drying experiments were performed in the summer seasons of 2005/2006 in Potsdam, Germany. Occasionally during these periods, desired weather conditions were found for solar supported drying, because the summer seasons these years had sufficient numbers of consecutive sunny, warm, and dry days to carry out experiments successfully for drying tomato halves. Also, during these experiments, there were noticeable mould developments when drying during night times or cloudy days. To overcome these problems, pre-treatment methods were developed and these are extensively discussed in this report.

The report is divided into five chapters each with a distinct subject and concluding remarks. In **chapter 1**, the determination of ripeness, using the colorimeter is described. Also briefly, the mechanical method for the determination of firmness and its correlation to

the ripeness is discussed. The optimal conditions for drying of tomatoes are elaborated in **chapter 2**. Half fruit drying is more recommended than drying slices or pieces. The optimal drying conditions are depicted there. Several drying models for thin layer drying of half tomato fruits are applied and analysed for the capability to predict the drying process. The models are compared and discussed in this chapter.

In **chapter 3**, the hybrid solar drying system is described and its performance discussed. Such type of dryer is well suited for small-scale farmers in tropical countries, but its performance could also be verified even under Mid-European climatic conditions. A specific feature of this dryer is its patent easy-to-use concept with modularity and adaptability, which gives good flexibility.

A mathematical model for the performance of the hybrid solar dryer was developed and is presented in **chapter 4**. The model was validated for its capability for providing design data of a solar drier.

The effects of storage environments and chemical pre-treatments on the conditions and bio-chemical changes of the final dried products are discussed in **chapter 5**.

This report finally concludes with a summary and recommendations for indirect drying of tomatoes and appropriate storage of the dried tomato halves derived from the research in Potsdam using the hybrid solar drying system.

The reader will find a concluding work with all relevant aspects about drying of tomato halves. The drying system described here in conjunction with the description of the developed methods for pre-treatment of the fresh fruits and the analysis of the drying process resulted in a model. The model depicts a dryer prototype for many kinds of fruits, herbs, vegetable, and fish which can be afforded and easily operated by small holders and farmers in developing countries.

The project was accomplished with support of the Alexander von Humboldt-Stiftung in 2005 and 2006. For funding of this research fellowship, the editors express their deep gratitude.

K. G., Potsdam-Bornim, March 2007.

SUMMARY AND RECOMMENDATION

The following recommendations are made based on the findings of various experiments and mathematical model as described in Chapters 1 to 5.

1. Surface colour and firmness have been identified as two important parameters to determine the ripeness of tomato. From red colour value ($+a^*$) +12 to +22 was found the range of optimum ripeness. Below the red colour value +12 may be under ripe and above +22 may be over ripe tomato. The rupture stress of optimum ripe tomato was found to be 12 to 22 N/mm². Above rupture stress 22 N/mm² the tomato may be classified as unripe and below the rupture stress 12 N/mm² the tomato be over ripe.
2. Tomato should be dried at air temperature of 45°C or above. Below the drying temperature of 45°C, tomato may be infected by micro-organisms (mould and fungus) during drying if no pre-treatment is applied. Optimum ripe half fruit tomato may be dried at an air temperature of 55°C and air velocity of 0.75 m/s to increase drying rate, to decrease shrinkage and to preserve better colour and lycopene. MIDILLI *et al.* (2002) model may be recommended to describe the single layer drying of tomato.
3. Thermal efficiency of solar collector may be increase about 10% using flat plate reflector. If tomato is dried with continuous air temperature of 45°C or above then no pre-treatment is required. If drying air temperature decreases below 45°C, then tomato should be pre-treated with 8 g/l sodium metabisulphite to prevent the microbial growth. Indirect solar drying produce a better quality of dried products in terms of colour, ascorbic acid, lycopene, total flavonoids, and rehydration ratio. The proposed solar drier may be recommend to dry fruits and vegetables for small holders in the developing countries after slight modification (for cost reduction).
4. The proposed mathematical model was tested for solar drying of tomato in day time and found good agreements between simulated and experimental data. Night time drying would be included in this model to predict whole drying time temperatures and moisture contents. Then, the model can be used for providing design data of a solar drying of fruits and vegetables.
5. After five months of storage of tomato in room (average temperature 20°C and relative humidity 60%) and cool chamber (average temperature 5°C and relative humidity 80%) colour and nutrients reduced about 50% and it is better than the commercial dried tomato available in European market. No visible micro-organisms (moulds and fungus) were detected in any of the samples during the storage period. It may be recommended to dry tomato halves with sodium metabisulphite pre-treatment (8 g/l) up to the final moisture content of 20% (wb) and store them in cool chamber (5-8°C) in glass container in dark place for better colour and antioxidants retention and maintenance of product moisture content.

INTRODUCTION

Tomato (*Lycopersicon esculentum* Mill.) is one of the most important vegetables and cash crop in the world, not only because of the volume of production but also because of its contribution to nutrition. Tomato is used in several forms and is widely used as a food ingredient. More than 80% of tomatoes are consumed in the form of processed products such as juice, paste, puree, ketchup, sauce etc. (KALOO 1993). In recent years the commercial importance of dried tomato has been increasing, since they can be used a component of several foods such as pizza. Epidemiological studies have shown that the consumption of tomato and tomato-based products can help to prevent various forms of cancers, especially prostate cancer and heart diseases (GIOVANNUCCI 1999, RAO & AGARWAL 2000, GEORGE *et al.* 2001). Demand for ready-to-use products, which have similar health benefits to the original raw products, has also increased in recent years (DEWANTO *et al.* 2002). Due to changing life styles especially in developed countries, there is now a great demand for a wide variety of dried food products with emphasis on high quality (NIJHUIS *et al.* 1996). In the tropical region tomato is a seasonal crop and hence there is surplus in one season and shortage in another. Each year a large quantity of tomato is being spoiled due to lack of proper processing and preservation facilities. These vegetables are highly perishable but have high nutritive value, ripen altogether within a short duration. A large quantity (20-50%) of tomato perishes during the harvesting season when the supply is abundant (DESAI *et al.* 1999). As a result, price of tomato falls drastically and producers cannot even get a return on their production cost. But the price of dried tomato always remains high even at the harvesting season. There is an increasing interest in dried tomato in the international market. The amount of tomato, which is being spoiled, can be minimized and value added by proper drying of freshly harvested product.

In Bangladesh small farmers in the rural areas usually produce vegetables. They do not have enough money to buy a modern drier or freezer to preserve the products. Therefore, one approach is to develop a package of solar drying systems for tomatoes as a means to help small producers to preserve their products from spoilage and seasonal low sale price. This will even out seasonal supply of the product by drying the excess production at harvest for sale out of season. Thus, they will be economically benefited with a small capital investment. There is also a benefit to be gained by improving the nutritional quality of peoples diet out of season. Dried tomato could also form a continuous input to processing industries and this could lead to new packaged products such as sauces and snack foods. This product can also be sold in the international market to earn foreign currency.

Bangladesh is a tropical country characterized by hot and humid weather. The climatic condition dictates the need of more effective drying of vegetables. Drying of vegetables in Bangladesh is normally carried out by traditional sun drying method. Although sun drying offers a cheap and easy method of drying but the drying rate is very slow and it often results inferior quality due to dependence of weather conditions and vulnerability to the attack and contaminated with insects, pests, micro-organisms, dust, and dirt. Fruits and vegetables are high moisture crops and take long times (5-15 days) for drying. Some

times adverse weather exists and the products are infected by insects and micro-organisms and these infected products are serious health hazards- not fit for human consumption. If continuous adverse weather exists for a couple of days together then the whole amount of products are spoiled. This creates serious negative economic impact on the farmers or processors to continue their further activities. Therefore, an effective attempt has to be taken to preserve the food losses, especially during the adverse weather conditions.

Fruits and vegetables have special morphological features quite distinct from other agricultural materials used as food that greatly influence their behaviour during processing and preservation especially by drying (JAYARAMAN & DAS GUPTA 1992). Over the last few years fresh tomato and tomato products, due to their antioxidant activity, have aroused new scientific interest. Tomato components include lycopene, ascorbic acid, flavonoids and other related compounds with an antioxidant activity (GIOVANELLI *et al.* 2002). Dried tomato, being commonly dried at high temperatures in the presence of oxygen, shows the highest sensitivity of oxidative heat damage. With regard to the nutrition of processed tomato, food processors are very concerned about the antioxidant activity of tomato products, with particular attention to the fate of lycopene. Fresh tomato contains high moisture content (about 95%, wb) and is very susceptible to disease and insect attack. Tomato is also very sensitive to drying air conditions (temperature, relative humidity etc.). If it is dried at higher air temperature then most of its nutrients (colour, lycopene, ascorbic acid, total flavonoids etc.) deteriorate and also affected by case hardening and if it is dried at a lower temperature then it is infected by micro-organisms. Hence, an optimum drying air temperature range should be selected to prevent nutrient losses as well as the microbial infections.

The technology used in industrialised countries and large industries in developing countries is neither technically or economically feasible for smallholders. In these countries solar drying is the most suitable method of preservation of vegetables by small farmers who produce more than 80% of food (ESPER & MÜHLBAUER 1998). Solar energy is a renewable source of energy and environment friendly. All the areas of Bangladesh receive abundant solar radiation almost all round the year. Solar drying of crop is economically viable in the developing countries due to low initial and operating cost. Solar drying is not simply an energy consuming process but a process for producing high quality products. The type of drier used and the way in which it is operated has a significant influence on the quality of the product. Solar drying system must be properly designed in order to meet particular drying requirements of specific crops and to give satisfactory performance with respect to energy requirements. Designers should investigate the basic parameters namely dimensions, temperature, relative humidity, airflow rate and quality and the characteristics of the product to be dried. However, full scale experiments for different products, drying season and system configuration is costly, time consuming and sometimes may not be possible. Simulation model enables the researcher to evaluate the performance of the solar drier before actual production of the prototype and experiment is done. The development of a mathematical model is a powerful tool for prediction of performance of solar drying system at various operating conditions without having to test experimentally at each operating

condition (BALA & WOODS 1994). Again, simulation of solar drying is essential to optimize the dimensions of the solar drying system and optimization technique can be used for optimal design of solar drier for production of high quality dried products.

This study will also cope with the international concerns of promoting high quality and standards in foods and development of clean and efficient technologies. In order to ensure continuous food supply to the growing population and enable small farmers to produce high quality marketable products, this study will help for the development of efficient drying methods suitable for the rural farmers of developing countries. This study will lead to a significance increase of the value of the dried products; reduce the risk of spoilage, thus resulting in higher income per unit. It will help the establishment of small-scale vegetables drying industry in the developing countries where about 80% people live. This will eventually lead to higher profit and thus will generate one of the income-earning sources of the rural poor and ultimately alleviate the rural poverty through participation of the rural women in solar drying of tomato. Hence such a piece of research has a great economic potential for developing countries in the tropics and subtropics.

A systematic research on the solar drying of tomato with both experimental investigation and mathematical modelling has not been reported in the literature. Therefore, the present study will cover experimental and theoretical aspects of solar drying of tomato including its quality and shelf life that will contribute to the knowledge on quality dried products for local consumption as well as exports to foreign countries. This research will also generate scientific information useful for academics, researchers, processors and other users.

OBJECTIVES

The specific objectives of the study are:

1. To study the drying behaviour and properties of tomato
2. To perform single layer drying experiments in a laboratory drier at different air conditions and develop single layer drying models
3. To design, construct and test a small-scale solar drier prototype for drying of tomato
4. To develop a mathematical model to simulate forced convection solar drying of tomato
5. To investigate the quality of the dried tomato with international standard.
6. To investigate the shelf life of dried tomato

Chapter 1

DETERMINATION OF RIPENESS OF TOMATO BY COLOUR AND FIRMNESS

ABSTRACT

The ripeness of tomato was determined by surface colour and firmness. The selected tomato was Roma variety of medium size (average diameter 58.7 mm) and weight (average weight 124.6 g) according to the classification of USDA (1991). Colour was measured by chromameter and expressed colours in numerical terms along the L^* (from white to black), a^* (from red to green) and b^* (from blue to yellow) axes within the CIELAB colour sphere which were mathematically combined to calculate the hue angle, chroma, colour index and colour difference. Firmness was determined by penetrometer and rupture stress versus deformation curves were recorded. The rupture stress of optimum ripe tomato was found to be 12 to 22 N/mm². Above rupture stress, 22 N/mm² the tomato may be classified as unripe and below the rupture stress 12 N/mm² the tomato be over ripe. Significant differences were found among under, optimum and over ripe tomatoes for the colour parameters a^* , b^* , a^*/b^* , $(a^*/b^*)^2$, hue angle, colour index and colour difference. The colour value a^* , a^*/b^* , $(a^*/b^*)^2$ and colour index increased with the ripeness but L^* , b^* , hue angle and colour difference decreased with the ripeness. Good correlations ($R^2 \geq 0.90$) were found between rupture stress and a^* , b^* , hue angle, colour index and colour difference. Therefore these parameters may be considered as good colour parameters to measure the colour of tomato. Firmness or rupture stress decreased linearly as red colour value $+a^*$ increased. From red colour value ($+a^*$) +12 to +22 was found the range of optimum ripeness. Below the red colour value +12 may be under ripe and above +22 may be over ripe tomato.

INTRODUCTION

Tomato (*Lycopersicon esculentum* Mill.) is one of the most important vegetables and cash crop in the world, not only because of the volume of production but also because of its contribution to nutrition (KALOO 1993). Tomato is used in several forms and is widely used as a food ingredient. It is rich in nutrient compounds including vitamin C, flavonoids and carotenoids, which are beneficial for human health (WOLD *et al.* 2004). Many nutrients content depend on the ripeness of fruits. For example, lycopene and β -carotene comprises about 78 and 7% respectively of the total carotenoid content, which depends mainly on the red colour of the fruit (RAO *et al.* 1998). Ripeness is very important factor for harvesting, transportation, marketing, processing, consumption, taste and nutrient content of tomato. Tomato fruits are harvested in different ripening stages depending on the marketing and consumers requirements. It reflects the consumers' acceptance as well as market price. Consumers first test the ripeness of tomato by colour with visual observation and then test the firmness with finger pressing and try to find out the optimum ripe tomato. They do not go for complex scientific measurements. Consumers classify the tomato mainly in three categories optimum ripe, unripe and over ripe.

Tomatoes are classified into six ripeness stages based on external colour reflecting human ability to differentiate ripeness by USDA (1991). These are green (100% green colour), breaker (less than 10% of surface is not green), turning (10 to 30% of surface is not green), pink (30 to 60% of surface is not green), light red (60 to 90% of surface is not green) and red (more than 90% surface is not green or more than 90% of surface is red). The USDA colour classification is widely used for tomato fruits. However, for general producer or consumer these six stages of classification create complexity during grading or purchasing tomatoes. Some European countries have established 10 or even more colour stages, but an average consumers have trouble in finding differences among them (LOPEZ CAMELO & GOMEZ 2004).

Human identification of colour is quite complex where sensation like brightness, intensity, lightness, vividness etc. modifies the perception of the primary colour (red, blue and yellow) and their combinations. Although some colour charts were available, the introduction of the NORM colour system in 1931 by the CIE (Commission Internationale de l'Éclairage) made it possible to express colour in exact quantitative and numerical terms. An improvement of this system was developed in 1976 by CIELAB (colour space system) which defines colour better related to human perception where all conceivable colours can be located within the colour sphere defined by three perpendicular axes: L* (from white to black), a* (from green to red) and b* (from blue to yellow) (HEIDELBERG 1999). SHEWFELT *et al.* (1988) stated that human and colorimeter measure colour in different ways. Human sees colours in terms of lightness, hue and chroma by integrating complex perceptions. But colorimeter are capable of measuring pure colours of L*, a* and b* in the absence of the others.

Although colour is a good indicator of fruit maturity but colour parameters do not provide a reliable ripeness determination (DE JAGOR & ROELOFS 1996). In contrast, the ripeness of tomato may be determined in terms of firmness. Firmness is an important character of fruits and vegetables to determine ripeness. Different rapid and non-destructive methods have been developed to describe the firmness characteristics of fruits and vegetables such as initial slope of stress deformation curve, coefficient of elasticity, acoustic stiffness coefficient, impact stiffness coefficient, and rupture stress (FEKETE & FELFÖLDI 2001). Therefore, this study has been undertaken to determine the ripeness of tomato in terms of colour and firmness and to classify them in limited categories so that average consumers (especially for developing countries) can identify them easily.

MATERIALS AND METHODS

Sample Preparation

The fresh tomato of Roma variety (origin: The Netherlands) was selected for this study. First tomatoes were classified into three ripeness groups testing them by colour with visual observation and by firmness with finger pressing. Before conducting of experiments, total 75 (25 under ripe, 25 optimum ripe and 25 over ripe) uniform size and shape of fresh tomato were procured from a supermarket at Potsdam, Germany. These tomatoes were washed with normal water, wiped and stored them at 7 to 10°C and used within two weeks of purchase (LANA *et al.* 2005). The diameter of each tomato was measured with slide caliper and mass was weighed with an electronic balance. The average diameter and mass of each tomato were found to be 58.2 mm and 124.6 g respectively. The selected tomato was medium size (diameter; $D: 57.2 \leq D \leq 64.3$ mm) and weight (weight, $W: 99.4 \leq W \leq 256.0$ g) according to the classification of USDA (1991). The initial moisture content of fresh tomato was determined by gravimetric method (AOAC, 1975) and found to be 94 to 95% (wet basis).

Determination of Firmness

Compression tests of tomato were performed using a 'Zwick' Universal Testing Machine (type: BZ2.5/TS1S, Germany, **Figure 1.8**) with a 60 mm width flat plate probe was pressed on the full tomato with a constant speed of 2 mm/min. The force and deformation were recorded during the test. The deformation was calculated for 10 to 30% range of the rupture stress (FEKETE & FELFÖLDI 2001) and the slope of the curve determined by regression analysis. Four readings were taken at four places on the surface of each tomato and then the mean value was calculated. From the results the rupture stress and the slope of the stress/deformation curve were determined. Then the ripeness was estimated from the rupture stress and the slope of the stress/deformation curve for different groups of tomatoes.

Determination of Colour

The colour of fresh and dried tomato surface was measured by a Minolta CR-300 Chromameter (Minolta Co., Japan) in L^* (from white to black), a^* (from green to red) and b^* (from blue to yellow) chromaticity coordinates (**Figure 1.1**) using a Hunterlab colour difference meter. The colour was measured using CIELAB scale at D65 (Daylight–Neutral) illuminant. The instrument was standardized each time with a white ceramic plate. Four readings were taken at four places on the surface of each tomato and then the mean values of L^* , a^* and b^* were calculated. The different colour parameters were calculated using the following equations (LOPEZ CAMELO & GOMEZ 2004).

$$\text{Hue angle} = \tan^{-1}(b^*/a^*) \quad (1.1)$$

$$\text{Chroma} = (a^{*2}+b^{*2})^{1/2} \quad (1.2)$$

$$\text{Colour index} = 2000 a^*/\{L^*(a^{*2}+b^{*2})^{1/2}\} \quad (1.3)$$

$$\text{Colour difference} = \{(L^*-50)^2 + (a^*-60)^2 + b^{*2}\}^{1/2} \quad (1.4)$$

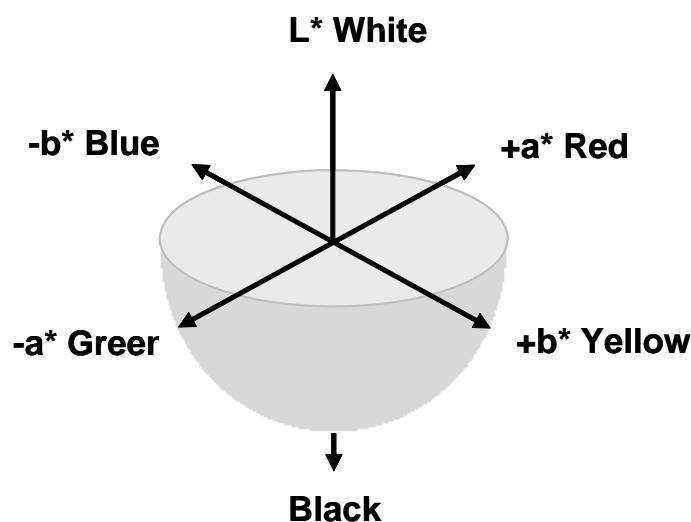


Figure 1.1: The CIELAB colour space system (LOPEZ CAMELO & GOMEZ 2004)

Also, the values of L^* , a^* , b^* , a^*/b^* and $(a^*/b^*)^2$ were calculated and the individual values from equation (1.1-1.4) were plotted and analysis of variance (ANOVA) was performed and compared the means by Duncan's multiple range test (DMRT) using software SPSS 9.0.

RESULTS AND DISCUSSION

Firmness

The firmness was determined by universal compression testing machine and curves were obtained for rupture stress and deformation as shown in **Figure 1.2**. For maximum stress, the slope of the curve was estimated. Then the slope versus rupture stress was plotted and a trend of the curve was obtained and a good fit was found at $R^2 = 0.91$ (**Figure 1.3**). It is observed from the Figure that firmness decreased with the ripeness. It is also observed that three sets of data were bounded to the straight line. Three clusters of data represent three stages of ripeness. FEKETE *et al.* (2000) found similar sets of data for different ripeness of tomato. The upper bounded data may be classified as unripe, middle bounded data as optimum ripe and lower bounded data were over ripe tomatoes. For about 3 mm deformation, the rupture stress of optimum ripe tomato was found to be 12 to 22 N/mm². Above rupture stress, 22 N/mm² the tomato may be classified as unripe and below the rupture stress of 12 N/mm² the tomato be over ripe. Therefore, rupture stress can be accepted as a good characteristic of the firmness as well as the ripeness of tomato. FEKETE & FELFOLDI (2001) reported that the rupture stress and stress/deformation curve is a suitable characteristic for tomato ripeness evaluation. They also reported that rupture stress could be accepted as the best method for determination of firmness as well as ripeness of tomato.

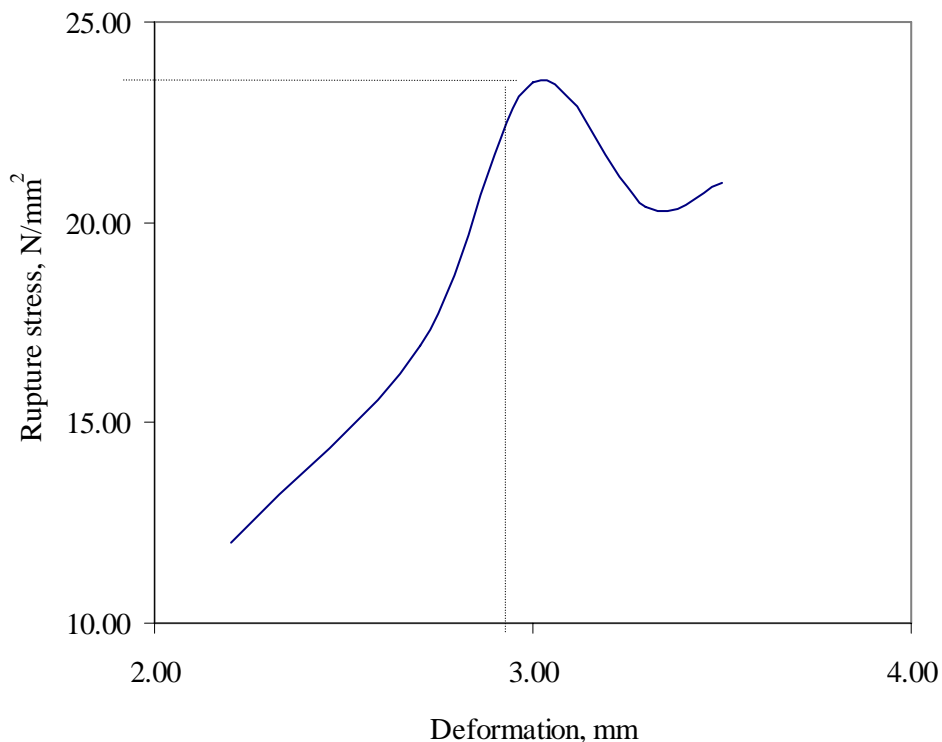


Figure 1.2: Rupture stress versus deformation curve

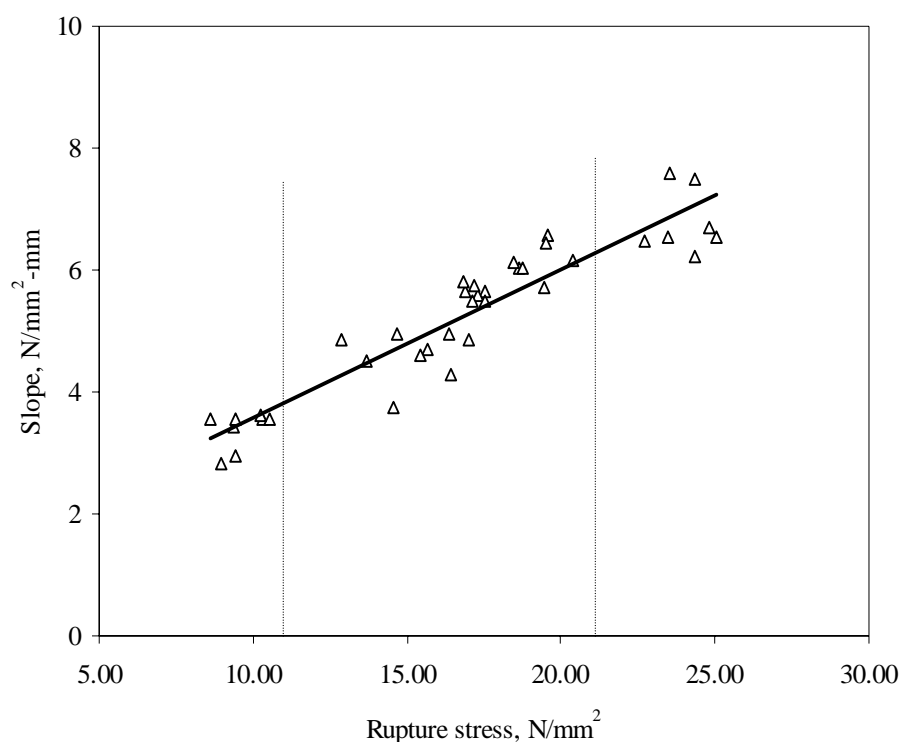


Figure 1.3: Slope versus rupture stress of tomato

Colour

Corresponding to the firmness, the colour L^* , a^* and b^* values were measured with chromameter and plotted the colour values against number of observations as shown in **Figure 1.4**. Each observation was a mean of four measurements at four places of the surface of a tomato. It is observed from the Figure that three ripeness stages indicated three distinct groups of data. The highest L^* and b^* but the lowest a^* values were observed for under ripe tomato. For under ripe tomato groups, some tomato were green in colour that represented negative values of a^* ($-a^*$) and some tomatoes were red in colour with positive but lower a^* ($+a^*$) values. Therefore, all tomato with red colours is not essentially ripe. For optimum ripe tomatoes, a^* values increased and subsequently L^* and b^* decreased. But the reduction of L^* values were found to be higher than b^* values. The reason might be that when ripeness progress then red colour pigments synthesized, L^* decreased rapidly to make the red colour darker (deep red). Some researchers (LOPEZ CAMELO & GOMEZ 1998 and 2004, ARIAS *et al.* 2000) showed that b^* values changed little during ripening stages.

This may be related to the fact that ζ -carotenes (pale-yellow colour) reach their highest concentration before full ripening, where lycopene (red colour) and β -carotene (orange colour) achieve their peaks (CHOI *et al.* 1995). For over ripe stage, the a^* values increased more and subsequently L^* and b^* values reduced further. But the degree of reduction of L^* and b^* values were opposite to optimum ripeness stage. In this case the

degree of reduction of b^* values were higher than those of L^* values. The reason might be that in over ripe stage all chlorophyll degraded and lycopine synthesized (LOPEZ CAMELO & GOMEZ 2004). As a result, a^* values increased and b^* values decreased.

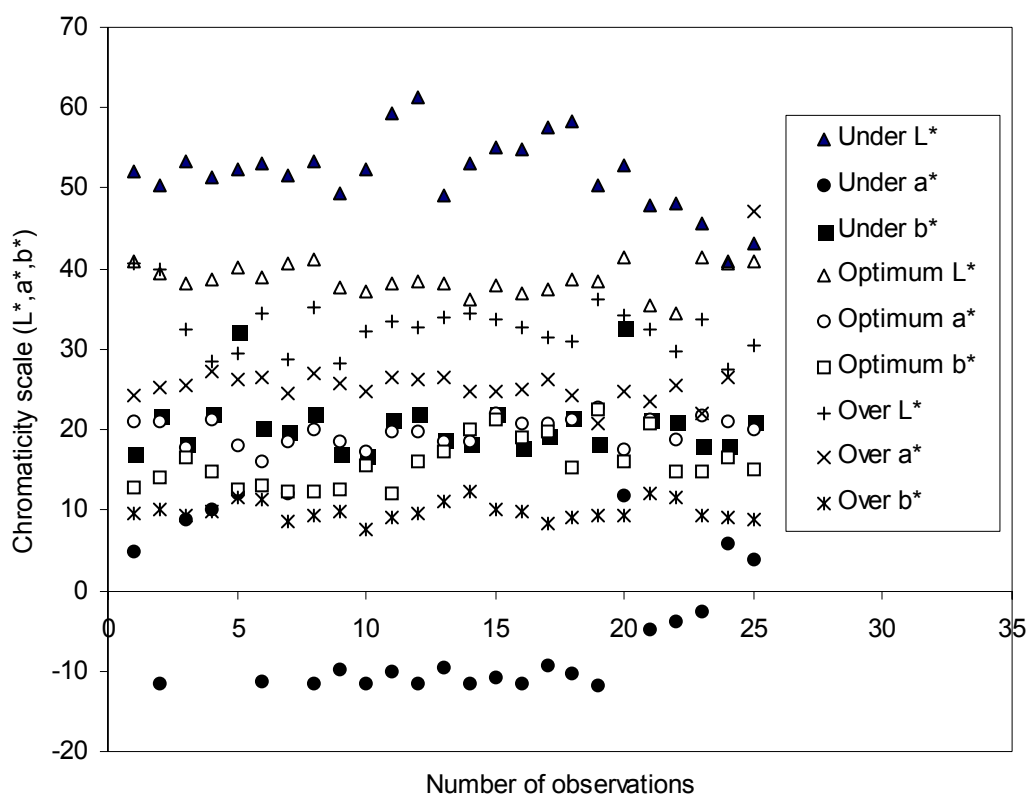


Figure 1.4: L^* , a^* and b^* values at different ripeness stages

The mean values of different colour parameters were calculated for different ripeness stages and presented in **Table 1.1**. Also the mean values of colour parameters were statistically analysed and compared by Duncan's multiple range test (DMRT) at different ripeness stages. The calculated colour parameters indicated that the differences in a^* , b^* , a^*/b^* , $(a^*/b^*)^2$, hue angle, colour index and colour difference among under, optimum and over ripe tomatoes were significantly differences from each other. For L^* value, there was significant difference from under and optimum ripe but the differences between optimum and over ripe were found to be insignificant. There was no significant difference of chroma between under and optimum ripe but for over ripe tomato the chroma was significantly higher than for both under and optimum ripe tomatoes. The colour values of a^* , a^*/b^* , $(a^*/b^*)^2$ and colour index increased with the ripeness. On the other hand, L^* , b^* , hue angle and colour difference decreased with the ripeness. This is due to that colour changed during tomato ripening were the result of L^* , a^* and b^* but a^* is the most dominant colour followed by b^* , related to chlorophyll degradation and lycopene synthesis to indicate the progress in ripening of tomato.

Table 1.1: Colour parameters of tomato at different ripeness stages

Ripeness	L*	a*	b*	a*/b*	(a*/b*) ²	Hue angle	Chroma	Colour index	Colour difference
Under	51.86a	-2.96c	20.76a	0.44c	1.31bc	63.71a	26.65b	-8.67c	72.37a
Optimum	38.72b	19.47b	15.93b	1.28b	1.68b	32.80b	25.50b	40.30b	44.82b
Over	32.69b	25.26a	9.86c	2.69a	7.64a	8.70c	27.92a	57.56a	39.62c

Values with the same letter in the same column are not significantly different at 5% level by DMRT.

The coefficient of determination between firmness (rupture stress) and different colour parameters were calculated and are given in **Table 1.2**. Higher coefficients of determination ($R^2 \geq 0.90$) were found for a*, b*, hue angle, colour index and colour difference. So, The best fit were found between rupture stress and a*, b*, hue angle, colour index and colour difference. Coefficients of determination for L* and a*/b* was reasonably good ($0.80 < R^2 < 0.90$). Hence, an acceptable fit was found between rupture stress and L* and a*/b*. But for (a*/b*)² and chroma, the coefficient of determination was insignificant ($R^2 < 0.80$).

Table 1.2: Coefficient of determination (R^2) of rupture stress and different colour parameters

Ripeness	L*	a*	b*	a*/b*	(a*/b*) ²	Hue angle	Chroma	Colour index	Colour difference
Under	0.81	0.92	0.90	0.82	0.74	0.97	0.73	0.93	0.93
Optimum	0.83	0.95	0.92	0.80	0.72	0.93	0.79	0.94	0.96
Over	0.79	0.94	0.92	0.83	0.85	0.91	0.78	0.95	0.97

However, most of the tomato literature mainly express colour changes in terms of different mathematical combinations of a* and b* on the chromatic equatorial plane. Some researchers (HAHN 2002, SACILIK *et al.* 2006) have used only a* values while others (YANG & CHINNAN 1987, McDONALD *et al.* 1999, Zanoni *et al.* 1999) have used a*/b* relationship to represent the ripeness of tomato. This ratio has been also used to develop mathematical models in order to express colour changes at different temperatures. Hue angle is another parameter that has been widely used to express tomato colour changes (THAI *et al.* 1990, CHOI *et al.* 1995).

Since, rupture stress is assumed the accepted and best characteristic to measure the firmness as well as the ripeness of tomato (FEKETE & FELFÖLDI 2001), therefore a*, hue angle, colour index and colour difference are the good colour parameters to measure the colour of tomato. Among them hue angle, colour index and colour difference are complex to calculate and not easily understandable by the common people. The colour parameter

a^* is directly measurable by colorimeter or chromameter and also easy to understand by the common people. For example, if the value of a^* is negative ($-a^*$), the tomato is green or unripe. If the value of a^* is positive ($+a^*$), the tomato is red and ripe. But all red tomatoes are not essentially ripe. They may physiologically mature but for consumer's acceptance they are not ripe. Then the under ripe, optimum ripe and over ripe tomatoes can be differentiated by the firmness of tomato. Other words, the rupture stress or firmness can be estimated from the red colour value (a^*). The following regression equations were developed for under ripe, optimum ripe and over ripe tomatoes in terms of red-green colour (a^*) and firmness or rupture stress (F , N/mm^2). The regression curves for under ripe, optimum ripe and over ripe tomatoes are shown in **Figures 1.5, 1.6** and **1.7** respectively. It is observed from the regression equations and regression curves that firmness or rupture stress decreased linearly as colour value a^* increased i.e. the firmness of tomato decreased as ripeness increased.

$$F_{\text{under}} = 15.372 - 0.4473a^* \quad (R^2 = 0.92) \quad (1.5)$$

$$F_{\text{optimum}} = 56.331 - 2.014a^* \quad (R^2 = 0.95) \quad (1.6)$$

$$F_{\text{over}} = 93.380 - 3.0291a^* \quad (R^2 = 0.94) \quad (1.7)$$

It has been observed from the Figs. (Figs. 1.5, 1.6 and 1.7) that from red colour value ($+a^*$) +12 to +22 were the range of optimum ripeness of tomato. Below the red colour value +12, tomato may be under ripe and above the red colour value +22, tomato may be classified as over ripe.

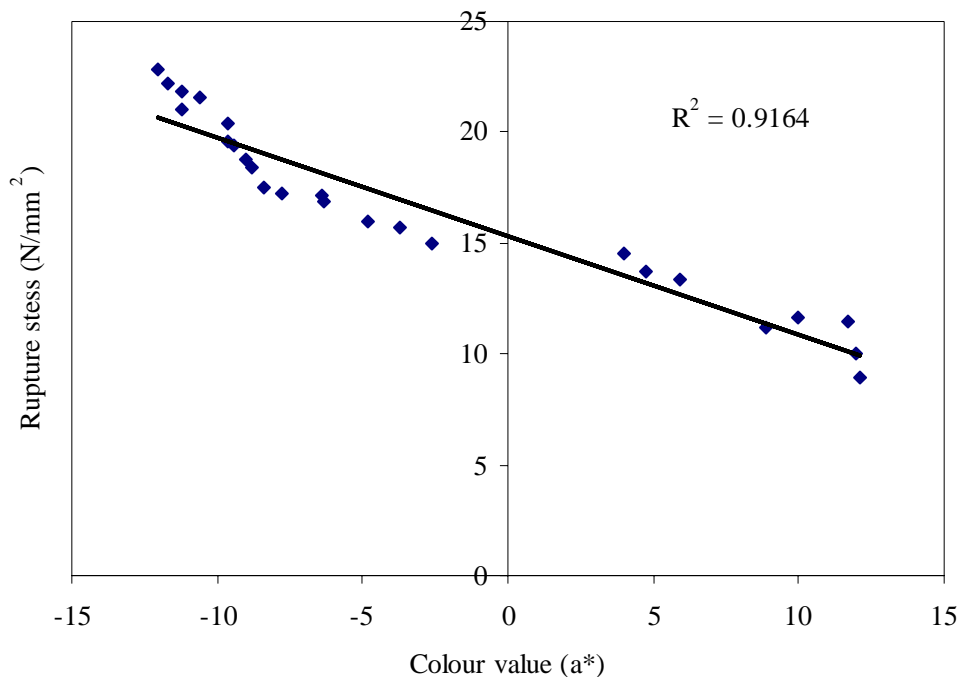


Figure 1.5: Rupture stress versus red chromaticity (a*) for under ripe tomato

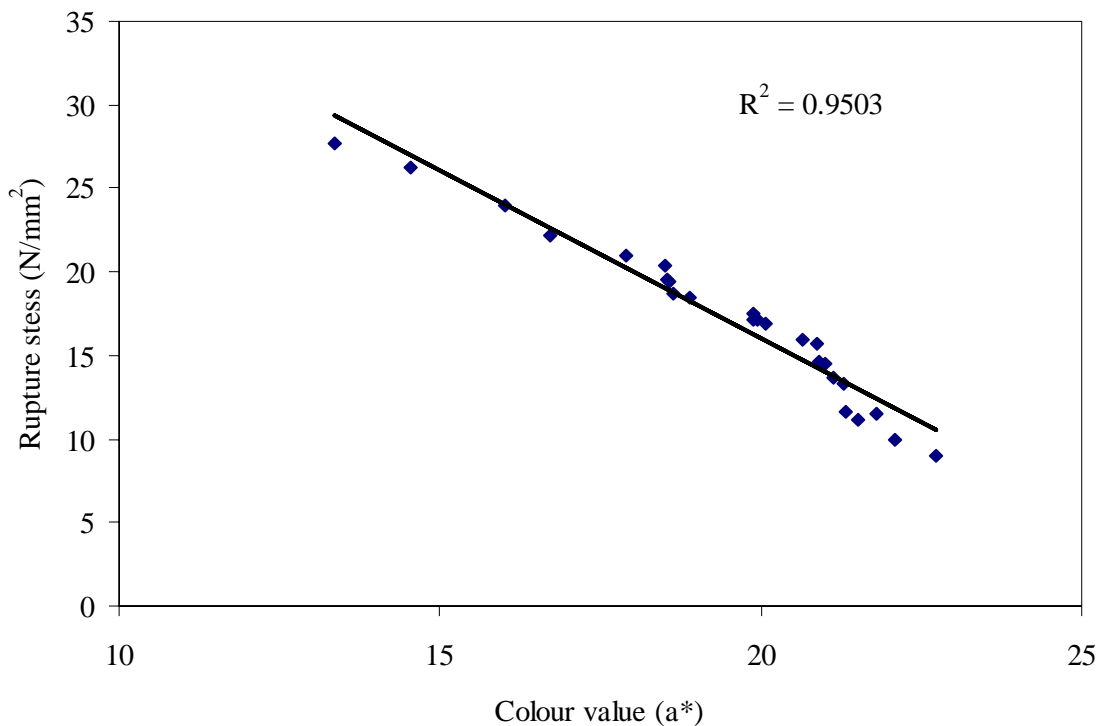


Figure 1.6: Rupture stress versus red chromaticity (a*) for optimum ripe tomato

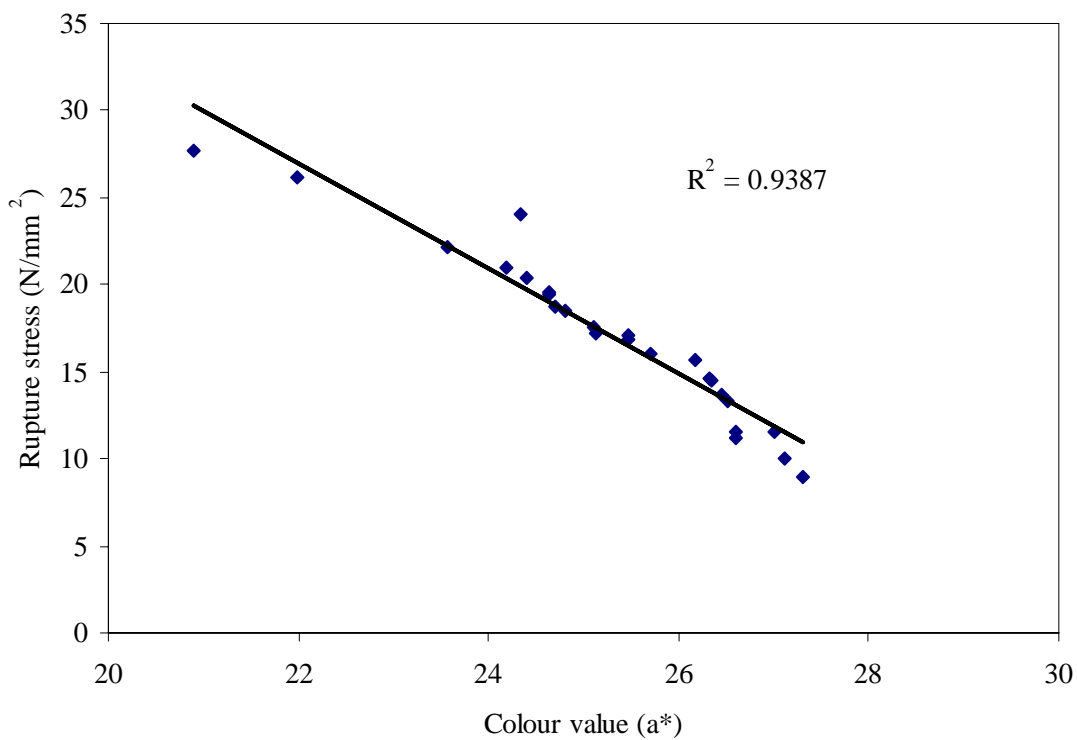


Figure 1.7: Rupture stress versus red chromaticity (a*) for over ripe tomato



Figure 1.8: Compression tests of tomato using a 'Zwick' Universal Testing Machine

CONCLUSIONS

The rupture stress of optimum ripe tomato was found to be 12 to 22 N/mm². Above rupture stress of 22 N/mm² the tomato may be classified as unripe and below the rupture stress 12 N/mm² the tomato be over ripe. Rupture stress can be accepted as a good characteristic of the firmness as well as the ripeness of tomato. Significant differences were found among under, optimum and over ripe of tomatoes for the colour parameters of a*, b*, a*/b*, (a*/b*)², hue angle, colour index and colour difference. The colour values of a*, a*/b*, (a*/b*)² and colour index increased with the ripeness but L*, b*, hue angle and colour difference decreased with the ripeness. Good correlations (R²= 0.90) were found between rupture stress and the colour parameters a*, b*, hue angle, colour index and colour difference. Therefore these colour parameters are the good measure of colour for tomato. Firmness or rupture stress decreased linearly as colour value a* increased i.e. the firmness of tomato decreased as ripeness increased. From red colour value (+a*) +12 to +22 was found the range of optimum ripeness. Below the colour value of +12, tomato may be under ripe and above +22, may be classified as over ripe tomato.

CHAPTER 2

DETERMINATION OF OPTIMUM CONDITIONS FOR HALF FRUIT DRYING CHARACTERISTICS OF TOMATO

ABSTRACT

Drying kinetics of half fruit tomatoes were investigated in a laboratory scale hot air dryer at an air velocity of 0.13 to 1.00 m/s and temperature range of 45 to 65°C to find out the optimum drying conditions in terms of drying rate and colour. This experiment was conducted at the Leibniz-Institut für Agrartechnik Potsdam-Bornim, during October to December 2005. Drying rate and shrinkage increased significantly with the increase in air temperature. But the value for green-red chromaticity coordinate colour (a^*) decreased significantly for increase in air temperature. Drying rate increased with the increase of air velocity up to 0.75 m/s. Above this air velocity, drying rate became independent of air velocity. Effect of air velocity was found insignificant on colour and shrinkage. The optimum drying air conditions was the temperature of 55°C and air velocity of 0.75 m/s, when both drying time and colour were considered. The drying rate of over ripe tomato was found higher than that of optimum ripe and unripe (green) tomato. The effective moisture diffusivity was determined including the shrinkage of tomato during drying and the shape of the half fruit tomato was assumed as slab shape. The effective moisture diffusivity of tomato increased linearly from 9.2×10^{-9} to 2.16×10^{-8} m²/s as drying air temperature increased from 45 to 64°C. The activated energy of tomato was calculated and found to be 37.72 kJ/mol. The experimental data were fitted to six different single layer drying models such as the Lewis, the Page, the Henderson and Pabis, the Two term exponential, the Approximation of Diffusion and MIDILLI *et al.* (2002) models by nonlinear regression method. Among the selected models the MIDILLI *et al.* (2002) model was found the best to predict the moisture content of tomato at different drying air conditions. Hence, optimum ripe half fruit tomato may be dried at an air temperature of 55°C and air velocity of 0.75 m/s and MIDILLI *et al.* (2002) model may be recommended to describe the single layer drying of tomato.

INTRODUCTION

Drying of tomato is carried out by open sun drying, solar drying or mechanical drying. Therefore, it is important to know the drying characteristics of tomato. The drying rate of tomato is closely associated with the drying air temperature, relative humidity and air velocity. One of the most important criteria of food is colour. Undesirable changes in the colour of food may lead to a decrease in consumers' acceptance as well as market value. It is essential to dry tomato in a suitable environment to produce a good quality dried products. The efficiency of the drying system can be improved by the analysis of the drying process. Analysis of the drying system can be greatly expedited by using computer simulation. A generalized single layer tomato drying equation is therefore, needed for this purpose. The equation must be suitable for use at any temperature, relative humidity and air velocity of the drying air used in tomato drying.

Investigators developed theoretical, semi-theoretical and empirical equations to express and explain the single layer drying of fruits and vegetables. Several thin layer drying models available in the literature for explaining thin layer drying characteristics of fruits and vegetables have been used by AFZAL & ABE (1999) for potato slices; KARATHANOS & BELESSIOTIS (1999) for fig; YALDIZ *et al.* (2001) for sultana grape; DANDAMRONGRAK *et al.* (2002) for banana; DOYMAZ & PALA (2002) for red paper; TOGRUL & PEHLIVAN (2003) for apricot and LAHSASNI *et al.* (2004) for prickly pear peel.

GIOVANELLI *et al.* (2002) studied the water diffusivity of tomato products at higher temperature (70 to 110°C), suitable for industrial drying. They calculated the apparent diffusivity including shrinkage of tomato products during drying. SACILIK *et al.* (2006) investigated the thin layer drying characteristics of half fruit organic tomato in solar tunnel drier. They fitted the experimental data to ten thin layer drying models and reported Approximation of diffusion equation was the best fitted model.

An understanding of the characteristics of tomato in terms of drying kinetics is essential for designing, modelling and optimisation of drying systems. Little information is available in the literature on half fruit drying characteristics of tomato in single layer at different air temperature and air velocity without significant loss of colour. Therefore this work has been undertaken to study the half fruit drying kinetics of tomato in single layer, to evaluate the suitability of some thin layer drying models and to optimise the drying parameters in terms of temperature, air velocity and colour.

MATERIALS AND METHODS

Laboratory Dryer

The experiments of drying of a single layer half fruit drying of tomato at various air temperature and air velocity were conducted in a laboratory scale dryer at the Leibniz-Institut für Agrartechnik, Potsdam-Bornim as shown in **Figures. 2.1** and **2.2**. The dryer

mainly consisted of a blower, heating unit, plenum chamber, drying chamber, sample container, a digital balance and data logger. A thermostat was used to control the temperature in the drying chamber. A controller was used to adjust the air velocity in the drying chamber. A series of sensors was inserted in the drying chamber to measure the air temperature and relative humidity. The sensors were connected with a PC via data logger for recording instantaneous data.

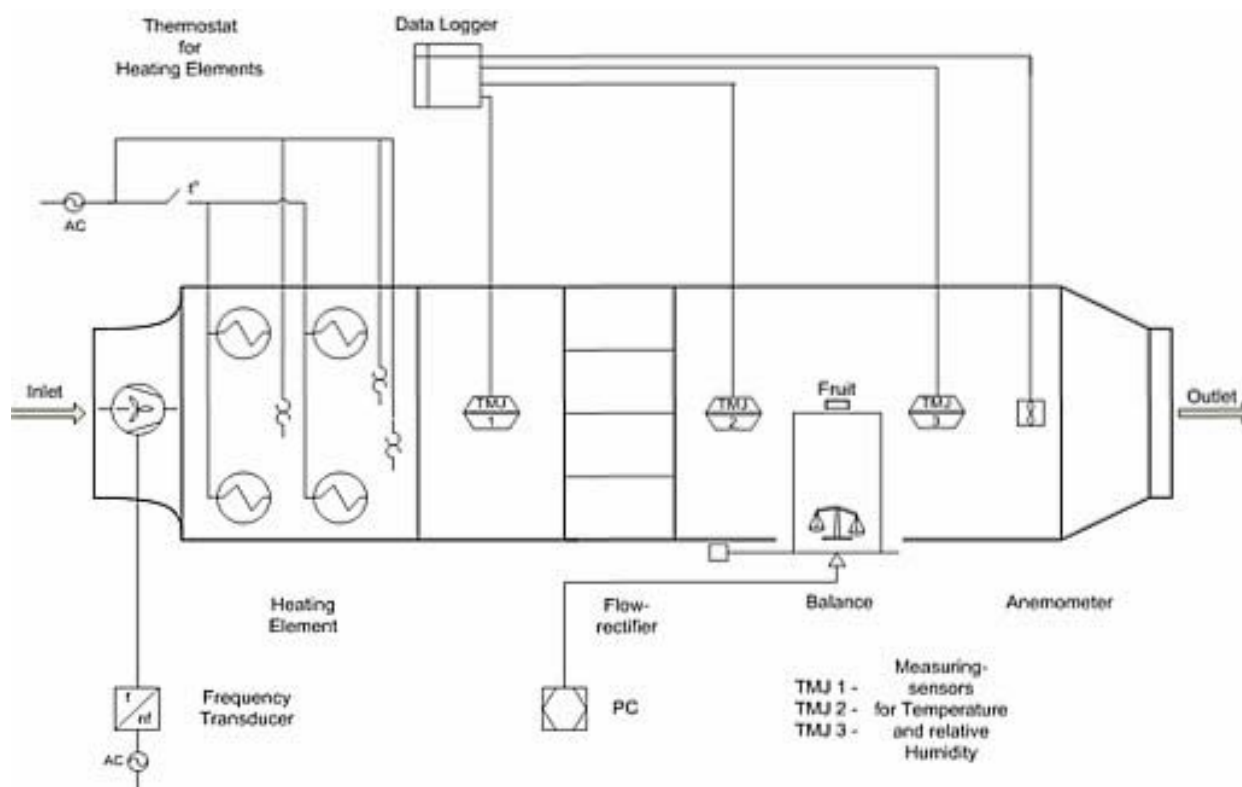


Figure 2.1: Schematic view of a laboratory scale single layer dryer

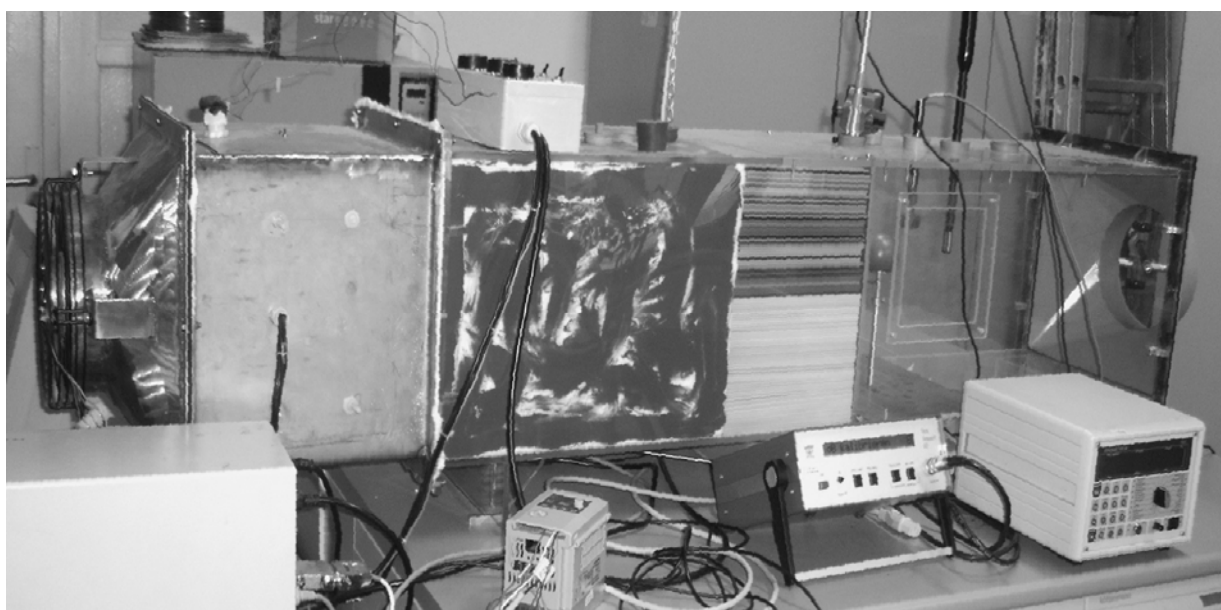


Figure 2.2: Photographic view of a laboratory scale single layer dryer

Determination of Shrinkage

For determination of shrinkage the length, diameter and thickness of half cut tomato were measured by Slide Caliper before and after drying. The diameter and thickness were measured at different places and the average values were calculated. Also the initial and final mass of the tomato half was measured by an electronic balance. Tomato shape is not regular. For our analysis, tomato shape is assumed as elliptical spheroid as shown in **Figure 2.3** and the cross-section area and volume of half cut tomato were calculated using the following formula.

Area of cross-section (A) = πcd and volume (V) = $4/3\pi cd^2$.

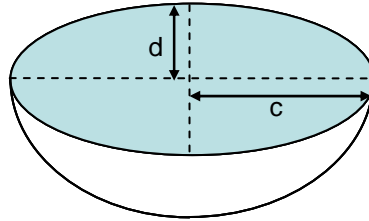


Figure 2.3: Elliptical spheroid shape of tomato

Volume, area and thickness were calculated using following formulas.

$$V_s = \frac{V_f}{V_i} \quad (2.1)$$

$$A_s = \frac{A_f}{A_i} \quad (2.2)$$

$$H_s = \frac{H_f}{H_i} \quad (2.3)$$

Single Layer Drying Experiment

Single layer drying experiments were conducted at 45, 50, 55, 60 and 65°C drying air temperatures and air velocity of 0.13, 0.25, 0.50, 0.75 and 1.00 m/s. Experiments were also conducted on different maturity stages of tomato such as under, optimum and over maturity conditions. Before starting the experiment all equipment was checked very carefully and was run for the required drying condition until the system had become stable. For each experiment a single half cut fruit with face upward was placed on the sample container in the drying chamber. Conditioned drying air flowed over and under the surfaces

and the weights; temperatures and relative humidity were recorded at every ten minutes with a data logger. The data-logging interval was adjusted at 10 minutes. The air off period for data recording was set at 30 seconds. After 9 minutes 30 seconds, the blower was automatically off and the balance became stable and data was recorded in still air in 10 seconds. The initial moisture content of fresh tomato was determined by air oven method (AOAC 1975). Before and after completion of each experiment, the length, width, thickness and colour of half fruit tomato were measured. Single layer experimental runs were conducted at 35 and 40°C temperatures. But during drying samples were infected by micro-organisms (mould/fungi). Therefore these data had not been included in this chapter.

Data Analysis and Model Development

Six commonly used thin layer equations (**Table 2.1**) available in the literature were used to fit the experimental data by the direct least square method using SPSS 9.0 (Statistical Package for Social Science) software. The test of significant was tested by complete randomised block design. The static equilibrium moisture content was obtained from the works of HUDA (2003).

Table 2.1: Different models used for experimental data fitting

Model No.	Name of model	Model expression
1	Lewis	$\frac{M_t - M_e}{M_0 - M_e} = \exp(-kt)$
2	Henderson and Pabis	$\frac{M_t - M_e}{M_0 - M_e} = a \exp(-kt)$
3	Page	$\frac{M_t - M_e}{M_0 - M_e} = \exp(-kt^n)$
4	Two term exponential	$\frac{M_t - M_e}{M_0 - M_e} = a \exp(-kt) + (1 - a) \exp(-kat)$
5	Approximation of diffusion	$\frac{M_t - M_e}{M_0 - M_e} = a \exp(-kt) + (1 - a) \exp(-kbt)$
6	MIDILLI <i>et al.</i> (2002)	$\frac{M_t - M_e}{M_0 - M_e} = a \exp(-kt^n) + bt$

The equations were evaluated in terms of coefficients of determination (R^2) and root mean square errors (RMSE) in the following statistical forms:

$$R^2 = \frac{(\sum M_{\text{exp}} M_{\text{pred}})^2}{\sum M_{\text{exp}}^2 \sum M_{\text{pred}}^2} \quad (2.4)$$

$$\text{RMSE} = \sqrt{\sum_1^N \left(\frac{M_{\text{pred}} - M_{\text{exp}}}{df} \right)^2} \quad (2.5)$$

Residuals of each model were plotted with experimental moisture contents. If residual plots indicate a systematic pattern, the model should not be accepted (CHEN & MOREY 1989, KALEEMULLAH & KAILAPPAN 2004). A model was considered best when the residual plots indicated uniformly scattered points, RMSE at a minimum value and R^2 at a maximum value.

Moisture Diffusivity and Activation Energy

Fick's second law of the unsteady state diffusion, neglecting the effects of temperature and total pressure gradient, can be used to describe the drying behavior of fruits and vegetables

$$\frac{\partial M}{\partial t} = \text{Div}(D \text{ grad } M) \quad (2.6)$$

This equation can be solved for slab shape of the drying material as follows.

$$\frac{M_t - M_e}{M_o - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left(- (2n-1)^2 \frac{\pi^2 D_e t}{z^2}\right) \quad (2.7)$$

Where n is number of order (1, 2, 3,...). For $n=1$, the Eqn (2.7) becomes

$$\frac{M_t - M_e}{M_o - M_e} = \frac{8}{\pi^2} \exp\left(-\pi^2 \frac{D_e t}{z^2}\right) \quad (2.8)$$

HAWLADER *et al.* (1991) proposed that z in Eqn (2.8) should be replaced with a modified thickness z' , related to the mass of sample by the following equation

$$\frac{z'}{z} = \left(\frac{W_t}{W_o} \right)^u \quad (2.9)$$

Where, W_o and W_t are the mass of sample at time zero and t respectively, u is an index is obtained by optimising experimental data from $\ln((M_t - M_e)/(M_o - M_e))$ as a function of t/z'^2 . Then the Eqn (2.8) for modified thickness was fitted to the experimental data of the half fruit of tomato and the diffusivity can be determined minimizing sum of squares of the deviations between the predicted and experimental data.

The effective moisture diffusivity can be expressed by simple Arrhenius equation as a function of temperature as follows (LOPEZ *et al.* 2000).

$$D_e = D_0 \exp\left(-\frac{E_a}{RT_a}\right) \quad (2.10)$$

From Eqn (2.10), activation energy was calculated by non-linear regression analysis.

RESULTS AND DISCUSSION

Effect of Temperature

The effect of air temperature on single layer drying of tomato is shown in **Figure 2.4**. Moisture loss increased with an increase in drying air temperature. There is no constant rate period of drying and drying took place only in the falling rate period. Differences of drying time between two consecutive drying temperatures were higher in lower temperature than those of in higher temperature. Time required for drying of tomato sample at 44.91, 51.13, 55.01, 61.06 and 64.30°C temperature were about 101.67, 77.00, 61.00, 56.67 and 45.17 hours respectively.

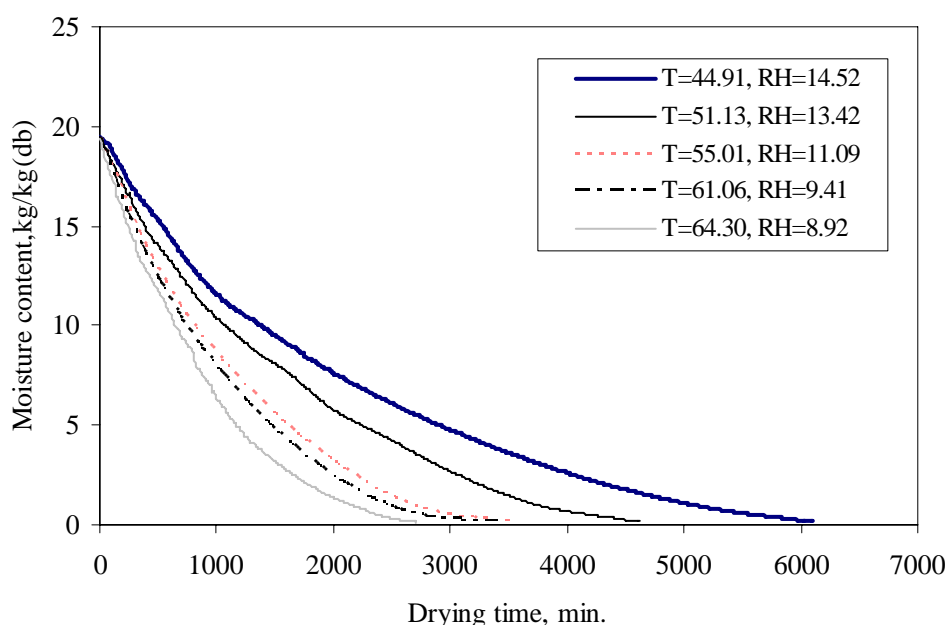


Figure 2.4: Single layer drying of tomato at different air temperatures ($v = 0.50$ m/s)

The increase in air temperature to accelerate the drying process was limited by the heat sensitivity of tomato. The effect of drying air temperature on colour of tomato is shown in

Table 2.2. It is observed from the Table that due to drying, the red colour of tomato decreased significantly from the fresh tomato. This reduction was significant for the air temperature of 44.91 and 51.13 and highly significant for the temperature of 55.01, 61.06 and 64.30°C. There was significantly difference of colour after drying among the temperatures but for the temperatures of 51.13 and 55.01°C the colour of dried tomato was statistically alike.

Table 2.2: Variation of colour of dried tomato at different air temperatures

Temperature (°C)	Before drying (a*)	After drying (a*)	Significance level
44.91	23.01	21.51a	5%
51.13	22.14	19.11b	5%
55.01	22.51	17.98b	1%
61.06	22.53	12.87c	1%
64.30	22.11	9.11d	1%
Significance level	Not significant	1%	

Effect of Air Velocity

The effect of air velocity on the single layer drying of red tomato is given in **Figure 2.5**. The moisture loss of tomato was faster at the higher air velocity and increased with air velocity. For an increase of air velocity from 0.12 to 0.75 m/s, the moisture loss of tomato increased but for an increase of air velocity from 0.75 to 1.00 m/s, the drying rate of tomato was almost constant. Time required for drying of tomato sample at 0.13, 0.25, 0.50, 0.75 and 1.00 m/s air velocity were about 89.83, 84.67, 81.5, 79.5 and 79.00 hours respectively. Hence, drying rate became independent of air velocities for the air velocity above 0.75 m/s. Air velocity above this value should be avoided to save energy. The effect of air velocity on colour of dried tomato is given in **Table 2.3**. There is no significant effect of air velocity on the red colour of tomato.

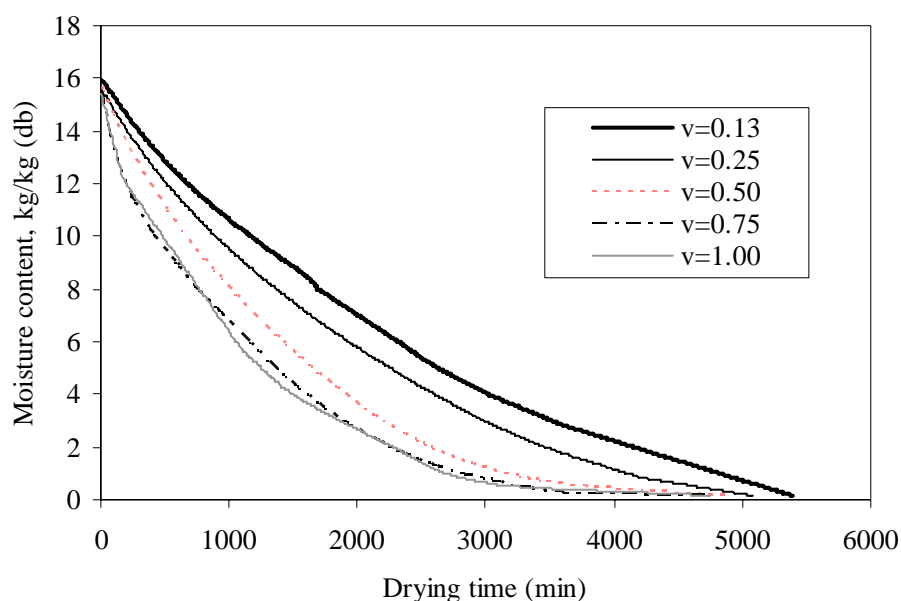


Figure 2.5: Single layer drying of tomato at different air velocity ($T=50^{\circ}\text{C}$, $\text{RH}=10\%$)

Table 2.3: Variation of colour of dried tomato at different air velocities

Air velocity (m/s)	Before drying (a^*)	After drying (a^*)	Significance level
0.13	19.65	18.35	1%
0.25	23.07	17.63	1%
0.50	21.05	18.32	1%
0.75	19.03	18.31	1%
1.00	19.39	17.43	1%
Significance level	Not significant	Not significant	

Effect of Ripeness

Effect of ripeness on moisture loss of tomato is given in **Figure 2.6**. It is observed from the Figure that the over-ripe sample dried faster than the optimum-ripe and under-ripe samples. This may be due to the fact that the cell walls and tissues of over-ripe tomato become softer than optimum-ripe and under-ripe samples and hence the moisture diffusivity as well as the drying rate became higher. The time required to reach final moisture content (about 15%, db) of over, optimum and under-ripe samples were 39.83, 48.17 and 53.16 hours respectively.

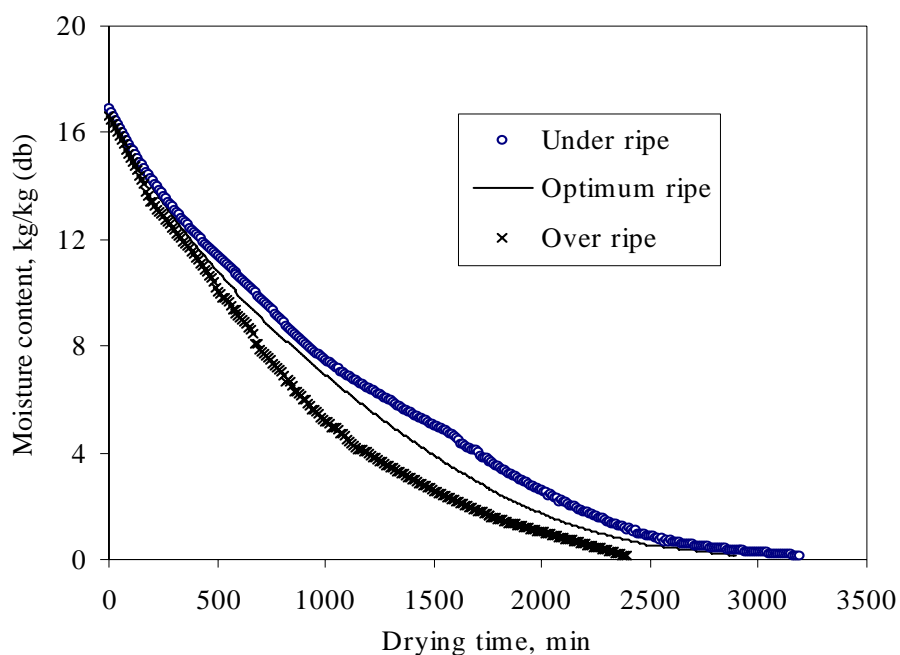


Figure 2.6: Half fruit drying characteristics of tomato at different ripeness stages

Optimisation of Drying Conditions

The drying air temperature, air velocity and ripeness were optimised based on the drying time and red colour value of dried samples. Scores were made based on the number of treatments. Such as for temperature, numbers of selected temperatures were five and total score for drying time or colour would be five. Lowest drying time got the highest score (5), highest drying time got the lowest score (1) and intermediated drying time got the intermediated scores ranged from 1 to 5. For colour, the scoring system was just opposite to drying time that the highest colour value got the highest score (5) and lowest colour value got the lowest score (1). The scores of drying time and red colour value of dried tomato samples at different drying conditions are tabulated in **Table 2.4**. It is observed from the Table that though the temperature 65°C got the highest score for drying time but it got the lowest score for colour. Similar scores were found for other temperatures, air velocities and ripeness. Hence, the overall drying conditions for full ripe half fruit tomato at the air temperature of 55°C and air velocity of 0.75 m/s was the best when drying time and colour were considered.

Air Temperature and Tomato Temperature

The drying air temperature, internal temperature, cut surface temperature and whole surface temperature of half fruit tomato during thin layer drying are shown in **Figure 2.7**. The drying air temperature was observed higher than the tomato temperature during the drying period. The whole surface temperature was found to be higher than the internal temperature followed by cut surface temperature but they were close to each other. At

the beginning of the drying process, the tomato temperature was much lower than the drying air temperature. This was due to the evaporative cooling on the surface of the tomato. As the drying process proceeded, the moisture on the surface decreased and the evaporation zone moved from the surface into the tomato and evaporation took place mainly from the cut surface. This is why whole surface temperature as well as internal temperature was higher than the cut surface temperature.

Table 2.4: The scores of drying time and red colour value of dried tomato samples at different temperature, air velocity and ripeness

Drying conditions		Drying time		Colour		Mean Score
		Hour	Score	a*	Score	
Temperature (°C)	44.91	101.67	1.00	21.51	5.00	3.00
	51.13	77.00	2.18	19.11	4.03	3.11
	55.01	61.00	3.59	17.98	3.58	3.58
	61.06	56.67	3.98	12.87	1.52	2.75
	64.30	45.17	5.00	9.11	1.00	3.00
Air velocity(m/s)	0.13	89.83	1.00	18.35	5.0	3.00
	0.25	84.67	2.38	17.63	2.08	2.23
	0.50	81.50	3.84	18.32	4.85	4.35
	0.75	79.50	4.77	18.31	4.78	4.77
	1.00	79.00	5.00	17.43	1.00	3.00
Ripeness	Under	53.16	1.00	-5.72	0.00	0.50
	Full	48.17	1.87	16.69	3.00	2.44
	Over	39.83	3.00	9.28	1.67	2.33

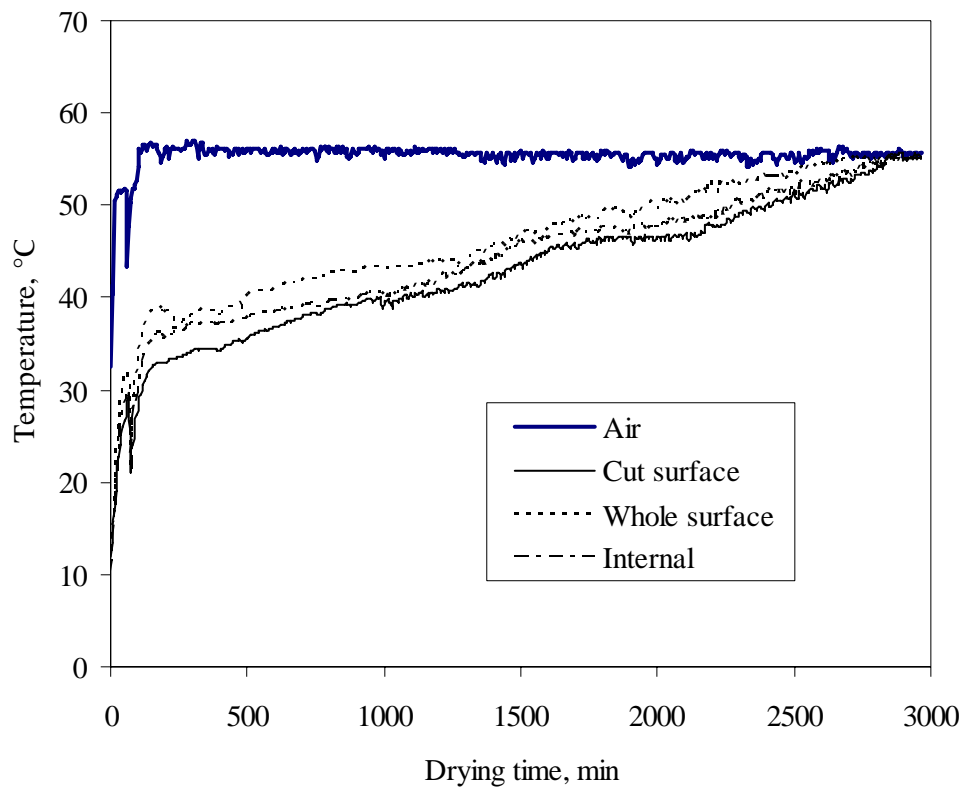


Figure 2.7: Temperature distribution at different position of a half fruit tomato during drying

Shrinkage

Volume, area and thickness shrinkages were calculated by direct measurement before and after drying of tomato samples. Shrinkages took place during drying of tomato. Effect of temperature on shrinkage of tomato is shown in **Figure 2.8**. Shrinkages took place linearly with the increase of temperature. Area shrinkage was found higher than thickness and volume shrinkage. Effect of air velocity on shrinkage of tomato is shown in **Figure 2.9**. There is no significant shrinkage observed due to air velocity. Also, area shrinkage was found higher than thickness and volume shrinkage. Over ripe samples shrunk more than the optimum and under ripe samples (**Figure 2.10**).

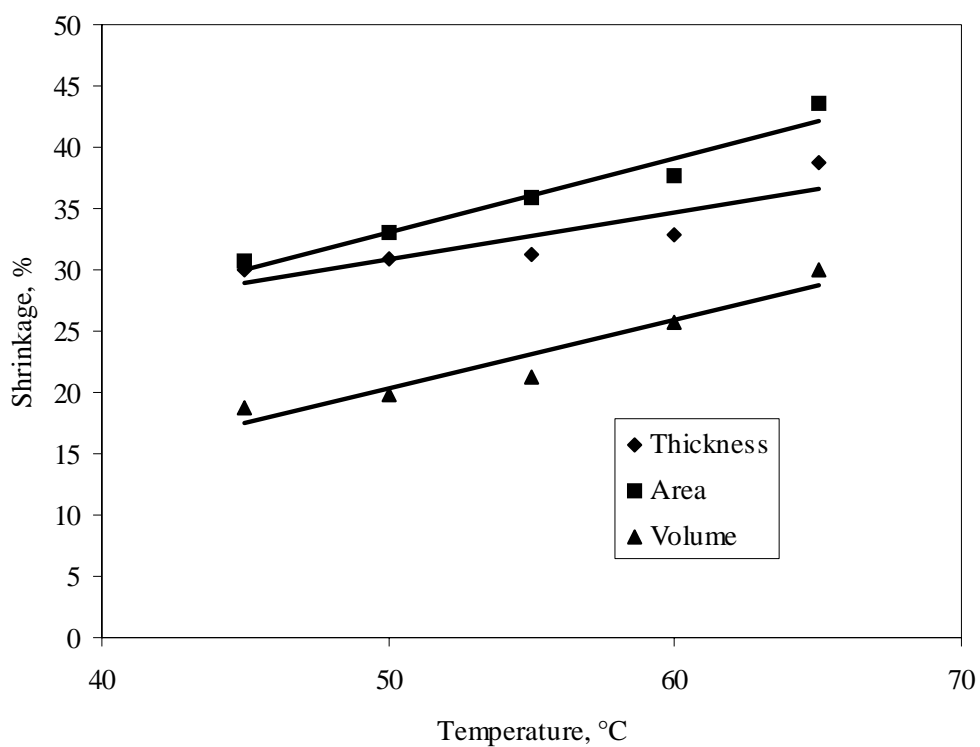


Figure 2.8: Effect of temperature on shrinkage of tomato

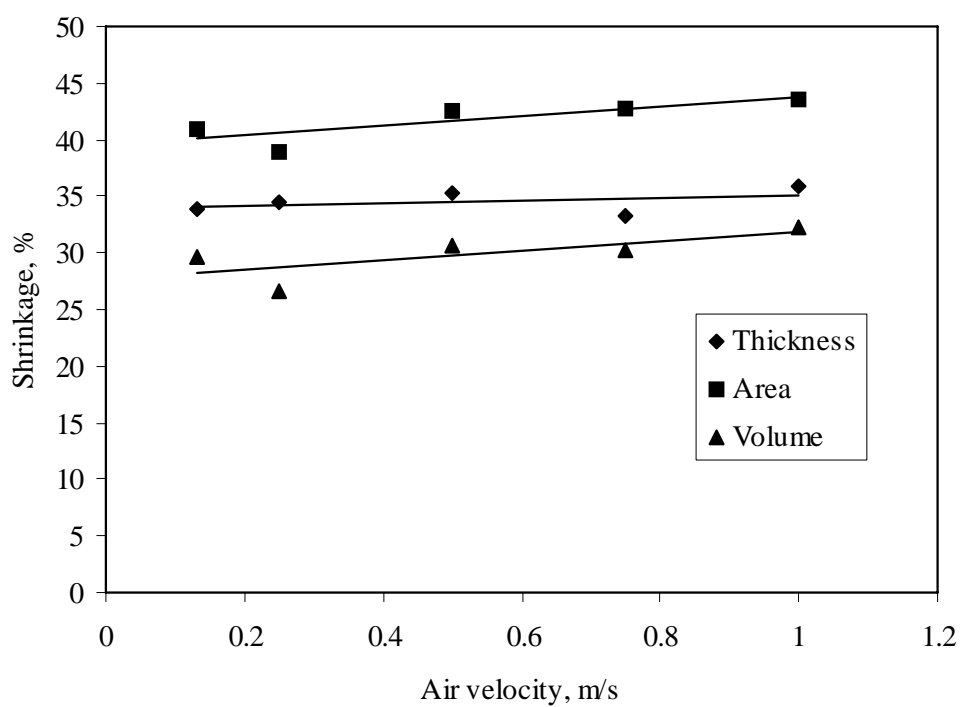


Figure 2.9: Effect of air velocity on shrinkage of tomato

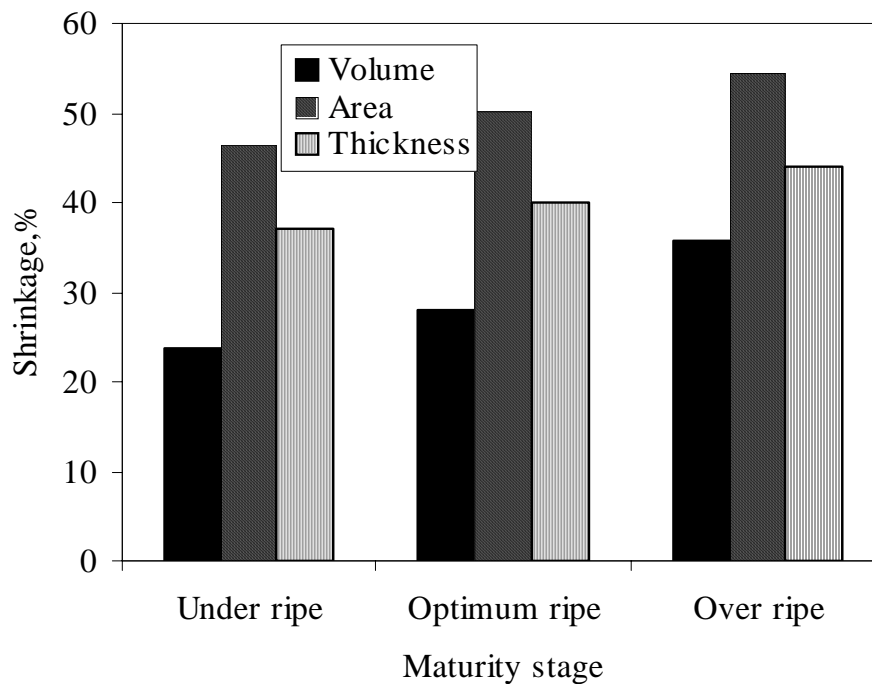


Figure 2.10: Effect of ripeness on shrinkage of tomato

Fitting of Experimental Data to the Models

Six thin layer equations were fitted to the experimental data for all experimental runs by direct least squares procedure. Model parameters, coefficient of determination (R^2), root mean square error (RMSE), grade and ranking of thin layer drying models at different air temperature and air velocity are presented in **Table 2.5** and **Table 2.6** respectively. From the Tables it is observed that MIDILLI *et al.* (2002) model gave the highest average coefficient of determination and lowest root mean square error followed by the Approximation of diffusion equation. Here, the highest R^2 and the lowest RMSE values indicated the lowest score and the lowest ranked model are considered to be the best fitted model. Hence, MIDILLI *et al.* (2002) model got the lowest average grade and ranked one and Approximation of diffusion equation ranked two followed by two term exponential equation and Page equation. Residual plots of different models for single layer drying of tomato are shown in **Figure 2.11**. For the MIDILLI *et al.* (2002) and the Approximation of diffusion models, the residual plots indicated a scattered pattern and the residuals are very close to X-axis leads to the inference that these models are suitable for predicting single layer drying of tomato. For other models, the residual plots indicated a systematic pattern and the residuals are not close to X-axis, which means that these models are not well fitted to experimental data. SACILIK *et al.* (2006) fitted the thin layer solar drying data of organic tomato in different thin layer models and reported that the Approximation of diffusion model was the best fitted model.

Table 2.5: Model parameters, coefficient of determination (R^2), root mean standard error (RMSE), grade and ranking of thin layer drying models at different air temperatures

Models	Temp. (°C)	a	b	k	n	R^2	RMSE	Avg. grade	Rank
Lewis	44.91			0.0004985		0.9935	0.01692	5.9	6
	51.13			0.0006227		0.9861	0.03041		
	55.01			0.0008859		0.9886	0.03079		
	61.06			0.0009708		0.9888	0.03112		
	64.30			0.0011573		0.9890	0.03459		
Page	44.91			0.0003402	1.04903	0.9944	0.01575	3.9	4
	51.13			0.0001749	1.16799	0.9945	0.01916		
	55.01			0.0003105	1.14505	0.9949	0.02062		
	61.06			0.0003305	1.15073	0.9954	0.01995		
	64.30			0.0003688	1.16443	0.9967	0.01892		
Hender-son and Pabis	44.91	1.0109609		0.0005041		0.9936	0.01676	5.1	5
	51.13	1.0469234		0.0006517		0.9886	0.02768		
	55.01	1.0440876		0.0009241		0.9905	0.02819		
	61.06	1.0469448		0.0010148		0.9909	0.02803		
	64.30	1.0460918		0.0012093		0.9912	0.03128		
Approxim-ation of Diffusion	44.91	1.0015057	-1.28756	0.0004761		0.9986	0.00801	1.6	2
	51.13	1.3027579	0.25560	0.0004367		0.9995	0.00556		
	55.01	1.2895901	0.31457	0.0006472		0.9992	0.00824		
	61.06	9.9332480	0.93847	0.0005452		0.9992	0.00827		
	64.30	10.801062	0.94285	0.0006468		0.9991	0.00997		
Two term exponential	44.91	1.459626		0.0005782		0.9948	0.01513	3.2	3
	51.13	1.675721		0.0008125		0.9946	0.01895		
	55.01	1.642528		0.0011320		0.9951	0.02031		
	61.06	1.651129		0.0012450		0.9855	0.01974		
	64.30	1.004240		0.0010776		0.9970	0.01801		
MIDILLI <i>et al.</i> (2002)	44.91	1.030338	-0.000018	0.0014199	0.84817	0.999	0.00499	1.4	1
	51.13	0.988831	-0.000019	0.0004014	1.03683	0.9995	0.00610		
	55.01	0.997026	-0.000021	0.0006779	1.01974	0.9990	0.00906		
	61.06	0.991952	-0.000018	0.0005951	1.05359	0.9989	0.00989		
	64.30	0.970869	-0.000015	0.0004024	1.13746	0.9992	0.00952		

Table 2.6: Model parameters, coefficient of determination (R^2), root mean standard error (RMSE), grade and ranking of thin layer drying models at different air velocity

Models	Air velo. (m/s)	a	b	k	n	R^2	RMSE	Avg. grade	Rank
Lewis	0.13			0.0004544		0.9846	0.02346	5.7	6
	0.25			0.0005407		0.9856	0.02302		
	0.50			0.0007447		0.9906	0.01886		
	0.75			0.0009127		0.9902	0.01751		
	1.00			0.0009234		0.9952	0.01237		
Page	0.13			0.0001132	1.17784	0.9942	0.01442	4.4	4
	0.25			0.0001493	1.16741	0.9941	0.01484		
	0.50			0.0002504	1.14676	0.9966	0.01138		
	0.75			0.0010266	0.98384	0.9903	0.01746		
	1.00			0.0078612	1.02223	0.9954	0.01218		
Henderson and Pabis	0.13	1.045162		0.0004757		0.9872	0.02148	4.8	5
	0.25	1.045731		0.0005645		0.9881	0.02106		
	0.50	1.039596		0.0007729		0.9920	0.01743		
	0.75	1.176133		0.0008712		0.9920	0.01762		
	1.00	1.212508		0.0009079		0.9955	0.01554		
Approximation of Diffusion	0.13	5.416245	0.818480	0.0002012		0.9994	0.00458	1.8	2
	0.25	1.161500	0.022692	0.0004026		0.9995	0.00441		
	0.50	13.69589	0.961873	0.0004469		0.9985	0.00752		
	0.75	1.012362	-0.15562	0.0008703		0.9920	0.01589		
	1.00	1.079830	0.340151	0.0008407		0.9966	0.01058		
Two term exponential	0.13	1.014027		0.0003947		0.9991	0.00558	3.4	3
	0.25	1.674720		0.0007063		0.9943	0.01459		
	0.50	1.648375		0.0009520		0.9969	0.01089		
	0.75	1.278933		0.0009759		0.9898	0.01785		
	1.00	1.397949		0.0001036		0.9958	0.01163		
MIDILLI <i>et al.</i> (2002)	0.13	0.986974	-0.000023	0.0003063	1.02256	0.9995	0.00431	1.1	1
	0.25	0.991084	-0.000021	0.0003991	1.01569	0.9995	0.00449		
	0.50	0.956333	-0.000005	0.0001834	1.17742	0.9986	0.00715		
	0.75	0.905695	-0.000006	0.0004943	1.06387	0.9964	0.01071		
	1.00	0.934753	-0.000003	0.0004192	1.09685	0.9978	0.00853		

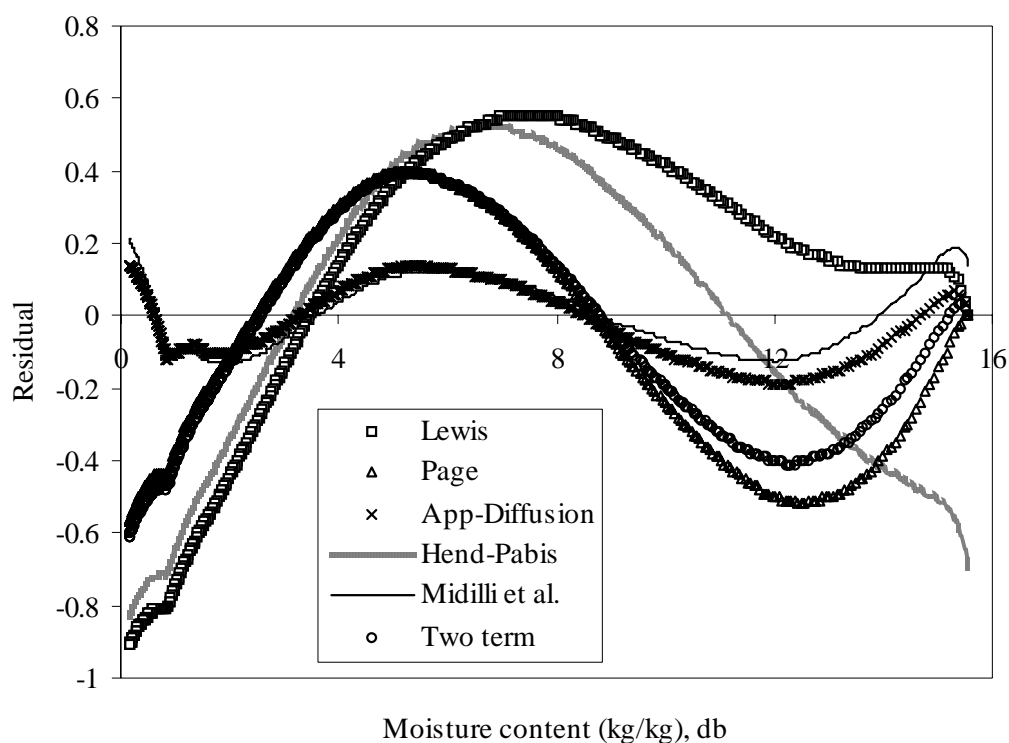


Figure 2.11: Residual plots of different models for single layer drying of tomato at $T=50.87^{\circ}\text{C}$, $\text{RH}=10.32\%$ and $\text{AV}=0.25 \text{ m/s}$

Development of models

The parameters of MIDILLI *et al.* (2002) model at variable temperatures (45 to 65°C) and relative humidity at constant air velocity (0.50 m/s) are found to be a multiple function of air temperature and relative humidity. Following regression equations were developed for the parameters of MIDILLI *et al.* (2002) model as a function of temperature, relative humidity and the product of temperature and relative humidity.

$$a = 1.454788 - 0.00393 \cdot T + 0.27268 \cdot \text{rh} - 0.04411 \cdot \text{rh} \cdot T \quad (R^2=0.98) \quad (2.11)$$

$$b = -0.00016 + 2.25 \times 10^{-6} \cdot T + 0.000924 \cdot \text{rh} - 1.41 \times 10^{-5} \cdot \text{rh} \cdot T \quad (R^2=0.99) \quad (2.12)$$

$$k = 0.005699 + 7.42 \times 10^{-6} \cdot T + 0.044428 \cdot \text{rh} - 0.00171 \cdot \text{rh} \cdot T \quad (R^2=0.99) \quad (2.13)$$

$$n = -0.61559 + 0.012895 \cdot T - 3.53225 \cdot \text{rh} + 0.214298 \cdot \text{rh} \cdot T \quad (R^2=0.98) \quad (2.14)$$

The parameters of MIDILLI *et al.* (2002) model at variable air velocities (0.13 - 1.00 m/s) are found to be a multiple function of air temperature, relative humidity, air velocity and the product of relative humidity and air velocity as follows.

$$a = -373.65 + 7.71703 \cdot T - 173.601 \cdot rh + 17.3014 \cdot v - 168.013 \cdot rh \cdot v \quad (R^2=0.99) \quad (2.15)$$

$$b = 0.139496 - 0.00287 \cdot T + 0.064258 \cdot rh - 0.00706 \cdot v + 0.06866 \cdot rh \cdot v \quad (R^2=0.98) \quad (2.16)$$

$$k = -2.37436 + 0.048823 \cdot T - 1.05443 \cdot rh + 0.131201 \cdot v - 1.27387 \cdot rh \cdot v \quad (R^2=0.99) \quad (2.17)$$

$$n = 1678.467 - 34.5278 \cdot T + 764.7873 \cdot rh - 87.7295 \cdot v + 852.2098 \cdot rh \cdot v \quad (R^2=0.99) \quad (2.18)$$

Figures 2.12 and **2.13** show the comparison the experimental and predicted moisture content from the MIDILLI *et al.* (2002) model. The predicted data mainly banded around the straight line which showed the suitability of the model in describing single layer drying behaviour of half fruit tomato. MIDILLI *et al.* (2002) fitted seven thin layer drying models to the experimental data of thin layer laboratory, forced solar and natural solar drying of mushroom, pollen and pistachio. They reported that this model was the best fitted model among the tested models. MIDILLI *et al.* (2002) model is the modification of the Page model incorporating two more parameters. These additional parameters increased the flexibility and degree of freedom of the model for fitting ability of thin layer drying data.

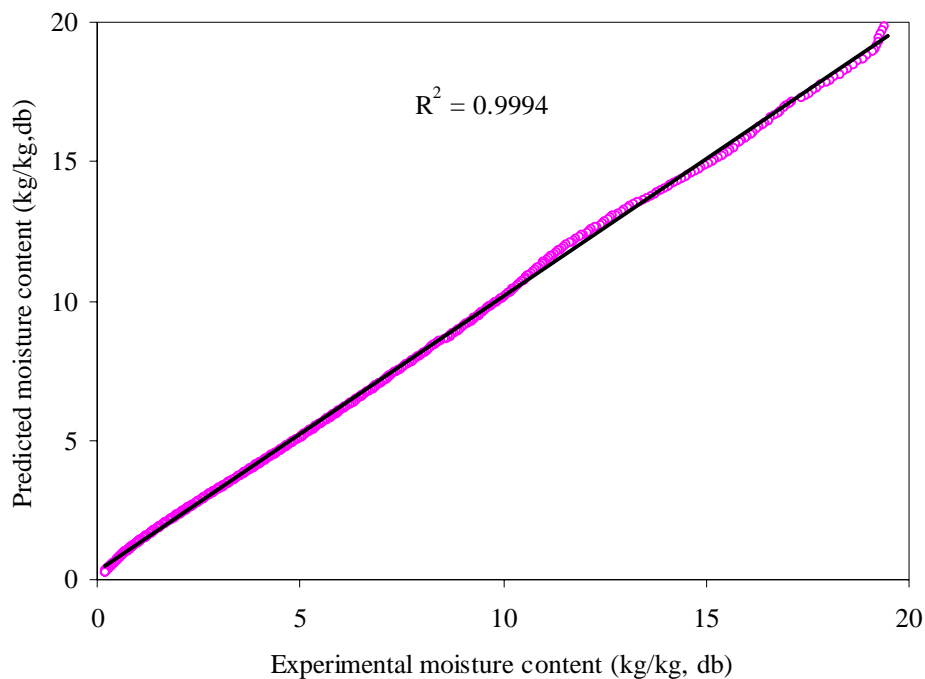


Figure 2.12: Experimental and predicted moisture content for single layer drying of tomato (T=44.91°C, RH=14.52%, v=0.50 m/s)

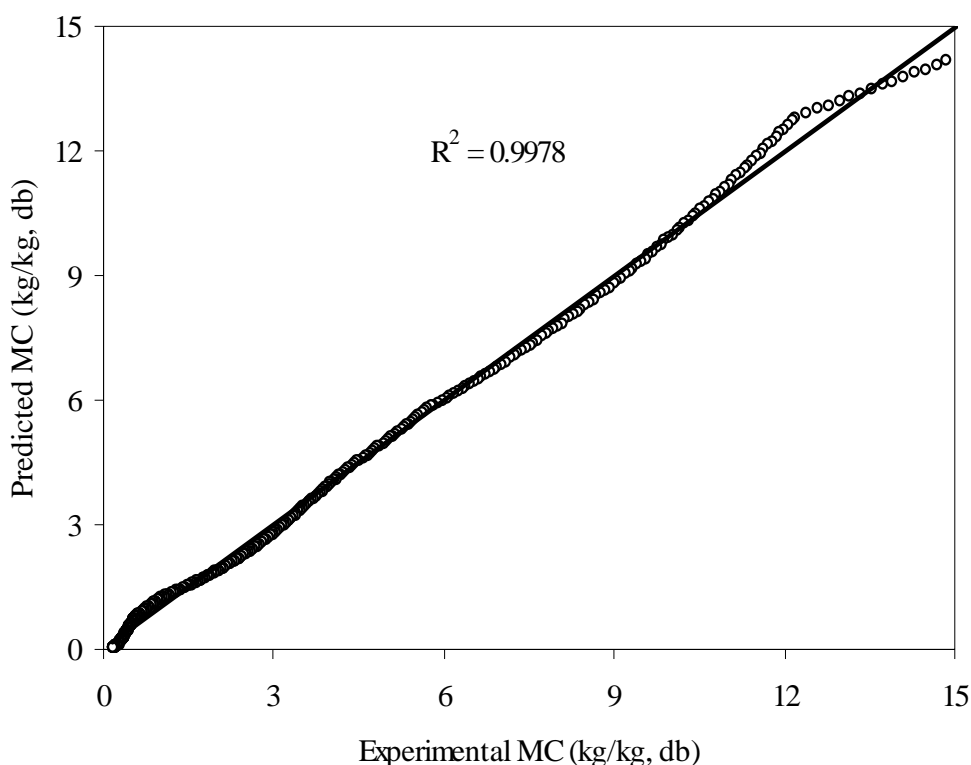


Figure 2.13: Experimental and predicted moisture content for single layer drying of tomato ($T=50.76^{\circ}\text{C}$, $\text{RH}=10.08\%$, $v=1.00$ m/s)

Moisture Diffusivity and Activation Energy

The effective moisture diffusivity was determined considering the shrinkage of tomato during drying and the shape of the half fruit tomato was assumed as slab shape. The effective moisture diffusivity of tomato increased linearly from 9.2214×10^{-9} to 2.1595×10^{-8} m^2/s as drying air temperature increased from 44.91 to 64.30°C (**Table 2.7**). The effective moisture diffusivity of tomato also increased linearly from 8.3144×10^{-9} to 1.7072×10^{-8} m^2/s as drying air velocity increased from 0.13 to 0.75 m/s. For increased of air velocity from 0.75 to 1.00 m/s, the effective moisture diffusivity remained almost similar. GIOVANELLI *et al.* (2002) presented the effective diffusivity of tomato ranged from 2.3×10^{-9} to 9.1×10^{-9} m^2/s considering shrinkage. Again, SACILIK *et al.* (2006) reported the effective diffusivity of tomato neglecting shrinkage ranged from 1.07×10^{-9} to 1.31×10^{-9} m^2/s for solar and sun drying of organic tomato respectively.

During drying of tomato halves, an increase in air temperature increases diffusion and also increases shrinkage, but shrinkage reduces diffusion (HAWLADER *et al.* 1991). Since the first phenomenon is more substantial, the resulting effect of increase in air temperature the moisture diffusion increases which results in a drying rate increase.

The activated energy of tomato was calculated and found to be 37.72 kJ/mol. The activation energy value of tomato was in the range of values (15 - 40 kJ/mol) reported by

RIZVI (1986) for various food materials such as green bean (37.716 kJ/mol), lettuce and cauliflower leaves (19.82 kJ/mol), *Agaricus biporus* (19.79 kJ/mol) and mushroom (23.59 kJ/mol).

Table 2.7: Effective moisture diffusivity of tomato at different air temperature, relative humidity, air velocity and slab thickness

Temperature (°C)	RH (%)	Air velocity (m/s)	Slab thickness (mm)	Index u	Effective diffusivity (m ² /s)	R ²
44.91	14.52	0.50	32.0	0.7016	9.2214×10 ⁻⁹	0.9434
51.13	14.42	0.50	31.1	1.0159	1.1566×10 ⁻⁸	0.9219
55.01	11.09	0.50	32.5	1.3427	1.6528×10 ⁻⁸	0.9296
61.06	9.41	0.50	31.2	1.4705	1.8171×10 ⁻⁸	0.9313
64.30	8.92	0.50	33.4	1.9223	2.1595×10 ⁻⁸	0.9291
50.76	9.89	0.13	35.4	0.8139	8.3144×10 ⁻⁹	0.9106
50.87	10.32	0.25	33.2	0.8906	1.0003×10 ⁻⁸	0.9193
50.86	10.30	0.50	31.3	1.0241	1.3988×10 ⁻⁸	0.9389
50.64	9.75	0.75	30.3	1.0939	1.7072×10 ⁻⁸	0.9702
50.76	10.08	1.00	32.6	1.1481	1.7282×10 ⁻⁸	0.9652

CONCLUSIONS

Moisture loss increased with an increase of drying air temperature. Air temperatures above 55°C affected significantly the red colour of tomato. The overall performance of the tomato dried at 55°C and was the best, when both drying time and colour were considered. Tomato should be dried at an air velocity equal to or just above 0.750 m/s. Above this air velocity, moisture loss became independent of air velocity. There was no significant effect of air velocity on colour of tomato. Shrinkage of tomato increased with the increase of drying air temperature. There was no change of shrinkage observed for increase of air velocity. The moisture loss of over-ripe tomato was found higher than that of optimum ripe and unripe (green) tomato. The experimental data were fitted to different single layer drying models and found that the MIDILLI *et al.* (2002) model was the best to predict the moisture content of tomato at different drying air conditions. The effective moisture diffusivity of tomato increased linearly from 9.2214×10⁻⁹ to 2.1595×10⁻⁸ m²/s as drying air temperature increased from 44.91 to 64.30°C. The activated energy of tomato was calculated 37.716 kJ/mol. Hence, ripe half fruit tomato may be dried at an air temperature of 55°C and air velocity of 0.75 m/s and MIDILLI *et al.* (2002) model may be recommended to describe the single layer drying of tomato.

NOMENCLATURE

a	parameter of single layer equation (dimension less)
A	cross-sectional area (m ²)
b	parameter of single layer equation (dimension less)
c	major semi-axis (m)
d	minor semi-axis (m)
df	degree of freedom
D _e	effective diffusivity (m ² /s)
D ₀	constant equivalent to the diffusivity at infinitely high temperature (m ² /s)
E _a	activation energy (kJ/mole)
H	height or thickness (m)
K	drying rate constant (min ⁻¹)
M	moisture content (kg/kg, db)
n	exponent of single layer drying equation
N	number of data points
R	universal gas constant (8.314 × 10 ⁻³ kJ/mol K)
RH	Relative humidity (decimal)
t	time (min)
T	Temperature (°C)
T _a	absolute temperature (K)
u	index
v	air velocity (m/s)
V	volume (m ³)
W	mass of tomato sample (g)
z	half thickness of product (m)
z'	modified half thickness of product (m)

Subscript

e	equilibrium
exp	experimental
f	final
i	initial
o	at zero time
pred	predicted
s	shrinkage
t	at time t

Chapter 3

DESIGN AND EVALUATION OF AN INDIRECT SOLAR DRIER FOR TOMATO

ABSTRACT

A prototype of indirect type forced convection solar drier was designed and constructed at Leibniz-Institut für Agrartechnik Potsdam-Bornim, Germany for drying of tomato. The drier consisted of a flat-plate concentrating collector, a heat storage cum auxiliary heating unit and a drying unit. The drier was a multi stack type with five trays had a loading capacity of 18 kg of fresh half cut tomato. The drier was tested in different weather and operating conditions such as day time drying using solar radiation and night time drying- without external heating, heating with hot water flow from the storage tank without using external heater, heating with hot water flow using external water heater and in adverse weather (cloudy, foggy or rainy) using external water heater. Day time average temperature rose at the outlet air of the collector was about 30°C over ambient air temperature and collector efficiency varied from 25 to 60% depending on the weather condition. The performance of the drier was compared with open sun drying method. Drying times saved by solar drying over open sun drying were about 56, 60 and 70% without hot water flow, hot water flow without water heater and hot water flow using water heater in night times respectively. The average drying system efficiency of the solar drier without hot water flow (at night), hot water flow without water heater, hot water flow using water heater and day-night hot water flow using water heater in adverse weather conditions were about 18, 22, 33 and 17% respectively.

Drying process reduced significantly the colour, ascorbic acid, lycopene and total flavonoids from those of fresh tomato. Significantly lowest red colour ascorbic acid and rehydration ratio were obtained for the solar dried sample with sample with lowest final moisture content (15%) and those of higher amounts for sample with higher final moisture contents. Tomato halves were pre-treated with UV radiation, acetic acid, citric acid, ascorbic acid, sodium metabisulphite and sodium chloride at different doses. All pre-treatments significantly improved the colour of tomato than non-treated sample. No pretreatment could completely control the microbial infestation except sodium metabisulphite (8 g/l) at lower temperature (<45°C). When tomato was dried at the drying air temperature 45°C or above, no molds and fungus growth was observed. Therefore, it is recommended that if tomato is dried with continuous air temperature of 45°C or above then no pre-treatment is required. If drying air temperature fallen below 45°C (temperature in night time or in adverse weather), then tomato should be pre-treated with 8 g/l sodium metabisulphite to prevent the microbial growth.

INTRODUCTION

Sun drying is a popular and economical method of food drying in the developing countries. But in this method, drying rate is very low and dependent on weather conditions. Inferior quality of product is also obtained due to uneven drying, mixing of dust and dirt and contaminated with insects and micro-organisms. Some times the whole amount of product is spoiled in adverse weather conditions. As an alternative to sun drying, solar drying is a promising alternative for tomato drying in developing countries, because mechanical drying is mainly used in industrial countries and is not applicable to small farms in developing countries due to high investment and operating costs (ESPER & MÜHLBAUER 1998). Solar energy for crop drying is environmentally friendly and economically viable in developing countries. The natural convection solar drier appears to have potential for adoption and application in the tropics and subtropics. It is suitable at a household level for drying of 10 to 15 kg of fruits and vegetables. But the natural convection solar drier suffers from limitations due to extremely low buoyancy induced airflow inside the driers (BALA & WOODS 1994). In addition, comparatively high investment, limited capacity and the risk of crop spoilage during adverse weather conditions have up to now prevented the wide acceptance of natural convection solar driers (SCHIRMER *et al.* 1996, ESPER & MÜHLBAUER 1998).

Fruits and vegetables have special morphological features quite distinct from other agricultural materials used as food that greatly influence their behaviour during processing and preservation especially by drying (JAYARAMAN & DAS GUPTA 1992). Due to changing life styles especially in developed countries, there is a great demand for a wide variety of dried food products with emphasis on high quality (NIJHUIS *et al.* 1996). Demand for ready-to-use products, which have similar health benefits to the original raw products, has also increased in recent years (DEWANTO *et al.* 2002). In the temperate region it is a seasonal crop and hence there is surplus in one season and shortage in another. Each year a large quantity of tomato is being spoiled due to lack of proper processing and preservation facilities. A large quantity (20-50%) of tomato perishes during the harvesting season when the supply is abundant (DESAI *et al.* 1999). As a result, price of tomato falls drastically and producers cannot even get a return on their production cost. On the other hand, there is an increasing interest in dried tomato in the international market. The amount of tomato, which is being spoiled, can be minimized by proper drying of freshly harvested product.

Tomato colour is an important parameter, which represents consumers' acceptance. Generally, more red is the colour more amount of carotenoid or lycopene content in tomato (LOPEZ CAMELO & GOMEZ 2004). Tomato is nutritionally recognised for ascorbic acid (vitamin C) and lycopene. These nutrients are very sensitive to drying and storage conditions (LATAPI & BARRETT 2006a). Ascorbic acid is a water-soluble organic acid, temperature sensitive and easily oxidised. Tomato and tomato products are the major source of lycopene, which has received particular interest in due to its antioxidant properties. Processing and storage conditions, including high temperature, light and oxygen exposure, may cause lycopene degradation and thereby affect the attractive

colour and nutritive value of the final products (SHI 2000). During sun drying, quality losses may result from colour degradation (browning caused by enzymatic and non-enzymatic reaction), microbial growth (mostly caused by moulds and yeasts), and poor rehydration (caused by injuries during processing) along with losses of colour, ascorbic acid and lycopene (LEWICKI 1998). Some investigators (ANON. 1996, YOON *et al.* 2002, LATAPI & BARRETT 2006 a,b) examined the effects of several pre-treatments like blanching, ascorbic acid, citric acid, sulphur, sodium metabisulphite and salt at different doses on drying and storage of tomato. YOON *et al.* (2002) reported that both ascorbic acid and citric acid reduced the bacterial population during 14 hours of drying. LATAPI & BARRETT (2006 a,b) reported that 8% (w/v) sodium metabisulphite and 8% (w/v) sodium metabisulphite plus 10% (w/v) salt had the best rehydration ratio, colour as well as effective to control micro-organisms. TAHMASBI *et al.* (2006) treated tomato slices with sucrose, sodium chloride and water before drying and dried those using microwave, sun and hot air dryings. They also reported that sucrose pretreatment and microwave drying gave better colour retention than other pretreatments and drying methods. Tomato is a high moisture (about 95%) vegetable and very sensitive to drying. Sun dried tomato requires generally 7 to 12 days depending on weather conditions. If it is dried at high temperature, it causes case hardening and losses its quality like colour, lycopene, ascorbic acid etc. On the other hand if it is dried at low temperature, moulds and yeasts grow during drying (ANDRITSOS *et al.* 2003). Scientific literature on methods of improving the quality of sun and solar drying tomatoes by applying pre-treatment is limited and variable.

BASSUONI & TAYEB (1982) studied the effect of temperature and thickness on tomato slices on solar and sun drying. GUPTA & NATH (1984) have analysed the chemical composition of fresh and compared nutritional loss during different methods of drying. HAWLADER *et al.* (1991) have studied the drying characteristics of tomato under various drying conditions. They developed a diffusion model considering tomato slice as a flat plate and taking shrinkage into account. HUDA (2003) studied the solar drying characteristics of tomato on open mesh and solid trays exposed to solar simulator under laboratory conditions. He also fitted the experimental data to the thin layer drying equations. ANDRITSOS *et al.* (2003) commercially dried tomato using a large (Dimensions: 14 m × 1 m × 2 m) geothermal energy dryer. SACILIK *et al.* (2006) investigated the thin layer drying characteristics of half fruit organic tomato in a polyethylene covered solar tunnel drier (Dimensions: 8 m × 2.5 m × 1.8 m). They fitted the experimental data to ten thin layer drying models. None of them conducted full-scale experiments using solar drier. Also the qualities of dried tomato have not been investigated. Tomato as well as some fruits and vegetables are very sensitive to drying air temperature and microbial infestation during drying. So, an effective solar drier need to be designed to dry tomato that can produce quality dried product by preventing quality loss and microbial growth. Therefore, this study has been undertaken to design an efficient solar drier and to test the drier for drying of tomato suitable for developing countries to produce quality dried products.

MATERIALS AND METHODS

An indirect type solar drier was designed, fabricated and installed at Leibniz-Institut für Agrartechnik Potsdam-Bornim, Germany during 2005-06. The drier basically consisted of a solar collector, a heat storage cum auxiliary heating unit and a drying unit. Descriptions of each unit are given below.

Solar Collector

The collector was originally designed and constructed by AMER (2006) for his PhD research and adapted in this study. The schematic diagram of the solar collector is shown in **Figure 3.1**. The dimensions of the horizontal solar collector were 2.8 m long, 1.8 m wide and 0.18 m high. It consisted of wooden frame of 60 mm thickness and supported in the middle by wooden bars with a thickness of 40 mm. The transparent cover of the collector was 4 mm thick glass that allowed the penetration of sun rays inside the solar collector. About 200 mm below the glass cover; 1.5 mm black painted corrugated iron sheet was used as an absorber plate. To increase the efficiency of receiving sun rays by the solar collector, flat type reflector made of brilliant aluminum was added on top of the solar collector. The dimensions of the reflector were the same as the solar collector so that it was used as a reflector in daytime and a cover in night time. The reflector was connected with the collector top such a way that its positions can be adjusted with the solar angle and also can be folded on the top of the collector. For easy of handling, the reflector was divided into three sections horizontally. Six legs with 150 mm wheel were used to turn and move the solar collector horizontally and change its direction according to the change of the sun's angle during the day. A 0.75 kW centrifugal fan was connected in one side of the collector to draw the atmospheric air in the collector and to push out the heated air to the drier with a desired air velocity. There was an automatic air controlling system using three air dampers-inlets, mixing and outlet. The three air controllers can be operated manually according to the quantity and the velocity of air needed or through a small motor fixed on each controller. The motors can be opened or closed using a special electric key, which exists on an electric board, fixed at the end of the solar collector.

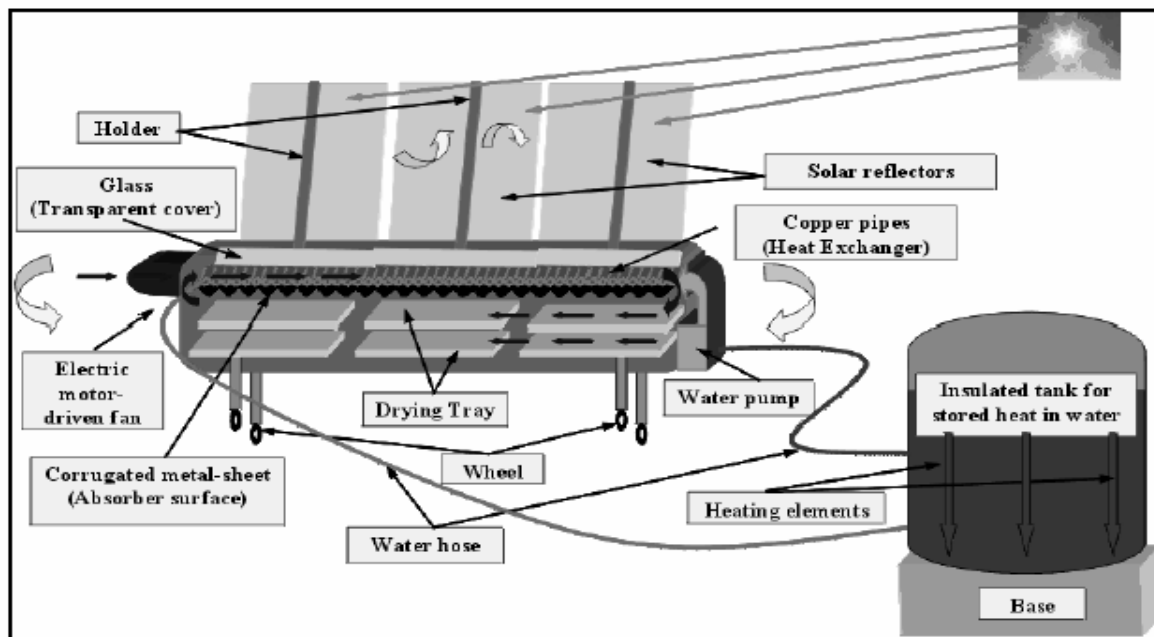


Figure 3.1: Schematic diagram of the solar collector (adapted from AMER (2006))

Heat Storage Unit

The heat exchanger consisted of 15 mm copper tubes placed inside the solar collector, 100 mm below the glass cover and 100 mm above the absorber plate. The effective length of the copper tubes was 1.80 m. The connection between the tubes was achieved through small curved parts that have the same diameter of the tubes and fixed together by soldering. One end of the copper tube was connected with the inlet end of a 500 liter insulated water tank and another end was connected with the outlet of the water tank through the insulated hose pipes (Figure 3.1). The heat exchanger gave a part of the heat collected during the hours of the sun shine, which was carried by air inside the solar collector, to the water inside the copper tubes. The water passed very slowly (about 2 m³/s) inside the pipes to be able to take a part of heat carried in the air contacted with the external surface of the tubes. The heat was then carried by the water, which moved inside the tubes by using a small pump of a discharge capacity ranging from 5 to 50 liters per hour. The heat stored during the day in the water tank could be used in night time again by recirculating the hot water from the water tank to the collector. The temperature of this water can be raised by using water heaters (6 kW) located inside the tank to reach a suitable temperature for drying during the night and in day of adverse weather conditions.

Drying Unit

A prototype of the drying unit was designed considering its low cost, simple in construction and easy in operation suitable for small farm holders in developing countries. The special feature of the drier was that air would flow through, over and under the tomato halves so

that drying rate would be higher than single mode airflow drier. The prototype of the drier was designed for drying of about 20 kg fresh half-cut tomato per batch. The details of the design procedure are given below.

Moisture to be removed from the product

The amount of moisture to be removed from a given quantity of fresh tomato to bring the safe moisture content was calculated using the following equation.

$$W_w = \frac{W_p (M_i - M_f)}{100 - M_f} \quad (3.1)$$

Harvesting and drying period

Harvesting and drying period of tomato are carried out in Bangladesh mainly from February to May. In this period ambient temperature, relative humidity, solar radiation and sunshine hours are necessary parameters to be known in designing a solar dryer. The average values of these parameters are given in **Table 3.1**. Average drying rate was determined from the following expression.

$$D_r = \frac{W_w}{t_d} \quad (3.2)$$

Quantity of air needed for drying

The quantity of air needed for drying was estimated from the energy balance equation or psychrometric chart. The basic energy balance equation for drying process is as follows.

$$W_w h_L = W_a C_a \rho_a (T_i - T_f) \quad (3.3)$$

The volumetric air flow rate was calculated using the following formula.

$$Q_a = \frac{W_a}{t_d} \quad (3.4)$$

Table 3.1: Design conditions and assumptions

Items/parameters	Condition/assumption
Product	Half fruit tomato
Drying per batch (for small prototype) , W_p	20 kg
Depth of product in the tray, d_p	35 mm (Half fruit)
Number of shelf	5
Vertical gap between two shelves	150 mm (actual 75 mm)
Bulk density of half fruit fresh tomato, ρ_p	900 kg/m ³
Spreading density of half fruit fresh tomato, ρ_s	13.6 kg/m ²
Temperature of the drying air, T_i	55°C
Initial moisture content, M_i	95% (wb)
Final moisture content, M_f	15% (wb)
Drying time, t_d	6 days (8 h/day)
Ambient air temperature, T_{am}	30°C
Ambient relative humidity, RH_{am}	70%
Sunshine hours	8 h (9:00 to 17:00 h)
Incident solar radiation, I	14 MJ/m ² .day
Wind speed, V_w	0.50 m/s
Collector efficiency, η_c	30%

Determination of collector area

From the total useful heat energy required to evaporate moisture and the net radiation received by the tilted collector, the collector area for solar drying was calculated from the following relationship.

$$E = A_c I \eta_c = Q_a \rho_a C_a (T_i - T_a) \quad (3.5)$$

Therefore, the area of solar collector is:

$$A_c = \frac{Q_a \rho_a C_a (T_i - T_a)}{I \eta_c} \quad (3.6)$$

Drier area and dimension

Total volume of drying bed of the solar dryer was calculated from the following expression.

$$V_d = \frac{W_p}{\rho_p} \quad (3.7)$$

For manual handling of the product in the tray, the width of the tray should not more than 0.90 m (BASUNIA & ABE 2001, HOSSAIN *et al.* 2005). There for the length of the drying chamber would be

$$L_d = \frac{V_d}{Bd} \quad (3.8)$$

Dimension of air vent

The air vent area was calculated by dividing the volumetric air flow rate by air speed.

$$A_v = \frac{Q_a}{V_a} \quad (3.9)$$

The length of air vent would be equal to the length of the drying chamber. So, the width of the air vent is given by

$$B_v = \frac{A_v}{L_v} \quad (3.10)$$

Construction

The overall dimensions of the drier were 1.0 m × 1.0 m × 1.0 m. The schematic diagrams of the drier are given in **Figure 3.2** and **Figure 3.3**. The air inlet and outlet of the drier was bottom or top i.e. air can be flown from the collector to the drying chamber either from bottom or top end of the drier. The air inlet connection was a 120 mm flexible pipe with insulation. There were five trays placed on after another in the drying chamber with an air gap of 120 mm between two trays. Each tray was 600 mm × 520 mm and made of wooden frame and plastic net. The trays were placed such a way that hot air can flow through, over and under the products. There was a door in front of the drier to open and close of the drying chamber. The sidewalls, roof and floor of the drier were made with 1 mm thick metal sheet insulated with 4 mm polystyrene. The drier was about 0.5 m above the ground surface and supported on four legs with 150 mm wheel for each leg so that it can be moved easily.

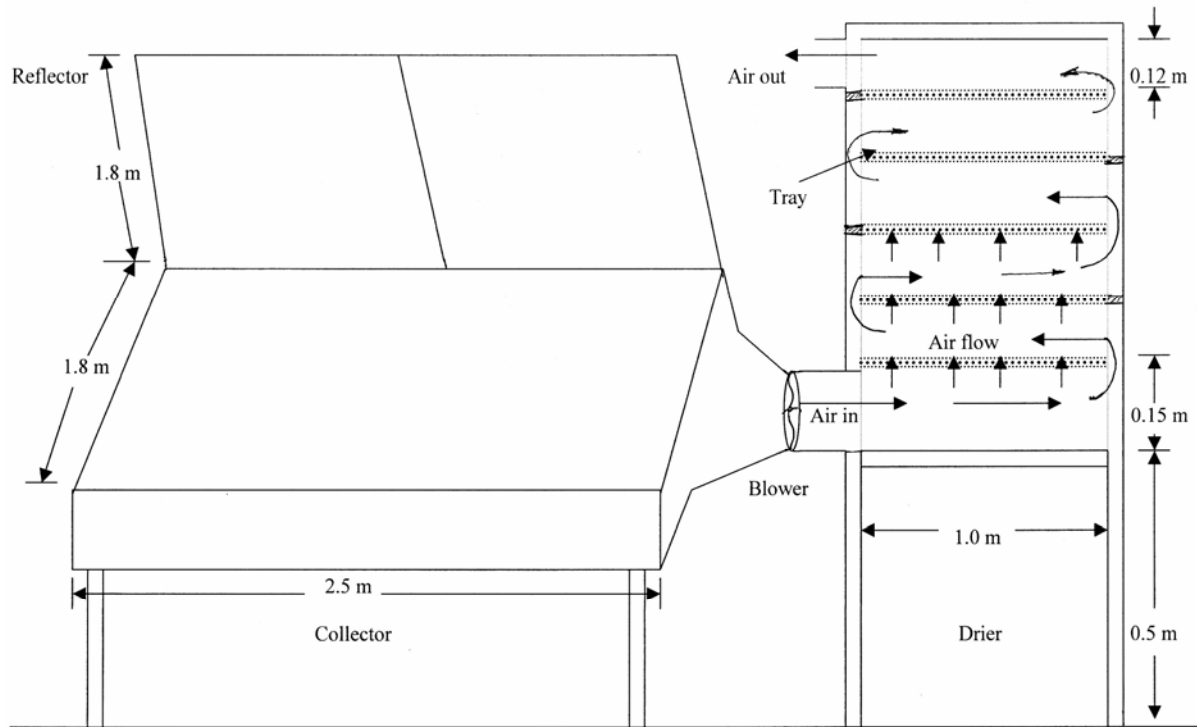


Figure 3.2: Schematic diagram of solar collector and drier

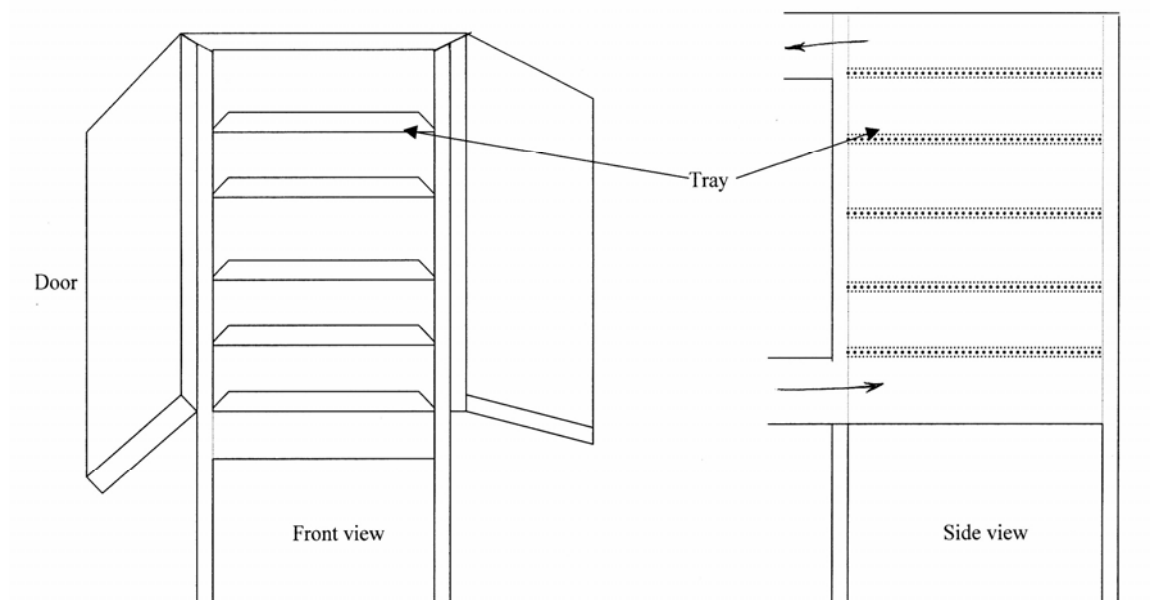


Figure 3.3: Front and side view of the multi stack solar drier

Experimental Procedure

Several experimental runs for different drying conditions for solar and sun drying of tomato were carried out at Leibniz-Institut für Agrartechnik Potsdam-Bornim (ATB), Germany dur-

ing the period of June to September 2006 (Mid-European summer conditions). Fresh and uniform size of ripe tomatoes was purchased from Potsdam supermarket. Average diameters of large and small size tomatoes were 61.7 and 49.3 mm and their average masses were 139.3 and 73.1 g respectively. Before starting each experiment, the tomatoes were washed with normal water and spread on plastic net to drain out excess water. Randomly selected 10 tomatoes were wiped with tissue paper and their colour was measured with a chromameter as described in Chapter 1. Before starting an experimental run, the whole apparatus was operated for at least one hour. This period of time was essential for the heated air to be stabilized and for the air flow rate to be adjusted.

For untreated experiments, tomatoes were cut into halves with a sharp knife and then placed them in single layer on the drying trays placing cut side up in the drier. To compare the performance of the drier with that of sun drying, control samples of half-cut tomatoes were also placed on trays in a single layer beside the drier in the open sun. Drying was started after completion of the loading, usually at 09:00 h and discontinued up to reach the final moisture content of tomato. Weight loss of both the samples in the solar drier and the control samples in the open sun were measured during the drying period in day time (09:00 to 17:00 h) at one hour interval with an electronic balance (Sartorius: model- BP 310S, accuracy- 0.001 g, Sartorius AG, Göttingen, Germany). During the day time, the positions of the collector and its reflector were adjusted with the solar angle so that maximum solar radiation can be captured by the solar collector as well as by the reflector. In the afternoon, after 17:00 h, the samples in the solar drier were kept in the drier and the collector was covered by reflector and the control samples were kept in the same place with a perforated cover on it so that air can easily moves on and around the samples. Next morning, at 09:00 h the cover of the drier and also the cover from the control samples were removed and subjected to dry by solar radiation. Photographs of drying process are shown in **Figure 3.4** and **Figure 3.5**.

A data logger (Model: ALMENO 5590, Ahlborn Mess- und Regelungstechnik GmbH, Germany) was used to record the ambient air, collector air, drying air (on different trays), inlet air and outlet air temperature and relative humidity at 10 minutes interval. Temperatures at different positions of glass cover, copper tube, absorber plate of the collector were also recorded at 10 minutes interval during the drying period. A solar meter (SOLARWATT, accuracy $\pm 2\%$, Zenit GmbH, Germany) was used to measure the global solar radiation and total radiation (global+ reflected from reflector) during the day time drying period. Velocity of drying air was measured with an anemometer (Model TA-5, velocity range- 0.01 to 30 m/s, Airflow Development Limited, England) at and when required. The moisture content of the tomato sample was measured at the starting and end of each run of the experiment by drying the samples in an air ventilated oven at 105°C for 24 hours. After completion of drying, the dried tomato was collected, cooled in a shade to the ambient temperature and then sealed it in the plastic bags. About 20 kg of fresh tomato was dried to about 2 kg of dried tomato.



Figure 3.4: Photograph of solar collector and drier in operation



Figure 3.5: Photograph of solar drier loaded with tomato for drying

Pre-treatment

Before drying, tomato halves of three experimental runs were treated with some chemicals and UV radiation to find out their effectiveness to control microbial infestation and enzymatic browning. These experiments were also carried out to study the effects of these treatments on quality of dried tomato during storage. The different treatments used before drying and the application methods are given in **Table 3.2**. After applying different treatments, the treated and control (with no treatments) were placed in the drier and dried up to the final moisture content as the procedure described above.

Table 3.2: Different treatments used before drying and their application method

Treatments	Application procedure
Control	No pre-treatment was applied
UV radiation (750 Ws/m ²)	Placed tomato halves under radiation with cut side up for 5 min
UV radiation (1500 Ws/m ²)	Placed tomato halves under radiation with cut side up for 10 min
Acetic acid (4 mg/l)	Placed the tomato halves in gas enclosure for 30 min
Acetic acid (6 mg/l)	Placed the tomato halves in gas enclosure for 30 min
Citric acid (3 g/l)	Sprayed on the tomato halves with cut side up
Citric acid (6 g/l)	Sprayed on the tomato halves with cut side up
Ascorbic acid (3 g/l)	Sprayed on the tomato halves with cut side up
Ascorbic acid (6 g/l)	Sprayed on the tomato halves with cut side up
Sodium metabisulphite (2 g/l)	Dipped the tomato halves for 3 min
Sodium metabisulphite (8 g/l)	Dipped the tomato halves for 5 min
Sodium chloride (10 g/l)	Dipped the tomato halves for 5 min

Efficiency Calculation

The thermal efficiency of the solar collector and system drying efficiency of the solar drier were calculated using following formula (STINE & GEYER 2001):

(a) Collector efficiency during day time (when solar radiation was available):

(i) Considering global solar radiation

$$\eta_{cdg} = \frac{\dot{m}_a C_{pa} (T_i - T_o)}{A_c I_g} \quad (3.11)$$

(ii) Considering total solar radiation (global+reflected from reflector)

$$\eta_{cdt} = \frac{\dot{m}_a C_{pa} (T_i - T_o)}{A_c I_t} \quad (3.12)$$

(b) Collector efficiency during night time:

$$\eta_{cn} = \frac{\dot{m}_a C_{pa} (T_i - T_o)}{\dot{m}_w C_w (T_w - T_i)} \quad (3.13)$$

(c) System drying efficiency of the solar drier:

(i) Solar drier efficiency in day time

$$\eta_{dd} = \frac{m_w h_L}{A_c I_t t + Q_f + Q_p} \quad (3.14)$$

(ii) Solar drier efficiency in night time

$$\eta_{nd} = \frac{m_w h_L}{Q_h + Q_f + Q_p} \quad (3.15)$$

Chemical Analysis

Amount of ascorbic acid, lycopene and total flavonoids of fresh tomato, solar dried tomato halves with 15, 25 and 30% (db) moisture content, a dried commercial tomato sample (produced by ORTICOLA MEDITERRANEA, Italy in July 2006) and pretreated solar dried tomato halves were determined by chemical analysis methods in the Bio-Technology-Department, ATB, Potsdam. A detail of each method is described below.

Ascorbic Acid

Ascorbic acid was analyzed according to the method described by DENNISTON & WIMMERS (2006) and GOULA & ADAMOPOULOS (2006). Ten gram of tomato sample was placed in a mortar and 20 ml oxalic acid (0.25 M) solution and a pinch of sand was added with it. Again 20 ml oxalic acid was added and macerated thoroughly for 3 minutes. Macerated mixture was thoroughly filtered with Whatman #1 filter paper. Filtrated extract was collected in a 100 ml volumetric flask. Calculation was made assuming the total weight per volume of this extract. Then 1.0 ml DCIP (2, 6-Dichloroindophenol) solution and 0.1 ml meta-phosphoric acid was added and diluted with 3.0 ml of tomato extract. The absorbance of the solution was measured at 520 nm on a UV-VIS spectrophotometer (Model:

CADAS 200, Photometer accuracy: 0.2%, Dr. Bruno Lange GmbH & Co. KG, Germany) with oxalic acid as blank. The ascorbic acid of tomato extract was determined from the standard curve.

Lycopene

Lycopene was analyzed according to the method described by DAVIS (1976) and OPIYO & YING (2005). For extracting lycopene, 1 g of homogenized fresh or dried tomato sample was weighed and covered with aluminum foil to exclude light and the lycopene from the sample. Approximately 12 to 15 ml of distilled water was added to 1 g of dried tomato powder. Reconstituted tomato powder was suitable for hexane extraction. The whole tomato was ground in an enamel mortar for uniform consistency. Then 39 ml mixture of hexane–acetone–ethanol (1:1:1, v: v: v) was added to the sample, which was placed on the rotary mixer for 30 min. Agitation was continued for another 2 min after adding 10 ml of distilled water. The solution was then left to separate into distinct polar and non-polar layers and then the hexane layer was collected in a 50 ml flask. The residual solids were re-extracted to ensure complete extraction of lycopene. The absorbance of the combined hexane layers was measured at 503 nm on a spectrophotometer using hexane as a blank. The amount of lycopene in the tomato samples was determined using the formula as: lycopene (mg/100g) = $312 \times \text{Absorbance at 503 nm}$ (OPIYO & YING 2005).

Total flavonoids

Total flavonoids were analyzed according to the method reported by ZHISHEN *et al.* (1999) and TOOR & SAVAGE (2006). The seeds were removed from the tomato. Then 4 g sample from each group was taken. The tomato was homogenized with a blender and the fresh juice was obtained (approx. 125 ml). Dried tomato was also homogenized with a blender. Four gram of finely homogenized sample was extracted twice with 10 ml of hexane in dark. The final extract was filtered through a 0.5 μm filter paper. A known volume (1 ml) of the extract or standard solution of rutin solutions was added to a 10 ml volumetric flask. Distilled water was added to make a volume of 5 ml. At zero time, 0.3 ml of 5% w/v sodium nitrite was added to the flask. After 5 min, 0.6 ml of 10% w/v AlCl_3 was added and, after 6 min, 2 ml of 1M NaOH was added to the mixture, followed by the addition of 2.1 ml distilled water. Absorbance was measured at 510 nm on a spectrophotometer against the blank (water) and total flavonoids and determined from the standard curve.

Rehydration ratio

Rehydration ratio is one of the quality of dried food, determines the water absorption capacity of dried food. About 20 g of dried tomato halves were submerged in distilled water with a product to water ratio of 1:8 at room temperature ($20 \pm 2^\circ\text{C}$) for 24 hours

(LEVI *et al.* 1988). Then the samples were drained out of excess water for about 3 minutes and adhering water was soaked into tissue paper and weighed the sample again. The rehydration ratio or index is the ratio of sample after rehydration to the original dried weight (LEWICKI 1998).

Micro-organisms Detection

During drying period microbial infestation in the sample was determined by manual enumeration method. When a micro-organism infected sample was observed, the sample was collected in a cleaned plastic petridish and put in a refrigerator at 5°C. This procedure was continued until the completion of a drying experiment. After completion of the drying experiments, the infected samples were observed on a microscope to diagnose the severity of infestation and identified the type of micro-organisms.

Statistical analysis

Mean differences of air temperature, relative humidity and moisture content of tomato in the drier were compared by t-test (for two variables) and F-test (more than two variables). The analysis of variance (ANOVA) of colour values, ascorbic acid, lycopene and total flavonoids of solar, sun dried and different pre-treated samples were statistically analysed using the software SPSS 9.0. The mean obtained from each set of variable was compared by Duncan's Multiple Range Test (DMRT) based on the complete randomised design (CRD).

RESULTS AND DISCUSSION

Collector Performance

The solar collector as well as solar drier was tested at four different operational modes. These were- (1) day time drying using solar radiation but night time no hot water or auxiliary heating used (2) day time drying and storing heat in the heat storage tank by circulating water in the collector and night time drying with recirculating hot water from the storage tank but no external heating was used (3) day time drying and storing heat in the heat storage tank and night time drying with recirculating hot water from the storage tank and also using additional water heater (4) in adverse weather, day and night time drying by circulating hot water in the collector from the heat storage tank using water heater.

The variations of ambient air temperature, air temperature at the outlet of the collector and absorber plate temperature with solar radiation in day and night without hot water flow in night time during solar drying of tomato (01.07.06-06.07.06) are shown in **Figure 3.6**. During this drying period, highest solar insolation was found to be about 780 W/m² and absorber plate temperature was about 80°C or more at the mid noon of the days. But, the

highest collector outlet air temperature was about 60°C. This collector outlet air temperature was maintained during high insulation by increasing airflow because above 60°C drying air temperature quality of the dried product deteriorates. Average ambient air temperatures in day and night times were found to be 24 and 18°C, respectively. In day time (9:00 to 17:00) collector outlet air temperature was about 30°C higher than the ambient air temperature. But in night time (without water flow), absorber plate temperature and collector outlet air temperature fell rapidly and became almost same as the ambient air temperature. Variations of ambient air temperature, outlet air temperature, absorber plate temperature and water temperature with solar radiation using hot water flow (without water heater) in night during the drying period (14.07.06-18.07.06) is shown in **Figure 3.7**. The day time temperature was about 30°C higher than the ambient air temperature. During day time (solar radiation period) solar heat energy was stored in the water tank by circulating water in the collector. This storage heat energy was released in night in the collector air (from water to air through copper tube) by recirculating hot water in the collector. As a result, air temperature in the collector did not dropped drastically (as happened for previous experiment), it was reduced slowly down to about 30°C in the next morning. During the night times, ambient air temperature dropped to about 15°C. Air temperature developed in the day time at the outlet of the collector was sufficient for tomato drying. But night time temperature was not suitable for tomato drying, because night time temperature (30°C) susceptible for microbial growth. It is reported in Chapter 2 that tomato should be dried in the air temperature range of 45 to 55 °C to prevent microbial growth and to prevent case hardening and quality loss.

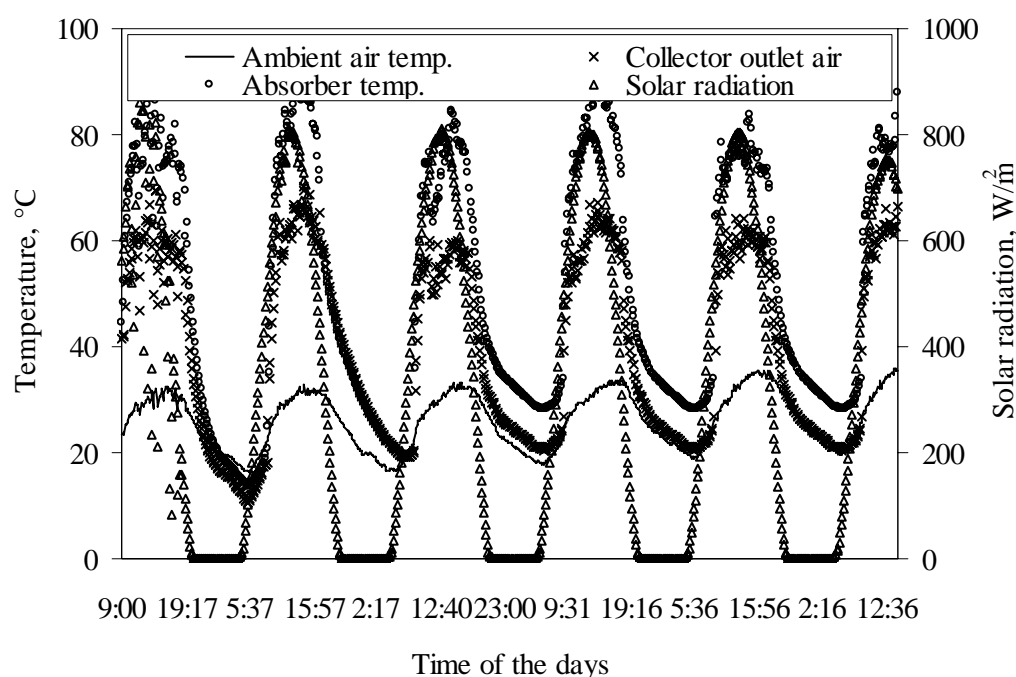


Figure 3.6: Variation of ambient air temperature and temperatures in the collector with solar radiation without hot water flow at nights (01.07.06-06.07.06)

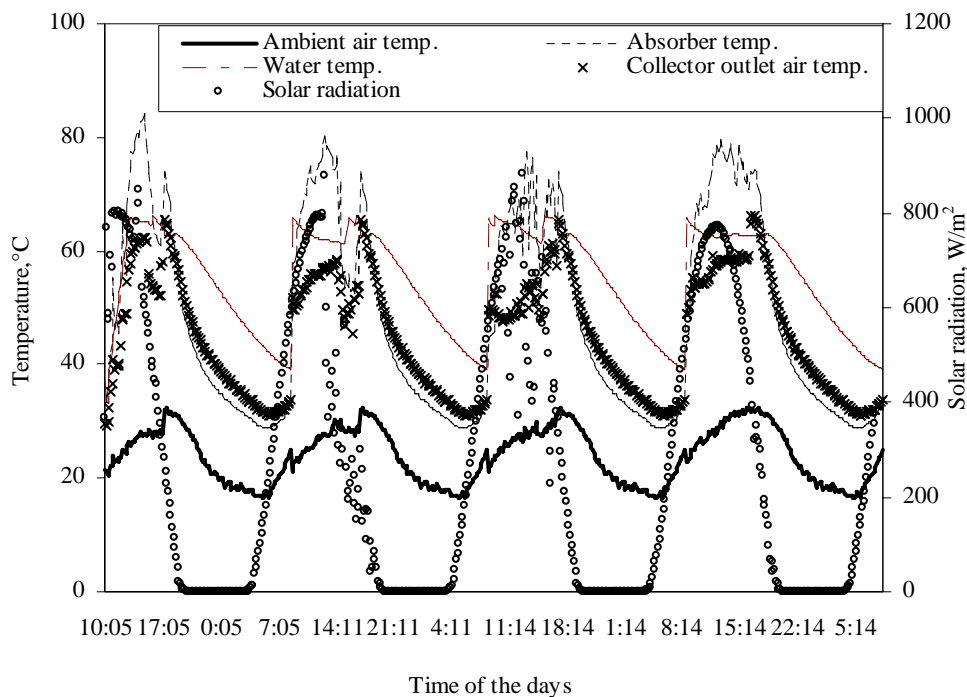


Figure 3.7: Variations of ambient air temperature and temperatures in the collector with solar radiation with hot water flow (without using heater) at nights (14.07.06-18.07.06)

Variations of ambient temperature, temperatures in the collector and water temperature with solar radiation with hot water flow (using water heater) in night during the drying period (11.09.06-14.09.06) is shown in **Figure 3.8**. During day time collector outlet air temperature was about 60°C and it was about 30°C higher than the ambient air temperature. During day time (solar radiation period) a part of solar heat energy was stored in the water tank by circulating water in the collector and in night time additional heat was supplied to water using a 6 kW thermostat controlled water heater. The water heater was adjusted such that water temperature did not fall below 65°C. During the night times, air temperature at the outlet of the collector was about 50°C when the ambient air temperature dropped to about 14°C. Hence, during the night times, collector outlet temperature was found to be about 36°C higher than ambient air temperature. This collector outlet air temperature is quite suitable to prevent microbial growth for night time drying. In adverse weather conditions (cloudy and rainy), the suitability of solar collector as well as drier was tested. The weather in this period was mostly cloudy with scattered rains. Day and night time ambient air temperature was low (<20°C). During this period solar radiation was very uncertain and irregular and not suitable for solar and sun drying (**Figure 3.9**). In this period (04.09.06-07.09.06), hot water flow was continued with water heater till the end of the drying experiment. Day and night time air temperature at the outlet of the collector was about 50°C against the ambient temperature of 15 to 20°C in the same period (Figure 3.9).

The collector was a concentrating type with a flat reflector. So, the solar radiation on the glass cover was the sum of direct global radiation on the cover and incoming reflected radiation from the reflector. The relationship between total radiation (global+ reflected from reflector) and global radiation on the glass cover is shown in **Figure 3.10**. The following regression equation was developed to calculate total radiation from the global radiation.

$$I_t = 117.72 + 1.1699I_g \quad (R^2=0.89) \quad (3.16)$$

The thermal efficiency of the collector was calculated considering both global solar radiation and total solar radiation on the glass cover. Variations of collector efficiency with global solar radiation at different times of a typical day are shown in **Figure 3.11**.

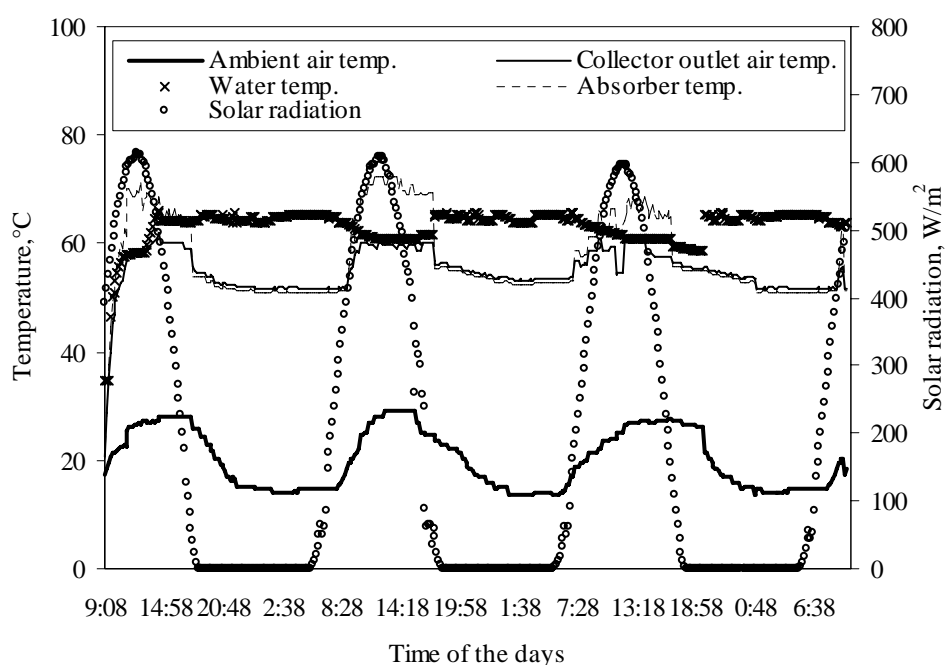


Figure 3.8: Variations of ambient air temperature and temperature in the collector with solar radiation in sunny days and water heating at nights (11.09.06-14.09.06)

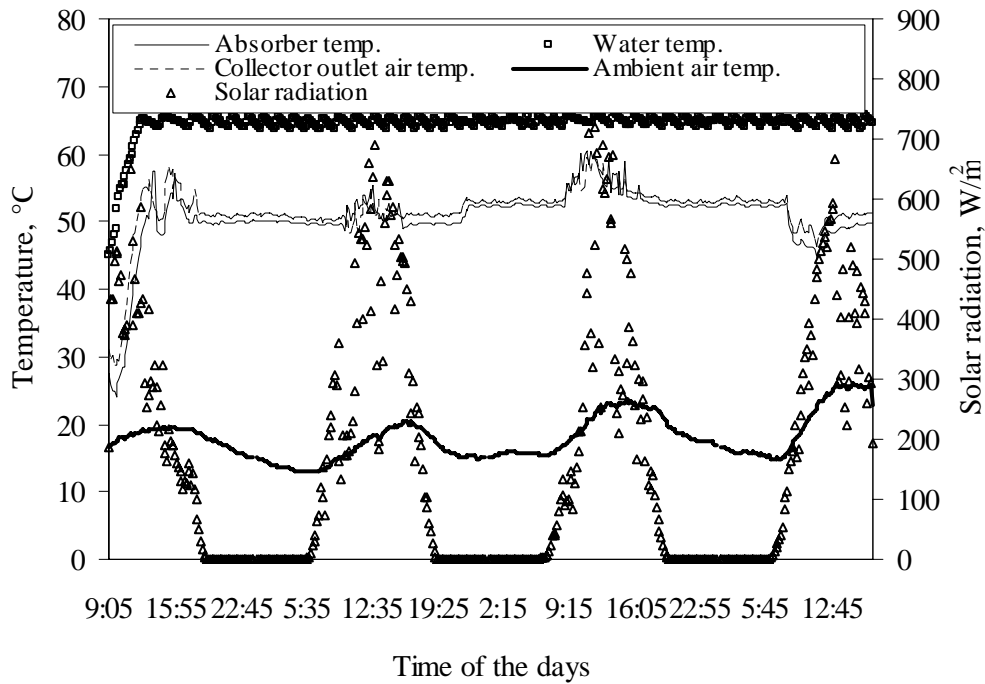


Figure 3.9: Variation of ambient air temperature and temperature in the collector with solar radiation in adverse weather conditions (04.09.06-07.09.06)

It is observed from the Figure that highest efficiency was obtained in the noon (10:00-14:00) of the day when solar radiation was higher. Thermal efficiency varied using reflector was 25 to 62% but without reflector, this variation was 17 to 52%. Using reflector thermal efficiency was increased by 26%. Variations of collector efficiency with hot water flow (without water heater) at night are shown in **Figure 3.12**. When solar radiation was off, the water temperature as well as air temperature in the collector began to fall rapidly. So, the collector efficiency decreased drastically from 7.5% to about 2%. This low efficiency was due to that energy from the water was released rapidly to the cool air (no additional heat was supplied to the water) and difference between collector air and ambient air temperatures became low. When external energy was added to the water using water heater then collector efficiency became high as 25 to 30% (**Figure 3.13**). Because of the water heating at night, the collector outlet air temperature was about 50°C higher against ambient air temperature of 15 to 25°C. Therefore it is evidence from the result that collector efficiency was increased about 10% using solar reflector.

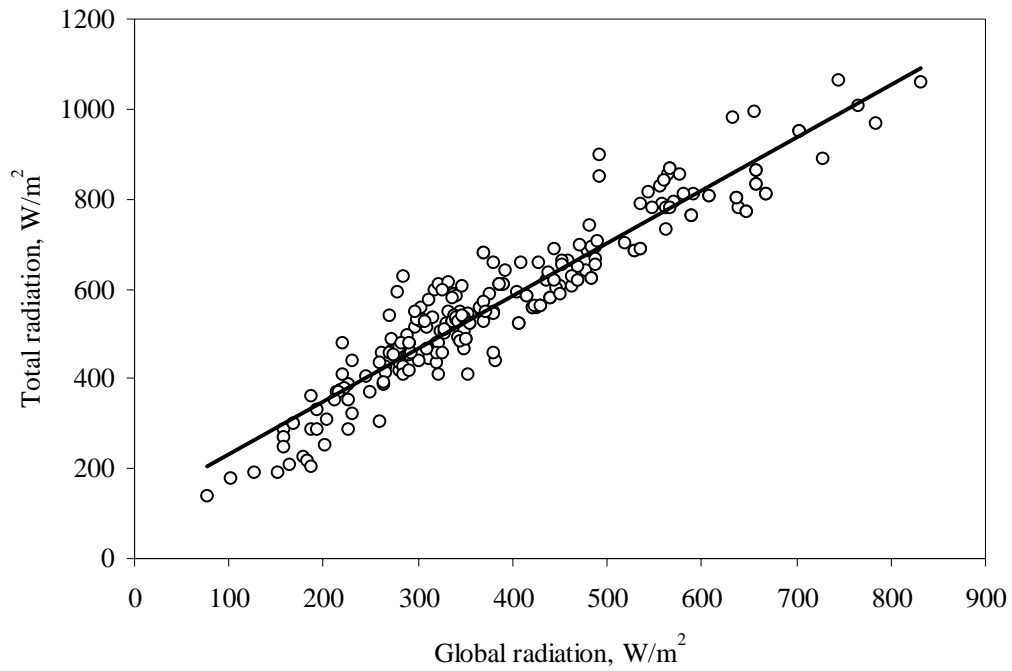


Figure 3.10: Relationship between global solar radiation and total solar (global+reflected radiation) on the glass cover

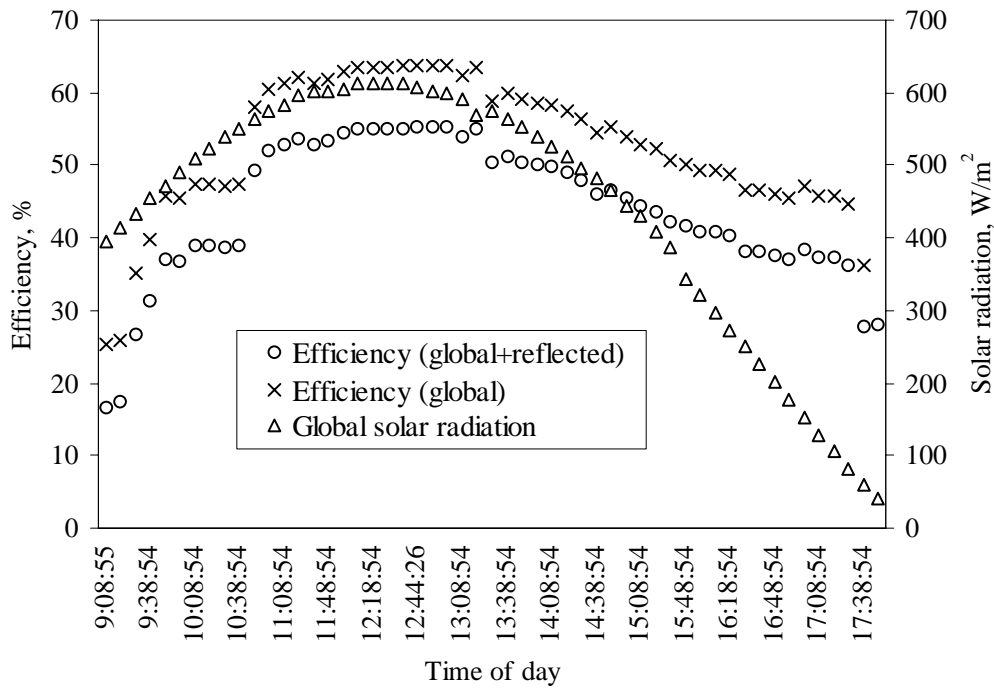


Figure 3.11: Variations of collector efficiency considering global radiation and both global and reflected at different times of a day (11.09.06)

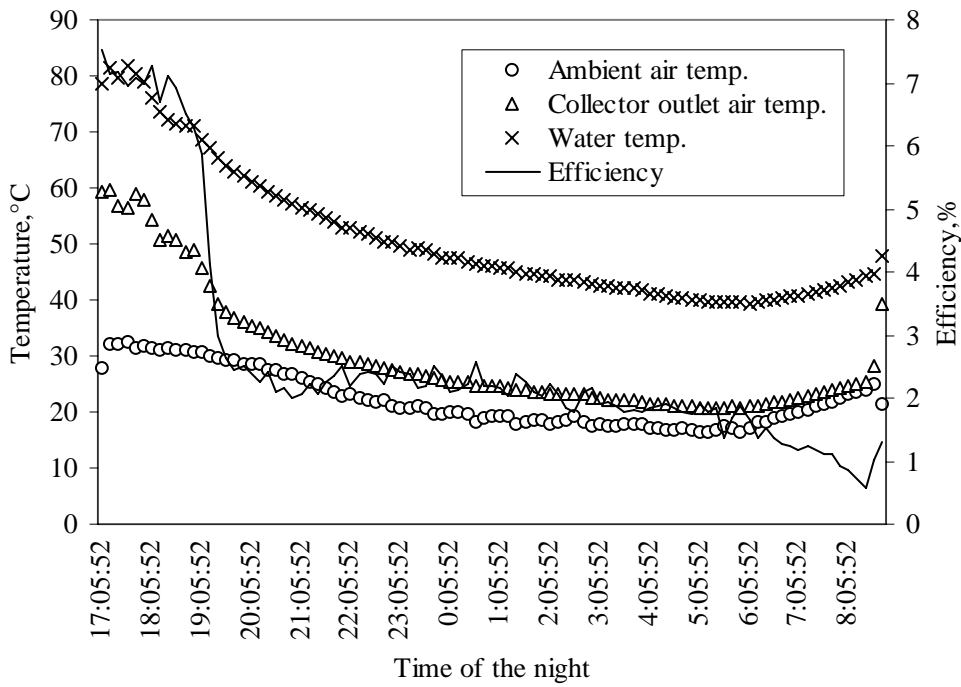


Figure 3.12: Variation of collector efficiency with temperatures with hot water flow (without heater) at night (14.07.06-15.07.06)

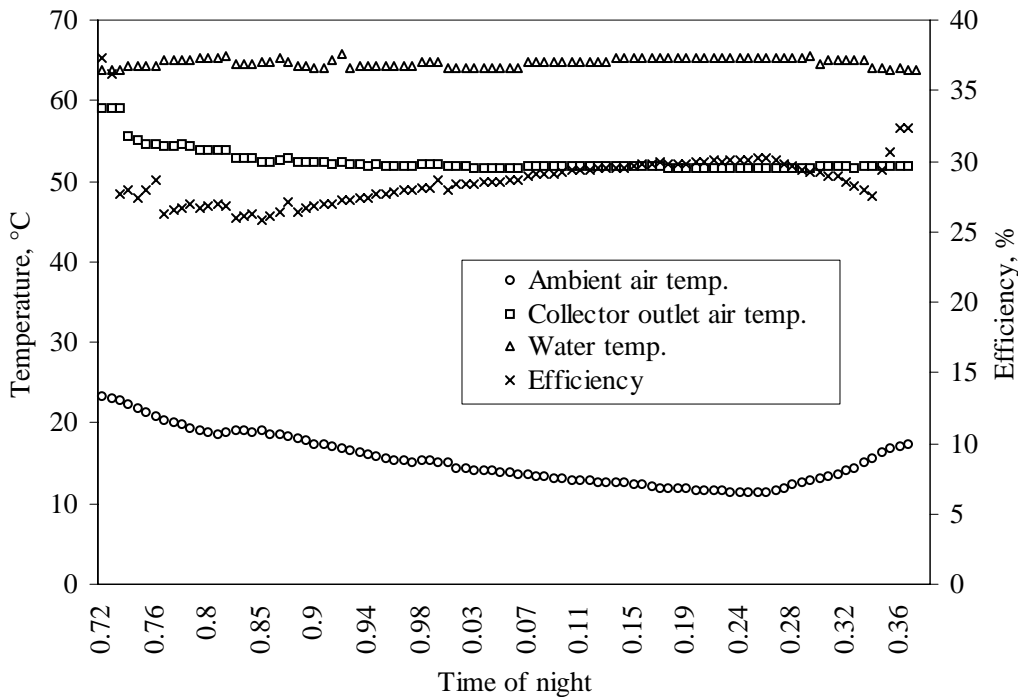


Figure 3.13: Variations of collector efficiency with temperatures with hot water flow (using water heater) at night (11.09.06-12.09.06)

Drier Performance

Drier air temperatures were measured at inlet, outlet and on all trays of the drier during solar drying of tomato. The drying air temperature distribution in the drier is shown in **Figure 3.14**. Day time solar drying and night time hot air drying was carried out with hot water flow without water heater. About 8°C lower temperature was found from outlet air than that of inlet air during the drying period and this difference was statistically significant by t-test ($p \leq 0.05$). At the end of the drying period the inlet and outlet air temperatures became similar. This is due to that outlet air carried moisture from the products and its relative humidity increased. Also there was some outside air effects since the outside air was much cooler than drier air. Lower air temperatures were obtained from tray 1 (bottom) followed to tray 5 (top) but their differences were insignificant ($p \leq 0.05$). In day time, the relative humidity of the inlet, inside (average) and outlet air of the drier varied from 6 to 12% and there were no significant differences among them but in night time significantly highest ($p \leq 0.05$) relative humidity was found from outlet air followed by inside air and inlet air of the drier (**Figure 3.15**).

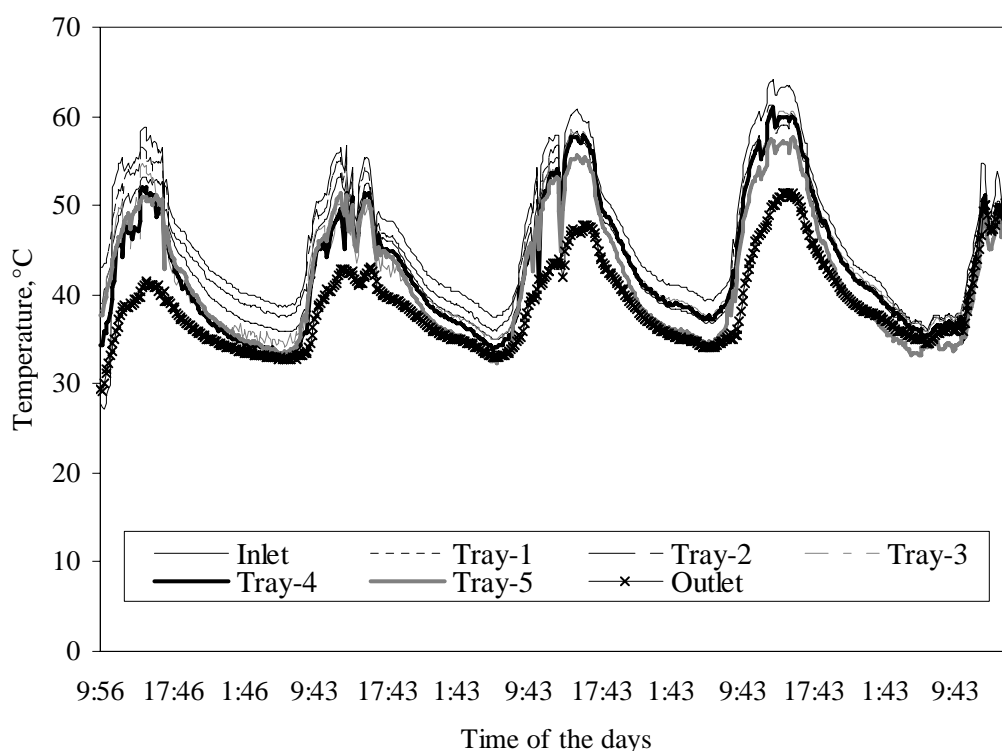


Figure 3.14: Air temperature at different positions in the drier during solar drying of tomato (24.07.06-28.07.06)

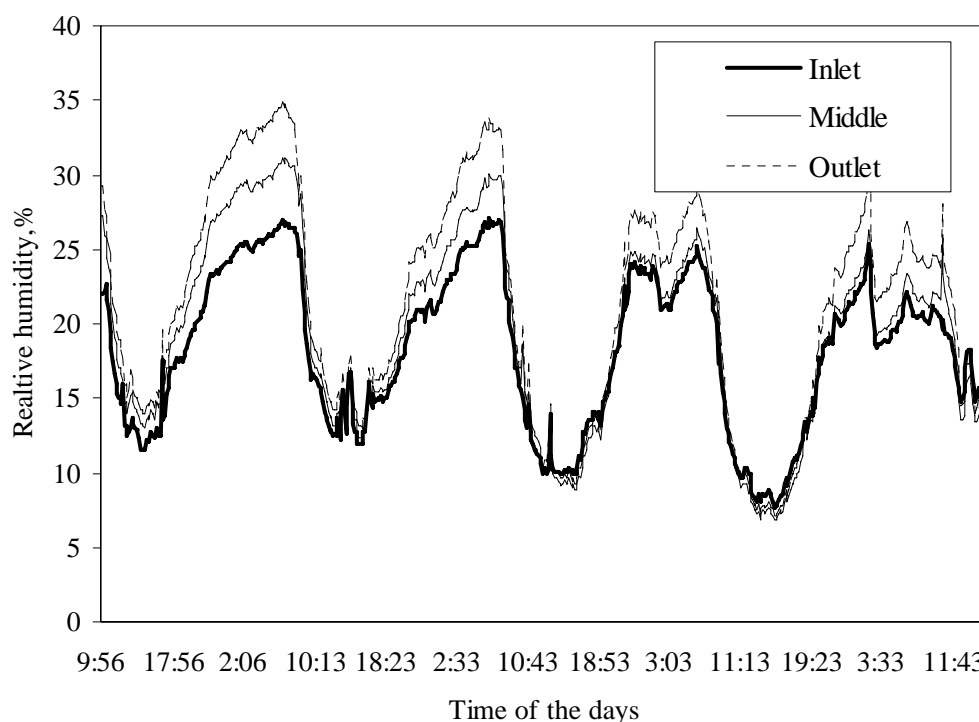


Figure 3.15: Air relative humidity at different positions of the drier during solar drying of tomato (24.07.06-28.07.06)

Variations of moisture content of tomato on different trays are shown in **Figure 3.16**. Higher moisture reduction was observed from tray-1 (bottom tray) followed by tray-2 to tray-5. But their differences were not statistically significant ($p \leq 0.05$). The reason was that the drying air carried moisture from the tray-1 (bottom) and became more humid than the entry air and it carried more and more moisture from the tray-2 to tray-5 and became more humid than the previous trays. As a result, the drying potential of the tray-5 (top) reduced and carried less moisture from the tomato than the previous trays. Since the moisture contents of tomato on top and bottom trays were insignificant, selection of five trays was justified. Effects of fruit and slice sizes on solar and sun drying of tomato are shown in **Figure 3.17**. The fruit sizes of tomato were large (average fruit diameter 61.7 mm and fruit mass 139.3 g) and small (average fruit diameter 49.3 mm and fruit mass 73.1 g) and slices were half fruit and quarter fruit. They were dried in the same weather conditions in the drier and as well as in the open sun. The moisture reduction of small tomato was higher than the large size for both solar and sun drying methods. The reason might be that the distance from centre to evaporating surface of slice of small size tomato was lower than that of large size and also the initial moisture content of large tomato was higher than smaller one. Again the moisture reduction of quarter size fruit was higher than half fruit. The reason might be that moisture was evaporated mainly from cut surfaces and quarter fruit had two cut surface and half fruit had only one cut surface. Also lesser is the fruit thickness higher is drying rate as well as diffusivity due to less distance of evaporating zone from the centre. But shrinkage of quarter cut fruit was found about higher (40%) than the half cut fruit. Also, the shrinkage of the half-cut small tomato was higher (20%) than the

half-cut large tomato. This may due to that moisture transport rate of small size tomato was higher than that of large size tomato. More is the shrinkage, less is the consumers' acceptance as well as market price. Hence, considering shrinkage, half cut fruit was better than that of quarter cut fruit. Therefore, rest of all experiments were conducted with half cut large size fruit tomato to reduce considerable shrinkage.

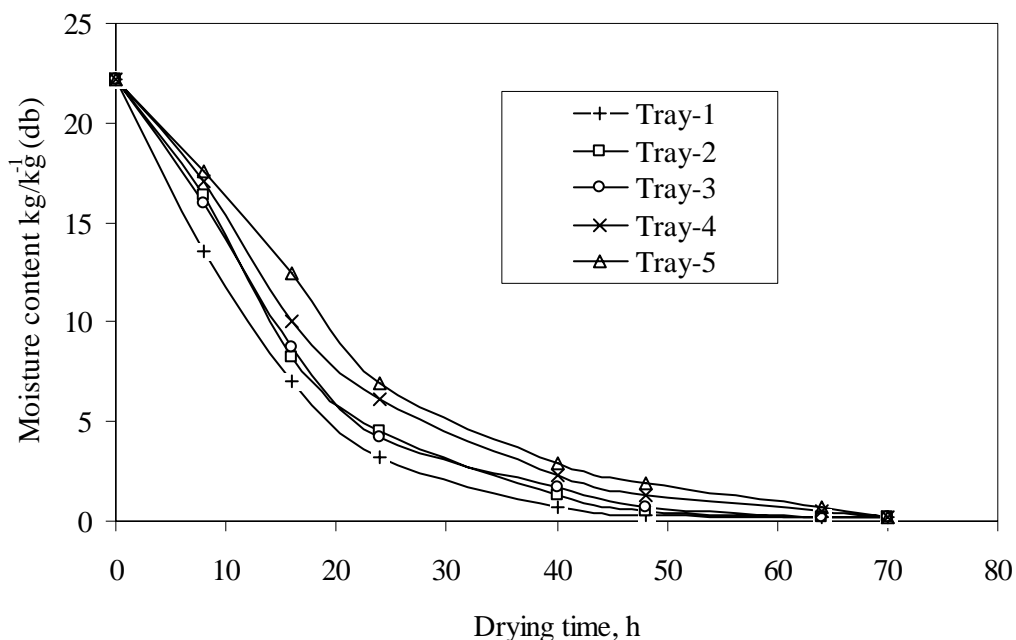


Figure 3.16: Effect of tray positions on solar drying of tomato (tray positions 1 to 5 indicate bottom to top)

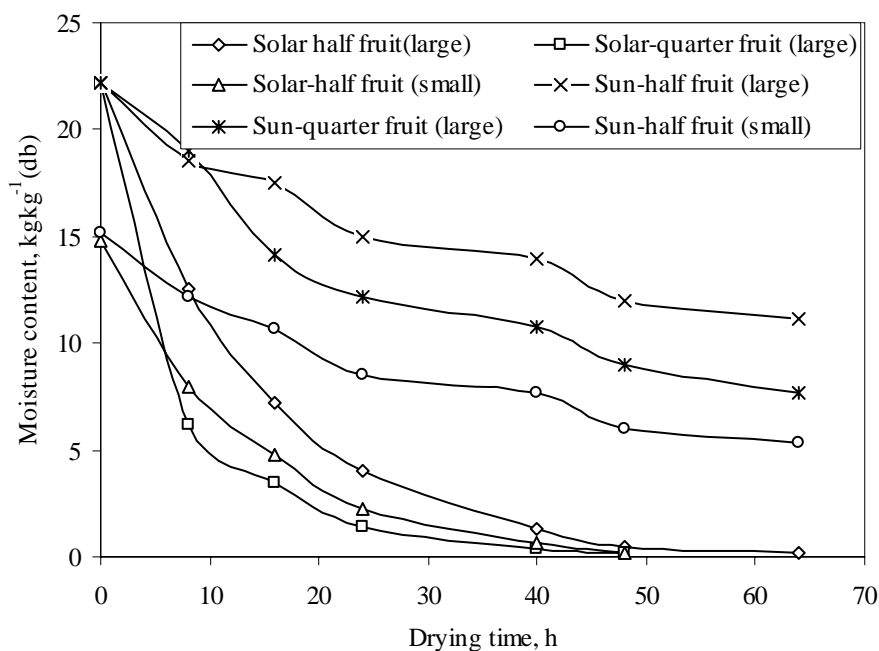


Figure 3.17: Effect of size and slices thickness on solar and sun drying of tomato (18.09.06-22.09.06)

Moisture reduction and average drying rate of tomato in days (09:00 to 17:00 h) and nights (17:00 to 09:00 h) in the solar drier and in open sun without hot water flow in nights during the drying period of 01.07.06 to 06.07.06 are shown in **Figure 3.18**. Moisture contents of identical samples were reduced from 27.74 kg/kg (db) to 0.18 and 4.58 kg/kg (db) in 126 hours (days and nights) by solar and sun drying methods respectively. Time required to reach final moisture content (about 0.18 kg/kg db) by sun drying method was 288 hours and hence time saved by solar drying was about 56% (**Table 3.3**). Drying rate in day times was much higher than that of night times for both solar and sun drying methods. This reason was that, during the day times, there was higher drying air temperature and lower relative humidity due to solar radiation than night times for both solar and sun drying methods. There was no hot water flow in the night times, so drier air temperature fell below the ambient temperature of about 10°C in the first night and about 3°C in the succeeding nights. This may be due to that air temperature in the drier became cooler due to the contact with moist tomato. In the succeeding nights, fruit became drier with lesser moisture than the first night and air temperature was higher than the first night. The trend of relative humidity of ambient air and in the drier air were just opposite to the ambient air temperature and drier air temperature in days and nights during solar and sun drying of tomato. As a result, drying rate of tomato in the solar drier during night times was low even lesser than the sun drying method. Due to low drying air temperature (<45°C), both solar and sun drying samples were infected by micro-organisms. The drying rate of tomato in solar drier was much higher than the sun drying method because the average air temperature in the drier in days was about 55°C against the ambient air temperature of 25°C in the same times (**Figure 3.19**). During the day time, air relative humidity was about 10 to 12% but in night time it rose 40 to 50%. After 56 hours of drying, drying rate of tomato in open sun was found higher than that of in the solar drier. This was due to that drying rate has a positive correlation with moisture content. After 56 hours of drying period moisture content of sun drying sample reduced to about 12.5 kg/kg (db) whereas the moisture content of solar drying sample was decreased to about 1.2 kg/kg (db).

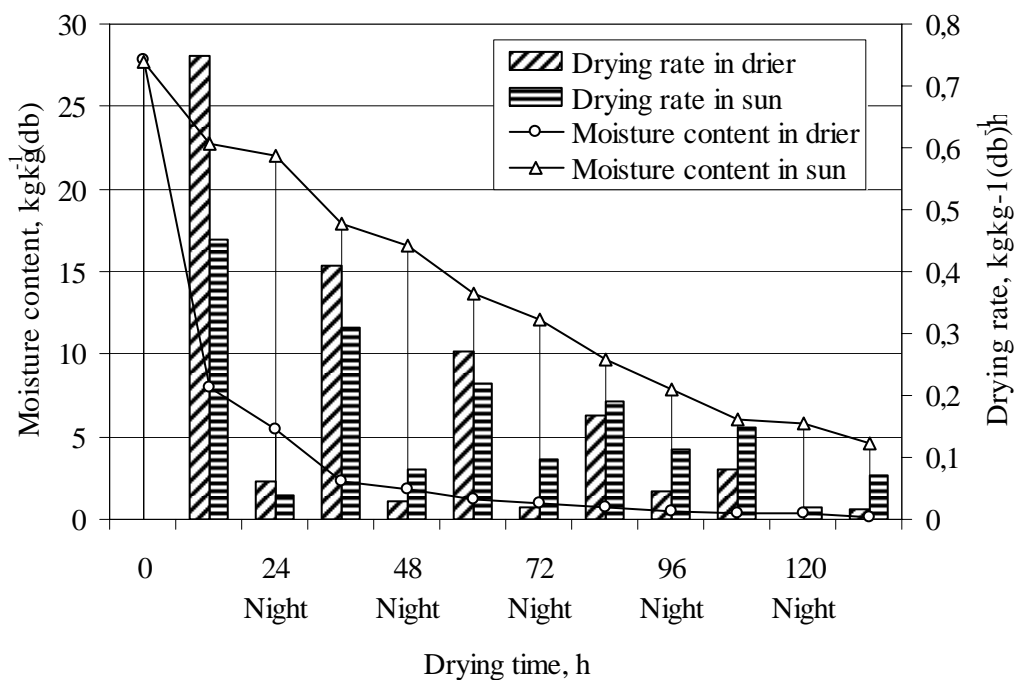


Figure 3.18: Moisture reduction and average rate of tomato in day (09:00-17:00 h) night (17:00-09:00 h) drying by solar and sun drying methods without hot water flow at nights (01.07.06-06.07.06)

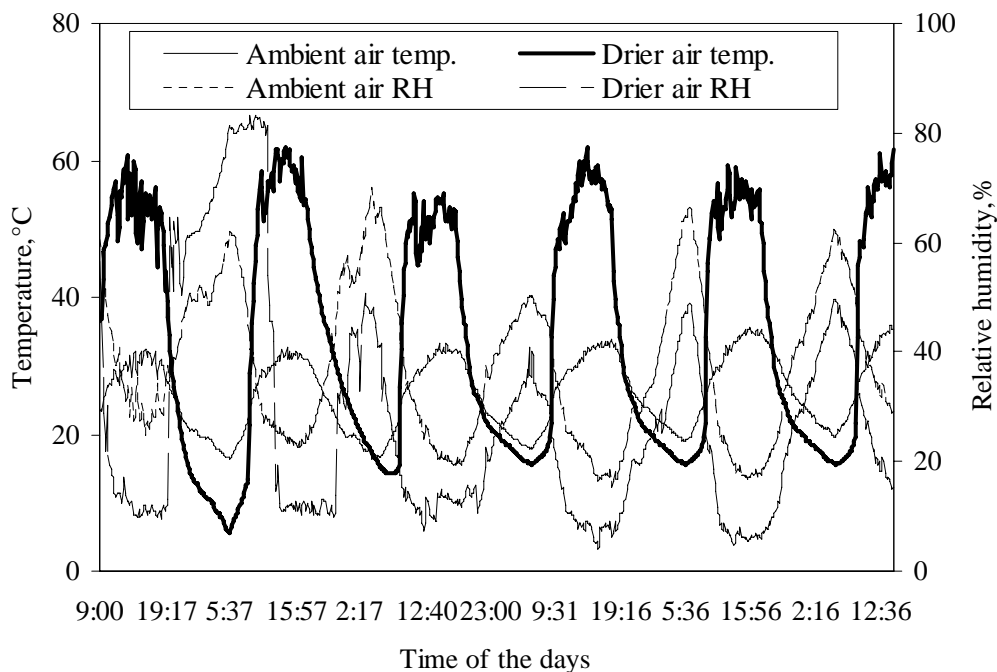


Figure 3.19: Ambient air and drier air temperatures and relative humidities without hot water flow at night during solar drying of tomato (01.07.06-06.07.06)

Solar and sun drying of tomato with hot water flow (without no extra water heating) at nights is given in **Figure 3.20**. Tomato samples were dried to safe moisture content of

about 0.18 kg/kg (db) from initial moisture content of 18.86 kg/kg (db) in 96 hours in solar drier. But in sun drying method moisture content was decreased to 5.35 kg/kg (db) in the same drying period. The drying rates of tomato in solar drying during both days and nights were higher than those of sun drying method. Because, air temperature in the drier was about 30°C higher during day times and about 10°C higher in night times than ambient air temperature due to hot water was circulated in the collector to heat up the air in night (**Figure 3.21**). Time required to reach final moisture content by sun drying method was 240 hours. Since the night time temperature fell below 45°C, micro-organisms grew both solar and sun drying samples. Solar and sun drying of tomato in sunny days and hot water flow in nights (using water heater) are shown in **Figure 3.22**. In 72 hour day-night drying, moisture content of tomato was reduced from 22.15 kg/kg (db) to 0.19 and 8.2 kg/kg (db) by solar and sun drying methods respectively. In sun drying it took about 220 hours of day-night drying to reduce the similar safe moisture content of about 0.18 kg/kg (db). In solar drying, drying rates were found higher than those of sun drying method both days and nights. During the drying periods, average day temperature in the solar drier was about 57°C and night temperature was about 48°C against average ambient air temperature in day and night of 28 and 15°C respectively (**Figure 3.23**). Relative humidity in the drying air varied from 10 to 20% whereas in ambient air it varied from 25 to 65% in day and night respectively. In this drying period no microbial growth was observed in the solar drying samples but sun drying samples were infected by micro-organisms. This reason might be that day-night drying air temperature in the drier was higher than 45°C but the ambient air temperature was lower than 45°C.

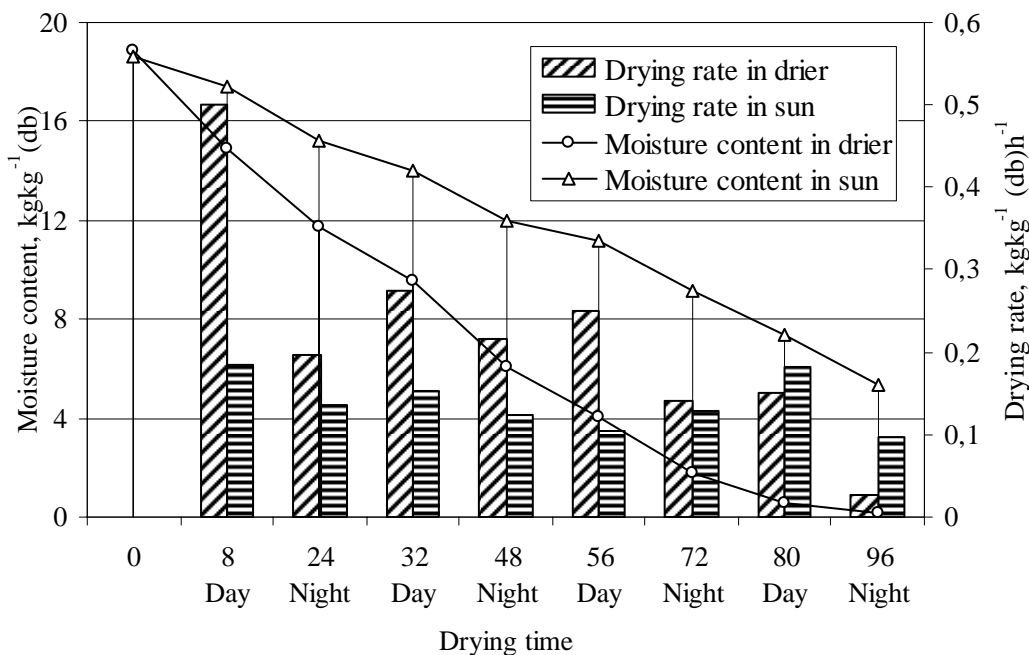


Figure 3.20: Moisture reduction and average rate of tomato in day (09:00-17:00 h) night (17:00-09:00 h) drying by solar and sun drying methods with hot water flow (without water heater) at nights (14.07.06-23.07.06)

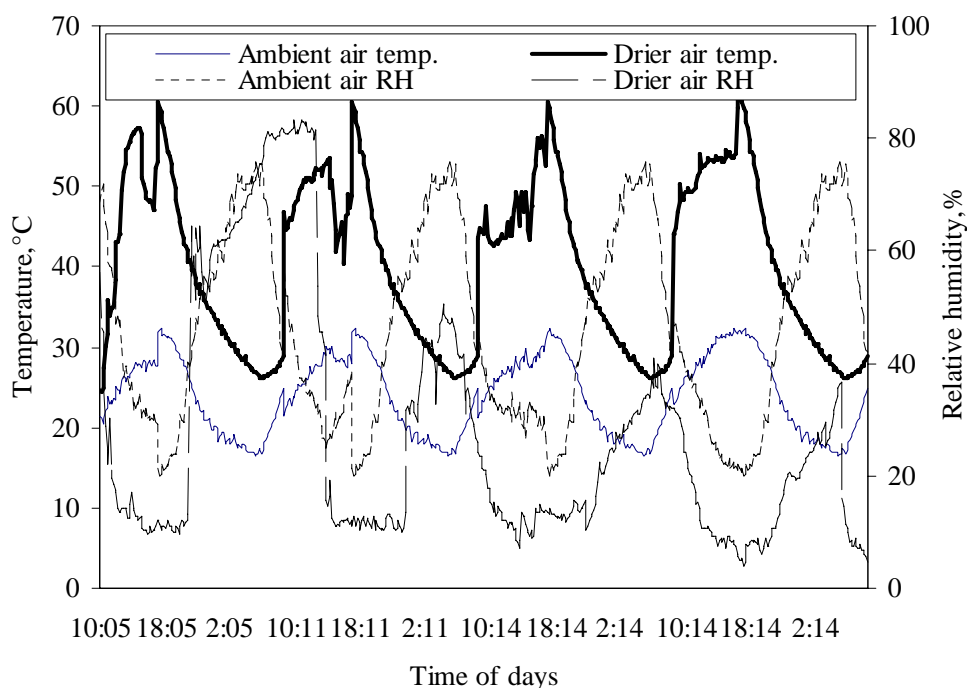


Figure 3.21: Variations of ambient air and drier air temperatures and relative humidities with hot water flow (without using heater) at nights during solar and sun drying of tomato (14.07.06-18.07.06)

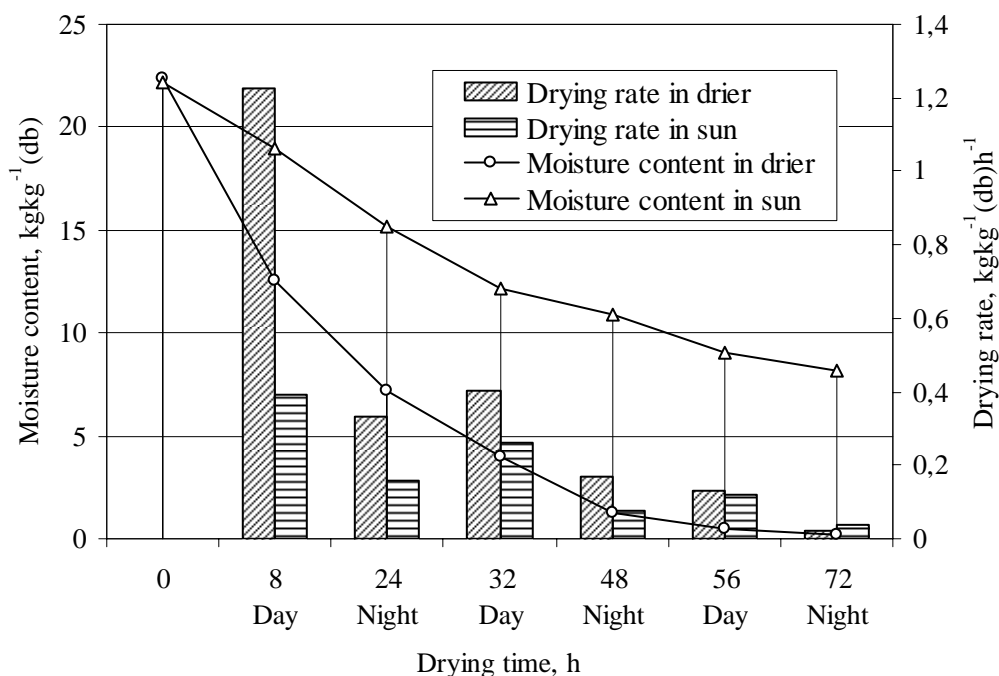


Figure 3.22: Moisture reduction and drying average drying rate of tomato in day (09:00-17:00 h) night (17:00-09:00 h) drying by solar and sun drying methods with hot water flow (using water heater) at nights (11.09.06-14.09.06)

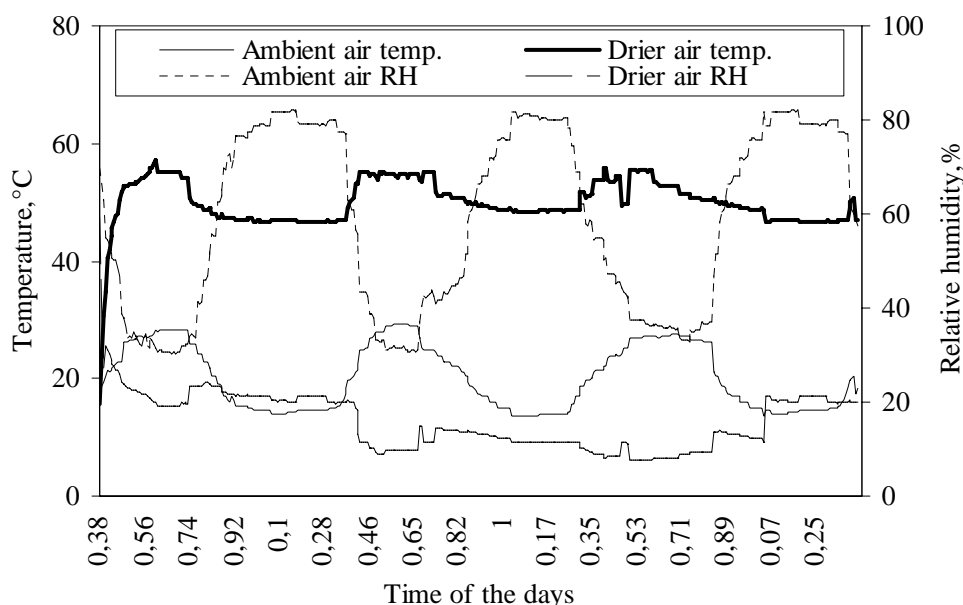


Figure 3.23: Variations of ambient air and drier air temperatures and relative humidities with hot water flow (using water heater in night) in sunny weather during solar drying of tomato (11.09.06-14.09.06)

Tomato was also dried in adverse weather (cloudy and sometimes rain) condition. In this drying period, drying air was heated by continuous hot water flow using water heater both in days and nights. Moisture content was reduced from 21.14 kg/kg (db) to 0.16 and 15.56 kg/kg (db) by solar and sun drying method in 96 hours of day-night drying (**Figure 3.24**). In adverse weather, safe moisture content of tomato was not achieved by sun drying method due to complete spoilage of samples. In adverse weather, drying rate of tomato in solar drier was much higher (about 3 times) than sun drying even at low moisture content of solar drying samples. This is due to that average temperature during the drying period (day and night) in the solar drier was about 48°C against an average ambient air temperature during the drying period (day and night) of 18°C (**Figure 3.25**). Average relative humidity in the drying air in day time and night time was about 20% whereas the average ambient air relative humidity at day and night were about 45 and 90% respectively. During the drying period no growth of micro-organisms was observed in the solar drying samples because drying air temperature was always maintained about 48°C (>45°C). Comparison of moisture reduction of tomato of present study with the works by SACILIK *et al.* (2006) is given in **Figure 3.26**. The moisture reduction of present study was without hot water flow in nights. SACILIK *et al.* (2006) conducted experiment in a solar tunnel drier for drying of organic tomato without supplementary heating in nights in the weather condition of Turkey. Variations of day time temperature of present study and the study by SACILIK *et al.* (2006) were 45 to 55°C and 30 to 50°C respectively. Similar moisture reduction pattern were observed from both the studies although the initial moisture content of present study was higher. It took about 20 hours more time of this study to reach the final moisture content than the report presented by SACILIK *et al.* (2006).

This variation might due to the difference of tomato variety and difference of initial moisture content. Therefore, this study agreed well with the study by SACILIK *et al.* (2006).

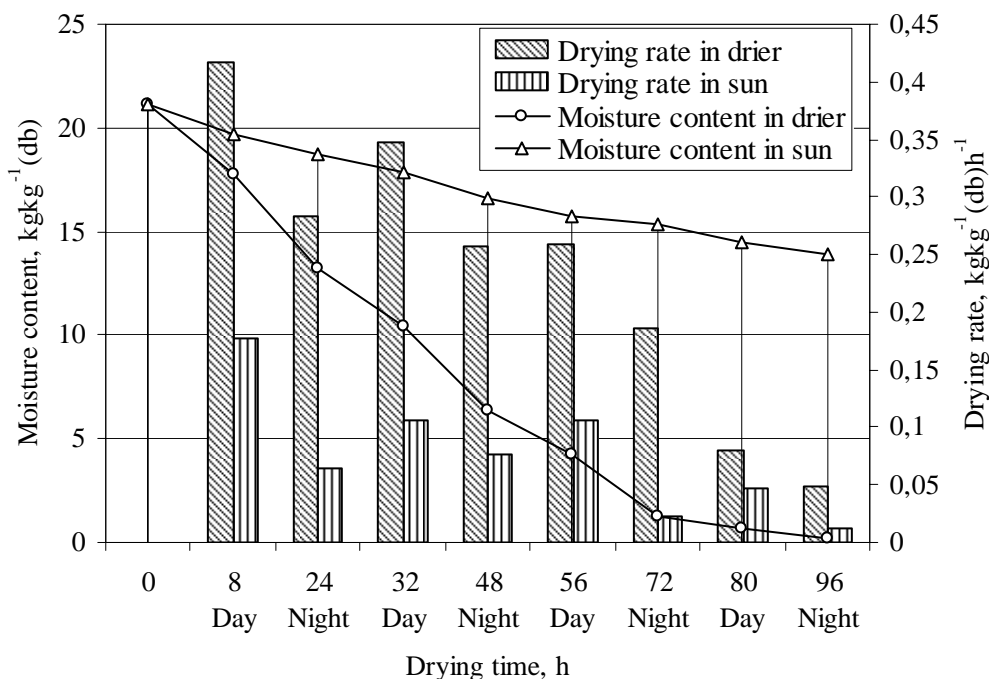


Figure 3.24: Moisture reduction and average drying rate of tomato in day (09:00-17:00 h) night (17:00-09:00 h) drying by solar and sun drying methods with hot water flow (using water heater) at nights in adverse weather conditions (04.09.06-07.09.06)

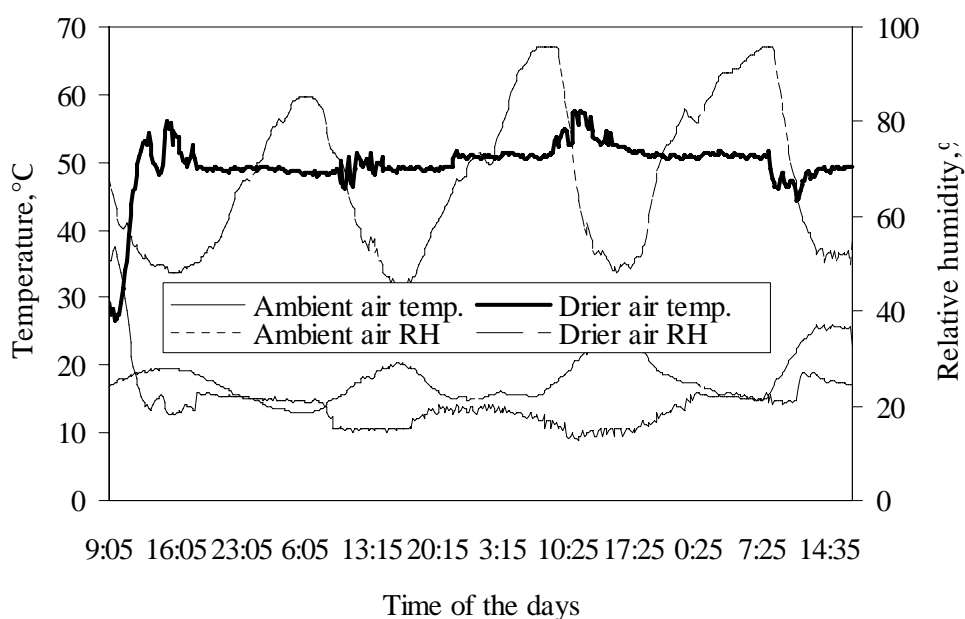


Figure 3.25: Variations of ambient air and drier air temperatures and relative humidity with hot water flow (using water heater in day and night) in adverse weather conditins during solar drying of tomato (04.09.06-07.09.06)

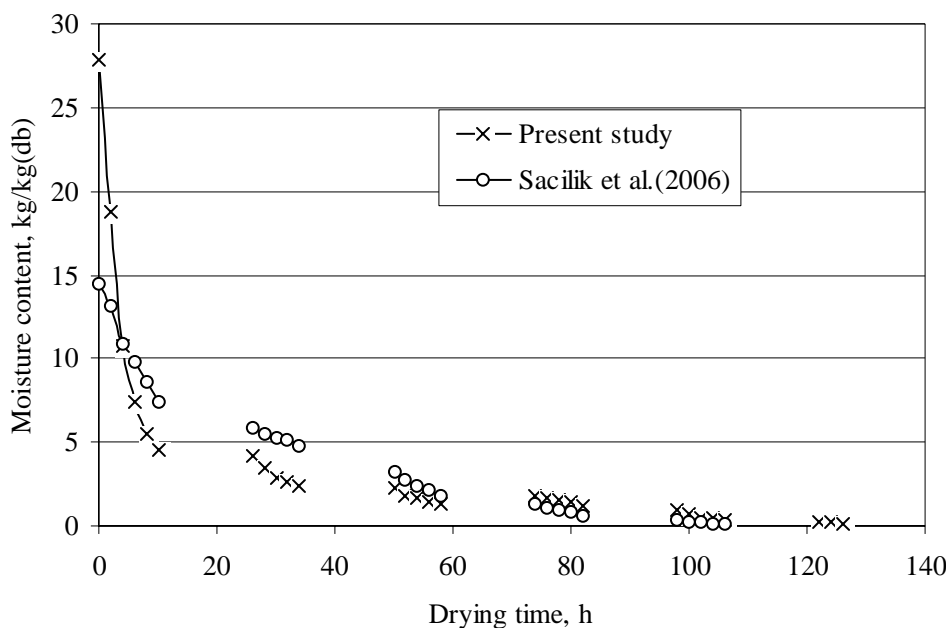


Figure 3.26: Comparisons of moisture content variations with time (space is night time) for solar drying of tomato of present study with the study by SACILIK *et al.* (2006)

Summary of drying performance of solar and sun drying of tomato at different drying conditions are given in **Table 3.3**. Drying was continued both days and nights for both solar and sun drying methods. Without hot water flow in nights, time required to reach safe moisture content (about 0.15 to 0.18 kg/kg (db)) by solar and sun drying were 126 and 288 hours respectively. Using solar drying time could be reduced by 56.25%. But in the second day, molds and fungus grew in both solar and sun drying samples. The reason might be that ambient temperature during drying varied from 15 to 25°C. In the drier, the night temperature fell to about 13°C. For hot water flow (without water heater) drying time reduced to 96 hours against 126 hours without hot water flow and 240 hours in open sun drying method. Time saving was 60% over sun drying method. Again, hot water was circulated in night using water heater to heat up the drying air to the desirable temperature to prevent the microbial development. About 48°C drying air temperature was achieved for use of water heater during the night times. No moulds or fungus grew in the solar drier samples during the entire drying period but sun drying sample was infected by moulds and fungus as before. Drying time was also reduced by 70.90% over sun drying method. One of the disadvantages of solar drier is to dry crop in adverse weather condition (cloudy, foggy or rainy). In adverse weather condition, crops are partially or completely damaged by micro-organisms and insects. So, the present solar drier was tested in adverse weather condition with day-night hot water flow (using water heater). During the drying period, tomato was not infected by insects and micro-organisms because minimum drying air temperature was about 48°C although there was cloudy and rainy (scattered) weather condition. Open sun drying samples were completely damaged by moulds and fungal attack although it was covered during rain.

Table 3.3: Summary of drying performance of solar and sun dryings at different drying conditions

Drying conditions	Average day temperature, (°C)		Average night temperature, (°C)		Average drying rate, (kg/kg(db)-h)		Drying time (h) (day + night)		Time saving by solar drier (%)	Microbial infection
	Solar drier	Ambient	Solar drier	Ambient	Solar drying	Sun drying	Solar drying	Sun drying		
Without hot water flow at nights	55	25	13	15	0.333	0.195	126	288	56.25	Microorganisms grew at 2 nd day
Hot water flow at nights without water heater	58	30	28	16	0.219	0.142	96	240	60.00	Microorganisms grew at 3 rd day
Hot water flow at nights with water heater	57	28	48	15	0.379	0.176	72	220	70.90	No microbial infestation
Adverse weather with hot water flow at days and nights	53	20	48	15	0.235	0.077	88	-	-	No microbial infestation

All sun drying samples were partially/completely spoiled by molds and fungus infection.

Average drying system efficiency of the solar drier at different drying conditions is shown in **Table 3.4**. Highest average drying efficiency (29.35%) was found for hot water flow in night using water heater because in this method drying time was become low as 72 hours in comparison to other method. Average drying efficiencies without hot water flow in nights and drying in adverse weather condition with day-night hot water flow (using water heater) were almost same. Because, without hot water flow in nights, night times temperature fell as to ambient air temperature and drying rate became very low, took long drying time (126 hours) and average drying efficiency was found low as 17.92%. On the other hand, in adverse weather condition, using electric water heater day-night temperature was high as 48°C and drying time reduced to 88 hours, but for electric power consumption average drying efficiency became low as 17.73%.

Table 3.4: Comparisons of solar drying system efficiencies at different drying conditions

Drying conditions	Initial moisture content, kg/kg (db)	Final moisture content, kg/kg (db)	Drying time (h) (day + night)	Average solar drying system Efficiency (%)
Without hot water flow at nights	27.73	0.17	126	17.92
With hot water flow at nights without water heater	18.86	0.18	96	22.48
With hot water flow at nights with water heater	22.15	0.19	72	29.35
Drying in adverse weather with hot water flow at days and nights with heater)	21.14	0.16	88	17.73

Quality of Fresh and Dried Tomato

Quality of fresh, solar dried (at different final moisture content), sun dried and commercial dried tomato is presented in **Table 3.5**. Significantly highest hue angle was found from fresh tomato followed by sun dried samples. Significantly lowest hue angles were found from solar dried sample with 15% and 30% moisture contents, they were statistically similar but significantly lower than solar dried sample with 25% moisture content and commercial sample. Hue angle is the actual colour and it a combination of green, red, blue and yellow colours and widely used to express tomato colour changes (THAI *et al.* 1990, CHOI *et al.* 1995). Hue angle generally decreases from 180 to -1.44° . A hue of 180° represents pure green and a hue of 0° pure red i.e. lower is the hue angle, more red is the colour (SCHEWFELT *et al.* 1988). The hue angles of all dried samples were significantly lower than that of fresh tomato. Hence, the red colour of tomato concentrated to deep red after drying. But for sun dried sample the hue angle was significantly higher than the solar dried samples. The reason might be that sun dried sample was contaminated with dust, dirt and micro-organisms and also exposed to direct sunlight and these might affect the colour of sun dried sample. On the other hand, solar dried samples were dried in the shed (in the drier) and protected from dust, dirt, and insect. Significantly higher hue angle was obtained for the sample with lower moisture content (15%). This may due to that more oxidation took place on sample with lower moisture compare to the sample with higher moisture content. Significantly lowest hue angle was found for sample with 30% moisture content but there was no significant difference with the sample with 25% moisture content. Different in colour of commercial sample was due to varietal difference and difference of other factors but its colour was similar to solar dried samples. Significantly lower ascorbic acid, lycopene and total flavonoids were found from all dried samples than those of fresh sample. These are antioxidant components and during drying these components reduce significantly. It is reported that ascorbic acid, lycopene and total flavonoids of tomato de-

creased during drying in different amounts by oxidative heat damage depending upon the drying air temperature and other drying conditions (ZANONI *et al.* 1999, TOOR & SAVAGE 2006, GOULA & ADAMOPOULOS 2006, GOULA *et al.* 2006). Significantly lowest ascorbic acid was obtained from the lowest moisture content (15%) followed by higher ascorbic acids for higher moisture contents of solar dried samples. Ascorbic acid contents of sun dried and commercial samples were statistically same. Lycopene reduced significantly from fresh to dried samples. There were no significant differences of lycopene among the dried samples. Total flavonoids of fresh tomato was significantly higher than those of dried samples i.e. drying reduced significantly the total flavonoids. Significantly the lowest amount of total flavonoids was found for commercial dried sample than solar and sun dried samples. Total flavonoids reduced with the reduction of moisture contents of dried samples but there was no significance difference between 15 and 25% moisture contents. Significantly lowest amount of total flavonoids were obtained for commercial sample. This may due to that the commercial sample was stored for longer period and the tomato variety was different. Significantly the highest and lowest rehydration ratio was found for solar dried sample with 15% moisture content and commercial sample with 37% moisture content.

Rehydration ratio

Rehydration ratio of solar dried, sun dried and commercial samples of tomato is also given in **Table 3.5**. There were no significantly differences of rehydration ratio for other samples. It is clear from the result that rehydration ratio mainly depends on the moisture content and surface hardness of the dried product i.e. more is the moisture content or hardness less is the rehydration ratio. Similar result presented by LATAPI & BARRETT (2006 a,b). Therefore, all dried samples had good rehydration ratio (>2.0) indicates that drying did not cause case hardening.

Table 3.5: Quality of fresh, solar dried, sun dried and commercial samples of tomato

Samples	Colour (hue angle,°)	Ascorbic acid (mg/100g)	Lycopene (mg/100g)	Total flavonoids (mg/100g)	Rehydration ratio
Fresh (95% MC)	39.09a	238.38a	62.59a	217.54a	-
Solar dried (15% MC)	18.26b	172.54e	44.52b	122.51d	3.26a
Solar dried (25% MC)	15.53c	181.58c	45.98b	128.54d	2.83b
Solar dried (30% MC)	14.29c	184.24b	49.04b	195.61b	2.80b
Sun dried (30% MC)	25.02b	176.69d	44.13b	145.71c	2.78b
Commercial (37%MC)	19.50c	176.71d	44.06b	96.76e	2.16c
Significance level (p)	≤0.05	≤0.05	≤0.05	≤0.05	≤0.05

MC = moisture content of sample in wet basis. Different letters in the same column are significantly different from each other by DMRT.

Effect of Pre-treatments

Effects of pre-treatments on quality and microbial prevention of solar dried tomato are given in **Table 3.6**. Significantly lower colour values (hue angle) were found for all pre-treated samples over control sample i.e. all pre-treatments improved the colour of tomato during drying. Significantly lowest hue angles were obtained from citric acid, ascorbic acid, sodium metabisulphite and sodium chloride treated samples than other samples but there were no significant differences among them. It is reported that sodium metabisulphite and citric acid protect the bright red colour of tomato after drying (ANON. 1996). LATAPI & BARRETT (2006 a) found better colour retention from sodium metabisulphite, sulphur dioxide and sodium chloride treated samples than untreated (control) samples. Significantly highest amount of ascorbic acid was obtained for ascorbic acid pre-treated samples and significantly lowest amount was found for sodium chloride treated sample. Statistically same amount of ascorbic acid was found for acetic acid, citric acid and sodium metabisulphite pre-treated samples. There was no significance difference between UV radiation and control samples. Significantly highest amounts of lycopene were obtained for 6 mg/l acetic acid and 2 g/l and 8 g/l sodium metabisulphite pre-treated samples. The lycopene content of other pre-treated samples were statistically same but significantly higher than control sample. Significantly highest amount of total flavonoids were found for sodium metabisulphite, ascorbic acid and citric acid pre-treated samples than other samples and they were statistically alike. Sodium chloride pre-treatment reduced significantly highest amount of total flavonoids followed by control, UV radiation and acetic acid pre-treated samples but there were no significant difference among them.

Table 3.6: Effect of different pre-treatment on quality of solar dried tomato (drying air temperature during day was 50-55°C and night was 25-40°C)

Pre-treatment	Colour (hue angle,°)	Ascorbic acid (mg/100g)	Lycopene (mg/100g)	Total flavonoids (mg/100g)
Control (No pre-treatment)	24.19a	118.29c	34.52c	124.18b
UV radiation (750 Ws/m ²)	22.75b	137.36c	43.98b	123.36b
UV radiation (1500 Ws/m ²)	19.87b	149.42c	46.04b	124.51b
Acetic acid (4 mg/l)	20.49b	176.69b	47.13b	124.09b
Acetic acid (6 mg/l)	17.64c	176.71b	49.06a	125.39b
Citric acid (3 g/l)	20.56b	181.58b	46.64b	129.14a
Citric acid (6 g/l)	18.19c	184.24b	45.91b	128.57a
Ascorbic acid (3 g/l)	17.35c	230.56a	44.75b	133.91a
Ascorbic acid (6 g/l)	18.09c	249.71a	47.15b	134.87a
Sodium metabisulphite (2 g/l)	18.79c	180.36b	48.50a	132.79a
Sodium metabisulphite (8 g/l)	16.65c	183.49b	49.57a	135.92a
Sodium chloride (10 g/l)	19.13c	90.41d	41.76b	119.52c

Different letters in the same column are significantly different from each other by DMRT at $p \leq 0.05$.

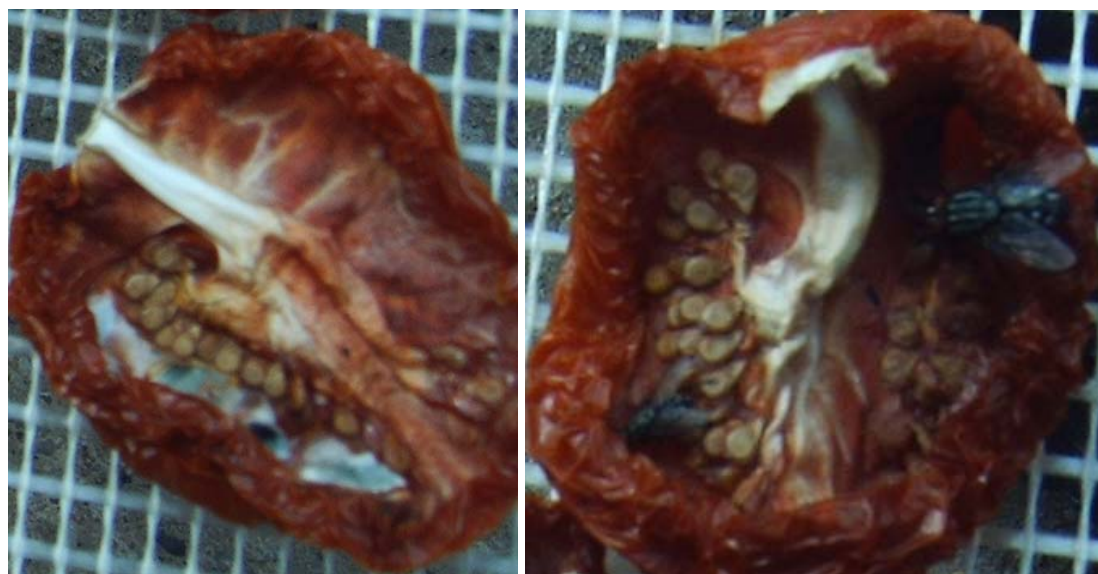
Effect of different pre-treatment on microbial infestation of solar dried tomato is given in **Table 3.7**. It is observed from the Table that all pre-treatments partially prevented the microbial attack but only 8 g/l sodium metabisulphite prevented completely the microbial infestation. Control sample was completely infested by micro-organisms. Micro-organisms were identified as *Zygomycetes*, *Aspergillus spec.*, *Aspergillus niger*, and *Fusarium spec.*, which were tropical molds and fungus. *Zygomycetes* is a class of fungi containing several species. They produce mould-like structure. *Aspergillus spec.*, and *Aspergillus niger* also fungi and produce mould-like structure. *Fusarium spec.* is a plant pathogenic fungus. *Zygomycetes*, *Aspergillus spec.* and *Aspergillus niger* are also contain some pathogenic fungi and some commercially important species, as well. All the plate of control sample was infected by *Zygomycetes* and *Aspergillus spec.* microorganisms. UV radiation, acetic acid, ascorbic acid and sodium chloride reduced 40 to 50% microbial infection. Efficacy of citric acid was found better, reduced 80% of microbial growth. Lower density (2 g/l) sodium metabisulphite could not completely prevent the microbial infestation and 10% plate was infected by *Zygomycetes* and *Aspergillus niger* microorganisms. On the other hand, higher density (8 g/l) sodium metabisulphite completely prevented the microbial infestation in the drying sample. During the drying period all sun drying samples were infected by micro-organisms (moulds and fungi) and some insects like fly (**Figure 3.27**). Solar dried products were free from insects, dust and dirt, because it was completely protected from such environments (**Figure 3.28**).

During the drying period, day time drying air temperature was 50 to 55°C and night was 25 to 40°C). Therefore moulds and fungus might grow due to low temperature in the night time. It is reported in Chapter 2 that temperature above 45°C successfully prevented the microbial infestation during 4 to 5 days of drying period but when temperature reduced below 45°C then micro-organisms (mould/fungi) grew after second or third days of drying. So, it is important to note that if tomato is dried with continuous air temperature of 45°C or above with auxiliary heating at night times or in adverse weather then no pre-treatment is required. If drying air temperature fell below 45°C (in night time or in adverse weather), then tomato should be pre-treated with 8 g/l sodium metabisulphite to control microbial infestation.

Table 3.7: Effect of different pre-treatment on microbial infestation of solar dried tomato (drying air temperature during day was 50-55°C and night was 25-40°C)

Pre-treatment	Observations	Percent infection	Microscopic diagnosis (mold/fungi)
Control	10 infected TP* with black and white spores	100	<i>Zygomycetes, Aspergillus spec.</i>
UV radiation (750 Ws/m ²)	5 infected TP with black spots and white spores	50	<i>Zygomycetes, Aspergillus spec., Fusarium spec.</i>
UV radiation (1500 Ws/m ²)	5 infected TP with white spores and edge black	50	<i>Aspergillus spec., Aspergillus niger</i>
Acetic acid (4 mg/l)	5 infected TP with white spores	50	<i>Zygomycetes, Aspergillus spec., Fusarium spec.</i>
Acetic acid (6 mg/l)	4 infected TP with white spores	40	<i>Zygomycetes</i>
Citric acid (3 g/l)	6 infected TP with white spores	20	<i>Zygomycetes, Aspergillus niger</i>
Citric acid (6 g/l)	2 infected TP with white spores	20	<i>Aspergillus niger</i>
Ascorbic acid (3 g/l)	6 infected TP white spores	60	<i>Zygomycetes, Aspergillus niger</i>
Ascorbic acid (6 g/l)	4 infected TP with white spores	40	<i>Zygomycetes, Aspergillus niger</i>
Sodium meta-bisulphite (2 g/l)	1 infected TP with white spores	10	<i>Aspergillus niger</i>
Sodium meta-bisulphite (8 g/l)	No infected TP	0	
Sodium chloride (10 g/l)	4 infected TP with black and white spores	40	<i>Zygomycetes, Aspergillus niger</i>

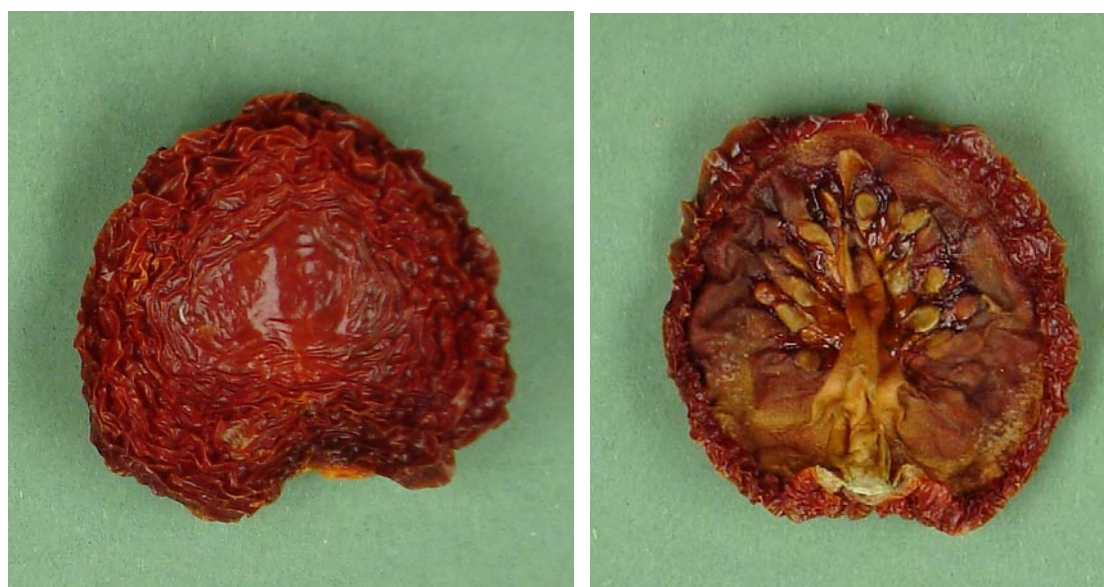
*TP = Tomato plate (half), Total number of tomato plate observed per sample was 10



(a)

(b)

Figure 3.27: Infected dried tomato halves (a) microbial infected (b) insect (fly) infected



(a)

(b)

Figure 3.28: Non-infected dried tomato halves (a) skin side up (b) cut side up

CONCLUSIONS

Average air temperature at the outlet of the collector was found about 30°C higher than the average ambient temperature during the normal sunny days. With hot water flow using water heater and without using water heater in night time, average collector outlet temperature were about 48°C and 35°C against the average night time ambient temperature of 20°C. Collector efficiency was increased about 10% using solar reflector. The capacity

of solar drier was to dry 18 kg of half-cut fresh tomato to produce about 2 kg of dried product per batch. The average drying system efficiency of the solar drier drying day time using solar radiation and drying night time without hot water flow, hot water flow without external water heating, hot water flow using external water heating and day-night hot water flow using external water heating in adverse weather were about 18, 22, 33 and 17% respectively.

Drying process reduced significantly the colour, ascorbic acid, lycopene and total flavonoids of tomato. Significantly lowest red colour ascorbic acid and rehydration ratio were obtained for the solar dried sample with lowest final moisture content (15%) and those of higher amounts for sample with higher final moisture contents. Effect of product final moisture content on lycopene and total flavonoids were found insignificant. Tomato halves were pre-treated with UV radiation, acetic acid, citric acid, ascorbic acid, sodium metabisulphite and sodium chloride at different doses. All pre-treatments significantly improved the colour of dried tomato than non-treated sample. No pretreatment could completely control the microbial infestation except sodium metabisulphite (8 g/l) at lower temperature (<45°C). When tomato was dried at the drying air temperature of 45°C or above, molds and fungus growth was not observed. Therefore, it is recommended that if tomato is dried with continuous air temperature of 45°C or above then no pre-treatment is required. If drying air temperature fallen below 45°C (temperature in night time or in adverse weather), then tomato should be pre-treated with 8 g/l sodium metabisulphite to prevent the microbial growth.

NOMENCLATURE

A_c	Area of collector (m^2)
B	Breadth of the drying chamber (m)
C_{pa}	Specific heat of air (kJ/kg K)
C_{pw}	Specific heat of water (kJ/kg K)
d	Depth of the drying chamber (m)
g	Acceleration due to gravity (9.81 m/s)
h_L	Latent heat of water in the tomato (kJ/kg)
H	Pressure head of air (vertical distance from air entry point to air exit point) (m)
I_g	Global solar radiation (W/m^2)
I_t	Total solar radiation (global + reflected) (W/m^2)
L	Length of the drying chamber (m)
M	Moisture content (% , wet basis)
\dot{m}_a	Mass flow rate of air (kg/s)
\dot{m}_w	Mass flow rate of water (kg/s)
m_w	Mass of evaporated moisture (kg)

Q_f	Heat used by fan for air flowing (kW)
Q_h	Heat used by water heater for heating (kW)
Q_p	Heat used by water pump for water flowing (kW)
t	Time (min)
T_i	Inside air temperature ($^{\circ}\text{C}$)
T_o	Outside air temperature ($^{\circ}\text{C}$)
T_w	Water temperature ($^{\circ}\text{C}$)
W_p	Weight of fresh product to be dried per batch (kg)
η_{cdg}	Collector efficiency in day time considering global solar radiation (ratio)
η_{cdt}	Collector efficiency in day time considering total solar radiation (ratio)
η_{cn}	Collector efficiency in night time (ratio)
η_{dd}	Drier efficiency in day time (ratio)
η_{nd}	Drier efficiency in night time (ratio)
ρ_p	Bulk density of product (kg/m^3)

Chapter 4

MATHEMATICAL MODELLING FOR SOLAR DRYING OF TOMATO

ABSTRACT

A mathematical model was developed for a concentrative flat plate solar collector and an indirect multi-rack type forced convection drier. The model was a physically based taking into account the heat transfer in the collector and coupled heat and mass transfer within the drier. One set of equations was developed to predict cover temperature, receiver (absorber) temperature and air temperature in the collector. Another set of partial differential equations was developed to predict the air and product temperatures, air humidity and moisture content for drying of tomato halves in the solar drier. First set of equation was solved iteratively and the second set of equations was solved numerically based on an exponential solution over the finite difference grid element using the outlet air conditions of the collector as inlet conditions of the drying unit. The simulated cover, air and receiver temperatures in the collector agreed well with the measured temperatures. Good agreements were also found between experimental and simulated air and product temperatures, air relative humidity and product moisture content in the drier for drying of tomato halves. This model can be used for providing design data of a solar drier for drying of tomato as well as other fruits and vegetables.

INTRODUCTION

Mathematical modelling and computer simulation of the drying of agricultural products are now widely used in the agricultural engineering research. Various simulation models for solar processes have appeared in the literature. They differ mainly in the assumptions made and strategies employed to solve the model equations. Several mathematical models have been used to describe the deep bed and thin layer drying of agricultural products. These are: heat and mass balance models, partial differential models and thin layer and equilibrium moisture content models. The simulation model is used to design and to optimise a solar drier. The development of a simulation model is a powerful tool for prediction of performance and can help designers to optimise the drier geometry at various operating conditions without having to test experimentally the drier performance at each condition (BALA & WOODS 1994). Simulation enables the researcher to evaluate the performance of the solar drier before actual production of the prototype and experiment is done. If simulation is combined with optimisation, the researcher is able to design a cost effective solar drier, that is, a solar drier with minimum cost and maximum moisture removal within given constraints.

SODHA *et al.* (1985) developed an analytical model for drying of sliced apple, peaches, cherries and mango in a solar cabinet drier and in open sun drying method. This model was based on the principle of simultaneous heat and mass transfers at the product surface. They reported that this model agreed well with the experimental data and drying rate of products was found higher in the solar cabinet drier than in open sun drying method. STEINFELD & SEGAL (1986) developed a mathematical model for forced convection solar drying of agricultural products. The model consisted of three sub-models such as, estimation of solar radiation, determination of the performance of flat-plate air heater and performance of solar drier. The analysis of the drying process was based on the Lewis analogy and equilibrium moisture content concept. They presented the simulated results of thin layer drying of shelled corn. GARG & SHARMA (1990) presented a mathematical simulation model and experimental study for mixed mode solar drier for drying agricultural crops. A single glazed flat plate air heater was connected with the drying unit that had a transparent cover. In the model, the radiation absorbed by the drying product was taken as equal to the product of the absorptivity of the drying product, the transmissibility of the glass cover and the solar radiation. This term was added to the energy transferred by convection from the air to the drying product so that the total energy for drying was increased whilst considering the drying material as a thin layer. They reported that simulated and experimental results were in good agreement. RATTI & MUJUMDAR (1997) developed a simulation model to predict the batch drying performance of a packed bed of slices of carrot and apple subjected to time-varying air conditions. They compared the predicted moisture content with the experimental data and found good agreement. PHOUNGCHANDANG & WOODS (2000) developed a mathematical model for sun drying of banana using a numerical solution procedure to generate a computer simulation. The model was in good agreement with

laboratory results obtained under artificial lights and also in field data from Thailand. They suggested that this model is applicable to the sun drying of crops in a single layer and is sufficiently adaptable to examine the effects of drying material, drier geometry, air temperature and air velocity. KARIM *et al.* (2001) developed a mathematical model for batch type solar drying of banana. Both material and equipment (drier) were included in the model. The predicted moisture content and temperature of banana and air temperature and humidity ratio agreed fairly well with the experimental results. IVANOVA & ANDONOV (2001) developed an analytical model for geothermal assisted solar drying of fruits and vegetables. They made comparisons between predicted and experimental results for solar drying of apricot and found adequate agreement. HODALI & BOUGARD (2001) developed a mathematical model for a forced convection solar drier connected with a desiccant unit. They developed non-linear partial differential equations and solved by the finite difference method. They compared the simulated air temperature and moisture content with the experimental results of drying of apricots in climatic conditions of Morocco and found good agreement. AMER (2006) developed simulation model for solar drying (hybrid type) of banana, apple and plum. He calculated the drying process in the day using solar energy and in the night by circulating hot water air in the collector from the heat storage tank which, was heated by solar radiation (day time) or water heater (night time). He validated the model for the weather conditions of Egypt. He found good agreement between experimental and simulated results. But the model was capable to predict the results for one hour or less drying time due to the limitation of software (EXCEL). Mathematical model on solar drying of tomato is scarce in literature. Therefore, this study has been undertaken to develop a mathematical model for solar drying of tomato using a newly designed indirect type forced convection solar drier (see Chapter 3) and to validate the model with experimental data.

METHODOLOGY

The computer simulation model involves two components that are used to describe the drying process in solar drier. These are:

- (a) The collector performance, which predicts the air temperature and relative humidity and cover and receiver temperatures at different positions of the collector at different drying time.
- (b) The thin layer simulation model that predicts the air temperature and humidity and product temperature and moisture content at different time and positions in the drier.

Analysis of Collector Performance

Flat plate collector is designed for applications requiring moderate temperature not exceeding 100°C. It is relatively cheap and can be easily constructed. It uses both beam

and diffuse solar radiation and is well suited for the drying of agricultural crops. The collector in this study is a concentrator type with a flat plate reflector. It may be termed as concentrator type flat plate air heater. Because air is the heating fluid to transfer heat energy from collector to drier by forced convection. Total incident radiation flux on the collector cover is the sum of global radiation (directly falls on the cover) and reflected radiation (reflection from the reflector) as shown in **Figure 4.1**.

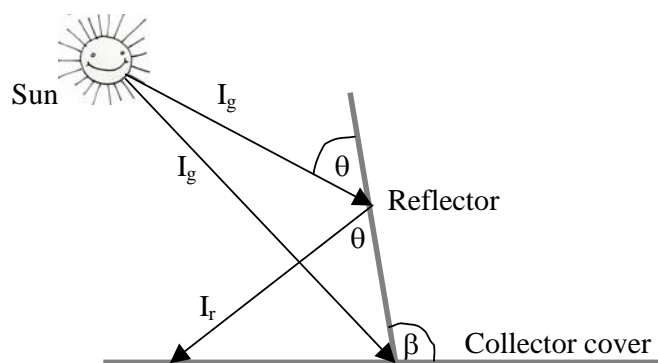


Figure 4.1: Solar insolation mechanism on the reflector and collector cover

According to the basic principle of light, the incident angle of both global radiation and reflected radiation will be same (θ). Therefore the reflected and total incident solar radiation (E) on the cover surface will be

$$I_r = \Gamma \rho I_g \sin \beta \quad (4.1)$$

$$E = (I_g + I_r) \cos \theta \quad (4.2)$$

Therefore,

$$E = I_g (1 + \Gamma \rho \sin \beta) \cos \theta \quad (4.3)$$

Energy balances on the plastic cover

Energy balance or energy inflow in and outflow from the glass cover is:

$$Q_{absor,c} - Q_{conv,c-am} - Q_{conv,c-a} - Q_{rad,c-s} + Q_{rad,r-c} - Q_{ref,c-am} + Q_{ref,r-c} = 0 \quad (4.4)$$

Amount of heat (Q) may be splitted into its components

$$\begin{aligned} & \alpha_{cs} EA_c - h_{conv,c-am} A_c (T_c - T_{am}) - h_{conv,c-a} A_c (T_c - T_a) - h_{rad,c-s} A_c (T_c - T_s) \\ & + h_{rad,r-c} A_c (T_r - T_c) - \Gamma \rho_c EA_c + \Gamma \rho_r EA_r = 0 \end{aligned} \quad (4.5)$$

Since, the area of cover and receiver (absorber plate) is the same i.e. $A_c=A_r$ then Eqn (4.5) becomes

$$\begin{aligned} T_c (h_{conv,c-am} + h_{conv,c-a} + h_{rad,c-s} + h_{rad,r-c}) &= \alpha_{cs} E + E\Gamma \rho_r - E\Gamma \rho_c + h_{conv,c-am} T_{am} \\ &+ h_{conv,c-a} T_a + h_{rad,c-s} T_s + h_{rad,r-c} T_r \end{aligned} \quad (4.6)$$

Therefore,

$$T_c = \frac{h_{conv,c-am} T_{am} + h_{conv,c-a} T_a + h_{rad,c-s} T_s + h_{rad,r-c} T_r + E(\alpha_{cs} + \Gamma \rho_r - \Gamma \rho_c)}{h_{conv,c-am} + h_{conv,c-a} + h_{rad,c-s} + h_{rad,r-c}} \quad (4.7)$$

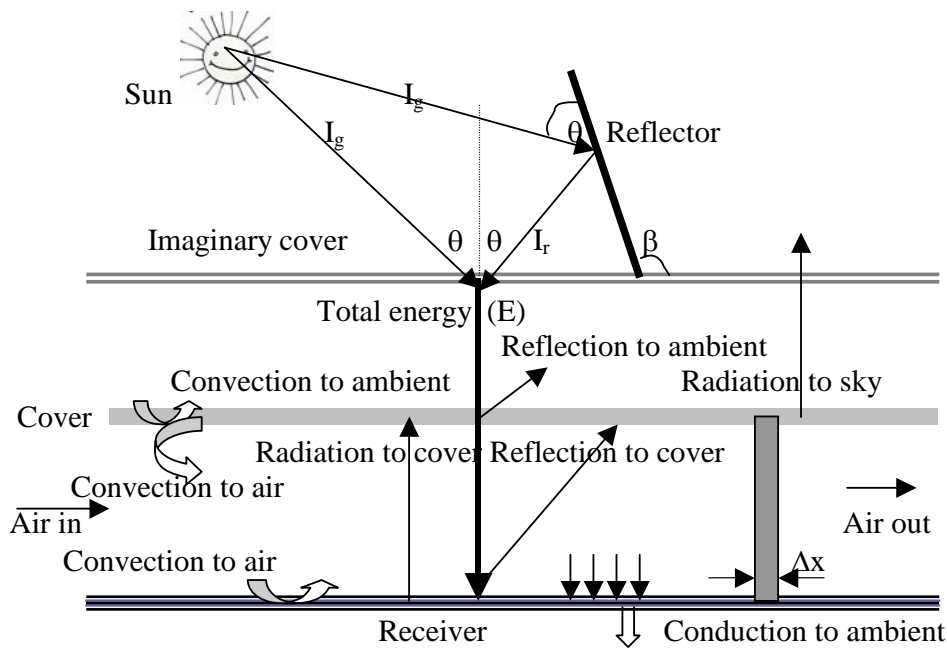


Figure 4.2: Energy flow in a flat plate concentrating solar air heater

Energy balances on the receiver (absorber plate)

Since this is a concentrating type flat plate air heater hence, the absorber plate is termed as receiver. The following equation gives the energy balance on the receiver.

$$Q_{absor,r} - Q_{conv,r-a} - Q_{cond,r-am} - Q_{rad,r-c} - Q_{ref,r-c} = 0 \quad (4.8)$$

$$\begin{aligned}
& h_{con,r-a} A_r (T_r - T_a) + k_{cond} \Delta y A_r (T_r - T_{am}) + h_{rad,r-c} (T_r - T_c) - \Gamma \rho_r E A_r \\
& = \frac{\tau_{cs} \alpha_{rs} E}{1 - (1 - \alpha_{rs}) \rho_{rs}} A_r
\end{aligned} \tag{4.9}$$

$$\begin{aligned}
T_r (h_{conv,r-a} + k_{cond,r-am} \Delta y + h_{rad,r-c}) & = \frac{\tau_{cs} \alpha_{rs} E}{1 - (1 - \alpha_{rs}) \rho_{rs}} + \Gamma \rho_r E + h_{con,r-a} T_a \\
& + k_{cond} \Delta y T_{am} + h_{rad,r-c} T_c
\end{aligned} \tag{4.10}$$

By rearranging,

$$T_r = \frac{\frac{\tau_{cs} \alpha_{rs} E}{1 - (1 - \alpha_{rs}) \rho_{rs}} + \Gamma \rho_r E + h_{conv,r-a} T_a + k_{cond} \Delta y T_{am} + h_{rad,r-c} T_c}{h_{conv,r-a} + h_{rad,r-c} + k_{cond,r-am} \Delta y} \tag{4.11}$$

Energy balances on the air stream

Air flows inside the collector (between the cover and receiver) along the length. If b is the width of the collector and x is the distance from the entry of the air in the collector the following equation gives the energy balances in the air inside the collector.

$$b \dot{m}_a C_{pa} \frac{dT_a}{dx} = h_{conv,a} A_a (T_r - T_a) + h_{conv,a} A_a (T_c - T_a) \tag{4.12}$$

$$\text{or, } b \dot{m}_a C_{pa} \frac{dT_a}{dx} = h_{conv-a} A_a (T_r + T_c - 2T_a)$$

Area of air stream, $A_a = b.L$

$$\frac{dT_a}{dx} = \frac{2h_{ca}(b.L)}{b \dot{m}_a C_{pa}} \left(\frac{T_r + T_c}{2} - T_a \right) \tag{4.13}$$

$$\text{Assume, } A = \frac{2L.h_{conv,a}}{\dot{m}_a C_{pa}} \text{ and } B = \frac{T_r + T_c}{2}$$

Then,

$$\frac{dT_a}{dx} = A(B - T_a) \tag{4.14}$$

Integrating,

$$\int_{T_{a,i-1}}^{T_{a,i}} \frac{dT_a}{B - T_a} = A \int_{x_{j-1}}^{x_j} dx \quad (4.15)$$

$$-\ln\left(\frac{B - T_{a,i}}{B - T_{a,i-1}}\right) = A(x_j - x_{j-1}) \quad (4.16)$$

$$\frac{B - T_{a,i}}{B - T_{a,i-1}} = \exp\{-A(x_j - x_{j-1})\} \quad (4.17)$$

$$1 - \frac{B - T_{a,i}}{B - T_{a,i-1}} = 1 - \exp\{-A(x_j - x_{j-1})\} \quad (4.18)$$

$$\frac{T_{a,i} - T_{a,i-1}}{B - T_{a,i-1}} = 1 - \exp\{-A(x_j - x_{j-1})\} \quad (4.19)$$

Equation (4.19) can be solved to compute the rise in air temperature, ΔT_a over the finite distance, Δx (collector thickness) as follows:

$$\Delta T = T_{a,i} - T_{a,i-1} = (B - T_{a,i-1})(1 - e^{-A\Delta x}) \quad (4.20)$$

The values of T_c , T_r and T_a can be obtained by the iterative solution of Eqns (4.7-4.20).

The radiative heat transfer coefficient is derived by (BALA 1998) using radiation network method and given in linearized form

$$h_{rad,r-s} = \frac{\sigma(T_r^2 + T_s^2)(T_r + T_s)}{\frac{1}{\epsilon_r} + \frac{1}{\tau_{cL}} - 1} \quad (4.21)$$

$$h_{rad,r-c} = \frac{\sigma(T_r^2 + T_c^2)(T_r + T_c)}{\frac{1}{\epsilon_{rL}} + \frac{1}{\tau_{cL}} + \frac{1}{1 - \tau_{cL}} - 2} \quad (4.22)$$

$$h_{rad,c-s} = \frac{\sigma(T_c^2 + T_s^2)(T_c + T_s)}{\frac{1}{\epsilon_{cL}} + \frac{1}{\tau_{cL}} - 1} \quad (4.23)$$

The convective heat transfer coefficient between the cover and the atmosphere is calculated from the correlation of SPARROW *et al.* (1979).

$$Nu = 0.86R_e^{0.5} Pr^{\frac{1}{3}} \quad (4.24)$$

In determining the convective heat transfer coefficient between the internal air stream and the cover or absorber, the correlations recommended by BALA (1998) are used

for $Re > 10,000$

$$Nu = 0.023Re^{0.8}Pr^{0.4} \quad (4.25)$$

for $Re < 10,000$ and $Re.Pr.2s/L > 70$

$$Nu = 7.6 \quad (4.26)$$

for $Re < 10,000$ and $Re.Pr.2s/L < 70$

$$Nu = 1.85(Re.Pr.2s/L)^{1/3} \quad (4.27)$$

Efficiency of the Collector

The energy collection efficiency of the collector may be calculated using the following general formula.

$$\eta_{collection} = \frac{\dot{Q}_{useful}}{\dot{Q}_{received}} \quad (4.28)$$

$$\eta_{collection} = \frac{\dot{m}_a C_{pa} (T_o - T_i)}{EA_c} \quad (4.29)$$

From Eqns (4.2 and 4.3), Eqn (4.29) may be expressed in terms of global and reflected radiation.

$$\eta_{collection} = \frac{\dot{m}_a C_{pa} (T_o - T_i)}{A_c (I_g + I_r) \cos \theta} \quad (4.30)$$

$$\eta_{collection} = \frac{\dot{m}_a C_{pa} (T_o - T_i)}{A_c I_g (1 + \Gamma \rho \sin \beta) \cos \theta} \quad (4.31)$$

Analysis of Solar Drier Performance

The drier under this study is a fixed bed with vertically divided into five layers (trays). There is an air gaps between two trays. Also inlet and out layers have similar air gaps for air entry and air exit. Heated air enters from the bottom and exits from the top of the

drier. During the air flow, it carries moisture from product from each of the layer. During air flow (drying), product losses moisture to air and air gains moisture from the product. Therefore, during drying both product and air properties (temperature, humidity, moisture content etc.) are continuously changed as shown in **Figure 4.3**.

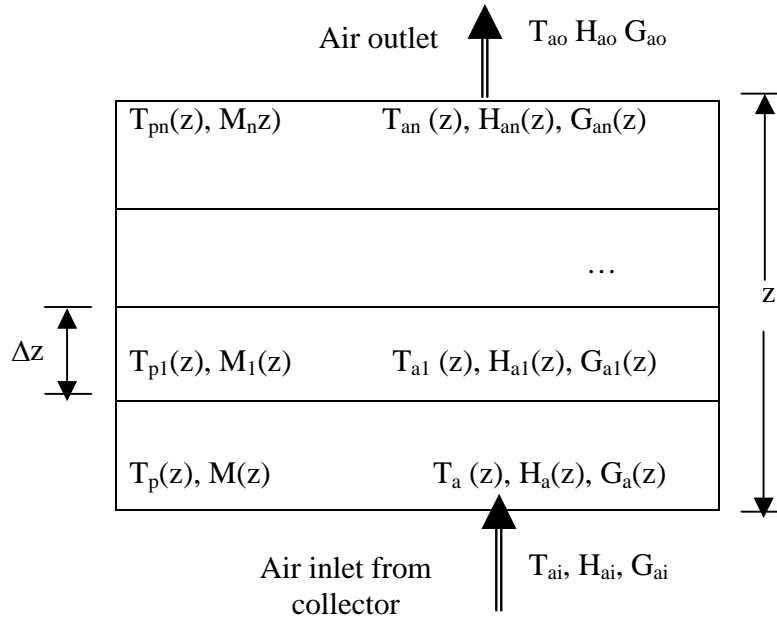


Figure 4.3: Schematic diagram of air and product properties during drying

Each tray in this study is considered each layer and total numbers of layers are assumed to be made a deep bed. As a classical way of modeling the physically-based model (PBM) are normally used for evaluation of the performance of drying process (FARKAS 2006) and ventilated storage of fresh produce (GOTTSCHALK 1999). This physically-based model generally consists of several partial differential equations- continuity equation, drying rate equation, mass balance equation, heat balance equation and heat transfer equation (BALA 1998, GOTTSCHALK & CHRISTENBURY 1998). This model is developed by a set of partial differential equations to describe the heat and mass transfer between drying air and product and also within a single layer of product during a small time increment. The following assumptions are made for simplification of the model.

- (1) Air flow is one dimensional
- (2) There is no heat flow perpendicular to the direction of air flow
- (3) Air properties does not change within the air gaps
- (4) Contribution to the energy and moisture balances from the rate of air properties is negligible.
- (5) Outlet air temperature and relative humidity of the collector is the same as inlet drier temperature and relative humidity.

Consider an elemental layer dz of the bed ($z, z + dz$) of unit cross-sectional area with airflow G_a from z to $z + dz$ (**Figure 4.4**). There are four unknowns: changes of product moisture content, humidity, product temperature and air temperature. Therefore, four differential equations are required to solve these unknowns.

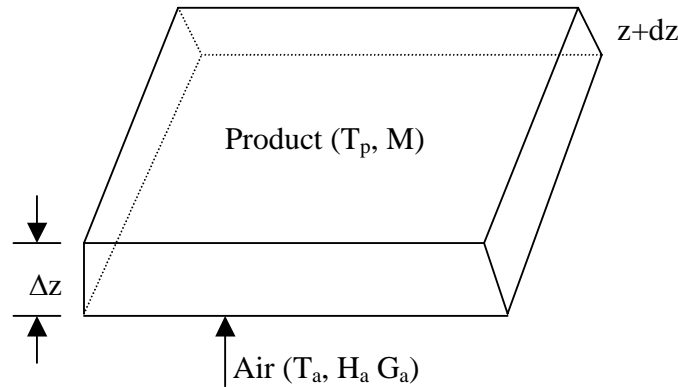


Figure 4.4: Element of product (tomato) bed

Mass balance equation

The flow of moisture into the element (z) at time dt is $G_a H_a(z)dt$ and out of the element ($z+dz$) is $G_a H_a(z+dz)dt$. The difference of this moisture is added to drying air from the product. The moisture lost from the product in the element of bed dz at time t is $-\rho_p M(t)dz$ and at time $(t + dt)$ is $-\rho_p M(t + dt)dz$. The mass balance equation is therefore given by:

Moisture lost by product = moisture gained by air.

$$-\rho_p M(t + dt)dz - (-\rho_p M(t)dz) = G_a H_a(z + dz)dt - G_a H_a(z)dt \quad (4.32)$$

Using Taylor series expansion for H_a and M and ignoring all terms of dz^2 and dt^2 and higher, Eqn (4.32) reduces to

$$G_a \left(\frac{\partial H_a}{\partial z} \right) dz dt = -\rho_p \left(\frac{\partial M}{\partial t} \right) dz dt \quad (4.33)$$

After simplification, Eqn (4.33) comes:

$$\left(\frac{\partial H_a}{\partial z} \right) = -\frac{\rho_p}{G_a} \left(\frac{\partial M}{\partial t} \right) \quad (4.34)$$

Therefore, the change of humidity in the finite difference form Eqn (4.34) comes as

$$\Delta H_a = -\left(\frac{\rho_p}{G_a}\right)\left(\frac{\Delta M}{\Delta t}\right)\Delta z \quad (4.35)$$

Heat balance equation

Heat balance equation in the drying element (layer) is the change in enthalpy of air is equal to change in enthalpy of product.

Heat flowing into the element (z, z+dz) of air at time dt is

$G_a[C_{pa}+C_{pw}H_a(z) T_a(z)+L_aH_a(z)]dt$ and heat flowing out of element of air at time dt is $G_a[C_{pa}+C_{pw}H_a(z+dz) T_a(z+dz)+L_aH_a(z+dz)]dt$

Therefore, change of enthalpy of air of element (z, z+dz) at time dt is:

$$G_a [C_{pa} + C_{pw}H_a(z+dz)T_a(z+dz) + L_aH_a(z+dz)]dt - G_a [C_{pa} + C_{pw}H_a(z)T_a(z) + L_aH_a(z)]dt \quad (4.36)$$

Again, heat flowing into the element dz of product at time t is

$-\rho_p [C_{pp}+C_{pl} M(t) T_p(t)]dz$ and heat flowing out of element dz of product at time (t + dt) is $-\rho_p [C_{pp}+C_{pl} M(t+dt) T_p(t+dt)]dz$.

So, change of enthalpy of product at time (t+dt) and t is:

$$-\rho_p [C_{pp} + C_{pl}M(t+dt)T_p(t+dt)]dz + \rho_p [C_{pp} + C_{pl}M(t)T_p(t)]dz \quad (4.37)$$

Applying the Taylor series expansion and neglecting higher second order terms and higher, expressions (4.36) and (4.37) are equated to as:

Change in enthalpy of air = change in enthalpy of product.

$$G_a \left[C_{pa} \left(\frac{\partial T_a}{\partial z} \right) dz dt + C_{pw} H_a \left(\frac{\partial T_a}{\partial z} \right) dz dt + C_{pw} T_a \left(\frac{\partial H_a}{\partial z} \right) dz dt + C_{pw} \left(\frac{\partial T_a}{\partial z} \right) \left(\frac{\partial H_a}{\partial z} \right) dz^2 dt + L_a \left(\frac{\partial H_a}{\partial z} \right) dz dt \right] \\ = -\rho_p \left[C_{pp} \left(\frac{\partial T_p}{\partial t} \right) dt dz + C_{pl} M \left(\frac{\partial T_p}{\partial t} \right) dt dz + C_{pl} T_p \left(\frac{\partial M}{\partial t} \right) dt dz + C_{pl} \left(\frac{\partial T_p}{\partial t} \right) \left(\frac{\partial M}{\partial t} \right) dt^2 dz \right] \quad (4.38)$$

Substituting for $\left(\frac{\partial H_a}{\partial z} \right)$ from Eqn (4.34) in the left hand side of the Eqn (4.38) and we have

the Eqn (4.38) in simplified form as:

$$\left(\frac{\partial T_a}{\partial t}\right) \left[C_{pa} + C_{pw} \left(H_a - \frac{\rho_p}{G_a} \left(\frac{\partial T_a}{\partial z} \right) dz \right) \right] = -\frac{\rho_p}{G_a} \left(\frac{\partial T_p}{\partial t} \right) \left[C_{pp} + C_{pl} \left(M + \left(\frac{\partial M}{\partial t} \right) dt \right) \right] + \frac{\rho_p}{G_a} \left(\frac{\partial M}{\partial t} \right) [C_{pw} T_a + L_a C_{pl} T_p] \quad (4.39)$$

Therefore, air temperature change in the finite difference form is given by

$$\Delta T_a = \frac{-\frac{\rho_p}{G_a} \Delta T_p \{C_{pp} + C_{pl} (M + \Delta M)\} \left(\frac{\Delta z}{\Delta t}\right) + \frac{\rho_p}{G_a} \Delta M (C_{pw} T_a + L_a - C_{pl} T_p) \left(\frac{\Delta z}{\Delta t}\right)}{C_{pa} + C_{pw} H_a - \frac{C_{pw} \rho_p}{G_a} \Delta z \left(\frac{\Delta M}{\Delta t}\right)} \quad (4.40)$$

Heat transfer rate equation

In time dt heat transferring in the element dz due to the result of heat of convection from the air to product is $h_{cv}(T_a - T_p)dzdt$. The change in sensible heat of product of the element dz at time t is, $\rho_p[C_{pp}T_p(t) + C_{pl}MT_p(t)] dz$ and at time $(t+dt)$ is, $\rho_p[C_{pp}T_p(t+dt) + C_{pl}MT_p(t+dt)]dz$. Again, enthalpy in evaporated moisture and enthalpy of moisture before evaporation of element dz at the time t is $\rho_p[C_{pw} + L_pM(t)]T_p(t)dz$.

Heat transfer between air and product = change in sensible heat of product + change in enthalpy in air just after drying and just prior to drying (evaporation).

$$h_{cv}(T_a - T_p)dzdt = \rho_p [C_{pp}T_p(t) + C_{pl}MT_p(t) + (C_{pw} + L_p)M(t)dzdt - C_{pl}M(t)T_p(t)dz] \quad (4.41)$$

Applying the Taylor series expansion and neglecting higher order terms Eqn (4.41) becomes

$$h_{cv}(T_a - T_p)dzdt = \rho_p \left[C_{pp} \left(\frac{\partial T_p}{\partial t} \right) dzdt + C_{pl}M \left(\frac{\partial T_p}{\partial t} \right) dzdt + (C_{pw} + L_p) \left(-\frac{\partial M}{\partial t} \right) dzdt - C_{pl}T_p \left(-\frac{\partial M}{\partial t} \right) dzdt \right] \quad (4.42)$$

Taking mean value of T_a and T_p in the finite difference form in Eqn (4.42),

$$\frac{T_a + T_a + \Delta T_a}{2} - \frac{T_p + T_p + \Delta T_p}{2} = \frac{\rho_p}{h_{cv}} \left[(C_{pp} + C_{pl}M) \left(\frac{\Delta T_p}{\Delta t} \right) - (C_{pw} + L_p) - C_{pl}T_p \left(\frac{\Delta M}{\Delta t} \right) \right] \quad (4.43)$$

After simplification,

$$\Delta T_p = \frac{2(T_a - T_p) + \Delta T_a + \frac{2\rho_p}{h_{cv}} (C_{pw} + L_p - C_{pl}T_p) \frac{\Delta M}{\Delta t}}{1 + \frac{\rho_p}{h_{cv}\Delta t} (C_{pp} + C_{pl}M)} \quad (4.44)$$

Putting the value of ΔT_a from Eqn (4.40) we get the value of ΔT_p in the following simplified form.

$$\Delta T_p = \frac{2(T_a - T_p) + \rho_p \frac{\Delta M}{\Delta t} \left[\frac{2A}{h_{cv}} + \frac{D\Delta z}{G_a C} \right]}{1 + \frac{\rho_p}{\Delta t} \left[\frac{2B}{h_{cv}} + \frac{\Delta z}{G_a C} (B + C_{pl} \Delta M) \right]} \quad (4.45)$$

Where,

$$A = L_p + C_{pw} T_a - C_{pl} T_p$$

$$B = C_{pp} + C_{pl} M_p$$

$$C = C_{pa} + C_{pw} \left(H - \frac{\rho_p \Delta z}{G_a} \frac{\Delta M}{\Delta t} \right)$$

$$D = L_a + C_{pw} T_a - C_{pl} T_p$$

Drying rate equation

The rate of change of moisture content of a thin layer product inside the dryer can be expressed by an appropriate thin layer drying equation. The Newton equation in differential form is

$$\frac{dM}{dt} = -K(M_o - M_e) \quad (4.46)$$

Taking the mean value of M and (M+ Δt) the Eqn (4.46) in the finite difference form can be expressed as.

$$\Delta M = -\frac{K(M_o - M_e)}{\left(1 + \frac{K}{2} \Delta t\right) \Delta t} \quad (4.47)$$

MIDILLI *et al.* (2002) model was found suitable to predict moisture content of tomato halves in single layer (Chapter 2). MIDILLI *et al.* (2002) model is:

$$\frac{M - M_e}{M_o - M_e} = a \exp(-Kt^u) + bt \quad (4.48)$$

By differentiating Eqn (4.48) becomes

$$\frac{dM}{dt} = (M_o - M_e)(-a \cdot K \cdot u \cdot t^{u-1} \exp(-Kt^u) + b) \quad (4.49)$$

Moisture change of MIDILLI *et al.* (2002) model in the finite difference form can be written as

$$\Delta M = -K \cdot a \cdot u \cdot t^{u-1} \Delta t (M_o - M_e) \exp(-Kt^u) + b(M_o - M_e) \Delta t \quad (4.50)$$

Drying rate constant (K) and equilibrium moisture content (M_e) were obtained from the thin single layer drying equation as described in Chapter 2.

Solution Procedure

Radiative properties (absorptivity, reflectivity, transmissibility, emissivity etc.) and heat transfer properties of air, glass, absorber plate, aluminium and other materials were collected from BALA (1998) and STINE & GEYER (2001).

Total amount of solar radiation on the collector cover in term of global solar radiation was calculated from Eqn (4.3). For a given incident solar radiation, ambient air temperature, relative humidity and air velocity, the mean cover temperature of the collector was computed using Eqn (4.7) and assumed receiver temperature and air temperature inside the collector. Using this recent value of cover temperature and air temperature, the receiver temperature of the collector was calculated using Eqn (4.11). Using the recent value of cover temperature and receiver temperature, the air temperature inside the collector was determined using Eqn (4.20). The iteration process is continued until the solution was within the required accuracy. For halting of iteration the difference of recent and previous values of temperature was taken as $\varepsilon \leq 0.001$ K.

The drying chamber was vertically divided into a number of sections (trays) ($L=j \cdot \Delta x$) along the direction of air flow in the drier. The drying time was also split into a number of intervals ($t = i \cdot \Delta t$). Based on the air temperature, relative humidity and airflow at the outlet of the collector or entry of the drier, drying constant (K) and equilibrium moisture content (M_e) of tomato were computed. Using these K and M_e values, the changes of moisture content of tomato halves for time interval, Δt was calculated from Eqn (4.50). The change in air humidity was computed using Eqn (4.35). The drying air temperature and product temperature were computed using Eqn (4.40) and Eqn (4.45) respectively. This process was repeated section by section until the end of the section was reached. This process was then repeated for each time increment. When air relative humidity exceeded 98%, the condensation routine deposited back the moisture from the over saturated air. Air and tomato temperature were adjusted for this condensation (BALA 1997). The numerical solution was programmed in BASIC language and output results were processed in numerical and graphical forms in Excel Worksheet. The flow diagram of the computer programme for solar collector and drier is given in Appendix A.

RESULTS AND DISCUSSION

Collector Performance

Predicted cover, receiver (absorber) and air temperatures and collector thermal efficiency along the length of the collector is shown in **Figure 4.5**. Temperatures and efficiency were predicted at 1 cm interval along the 250 cm length of the collector. It is observed from the Figure that cover, receiver and air temperatures and collector thermal efficiency increased linearly with the length of the collector. But collector thermal efficiency increased more sharply than temperatures. At the entry of the collector, air temperature was lower than the cover temperature and it crossed up at about 60 cm length of the collector i.e. air was heated more than the glass cover. Cover and receiver temperatures followed the similar increasing trend up to the end of the collector length. It is observed from the predicted results that maximum cover, air and receiver temperatures and efficiency were found at the end of the collector. At the end point of collector cover, receiver and air temperatures were found to be 50.15, 88.31 and 62.36°C respectively and collector thermal efficiency was 21.26%.

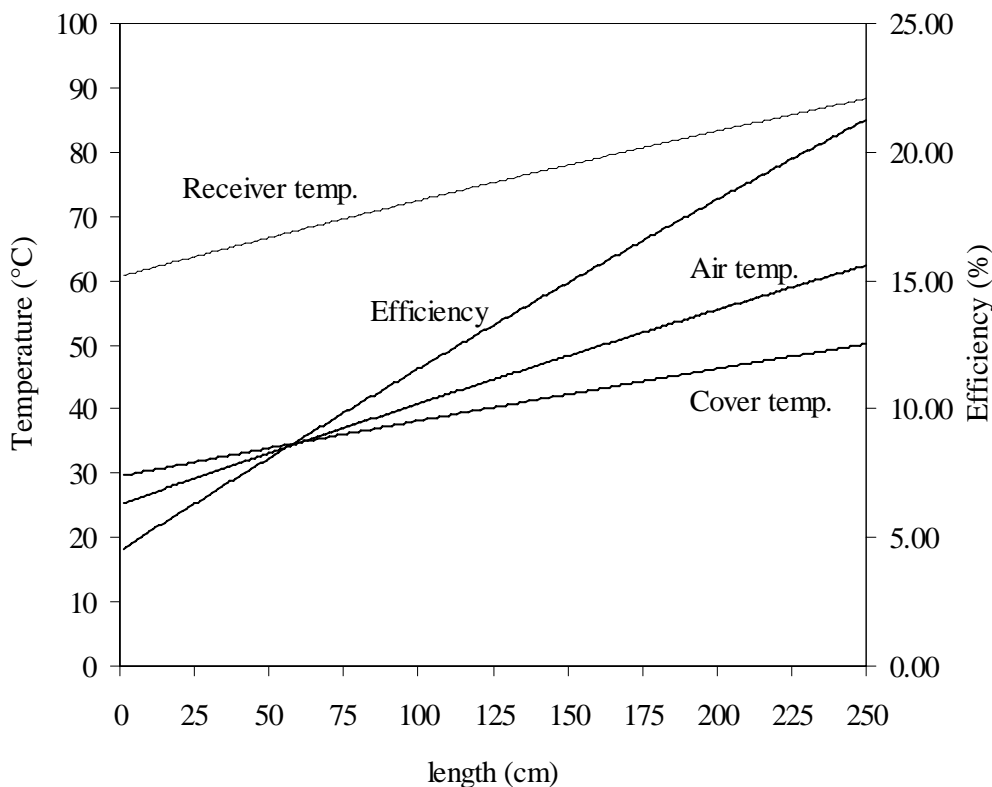


Figure 4.5: Predicted cover, air and receiver temperatures and collector thermal efficiency along the length of the collector (for time 09:40 h)

The collector cover, receiver and air temperatures were measured for solar drying of tomato as well as predicted using the model. The measured and predicted cover (glass)

temperatures during solar drying of tomato of a typical day are shown in **Figure 4.6**. A good fit was found between measured and predicted temperatures. There was no significant difference between measured (50.09°C) and predicted (48.53°C) temperature by statistical t-test ($p \leq 0.069$). The measured and predicted cover temperatures are given in **Figure 4.7**. The trend line merely passed through the origin of the measured and predicted temperatures with the coefficient of determination (R^2) 0.88. Therefore the predicted cover temperature agreed well with the measured temperature. The measured and predicted air temperature at the out let (last length point) of the collector for a typical day is shown in **Figure 4.8**. It is observed from the Figure that the predicted air temperature fitted well with the measured air temperature during solar drying of tomato. No significance difference was found between the measured (56.76°C) and predicted (55.64°C) air temperatures by t-test ($p \leq 0.052$). The measured and predicted air temperatures during solar drying of tomato are shown in **Figure 4.9**. The predicted air temperature agreed well with the measured air temperature as the trend line passed merely through the origin with the R^2 value of 0.89. The measured and predicted receiver temperature for typical day during solar drying of tomato is shown in **Figure 4.10**. The predicted receiver temperature followed the same pattern of the measured temperature. Predicted temperature was little higher than measured temperature but there was no significant difference between measured (74.78°C) and predicted (78.71°C) receiver temperatures by t-test ($p \leq 0.029$). The measured and predicted receiver temperature is plotted in **Figure 4.11**. The agreement between measured and predicted temperatures was reasonably good ($R^2=0.82$). The measured and predicted air relative humidity at the outlet of the collector during solar drying of tomato of a typical day is shown in **Figure 4.12**. The measured and predicted mean average relative humidities were 16.94 and 16.99% respectively. There was no significant difference between measured and predicted relative humidities by t-test ($p \leq 0.0489$).

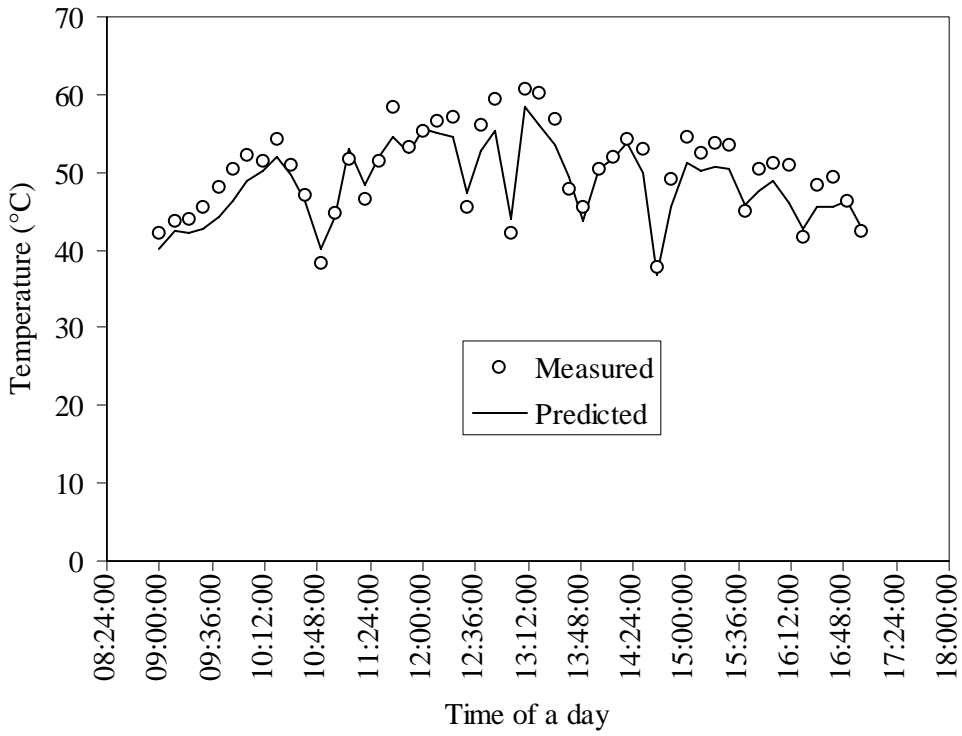


Figure 4.6: Measured and predicted cover temperatures of the collector for a typical day

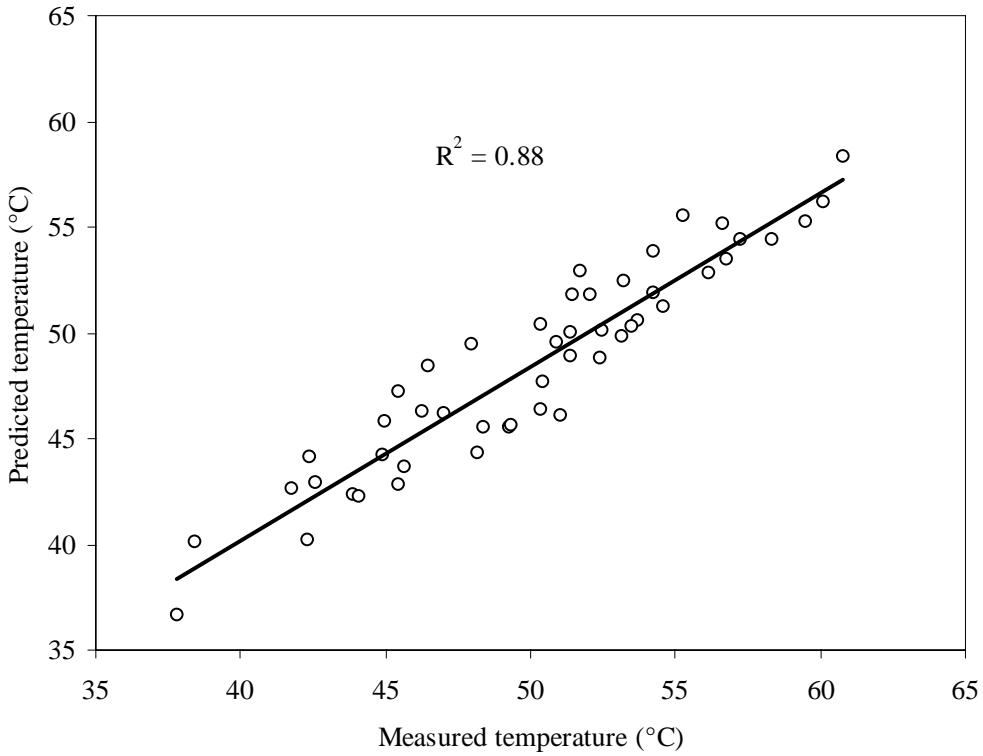


Figure 4.7: Comparison of measured and predicted cover temperatures of the collector during solar drying of tomato

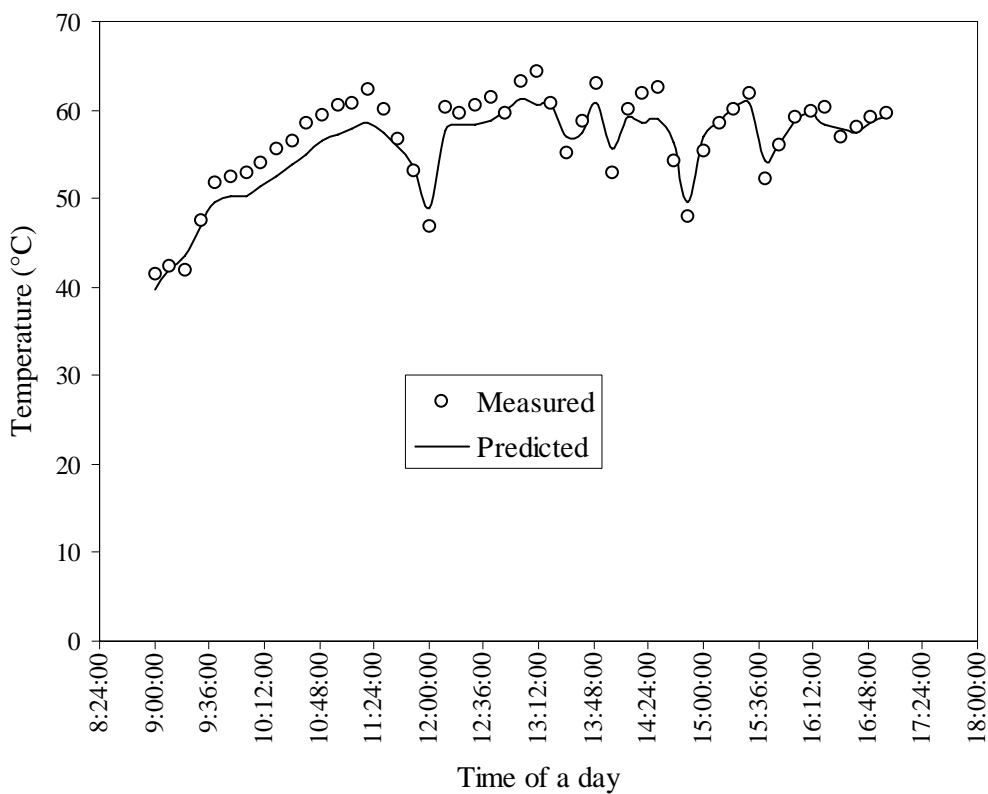


Figure 4.8: Measured and predicted air temperatures of the collector for a typical day

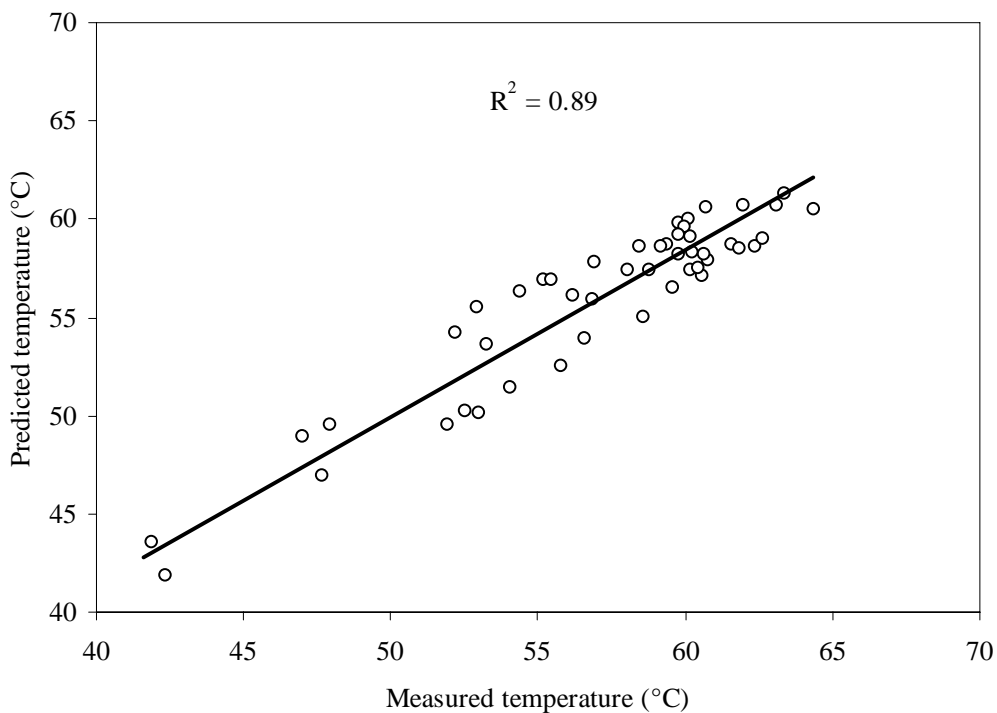


Figure 4.9: Comparison of measured and predicted air temperatures of the collector during solar drying of tomato

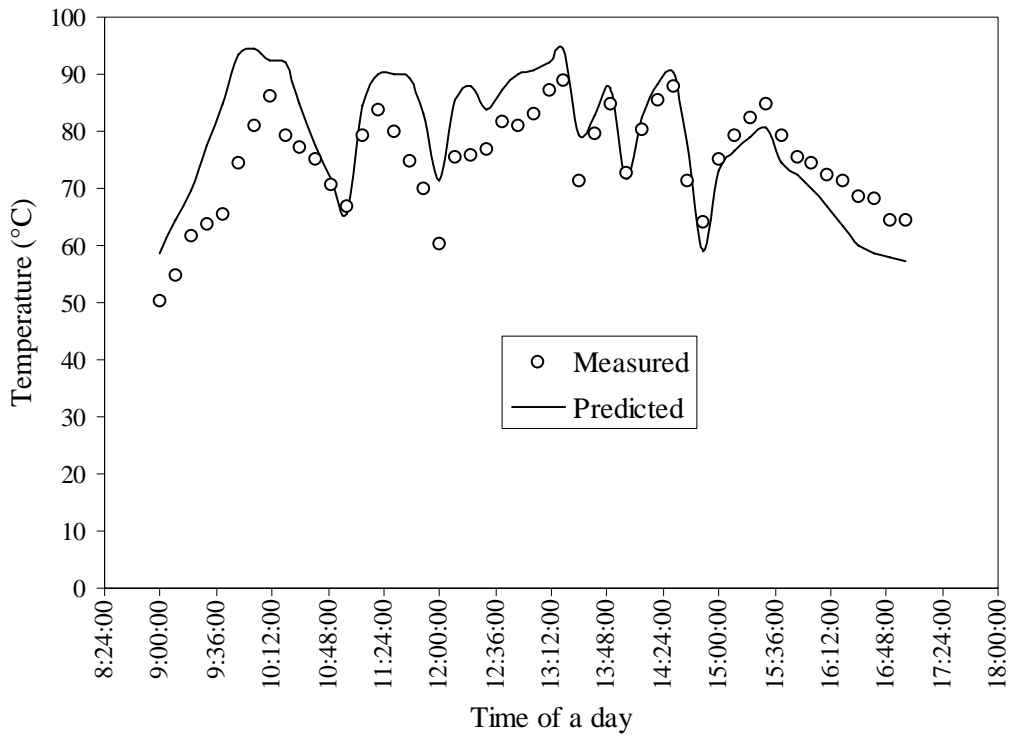


Figure 4.10: Measured and predicted receiver temperatures of the collector for a typical day

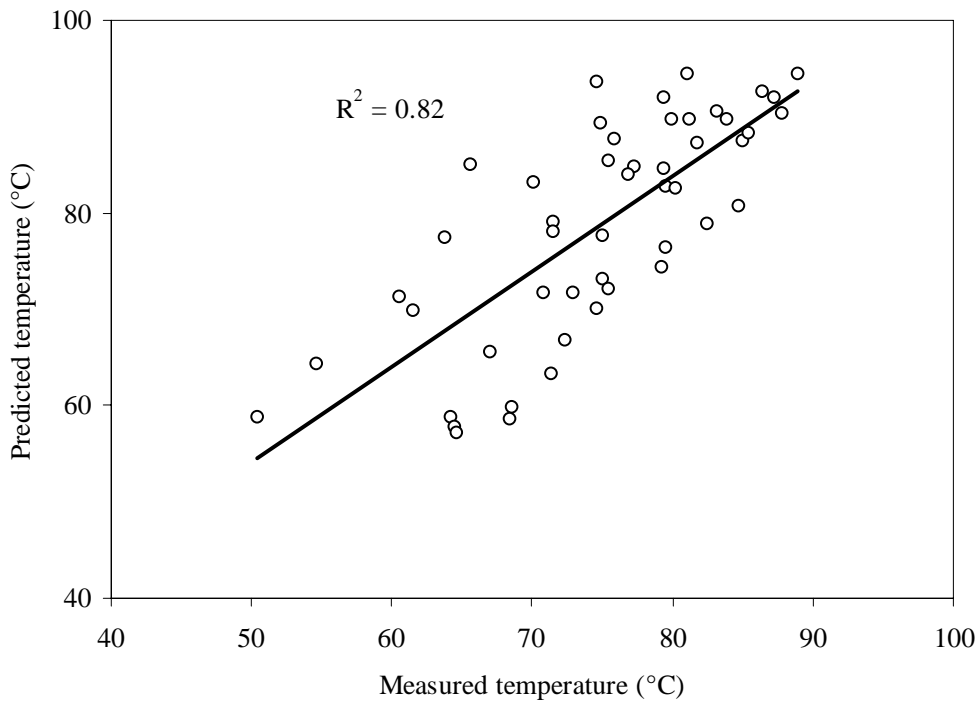


Figure 4.11: Comparison of measured and predicted receiver temperatures of the collector during solar drying of tomato

The measured and predicted relative humidities are presented in **Figure 4.13**. Good agreement was found between measured and predicted relative humidities with R^2 value of 0.90. Calculated and predicted collector thermal efficiency of a typical day during solar drying of tomato is shown in **Figure 4.14**. Predicted collector efficiency followed the similar trend of calculated collector efficiency. Calculated collector efficiency (33.47%) was found little higher than the predicted collector efficiency (30.28%). There was significant difference between calculated and predicted collector efficiency by t-test with 5% level of significance ($p \leq 0.0002$) but at 1% level the difference was insignificant ($p \leq 0.0003$). The calculated and predicted collector thermal efficiency is plotted in **Figure 4.15**. Reasonably good agreement was found between the calculated and predicted collector thermal efficiencies ($R^2=0.89$).

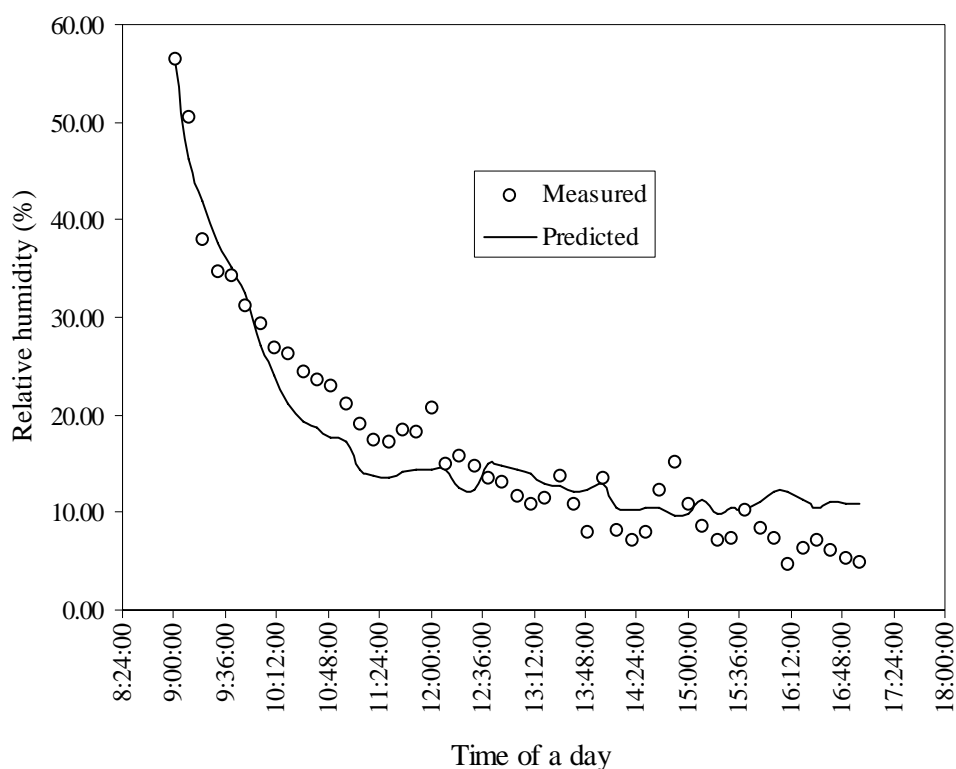


Figure 4.12: Measured and predicted air relative humidity of the collector for a typical day

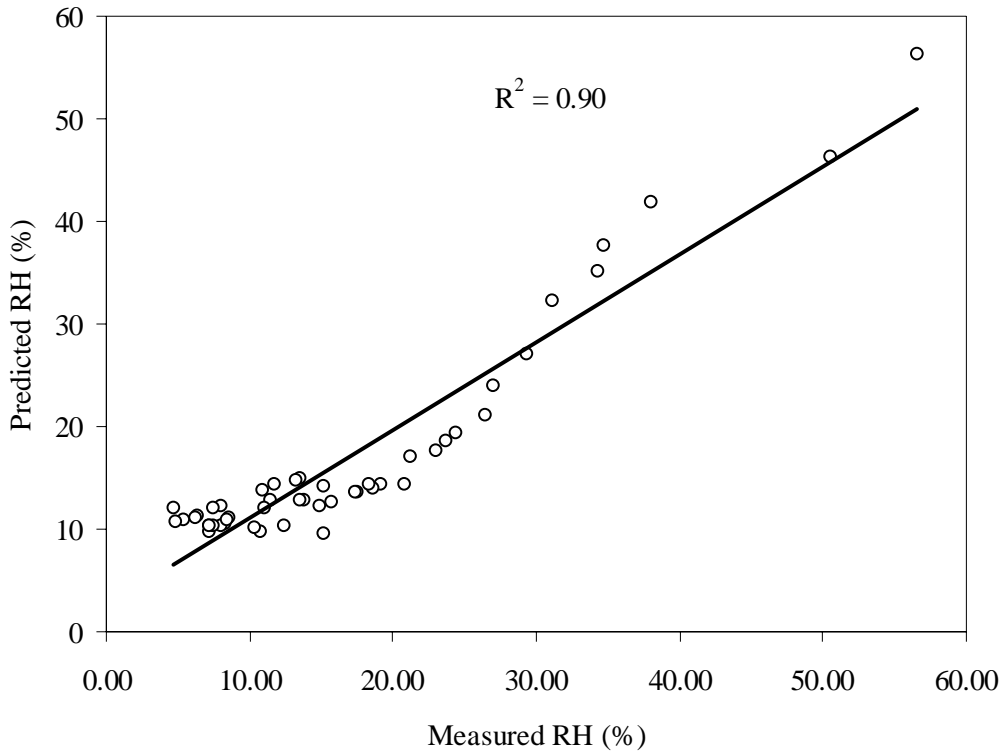


Figure 4.13: Comparison of measured and predicted air relative humidity of the collector during solar drying of tomato

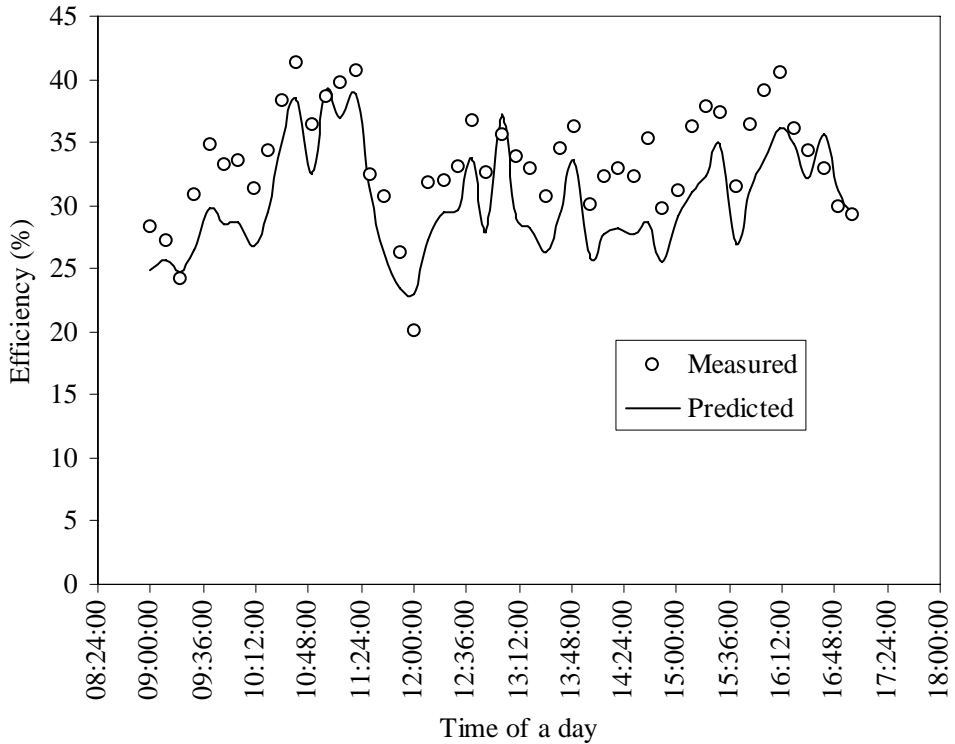


Figure 4.14: Calculated and predicted collector efficiency for a typical day

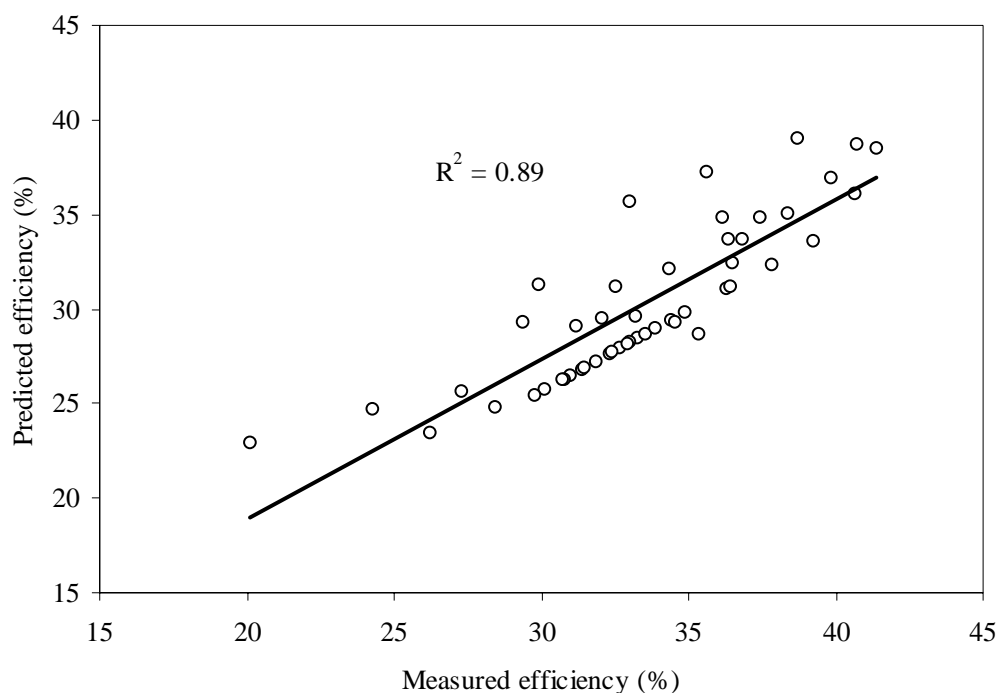


Figure 4.15: Comparison of calculated and predicted collector efficiency during solar drying of tomato

Drier Performance

The solar drier was an indirect and multi-rack type. Heated air flew from the bottom of the drier, passed through the trays loaded with the products and exhausted from the top. The outlet air conditions (temperature, relative humidity etc.) of the collector were assumed same as the inlet air conditions of the drier. The mathematical model was run for prediction of air temperature, product temperature, air relative humidity and product moisture content at 10 minute interval. The predicted air temperature, product temperature and product moisture content on different trays are shown in **Figure 4.16**. These predictions were done at 320 minutes after starting of drying time (14:20 h). Both air temperature and product temperature reduced linearly with the number of trays. But product moisture content increased linearly with the number of trays at the same drying time i.e. moisture removal was not same from all the trays due to difference of drying air temperature. Product temperature was found lower than the drying air temperature due the evaporating cooling on the product surface. Hence, the predictions agreed with the fundamental theories of drying.

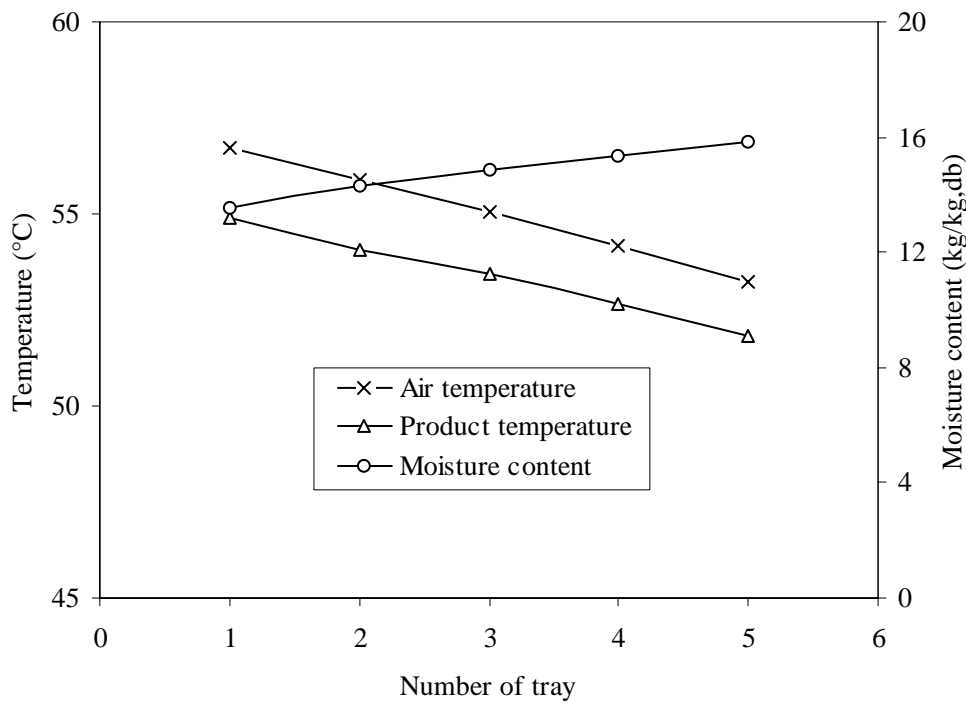


Figure 4.16: Predicted drying air temperature, product temperature and moisture content on different trays of the drier (after 320 minutes starting of drying)

The predicted temperatures on different trays in a typical day (09:00-17:00 h) during solar drying of tomato are shown in **Figure 4.17**. The predicted temperatures on different trays varied with drying time due to the variations of collector temperature as well as solar radiation. The highest air temperature was found on tray-1 followed by tray-2, tray-3, tray-4 and tray-5 but they followed the similar pattern. There was significant difference between the air temperature on tray-1 and tray-5 by t-test ($p \leq 0.048$). But no significant differences were between tray-1 and tray-2 ($p \leq 0.035$), tray-2 and tray-3 ($p \leq 0.063$), tray-3 and tray-4 ($p \leq 0.045$) and tray-4 and tray-5 ($p \leq 0.043$).

The variations of predicted air temperature, product temperature and relative humidity on tray-5 in a typical day (09:00-17:00 h) during solar drying of tomato are shown in **Figure 4.18**. Predicted air temperature, product temperature and relative humidity varied with drying time due to variations of solar radiations. Air temperature was found to be higher than the product temperature during the drying period.

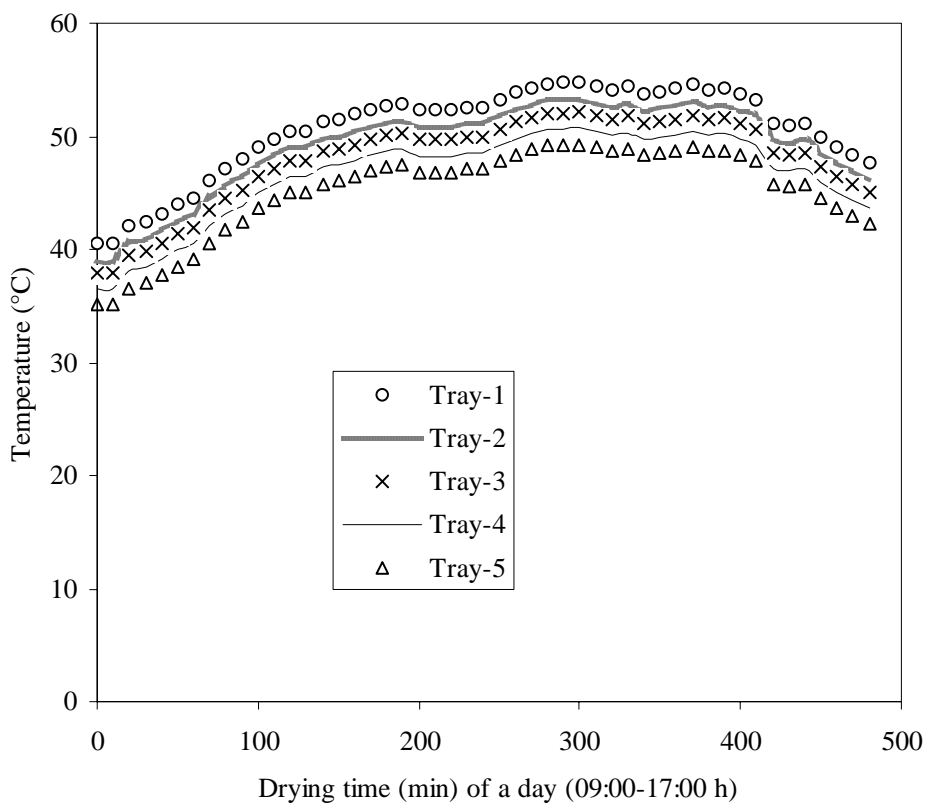


Figure 4.17: Variations of predicted air temperatures on different trays in the drier in a typical day (09:00-17:00 h) during solar drying of tomato

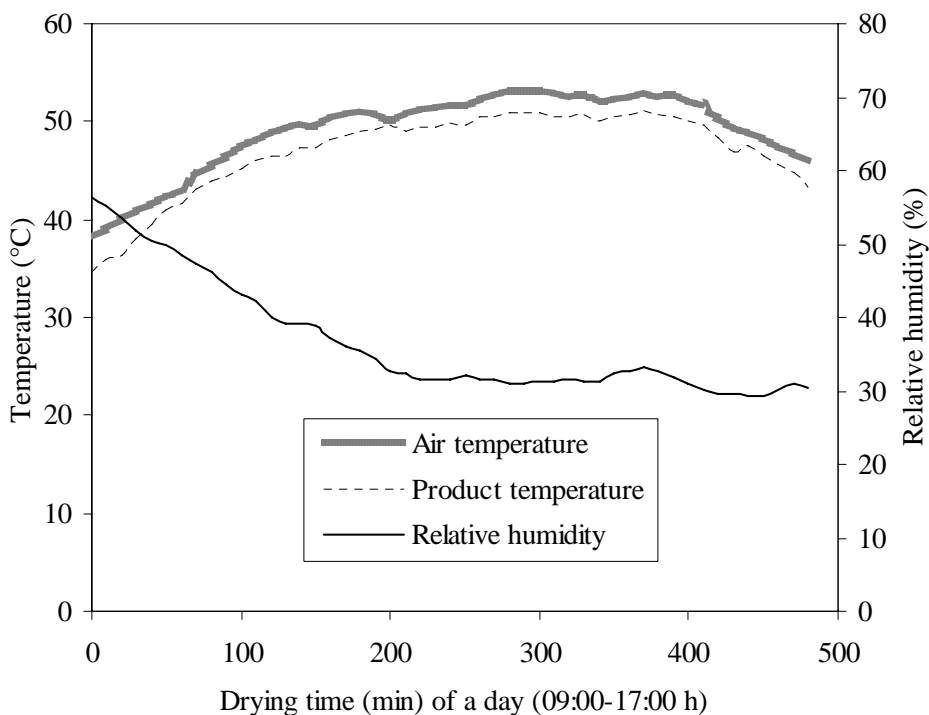


Figure 4.18: Variations of predicted air temperature, product temperature and relative humidity on tray-5 in a typical day (09:00-17:00 h) during solar drying of tomato

Variations of predicted moisture content on different trays in time of a typical day (09:00-17:00 h) during solar drying of tomato are shown in **Figure 4.19**. It is observed from the predicted curves that product moisture content decreased exponentially with drying time on different trays. All the predicted curves on five trays follow the similar moisture reduction pattern. There was no significant difference between bottom (tray-1) and (top tray-5) trays by t-test ($p \leq 0.0016$). Therefore, there were no significance differences of predicted moisture contents of the products placed on the trays.

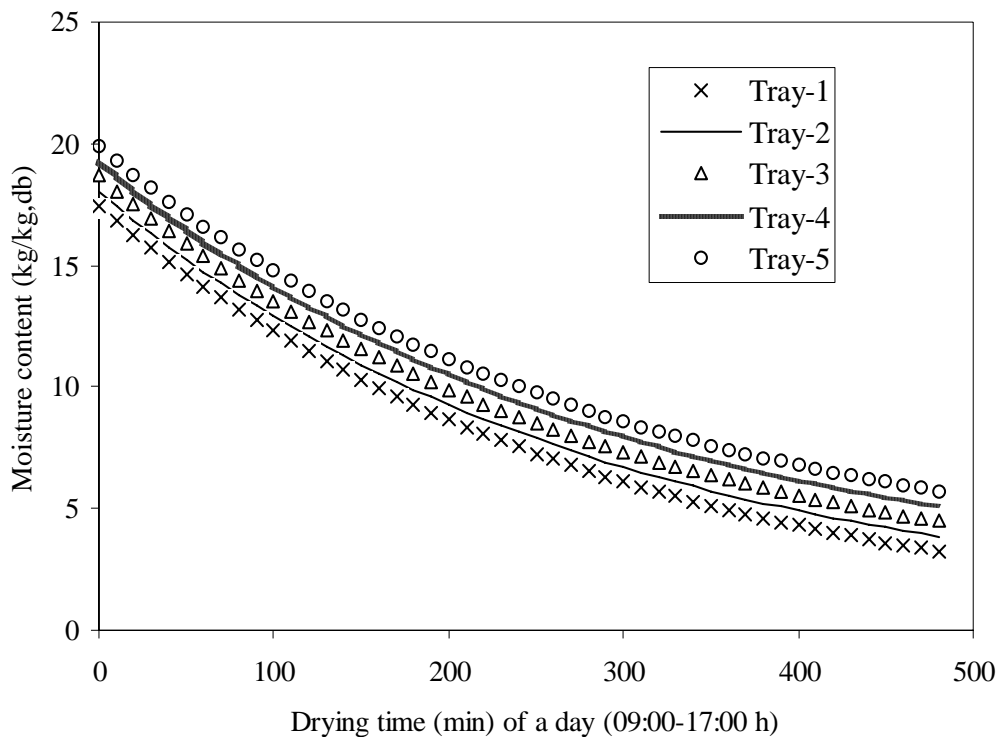


Figure 4.19: Variations of predicted moisture content on different trays in time of a typical day (09:00-17:00 h) during solar drying of tomato

The measured and predicted air temperature in the drier (on tray-5) in a typical day (09:00-17:00) during solar drying of tomato is shown in **Figure 4.20**. The predicted air temperature followed the similar pattern of measured temperature. But from drying time about 150 to 300 minutes (11:48:54-13:48:54 h) and from 350 to 480 minutes (14:58:54-17:08:54 h) the measured air temperatures deviated little downward from the predicted air temperatures. This might be due to the measurement error. There was no significance difference between measured and predicted air temperature during the drying period by t-test ($p \leq 0.064$). Comparison of measured and predicted air temperature in the drier (on tray-5) during solar drying of tomato is given in **Figure 4.21**. The relationship between measured and predicted air temperature was found better in higher temperature ($>42^\circ\text{C}$) than the lower range of temperature ($<42^\circ$). But overall agreement was good with R^2 value of 0.79.

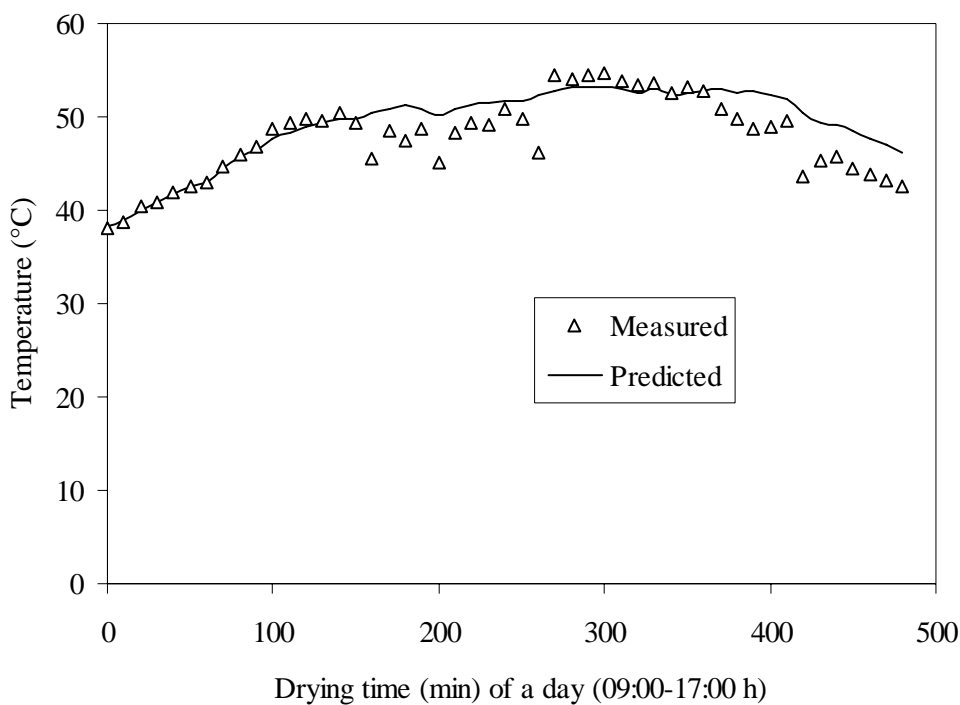


Figure 4.20: Measured and predicted air temperature in the drier (on tray-5) in a typical day (09:00-17:00) during solar drying of tomato

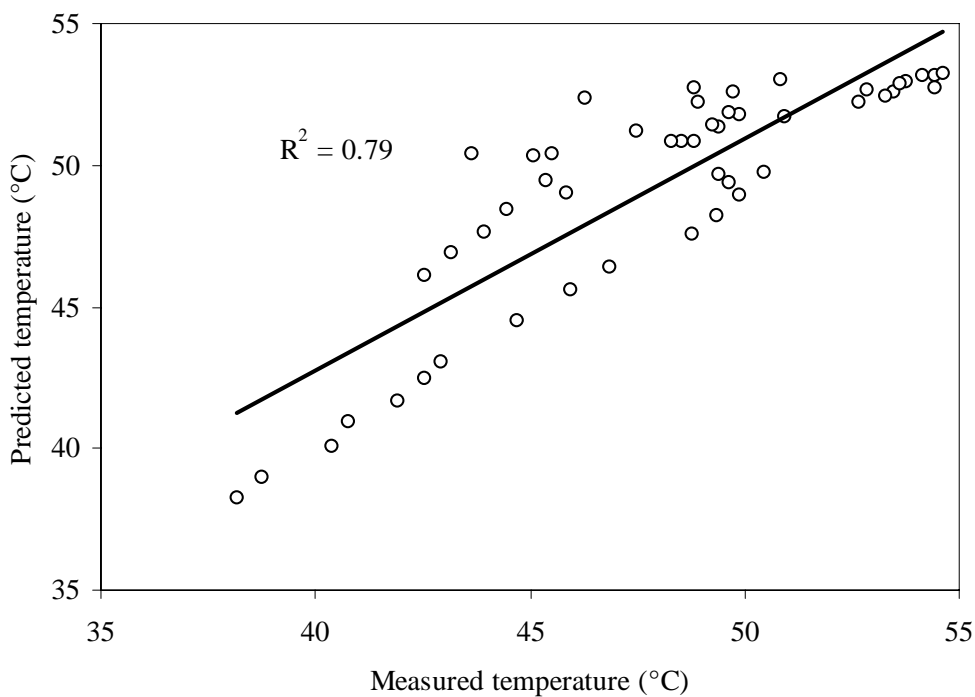


Figure 4.21: Comparison of measured and predicted air temperature in the drier (on tray-5) during solar drying of tomato

The measured and predicted product temperature with drying time in the drier (on tray-5) in a typical day (09:00-17:00 h) during solar drying of tomato is shown in **Figure 4.22**. The predicted product temperature followed the similar pattern of the measured temperature during the drying time. There was no significance difference between measured and predicted product temperatures by statistical t-test ($p \leq 0.0495$). Comparison of measured and predicted product temperature during the solar drying period is shown in **Figure 4.23**. Good agreement was found between measured and predicted product temperatures ($R^2=0.88$).

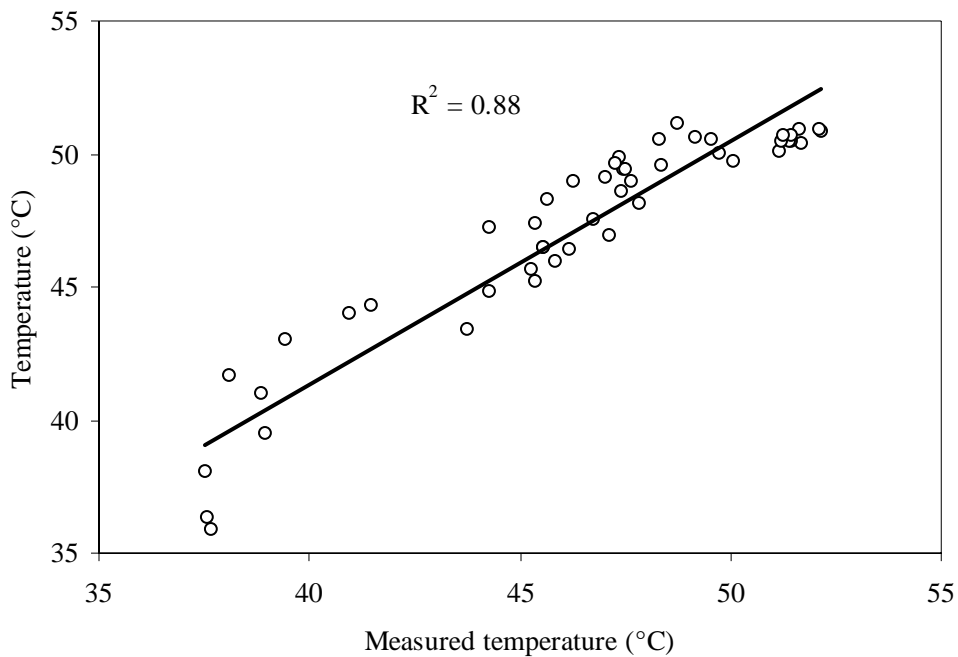


Figure 4.22: Measured and predicted product temperature with drying time in a typical day (09:00-17:00 h) in the drier (on tray-5) during solar drying of tomato

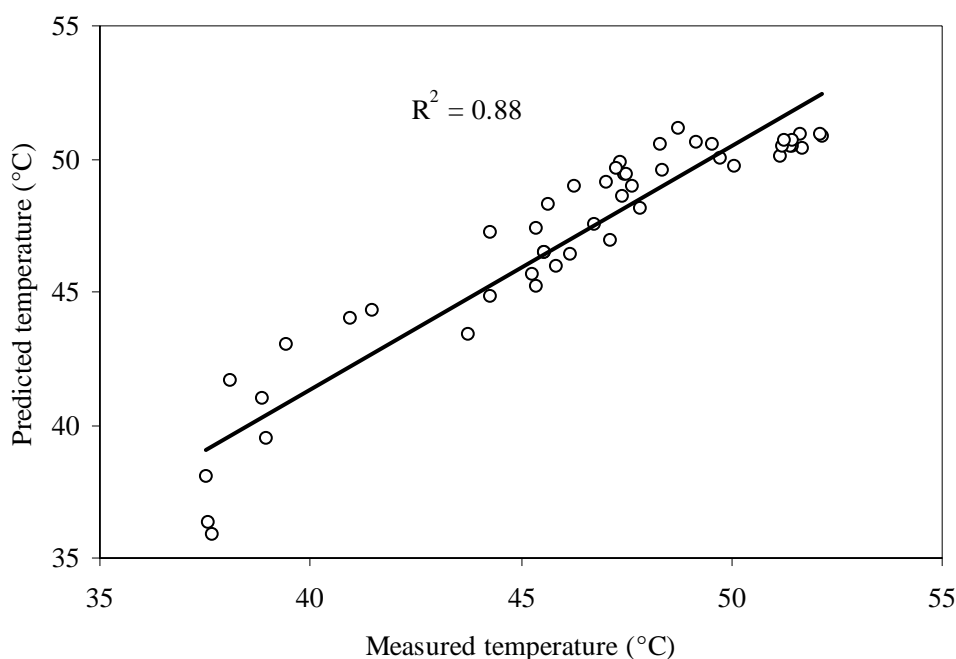


Figure 4.23: Comparison of measured and predicted product temperature during solar drying

The measured and predicted relative humidity with drying time of a typical day (09:00-17:00 h) on tray-5 during solar drying of tomato is shown in **Figure 4.24**. During the drying period, the predicted relative humidity followed the similar pattern of measured relative humidity. There was no significant difference between measured and predicted relative humidities by t-test ($p \leq 0.0417$). The comparison of measured and predicted relative humidity during the drying period is given in **Figure 4.25**. Good agreement was found between the measured and predicted relative humidities during the drying period with R^2 of 0.97. The measured and predicted moisture content with drying time of a typical day (09:00-17:00 h) on tray-5 during solar drying of tomato is shown in **Figure 4.26**. The predicted moisture reduction followed the similar pattern of measured moisture reduction during the drying period but predicted moisture reduction was always higher than measured moisture reduction. There might be some systematic errors during measurement of moisture content. However, no significant difference was observed between measured and predicted moisture content by t-test with 5% level of significance ($p \leq 0.0281$). The comparison of measured and predicted moisture content during the drying period is given in **Figure 4.27**. Good agreement was found between the measured and predicted moisture content during the drying period with R^2 value high as 0.98.

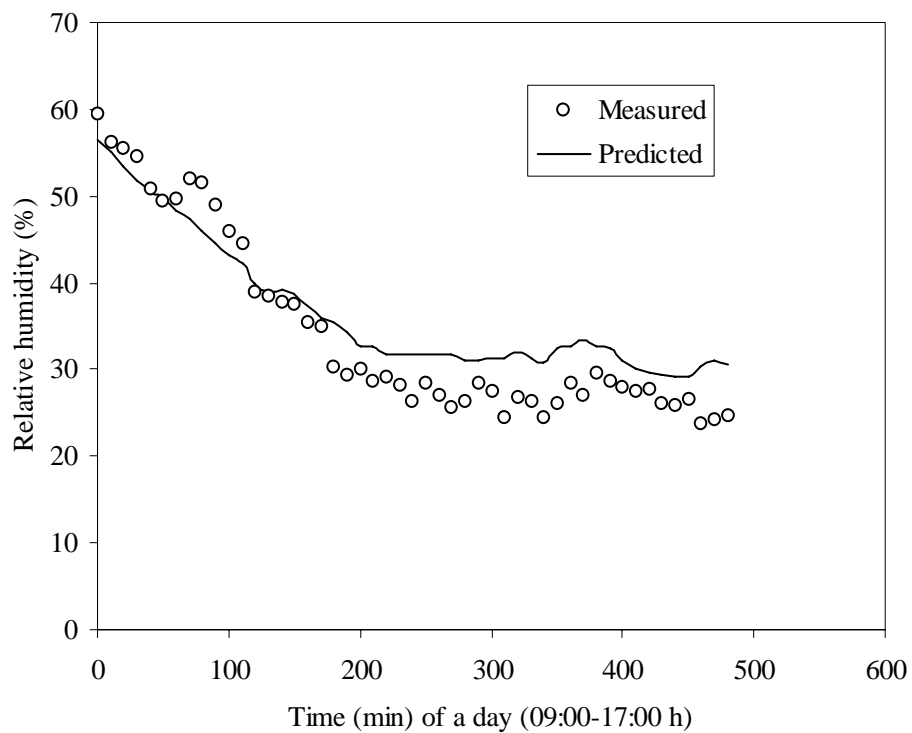


Figure 4.24: Measured and predicted relative humidity with drying time of a typical day (09:00-17:00 h) on tray-5 during solar drying of tomato

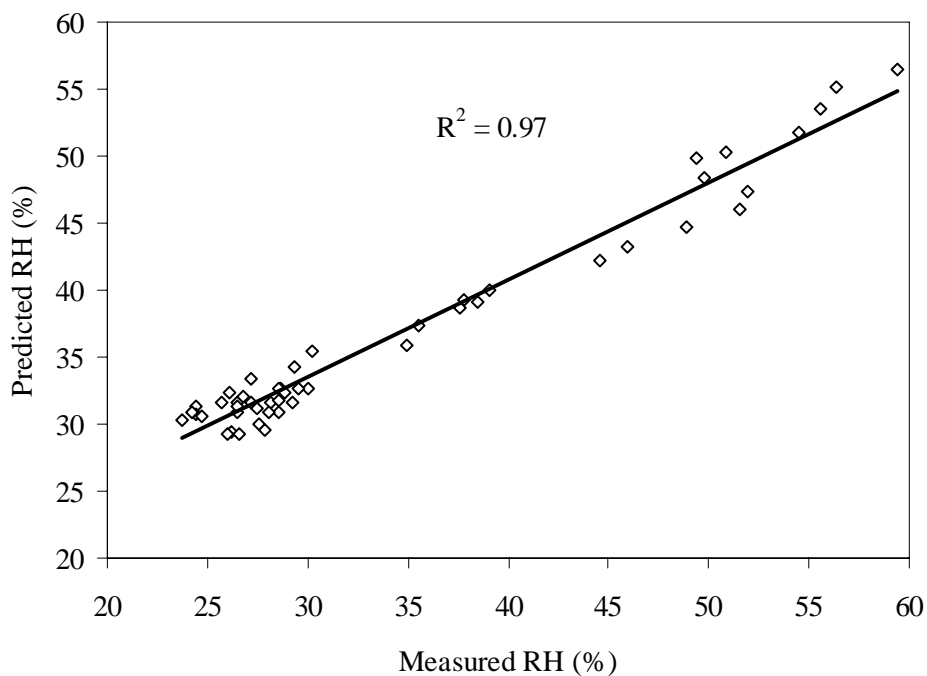


Figure 4.25: Comparison of measured and predicted relative humidity during the drying period

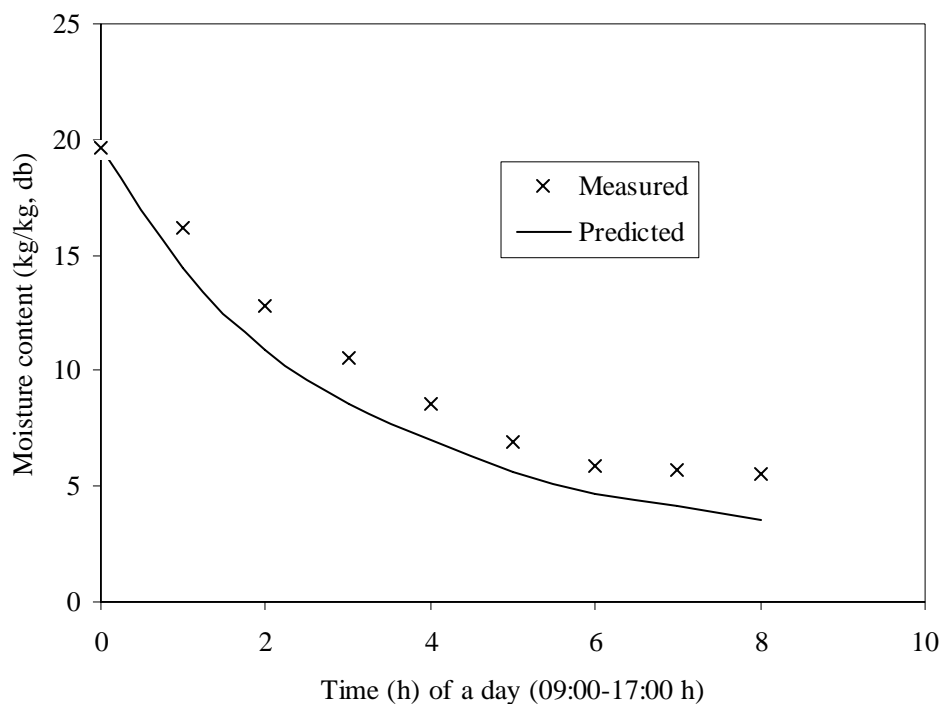


Figure 4.26: Measured and predicted moisture content with drying time of a typical day (09:00-17:00 h) on tray-5 during solar drying of tomato

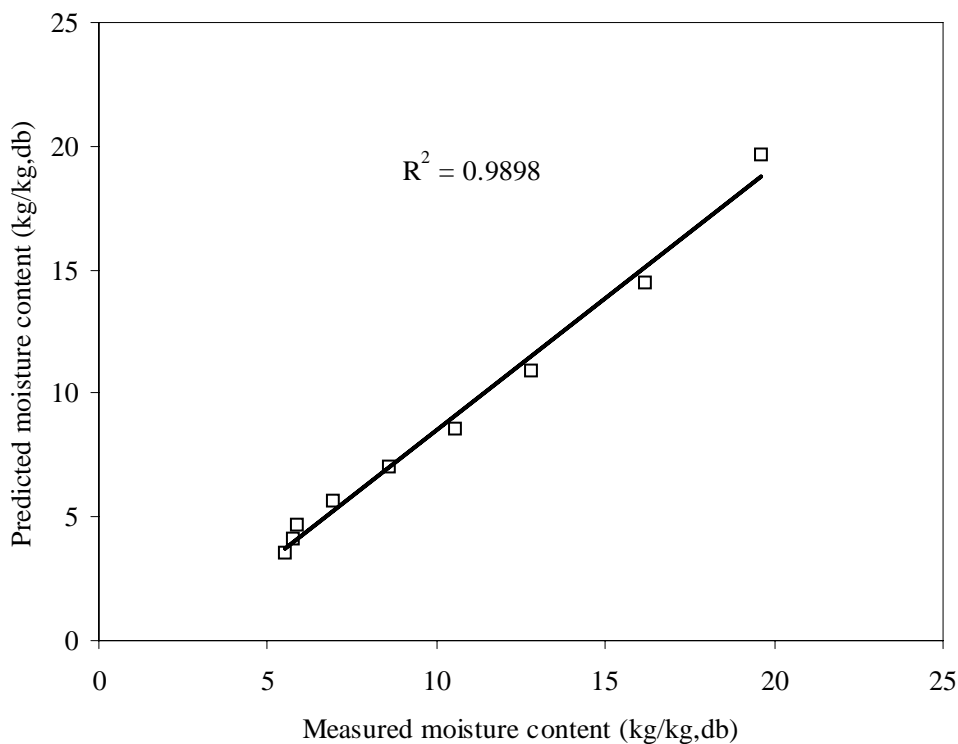


Figure 4.27: Comparison of measured and predicted moisture content during the drying period

Sensitivity Analysis

Before the model is validated against experimental data (field data), it is useful to examine the effect of ambient conditions on drying. In solar drying, ambient temperature, relative humidity and solar radiation always vary with time. In a solar drying model all these variables should be included. In the present model, it was assumed that the tomato halves were dried in the solar drier in single layer. The single layer drying model (MIDILLI *et al.* model) used in this model was developed to include wide variations of temperature, relative humidity and air velocity, on the basis of actual field conditions.

The present model was not very sensitive to ambient temperature and relative humidity but was found to be sensitive to solar radiation and air velocity. Air temperatures inside the collector as well as in the drier increased with the increase of solar radiation. On the other hand, air temperature in the collector and in the drier decreased with the increase of air velocity. Drying rate constant (K), equilibrium moisture content, exponent (u) and model coefficients (a and b) of the MIDILLI *et al.* (202) model was also a function of drying air temperature, relative humidity and air velocity. K and u were found to be sensitive but a and b were not much sensitive to model. Model was tested to find the effect of variation of heat transfer coefficients. The model was not found much sensitive with heat transfer coefficients. Bulk density had significant effect on air temperature and product moisture content. Initial moisture content of tomato had no significant in prediction of air temperature in the drier. The time step used this model was $\Delta t = 10$ minutes, as numerical solution was found to be insensitive to $\Delta t \leq 600$ minutes. The position step used this model was $\Delta x = 1$ cm, as numerical solution was found to be insensitive to $0.01 \leq \Delta x \leq 1000$ cm.

CONCLUSIONS

Collector cover, air and receiver temperatures and collector thermal efficiency were predicted along the length of the collector and their highest values were found at the end of the collector length. The predicted cover temperature, air temperature and relative humidity at outlet of the collector, receiver temperature and collector thermal efficiency were validated with measured data and found to be agreed well with the measured data. Air temperature, product temperature and product moisture content were predicted on different trays along the height of the drier (along the direction of air flow) and also with drying times and they agreed with the fundamental theories of drying. Good agreement was found between experimental and simulated air temperature, air relative humidity, product temperature, and product moisture content of tomato halves during drying. This model can be used for providing design data of a solar drier.

NOMENCLATURE

a	Constant of single layer drying equation (dimensionless)
A_c	Collector area (m^2)
A_{ref}	Reflector area (m^2)
b	Constant of single layer drying equation (dimensionless)
C_{pa}	Specific heat of air (kJ/kg K)
C_{pp}	Specific heat of product (tomato) (kJ/kg K)
C_{pl}	Specific heat of liquid (kJ/kg K)
C_{pw}	Specific heat of water (kJ/kg K)
G_a	Mass flow rate of air (kg/m^2s)
h_c	Convective heat transfer coefficient ($W/m^2 K$)
h_{fgl}	Heat of vapourisation of water (2402×10^3), J/kg
h_r	Radiative heat transfer coefficient ($W/m^2 K$)
H_a	Humidity ratio of air (kg/kg)
i	Integer
I_g	Global incident solar radiation flux (W/m^2)
I_r	Reflected incident solar flux from the reflector (W/m^2)
j	Integer
k	Thermal conductivity (W/m-K)
K	Drying rate constant of tomato (per min)
L	Length of the collector (m)
M	Moisture content (kg/kg, db)
M_o	Initial moisture content (kg/kg,db)
M_e	Equilibrium moisture content (kg/kg,db)
\dot{m}_a	Mass flow rate of air (kg/s)
Nu	Nusselt number (dimensionless)
Pr	Prandtl number (dimensionless)
Q_{absor}	Absorbed energy (kJ)
Q_{conv}	Convective energy (kJ)
Q_{rad}	Radiation energy (kJ)
Q_{ref}	Reflected energy (kJ)
Q_{useful}	Energy used for heating the air in the collector (kJ)
$Q_{solar-received}$	Incident global radiation on the reflector and collector (kJ)
E	Total net solar radiation flux on the cover (W/m^2)
Re	Reynold number (dimensionless)
T_a	Air temperature (Kelvin)
T_{am}	Ambient temperature (Kelvin)
T_c	Cover temperature (Kelvin)

T_r	Receiver temperature (Kelvin)
T_{dp}	Dew point temperature (Kelvin)
T_i	Inlet temperature (Kelvin)
T_o	Outlet temperature (Kelvin)
T_s	Sky temperature (Kelvin)
t	Time (min)
u	Exponent of MIDILLI <i>et al.</i> (2002) equation (dimensionless)
x	Space coordinate
y	Space coordinate
z	Height of tomato bed (m)
α	Absorbity (dimensionless)
β	Reflector inclination (degree)
θ	Solar incident angle (degree)
Γ	Capture fraction (dimensionless)
ε	Emittance (dimensionless)
η	Efficiency (%)
ρ	Reflectance (dimensionless)
ρ_p	Bulk density of product (kg/m^3)
σ	Stefan-Boltzmann constant ($\text{W/m}^2\text{K}^4$)
τ	Transmittance (dimensionless)
Δx	Thickness of collector (m)
Δy	Thickness of collector receiver (m)
Δz	Thickness of tomato bed layer (m)

Subscript:

a	Air
amb	ambient
c	Cover
conv	Convective
cond	Conductive
r	Receiver
rad	Radiative
ref	Reflective
s	Sky
S	Short wave

Chapter 5

EFFECT OF STORAGE ON QUALITY OF DRIED TOMATO

ABSTRACT

Dried tomato halves were stored in glass jar, plastic container and polyethylene bag in two storage environments such as room environments (average temperature 20°C and relative humidity 60%) and cool chamber (average temperature 5 and relative humidity 80%) with three initial storage moisture contents (18, 24 and 38%, wb) for five months. Eleven pre-treated samples and control sample were also stored in glass jar for five months in room environments. Change of colour, ascorbic acid, lycopene, total flavonoids and moisture content were monitored one month interval. Significantly higher losses of colour, ascorbic acid, lycopene and total flavonoids were found for room environment than those of cool chamber environment. Significantly lowest colour, ascorbic acid, lycopene and total flavonoids changes were found for sodium metabisulphite pretreated samples followed by ascorbic acid and citric acid treated samples. No significance effects of storage containers were observed during storage of dried tomato either in room or cool chamber environments regarding the changes of colour and nutrients. There were no significant effects of storage containers on product moisture content in room environment. In cool chamber environment, product moisture contents increased with storage time for plastic container and polyethylene bag but for glass container, product moisture contents were almost same. Colour, ascorbic acid, lycopene and total flavonoids decreased linearly with the product initial storage moisture content and storage time. A set of regressions equations had been developed for colour, ascorbic acid, lycopene and total flavonoids as a function of storage time. No visible micro-organisms (moulds and fungus) were detected in any of the samples during the storage period.

INTRODUCTION

Dried products are stored in short and long term for later use or local sale or export. Main objective of storage is to prevent deterioration of quantity and quality of the product. This is done directly or indirectly by controlling the moisture content of the product and storage environment. Quantitative loss of the product is the deterioration caused by insects and micro-organisms. Qualitative loss is associated by insects and microbial infestation and loss of nutrients. This loss can be prevented by a number of ways. Maintaining the moisture content of the products that metabolic activities reduce to such a low level that the product is sufficiently stable with minimal deterioration. Also reduction of moisture content of product reduces the microbial and insect growth. Modifying the atmospheric condition in the storage system that metabolic, insect and microbial activities reduce to a minimum level to prevent product deterioration. Another method of storage of dried product is by applying pre-treatments (chemicals, biological, thermal, radiation etc.) in the products to inactivate the insect and microbial activities in the storage system.

A storage system is a man made ecological system in which living organisms and environment interact each other (BALA 1997). In this ecosystem, the most important thing is the stored product itself. The abiotic environment of the product includes physical variables such as temperature and relative humidity, inorganic chemical variables such as carbon dioxide and oxygen, physio-chemical variables such as moisture content and enzymes of the product and the array of organic compounds, which are by-products of biological activities. The major biotic variables are micro-organisms such as fungi, moulds, yeasts and bacteria and arthropods such as insects and mites. Their ecological system develops in time with the product and amongst themselves, supported by certain other sets of variables in the complex process of deterioration of the quantity and quality of the products.

Tomato is a versatile vegetable that is consumed fresh as well as processed products. But most of the tomatoes (about 80%) are consumed as processed form (KALOO 1993). Recently attention has been given to antioxidant components of tomato products because they play an important role in preventing cancer (GIOVANNUCCI 1999, RAO & AGARWAL 2000). Tomato components like lycopene, phenolics, flavonoids and ascorbic acid are main antioxidant substances (STEWART *et al.* 2000, BEUTNER *et al.* 2001). During processing especially in drying causes oxidative damage of tomato products (ZANONI *et al.* 1999, TOOR & SAVAGE 2005). Several studies have shown that oxidative damage of dried tomato also occurs during storage (SHARMA & LE MAGUER 1996, ZANONI *et al.* 2000). So, it is now the growing interest of scientists to know the oxidative damage of tomato during storage and to optimise the storage systems to minimize them.

Some investigators studied the storage behaviour of dried tomato. Dried tomato was stored in air tight glass container and vacuum sealed plastic bag and put them in dark at room temperature and in freezer (WEB1). It is reported that these dried tomato could be stored in room temperature up to one year and in freezer up to 18 months without

significant loss of flavour and nutrition. But no technical data was provided in this report. It is shown in another report (WEB2) that dried tomato could be stored in air tight glass jar, plastic jar or plastic bag in room temperature up to 8 months or in freezer more time without deterioration of colour, aroma, flavour and nutritive value. It is also reported that during storage sometimes dried tomato might be infected by Indian meal moth (an insect). But no scientific data was provided in the report. Sun dried tomato could be stored in airtight container in the home refrigerator or freezer from 6 to 9 months for its optimum shelf life (WEB3).

LATAPI & BARRET (2006 b) determined the effect of some pre-treatment on quality of stored dried tomato. They treated the tomato halves with direct gas sulphur, sulphur dioxide, 10% salt for 5 minutes, 8% sodium metabisulphite for 5 minutes and 10% salt plus 8% sodium metabisulphite for 5 minutes before cabinet drying. These dried tomatoes were stored in sealed polyethylene bags at 25°C for 3 months. They reported that 8% sodium metabisulphite and 8% sodium metabisulphite plus 10% salt pre-treated dried tomato had the best rehydration ratio and colour values. They also reported that direct sulphur and sulphur dioxide gas treated samples had better ascorbic acid retention. None of the samples were found infected by insects or micro-organisms. AKANBI & OLUDEMI (2004) investigated the lycopene degradation of tomato products (dried slice, juice and pulp) during storage. They stored tomato products in different packaging materials such as can, glass bottle, plastic bottle and LMA (laminated metallized aluminium) foil at 29, 35 and 40°C temperature for 12 weeks. They reported that lycopene as well as colour degradation was higher in can and at 40°C storage temperature. They also found good lycopene retention in plastic and glass bottles when shielded them completely from light and stored at 29°C. ZANONI *et al.* (2000) determined the optimum conditions for storage of dried tomato halves by saturated factorial design model. Dried tomato halves were stored in air tight plastic box at the moisture content range of 10 to 60% (wb) and temperature range of 5 to 30°C for 1 to 38 days. They reported that storage temperature at or below 18°C minimized the oxidation damage during storage. Low product moisture content prevented the microbial growth but increased the oxidative damage. The evolution of oxidise heat damage during storage of processed tomato (pulp, puree and paste) was studied by GIOVANELLI & LAVELLI (2002). They stored the tomato products at 30, 40 and 50°C for 90 days. They reported that heat damage reactions were favoured by high temperature and long storage period. But heat damage was also proceeded at relatively low temperature (30°C). Heat damage reactions occurred faster in tomato paste than pulp and puree.

A lot of works have been carried out on storage of grains and fresh fruits and vegetables. Works on storage system of dried fruits and vegetables especially dried tomato are limited in literature. Therefore, this study has been undertaken to find out the safe storage conditions to prevent nutritional loss as well as microbial infection.

MATERIALS AND METHODS

Different pre-treatments were applied before solar drying of tomato halves. The pre-treatments were UV radiation, acetic acid, citric acid, ascorbic acid, sodium metabisulphite and sodium chloride at different doses. The list of pre-treatments with doses and their application procedures are given in Chapter 3 (**Table 3.2**). Then the pre-treated and control samples were dried in the indirect type solar drier at the drying air temperature not exceeding 60°C. The details of the drying procedure have been described in Chapter 3. The dried samples were cooled in the room temperature for about 6 hours. It was also made sure that no sample was infected by insect and micro-organisms during drying. Then the representative samples were taken for colour and chemical analysis. All pre-treated samples and one control samples were stored in glass jar in dark at the room environment. These samples were also replicated three times. Colour, ascorbic acid, lycopene, total flavonoids and rehydration ratio of the stored pre-treated samples were measured one month interval. The measurement methods of these parameters have been described in details in Chapter 2 and Chapter 3. The experiment started on 9 September 2006 and discontinued on 9 February 2007.

Three types of storage containers, three storage initial moisture contents and two storage environments were selected for storage of dried tomato halves. The storage containers were, glass jar (cylindrical: 7.5 cm diameter and 11 cm high), plastic jar (cubic: 9.1×9.1×9.1 cm) and polyethylene (PE) bag (18 ×18 cm, 1.4 L), **Figure 5.1**. Three initial moisture levels were 18, 24 and 30% (wb) and the storage environments were room environment (average temperature 20°C and relative humidity 60%) and cool chamber environment (average temperature 5°C and relative humidity 80%). For comparison, a commercial sample (produced by ORTICOLA MEDITERRANEA, Italy in July 2006) purchased from the Potsdam supermarket was included in this study. All storage containers were made clean and sufficient dry before storage. All the storage containers were replicated three times. Ten pieces of tomato halves were put in each of the container and made them airtight. Three non-treated (with 18, 24 and 30% (wb) moisture contents) samples along with commercial samples (with 37% (wb) moisture content) were stored in dark in two storage environments- room temperature environment and cool chamber environment. For room environment, sensors were inserted in one each type of the storage container and made air tight to continuous monitoring the temperature and relative humidity of storage containers. Temperature and relative humidity in the room and in the storage containers were measured at one hour interval up to the end of the experiments by a data logger (Model: ALMENO 5590, Ahlborn Mess-und Regelungstechnik GmbH, Germany). Colour, weight, ascorbic acid, lycopene and total flavonoids of the stored samples of both of the room and cool chamber environments were measured one month interval. The experiment was also started on 9 September 2006 and ended on 9 February 2007.



Figure 5.1: Storage containers with samples; left: PE bag, middle: plastic jar, right: glass jar with temperature/rH sensor

The change in surface colour of stored tomato halves was calculated as follows (ZANONI *et al.* 2000):

$$\Delta E = \sqrt{(L_t^* - L_o^*)^2 + (a_t^* - a_o^*)^2 + (b_t^* - b_o^*)^2} \quad (5.1)$$

Colour was measured triplicate on the same tomato surface from each of the samples at different storage time. Percentage degradation of colour and antioxidants were calculated using the following formula.

$$\text{Degradation(\%)} = \frac{\text{Initial value (begining of storage)} - \text{Final value (after 5 months)}}{\text{Initial value (begining of storage)}} \times 100$$

Growth of micro-organisms was observed by two-step method involving olfactory (presence of off-flavours) and visual perception of the samples.

Statistical Analysis

Mean differences of ascorbic acid, lycopene, total flavonoids and rehydration ratio of stored tomato at different storage times between room environment and cool chamber

environment were compared using complete randomised design (CRD). The analysis of variance (ANOVA) of colour values, ascorbic acid, lycopene and total flavonoids of different pre-treated samples were statistically analysed using the software SPSS 9.0. The mean obtained from each set of variable was compared by Duncan's Multiple Range Test (DMRT) based on the complete randomised design (CRD).

RESULTS AND DISCUSSION

Effect of Pre-treatments

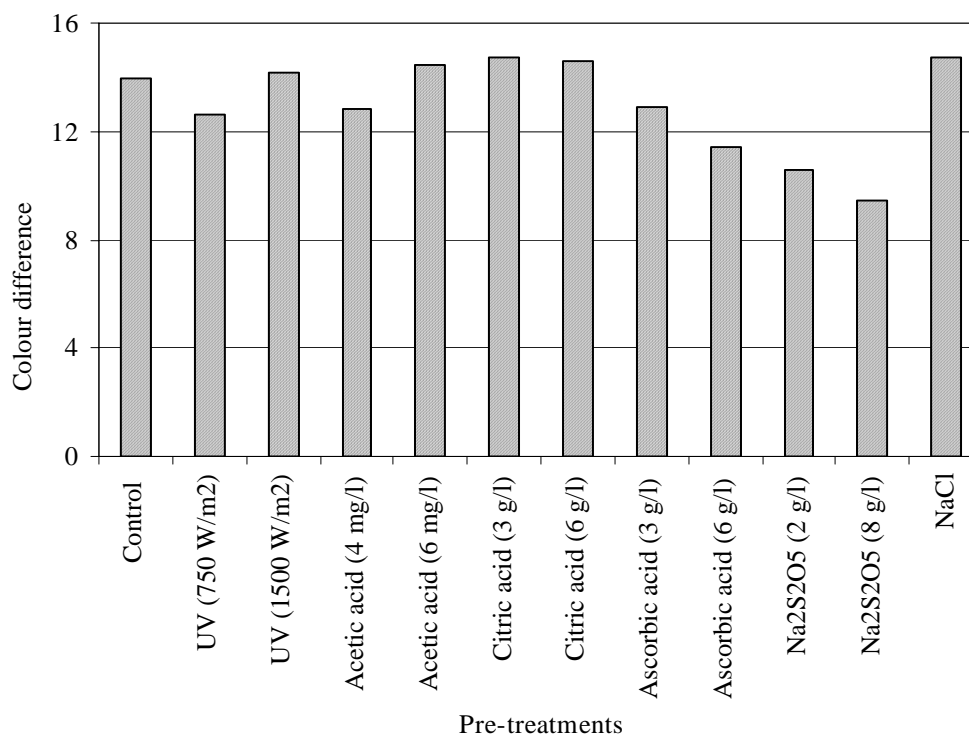
Colour

Effect of different pre-treatments on colour difference of dried tomato halves during storage is given in **Table 5.1**. At the beginning of storage colour difference was zero. Colour differences of all the samples increased with the storage time. After one and two months of storage, significantly highest colour differences were found for sodium chloride pre-treated samples followed by UV radiation, acetic acid and control samples. But for third and fourth months, significantly highest colour difference were obtained for sodium chloride pre-treated samples followed by acetic acid, citric acid, UV radiation and control samples. At the end of the storage time (fifth month), significantly highest colour degradations were observed for sodium chloride, acetic acid, UV radiation pre-treated and control samples and lowest for sodium metabisulphite pre-treated samples followed by ascorbic acid and citric acid pre-treated samples. During the storage period, colour changed rapidly in sodium chloride pre-treated sample and slowly in sodium metabisulphite and ascorbic acid treated samples. Colour degradation during storage was a continuous process. Decrease of colour during storage may be due to the oxidation of tomato components (lycopene, phenols), enzymatic browning, non-enzymatic browning and Maillard reaction. LATAPI & BARRETT (2006 b) found more intense red colour from sodium metabisulphite pre-treated dried tomato than those of sulphur and sodium chloride pre-treated samples after three months of storage. At the end of the storage period, the colour differences of different pre-treated samples are shown in **Figure 5.2**. Higher colour difference was found for control and most of the pr-treated samples except sodium metabisulphite and 6 g/l ascorbic acid pre-treated samples. It is interesting to note that some pre-treated samples (UV-750 W/m², 6 mg/l acetic acid, citric acid and sodium chloride) made the colour difference even higher than the control sample. Sodium metabisulphite (8 g/l) reduced about 35% colour difference than control sample. BELITZ & GROSCH (1999) reported that sulphur dioxide inhibits discolouration by blocking compounds with reactive carbonyl group (Maillard reaction, non-enzymatic browning) or by inhibiting oxidation by phenol oxidise enzymes (enzymatic browning). The result of this study is supported by the findings of LATAPI & BARRETT (2006 b). But BRENNENDORFER *et al.* (1985) reported that salts prevent enzymatic browning and discolouration during processing and storage.

Table 5.1: Effect of different pre-treatments on colour difference (ΔE) during storage of dried tomato halves

Prtreatments	Storage time (month)					
	0 (9 Sep)	1 (9 Oct)	2 (9 Nov)	3 (9 Dec)	4 (9 Jan)	5 (9 Feb)
Control (no pre-treatment)	0.00	3.89bc	5.58bc	7.06bc	9.87ab	13.99a
UV radiation (750 W/m ²)	0.00	4.99bc	4.49bc	6.56bc	11.03a	12.65ab
UV radiation (1500 W/m ²)	0.00	6.67ab	7.26ab	7.65bc	12.53a	14.16ab
Acetic acid (4 mg/l)	0.00	3.87bc	4.74bc	7.36bc	9.09ab	12.85ab
Acetic acid (6 mg/l)	0.00	4.49bc	5.09bc	6.53bc	9.35ab	14.46a
Citric acid (3 g/l)	0.00	5.60ab	6.20bc	9.32ab	11.60a	14.75a
Citric acid (6 g/l)	0.00	4.70bc	5.29bc	8.26ab	9.67ab	14.61a
Ascorbic acid (3 g/l)	0.00	3.29bc	3.46bc	7.16bc	9.13ab	12.87ab
Ascorbic acid (6 g/l)	0.00	2.87bc	3.89bc	5.52bc	6.51bc	11.41b
Sodium metabisulphite (2 g/l)	0.00	4.14bc	3.24c	6.80bc	4.74c	10.60bc
Sodium metabisulphite (8 g/l)	0.00	2.65c	4.46bc	4.49c	4.01c	9.42c
Sodium chloride (10 g/l)	0.00	8.63a	9.21a	11.28a	12.58a	14.73a

Common letter in same column is not significantly difference from each other by DMRT.

**Figure 5.2:** Colour differences of different pre-treated samples at the end of the storage period (5th month)

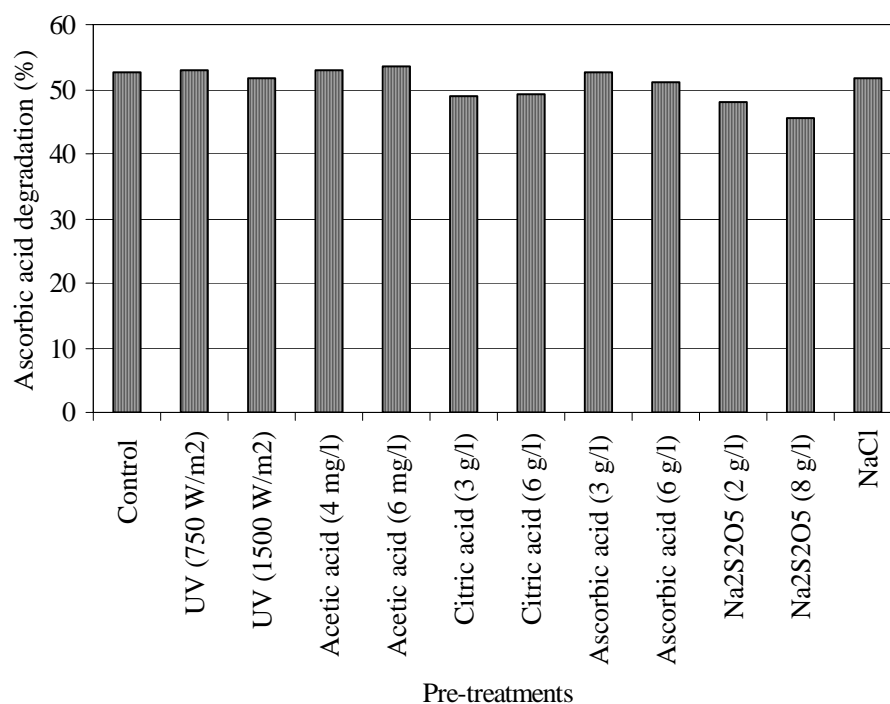
Ascorbic acid

Effect of different pre-treatments on ascorbic acid degradation during storage of dried tomato is shown in **Table 5.2**. At the starting of storage, significantly highest amount of ascorbic acid content was found for ascorbic acid pre-treated sample followed by sodium metabisulphite, citric acid and acetic acid pre-treated samples. Significantly lowest amount of ascorbic acid found for sodium chloride pre-treated sample followed by control and UV radiation pre-treated samples. These variations were due to the effect of different pre-treatments during drying as discussed in Chapter 3. During the storage period of 1 to 5 months, significantly highest amount of ascorbic acid was obtained for ascorbic acid pre-treated sample followed by sodium metabisulphite and citric acid pre-treated samples. Significantly lowest amount of ascorbic acid was found for sodium chloride pre-treated sample followed by control, UV radiation and acetic acid pre-treated samples. After five months of storage, above 50% ascorbic acid degradation was found for control and all pre-treated samples except sodium metabisulphite and citric acid pre-treated samples (**Figure 5.3**). Lowest ascorbic acid degradation was for 8g/l sodium metabisulphite (about 45%) followed by 2g/l sodium metabisulphite (about 48%) pre-treated samples. Ascorbic acid degradation by citric acid pre-treatment was slightly lower than 50%. Therefore, the highest amount of ascorbic acid (122.36 mg/100g-dm) was found for ascorbic acid pre-treated sample and the lowest percentage of ascorbic acid degradation was found for sodium metabisulphite (8 mg/l) pre-treated samples after 5 months of storage period. LATAPI & BARRETT (2006 b) found 76 and 21% ascorbic acid losses of dried tomato for 10% sodium chloride and sulphur gas pre-treatments respectively after three months of storage at 25°C temperature. They also concluded that sulphur dioxide can minimize the loss of ascorbic acid both during processing and storage. But in this study, ascorbic losses for sodium chloride and sodium metabisulphite pre-treatments were found to be about 52 and 45% respectively for dried tomato after five months storage. This difference may due to the varietal difference and difference of storage temperatures.

Table 5.2: Effect of different pre-treatments on ascorbic acid (mg/100g-dm) degradation of dried tomato halves during storage

Pr-treatments	Storage time (month)					
	0 (9 Sep)	1 (9 Oct)	2 (9 Nov)	3 (9 Dec)	4 (9 Jan)	5 (9 Feb)
Control (no pre-treatment)	118.29c	106.33cd	87.49cd	73.68c	65.27d	58.67cd
UV radiation (750 W/m ²)	137.36c	113.85cd	96.58cd	81.46bc	74.53cd	64.84c
UV radiation (1500 W/m ²)	149.42c	126.30c	108.43cd	91.67bc	79.64cd	74.71c
Acetic acid (4 mg/l)	176.69b	139.46c	120.17c	105.43bc	94.73c	83.26b
Acetic acid (6 mg/l)	176.71b	148.35bc	126.39c	109.52bc	97.27c	81.96b
Citric acid (3 g/l)	181.58b	162.78b	143.39b	122.52b	108.42b	95.72b
Citric acid (6 g/l)	184.24b	163.95b	145.58b	125.76b	112.63b	102.84b
Ascorbic acid (3 g/l)	230.56a	201.32a	173.44a	151.26a	121.15ab	109.55b
Ascorbic acid (6 g/l)	249.71a	209.35a	183.43a	162.37a	135.82a	122.36a
Sodium metabisulphite (2 g/l)	180.36b	163.18b	139.35b	119.18b	108.45b	97.28b
Sodium metabisulphite (8 g/l)	183.36b	159.77b	136.57b	116.33b	104.56b	91.08b
Sodium chloride (10 g/l)	90.13d	72.60d	66.48d	59.19d	51.82d	46.38d

Common letter in same column is not significantly difference from each other by DMRT

**Figure 5.3:** Ascorbic acid degradation of different pre-treated samples at the end of the storage period (5th month)

Lycopene

Effect of different pre-treatments on lycopene degradation during storage of dried tomato is presented in **Table 5.3**. At the beginning of storage, significantly highest amount of lycopene was found for sodium metabisulphite and 6 mg/l acetic acid treated samples followed by ascorbic acid, citric acid, acetic acid (4 mg/l), UV radiation and sodium chloride pre-treated samples. Significantly lowest amount of lycopene was obtained control sample. During the storage period of 1 to 5 months, significantly highest amount of lycopene was obtained for ascorbic acid pre-treated and sodium metabisulphite pre-treated samples followed by citric acid, acetic acid and UV radiation pre-treated samples. Significantly lowest amount of lycopene was found for sodium chloride pre-treated and control samples. At the end of the storage period (5th month) the highest (about 60%) lycopene degraded for control, UV radiation (750 W/m²) and sodium chloride pre-treated samples (**Figure 5.4**). About 50 to 55% lycopene degradations were obtained for UV radiation (1500 W/m²), acetic acid, citric acid and ascorbic acid (3 g/l) pre-treated samples. About 40% lycopenes were reduced for 6 g/l ascorbic acid and 2 g/l sodium metabisulphite pre-treated samples. The lowest lycopene degraded (35%) for 8 g/l sodium metabisulphite pre-treated samples. Hence, the significantly highest amounts of lycopene retentions were found for 6 g/l ascorbic acid and sodium metabisulphite pre-treated samples after five months of storage. The main cause of decrease of lycopene during storage is oxidation. Sodium metabisulphite functions as an effective antioxidant preventing lycopene oxidation. GIOVANELLA & LAVELLI (2002) found similar results for storage of dried tomato.

Table 5.3: Effect of different pre-treatments on lycopene (mg/100g-dm) degradation of dried tomato halves during storage

Pr-treatments	Storage time (month)					
	0 (9 Sep)	1 (9 Oct)	2 (9 Nov)	3 (9 Dec)	4 (9 Jan)	5 (9 Feb)
Control (no pre-treatment)	34.52c	31.98c	28.08c	22.41c	17.86c	13.73d
UV radiation (750 W/m ²)	43.98b	38.73bc	33.19b	25.55b	21.29b	17.14c
UV radiation (1500 W/m ²)	46.04b	41.45b	35.81b	29.12b	23.66b	20.28bc
Acetic acid (4 mg/l)	47.13b	41.84b	35.79b	32.26ab	26.54b	22.47bc
Acetic acid (6 mg/l)	49.06a	43.56b	37.92ab	32.94ab	28.27b	25.35b
Citric acid (3 g/l)	46.64b	41.35b	36.41b	33.56ab	28.72b	23.96b
Citric acid (6 g/l)	45.91b	41.19b	36.68b	30.81ab	26.06b	21.80b
Ascorbic acid (3 g/l)	44.75b	39.88b	35.49b	29.48ab	25.35b	21.62b
Ascorbic acid (6 g/l)	47.15ab	43.64a	37.63ab	34.73a	31.34a	27.19a
Sodium metabisulphite (2 g/l)	48.53a	44.34a	39.25a	36.09a	31.64a	28.48a
Sodium metabisulphite (8 g/l)	49.57a	45.53a	41.63a	37.66a	34.35a	31.65a
Sodium chloride (10 g/l)	41.76b	38.14bc	32.67c	26.66b	22.54c	17.82c

Common letter in same column is not significantly difference from each other by DMRT

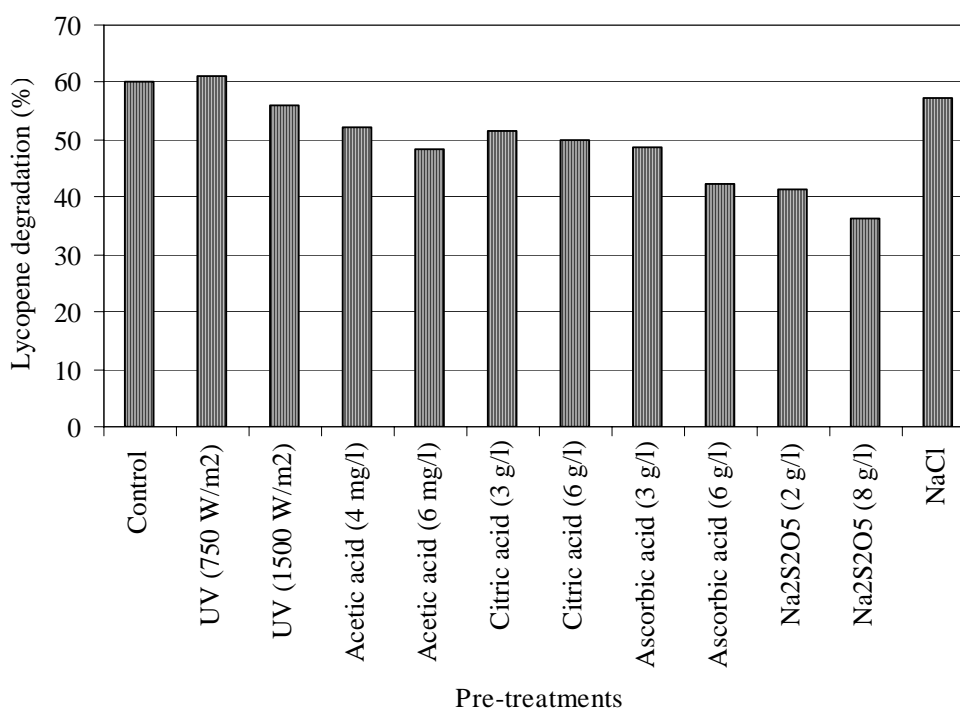


Figure 5.4: Lycopene degradation of different pre-treated samples at the end of the storage period (5th month)

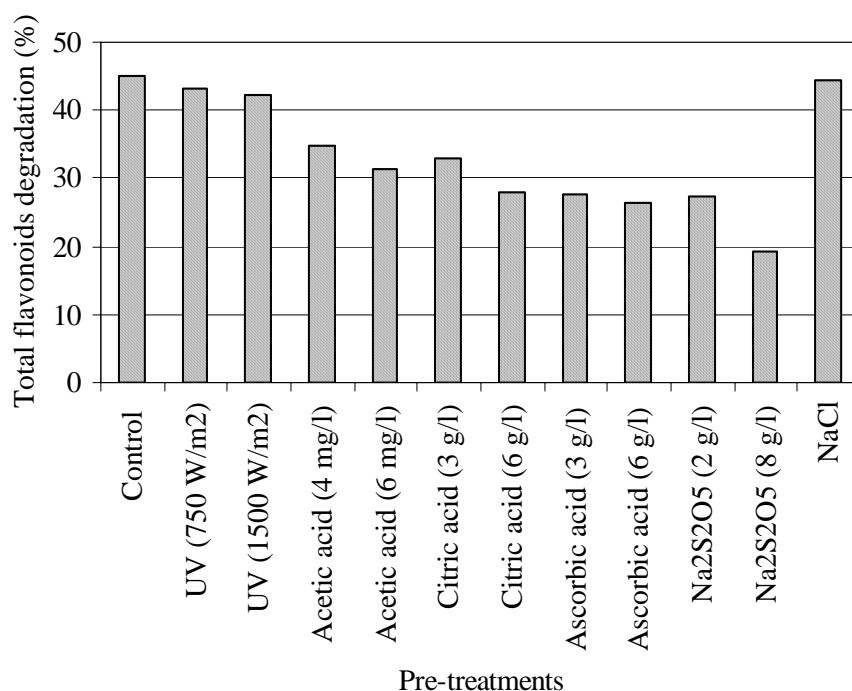
Total flavonoids

Effects of different pre-treatments on total flavonoids (mg/100g-dm) degradations during storage of dried tomato halves are given in **Table 5.4**. Significantly highest amount of total flavonoids were found for citric acid, ascorbic acid and sodium metabisulphite pre-treated samples followed by acetic acid, UV radiation treated and control samples at the beginning of storage. Significantly lowest total flavonoids were obtained for sodium chloride pre-treated sample. These variations were due to the effect of different pre-treatments during drying. During the storage period of 1 to 5 months, significantly highest amount of total flavonoids were obtained for 8 g/l sodium metabisulphite followed by 2 g/l sodium metabisulphite and ascorbic acid pre-treated samples. During this storage period, significantly lowest amount of total flavonoids was found for UV radiation followed by sodium chloride pre-treated samples and control sample. Total flavonoids degradation of different pre-treated samples at the end of the storage period is shown in **Figure 5.5**. After five months of storage, about 40 to 45% total flavonoids degradations were found for control, UV radiation and sodium chloride pre-treated samples. About 30 to 35% total flavonoids degradations were found for acetic acid and 3 g/l citric acid pre-treated samples and about 25% degradations were found for 6g/l citric acid, ascorbic acid and 2 g/l sodium metabisulphite pre-treated samples. The lowest (about 20%) total flavonoids degraded for 8 g/l sodium metabisulphite pre-treated samples. Flavonoids are polyphenolic compounds and they have antioxidant properties and inhibit the oxidation. TOKUSOGLU *et al.* (2003) reported that total flavonoids degrade with processing as well as storage.

Table 5.4: Effect of different pre-treatments on total flavonoids (mg/100g-dm) degradation during storage of dried tomato halves

Pr-treatments	Storage time (month)					
	0 (9 Sep)	1 (9 Oct)	2 (9 Nov)	3 (9 Dec)	4 (9 Jan)	5 (9 Feb)
Control (no pre-treatment)	124.18b	112.45c	104.67d	89.34d	79.41d	68.26c
UV radiation (750 W/m ²)	123.36b	116.83b	105.47d	92.04d	82.63d	74.95d
UV radiation (1500 W/m ²)	124.51b	113.94b	103.54d	92.86d	82.62d	73.27d
Acetic acid (4 mg/l)	124.09b	117.62b	110.16c	97.93cd	89.64c	81.97c
Acetic acid (6 mg/l)	125.39b	117.82b	112.28c	105.68c	96.63c	91.56b
Citric acid (3 g/l)	129.14a	119.56b	110.75c	103.46c	96.25c	86.44
Citric acid (6 g/l)	128.57a	123.81ab	116.37b	109.53bc	104.18b	96.63b
Ascorbic acid (3 g/l)	133.91a	124.33a	117.72b	112.54b	106.35b	96.93b
Ascorbic acid (6 g/l)	134.87a	126.05a	117.45b	114.34ab	108.67b	99.16b
Sodium metabisulphite (2 g/l)	132.79a	124.56a	116.53b	112.19b	103.46b	96.67b
Sodium metabisulphite (8 g/l)	135.92a	128.34a	122.41a	118.72a	112.54a	105.60a
Sodium chloride (10 g/l)	119.52c	112.37c	105.63d	93.29d	82.56d	66.49c

Common letter in same column is not significantly difference from each other by DMRT

**Figure 5.5:** Total flavonoids degradation of different pre-treated samples at the end of the storage period (5th month)

Effect of Moisture Content and Environment

Colour

Colour differences (ΔE) of different solar dried samples and commercial samples stored in room environment and cool chamber environment are shown in **Figure 5.6**. For first month (9 September to 9 October 2006), colour differences of all the solar dried samples and commercial samples stored in room and cool chamber environments increased steeply but the later storage periods (9 October 2006 to 9 February 2007) colour differences of all solar dried samples became mostly flat but the colour differences of commercial samples remained steep trends with lower slope. Therefore, the colour degradations of solar dried samples after first month were not significant. But the colour difference of commercial samples continued to degrade up to the fifth month. This variation might due to the varietal difference and higher moisture content at the beginning of storage of the commercial samples (38%, wb). Effect of storage environment for solar and commercial samples was found significant (**Table 5.5**). Colour differences of tomato halves stored in room environment were found significantly higher (t-test) than those stored in cool chamber. This may be due to the storage temperature difference. In room environment the average storage temperature range was 20°C but the cool chamber the average temperature was 5°C. Colour difference was found higher for sample with higher moisture content. Significantly highest colour differences were found for commercial sample with 38% (wb) moisture content for both room and cool chamber environments. For solar dried samples, colour difference increased with product moisture content but their differences were insignificant for cool chamber but significant for room environments. ZANONI *et al.* (2000) reported that colour difference increase with storage temperature, storage time and product moisture content.

Red colour value ($+a^*$) degraded linearly with storage time both in room and cool chamber environments. Following regression equations were developed for red colour ($+a^*$) of dried tomato during storage function of storage time (month) in the product moisture range of 18 to 30% (wb). The regression lines are shown in **Figure 5.7**.

$$+a^*_{(\text{room})} = 12.25 - 0.7594t_m \quad (R^2=0.86) \quad (5.2)$$

$$+a^*_{(\text{cool chamber})} = 13.30 - 0.2837t_m \quad (R^2=0.83) \quad (5.3)$$

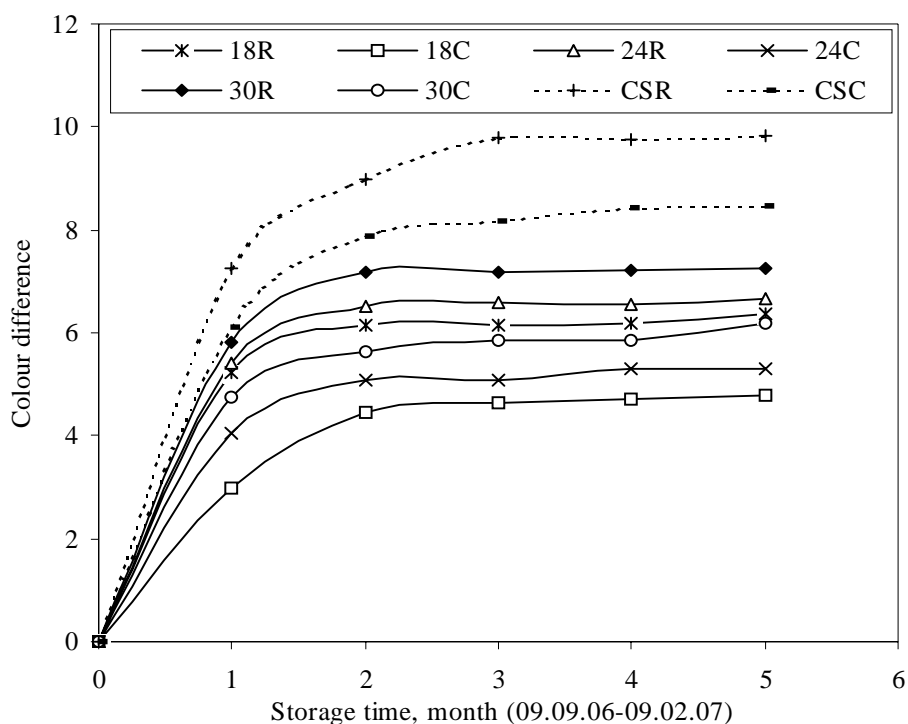


Figure 5.6: Colour difference (ΔE) with storage time of different dried tomato samples and storage environments (18, 24, 30 are initial storage moisture content % (wb) of solar dried samples, CS = commercial sample, R = room and C = cool chamber)

Table 5.5: Effect of storage environment and product moisture content on colour difference (ΔE) during storage of dried tomato halves

Samples	Room environment	Cool chamber environment	Level of significance
Solar dried sample with 18% MC	6.00c	4.32b	$p \leq 0.0026$
Solar dried sample with 24% MC	6.33bc	4.96b	$p \leq 0.0016$
Solar dried sample with 30% MC	6.93b	5.15b	$p \leq 0.0146$
Commercial sample with 38% MC	9.12a	7.81a	$p \leq 0.0405$

MC= product moisture content (wb). Common letter in the same row is not significantly difference from each other by DMRT

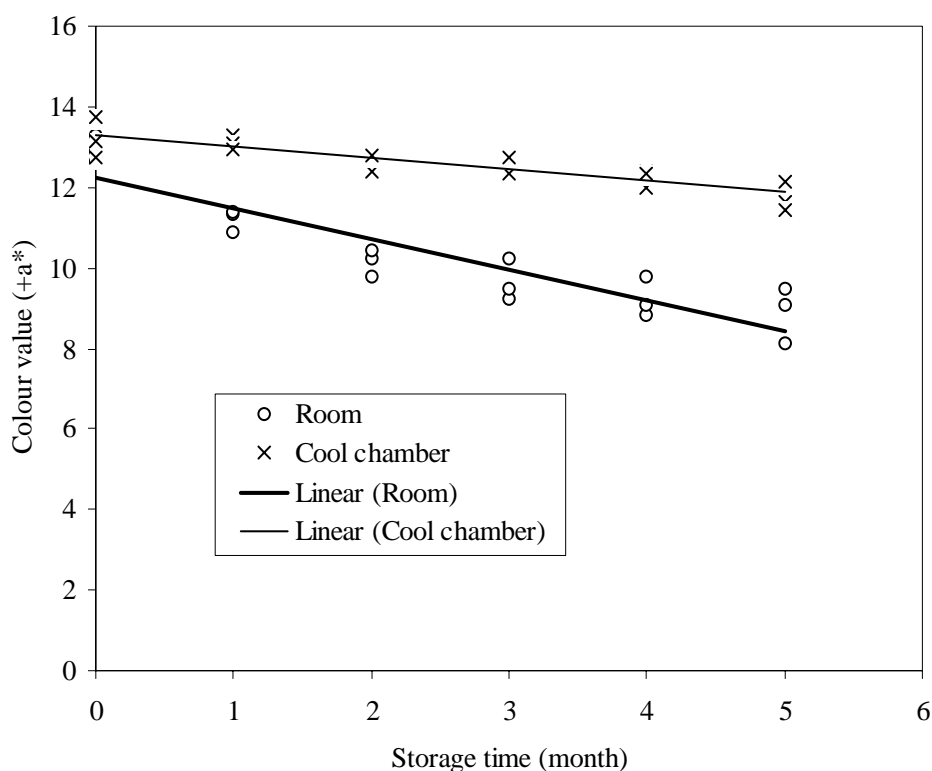


Figure 5.7: Changes of red colour as a function of storage time during storage of dried tomato

Ascorbic acid

Changes of ascorbic acid of different dried tomato samples with storage time, initial storage moisture contents and storage environments are shown in **Figure 5.8**. It is observed from the Figure that ascorbic acid decreased linearly with the storage time for all the samples. It is also observed that ascorbic acid was degraded rapidly in room environment than that of cool chamber environment. The initial storage ascorbic acid was higher in solar dried samples than the commercial sample. This may be due to that some ascorbic acid of commercial sample was already degraded (in shop or elsewhere) before purchasing the sample. For solar dried samples, the sample with higher moisture content had more ascorbic acid than lower moisture samples. The reason might be that, more time is required to reduce the moisture content to a low level for the sample with lower moisture content than the sample with higher moisture content. As a result, some ascorbic acid of the sample (lower moisture content) might be lost due to more oxidation in the drying chamber. After five months of storage, higher ascorbic acid degradation was found for room environment than the cool chamber environment (**Figure 5.9**). The highest ascorbic acid degradation was found for commercial sample stored in room (>50%) but when it was stored in cool chamber the ascorbic acid degradation was about 40%. In room environment the ascorbic acid degradations of samples with 18, 24 and 30% moisture content were about 37, 39 and 42% respectively but in cool chamber the ascorbic acid degradations were about 29, 31 and 32%, respectively. Ascorbic acid degradation was

higher for samples with higher moisture content. Again, the degradation of ascorbic acid was higher for sample stored in higher temperature. GOULA & ADAMOPOULOS (2006) reported that the degradation rate of ascorbic acid of tomato pulp increased with temperature as well as the moisture content.

Ascorbic acid degraded linearly with storage time both in room and cool chamber environments. Following regression equations were developed for ascorbic acid content of dried tomato as a function of storage time (month) in the product moisture range of 18 to 30% (wb). The regression lines of ascorbic acid content during storage of dried tomato are shown in **Figure 5.10**.

$$\text{Ascorbic acid (mg/100 g)}_{(\text{room})} = 180.34 - 14.214t_m \quad (R^2=0.96) \quad (5.4)$$

$$\text{Ascorbic acid (mg/100 g)}_{(\text{cool chamber})} = 180.12 - 10.314t_m \quad (R^2=0.91) \quad (5.5)$$

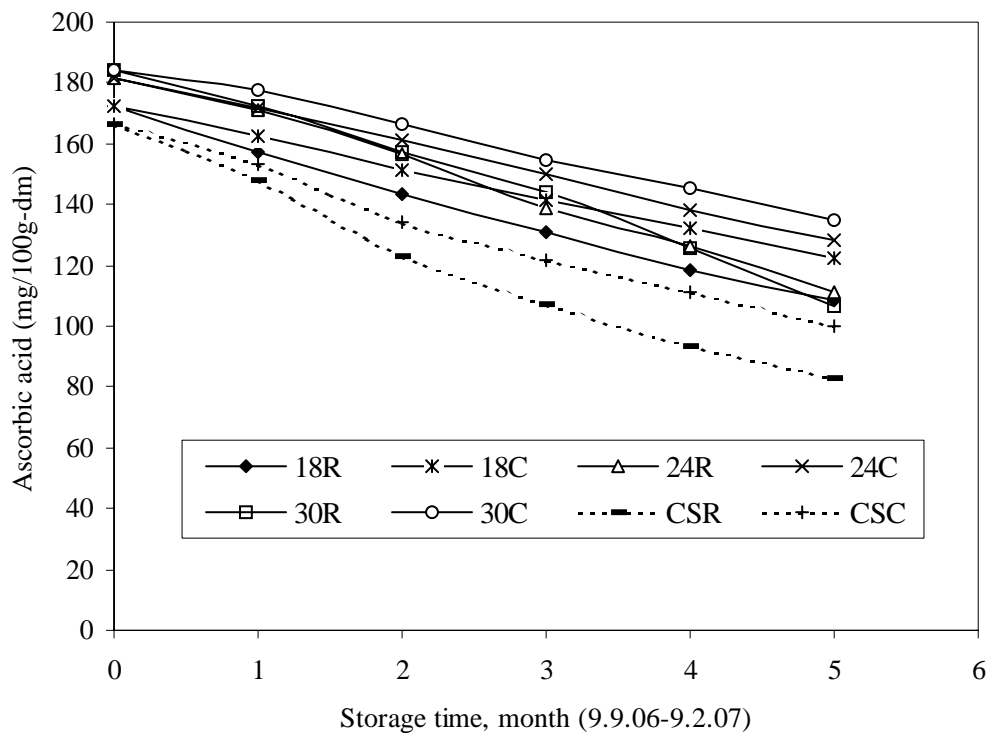


Figure 5.8: Changes of ascorbic acid of different dried tomato samples with storage time at two storage environments (18, 24, 30 are initial storage moisture content % (db) of solar dried samples, CS= commercial sample, R=room and C=cool chamber)

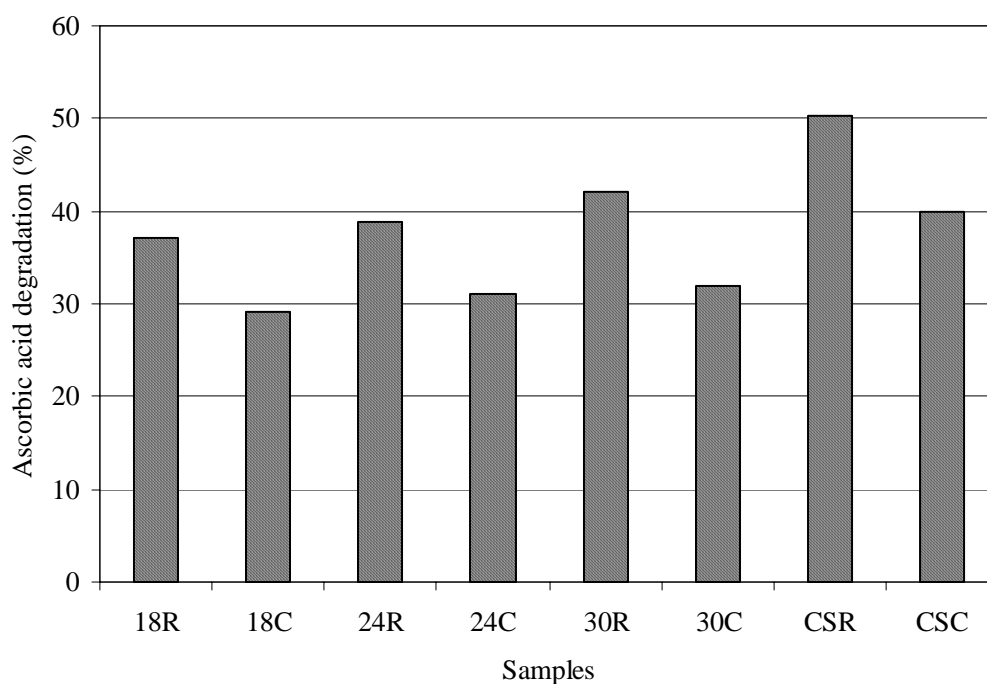


Figure 5.9: Comparison of ascorbic acid degradation after five months of storage of different dried tomato samples (18, 24, 30 are initial storage moisture content % (db) of solar dried samples, CS = commercial sample, R = room, C = cool chamber)

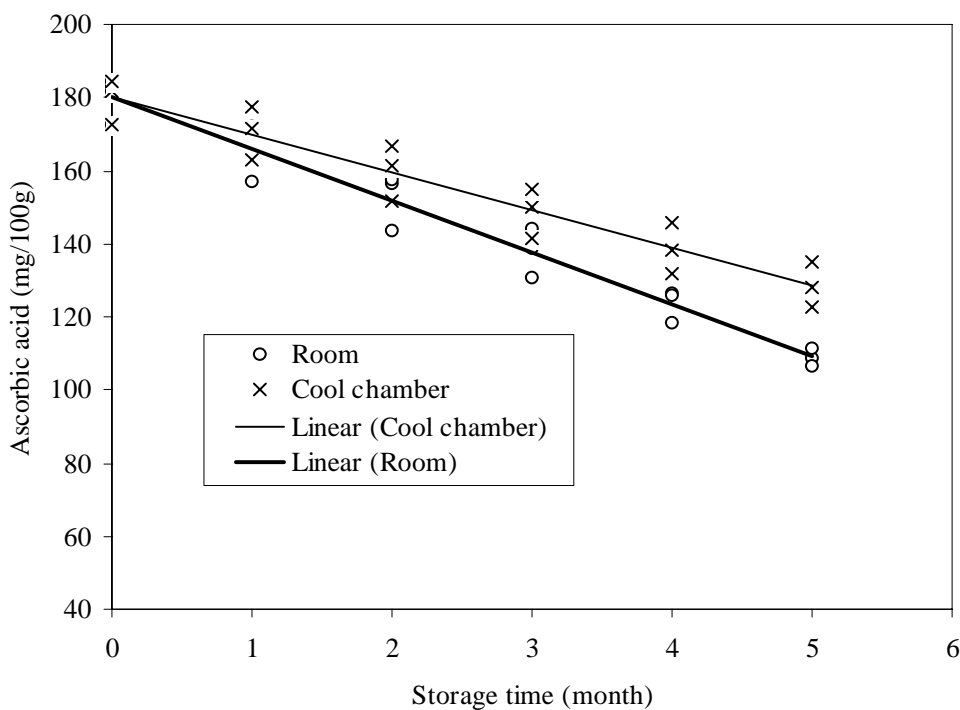


Figure 5.10: Changes of ascorbic acid as a function of storage time during storage of dried tomato

Lycopene

Changes of lycopene content of different dried tomato samples with storage time at two storage environments are shown in **Figure 5.11**. Lycopene contents of solar dried samples were found higher than the commercial sample. This may be due to that the commercial sample was dried a few months before the solar dried samples. Also there was varietal difference of solar dried and commercial samples. Higher initial lycopene was obtained for sample with 30% moisture content followed by samples with 24 and 18% moisture contents. It is observed from the Figure that lycopene content of all samples decreased linearly with storage time. Lycopene degradation of room environment was higher than that of the cool chamber environment. This may be due to that room temperature had higher temperature (20°C) than the cool chamber (5°C). After five months of storage, higher lycopene degradation was found for commercial sample than the solar dried samples in both room environment and cool chamber environment (**Figure 5.12**). Among the solar dried samples more lycopene degradation was observed sample with higher moisture content. AKANBI & OLUDEMI (2004) reported that lycopene in storage tomato degraded with the storage temperature and storage time. The main cause of lycopene degradation during storage is oxidation. Low oxygen content, low temperature, and low moisture content of sun dried tomato prevent oxidation as well as lycopene degradation (SHI 2000).

Lycopene content of dried tomato reduced linearly with storage time both in room and cool chamber environments. Following regression equations were developed for lycopene content of dried tomato as a function of storage time (month) in the product moisture range of 18 to 30% (wb). The regression lines of lycopene content during storage of dried tomato are given in **Figure 5.13**.

$$\text{Lycopene (mg/100 g)}_{(\text{room})} = 46.54 - 4.5079t_m \quad (R^2=0.96) \quad (5.6)$$

$$\text{Lycopene (mg/100 g)}_{(\text{cool chamber})} = 47.073 - 3.4173t_m \quad (R^2=0.92) \quad (5.7)$$

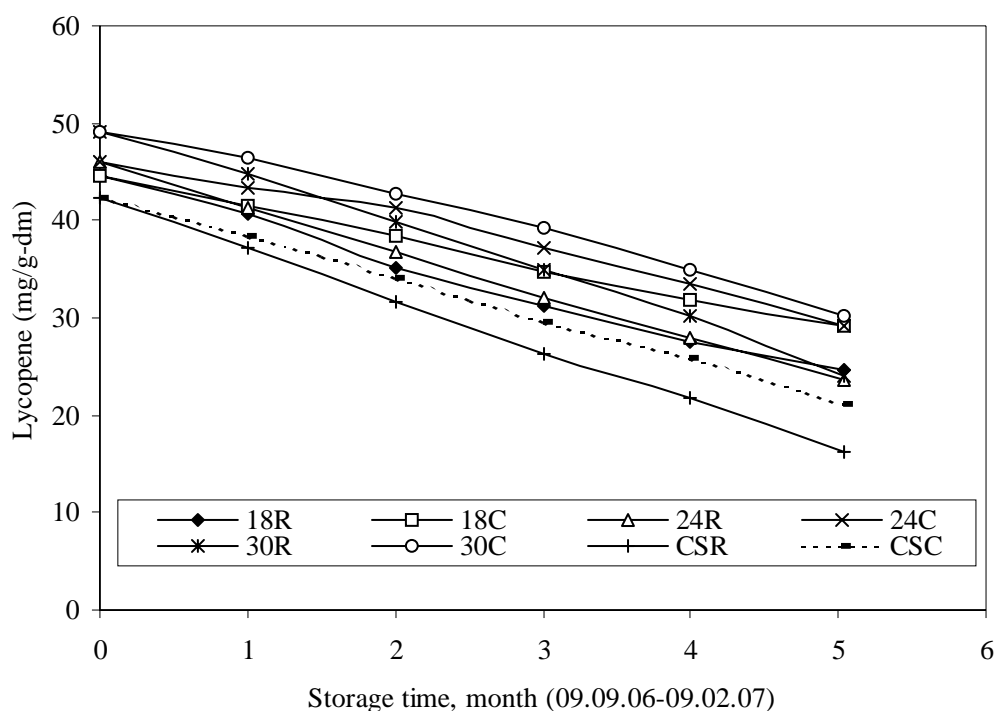


Figure 5.11: Changes of lycopene of different dried tomato samples with storage time at two storage environments (18, 24, 30 are initial storage moisture content % (wb) of solar dried samples, CS= commercial sample, R=room and C=cool chamber)

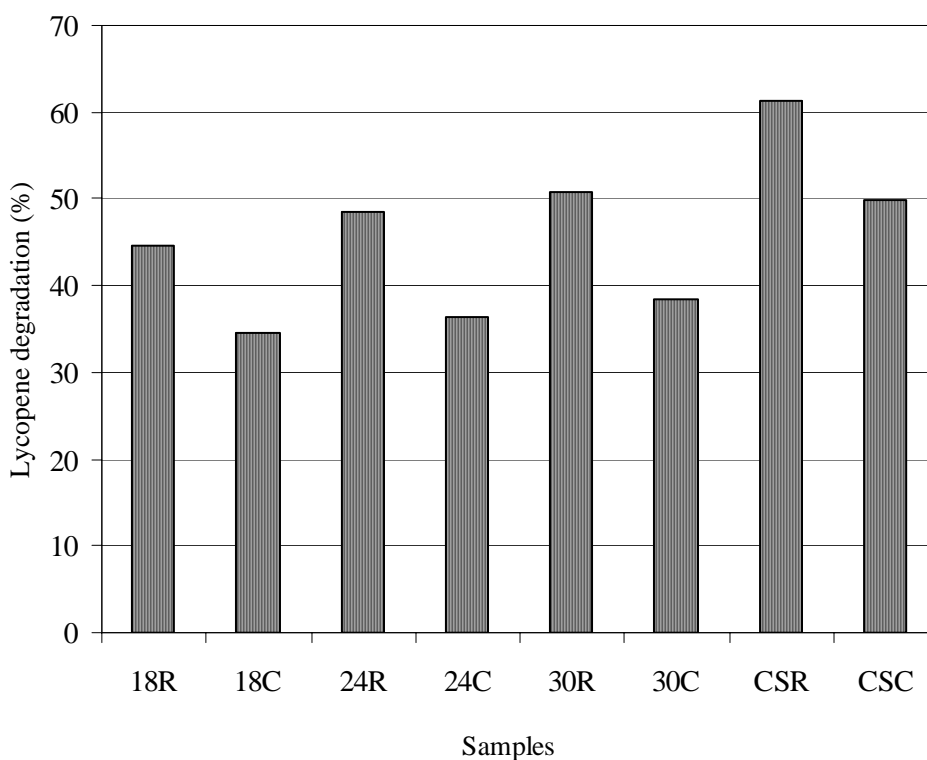


Figure 5.12: Comparison of lycopene degradation after five months of storage of different dried tomato samples (18, 24, 30 are initial storage moisture content % (wb) of solar dried samples, CS = commercial sample, R = room, C = cool chamber)

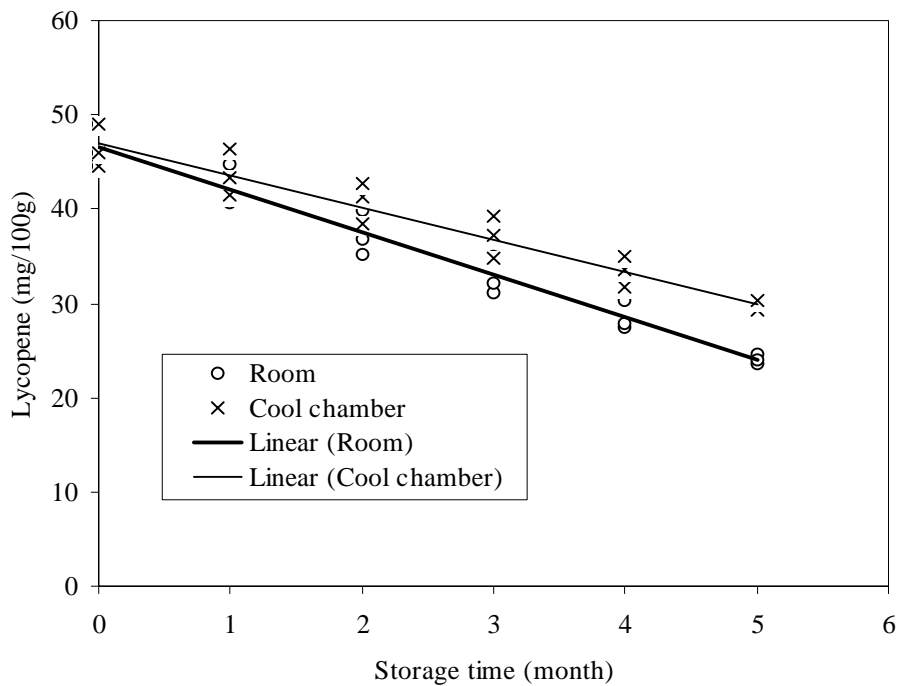


Figure 5.13: Changes of lycopene as a function of storage time during storage of dried tomato

Total flavonoids

Changes of total flavonoids with storage time and environment of solar dried and commercial samples are shown in **Figure 5.14**. Total flavonoids of solar dried samples were found higher than the commercial sample. This may be due to the varietal difference and difference of drying conditions of solar dried and commercial samples. Higher initial total flavonoids were obtained for sample with 30% moisture content followed by samples with 24 and 14% moisture content. But there were no significance difference between samples with 18 and 24% moisture contents. Total flavonoids of all samples decreased linearly with storage time. After five months of storage, total flavonoids degradations of room environment were higher than the cool chamber environment (**Figure 5.15**). Higher total flavonoids degradations were obtained for commercial sample than the solar dried samples in both room environment and cool chamber environment. Among the solar dried samples total flavonoids degradations were higher for samples with higher moisture content both in room environment and cool chamber environment.

Total flavonoids of dried tomato decreased linearly with storage time both in room and cool chamber environments. Following regression equations were developed for total flavonoids content of dried tomato as a function of storage time (month) in the product moisture range of 18 to 30% (wb). The regression lines of total flavonoids during storage of dried tomato are given in **Figure 5.16**.

$$\text{Total flavonoids (mg/100 g)}_{(\text{room})} = 139.43 - 11.5390t_m \quad (R^2=0.81) \quad (5.8)$$

$$\text{Total flavonoids (mg/100 g)}_{(\text{cool chamber})} = 151.55 - 4.9286t_m \quad (R^2=0.83) \quad (5.9)$$

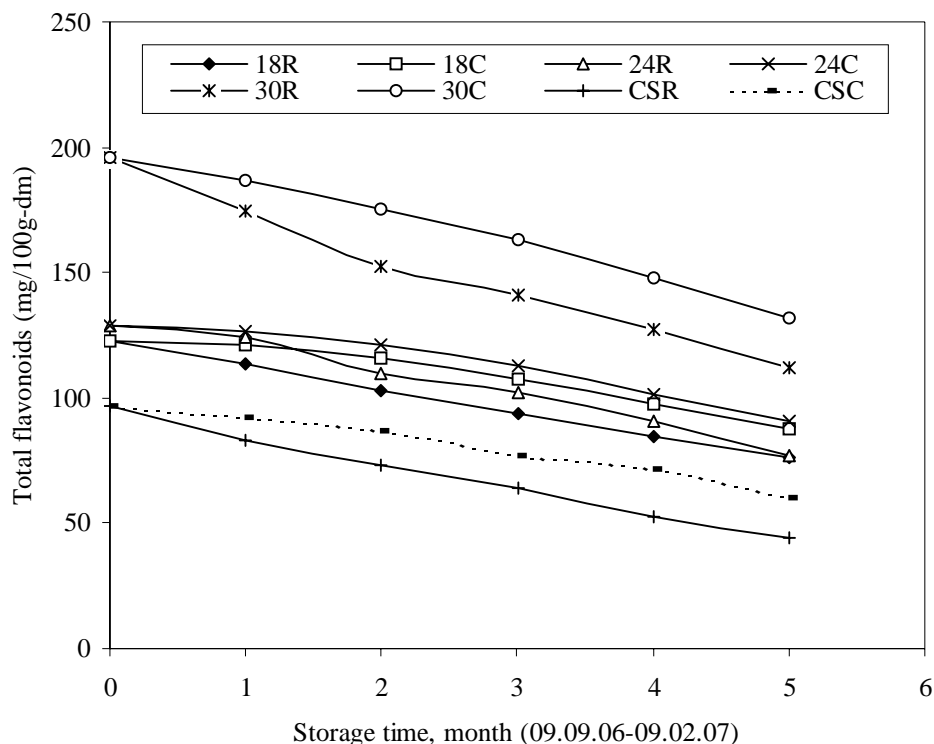


Figure 5.14: Changes of total flavonoids of different dried tomato samples with storage time at two storage environments (18, 24, 30 are initial storage moisture content %, (wb) of solar dried samples, CS=commercial sample, R=room and C=cool chamber)

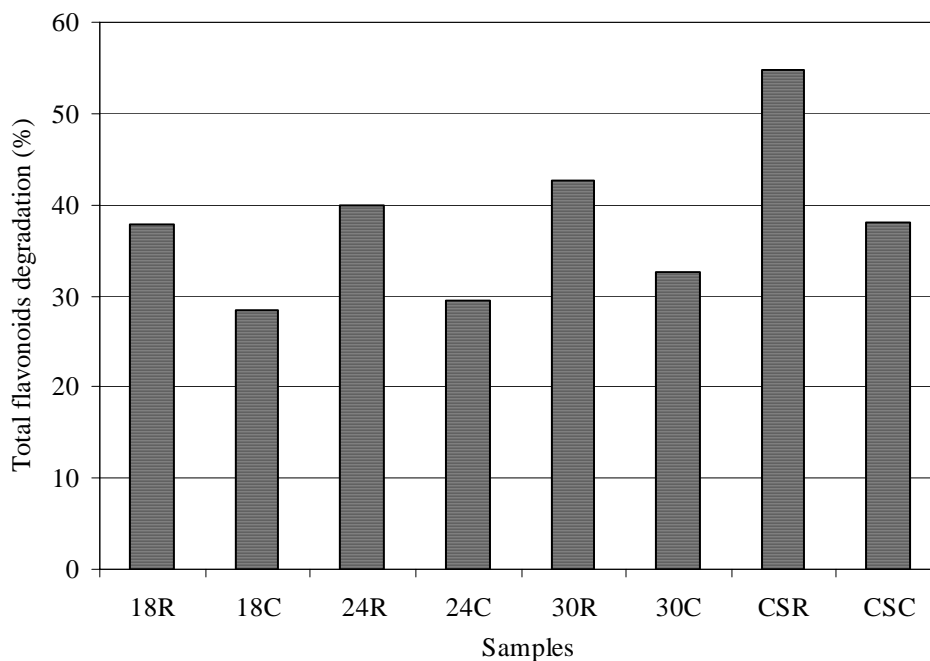


Figure 5.15: Comparison of total flavonoids degradation after five months of storage of different dried tomato samples (18, 24, 30 are initial storage moisture content % (wb) of solar dried samples, CS=commercial sample, R=room, C= cool chamber)

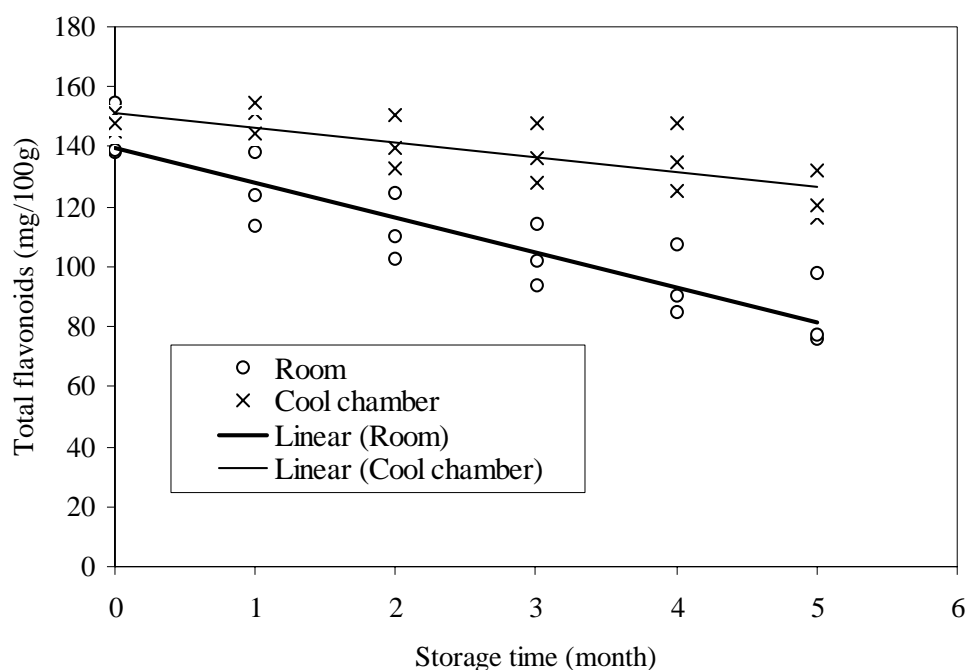


Figure 5.16: Changes of total flavonoids as a function of storage time during storage of dried tomato

Rehydration ratio

Changes of Rehydration ratio of different dried tomato samples with storage time at two storage environments are shown in **Figure 5.17**. The Figure represents that higher rehydration ratios were obtained for solar dried sample than that of commercial sample. Sample of 18% moisture content had the higher rehydration ratio than other solar dried samples. The initial rehydration ratio of the samples with moisture content 24 and 30% were close to each other. The reason might be that samples with less moisture content had high water absorbity. But when the product moisture content reduced to case hardening stage, the water absorbity of the product reduced. The rehydration ratios of all samples decreased linearly with the storage time but their reduction rates were small. After five months of storage, the rehydration ratio reductions of different samples are shown in **Figure 5.18**. It is observed from the Figure that rehydration ratio reductions were higher in room environment than those of cool chamber environment for all samples. Highest rehydration ratio reduction was found for the sample with 18% followed by 24 and 30% moisture contents for both room and cool chamber environments. The lowest rehydration reduction was obtained for commercial sample. These results are supported by the study reported by TRIPATHI & NIRANKAR (1989). After five months of storage, good rehydration ratio (>2.0) was obtained and the reduction of rehydration ratio was less than 10%. Therefore, after five months of storage in room and cool chamber environments, the tissue damage was minimum and quality of dried tomato halves was good regarding the rehydration ratio.

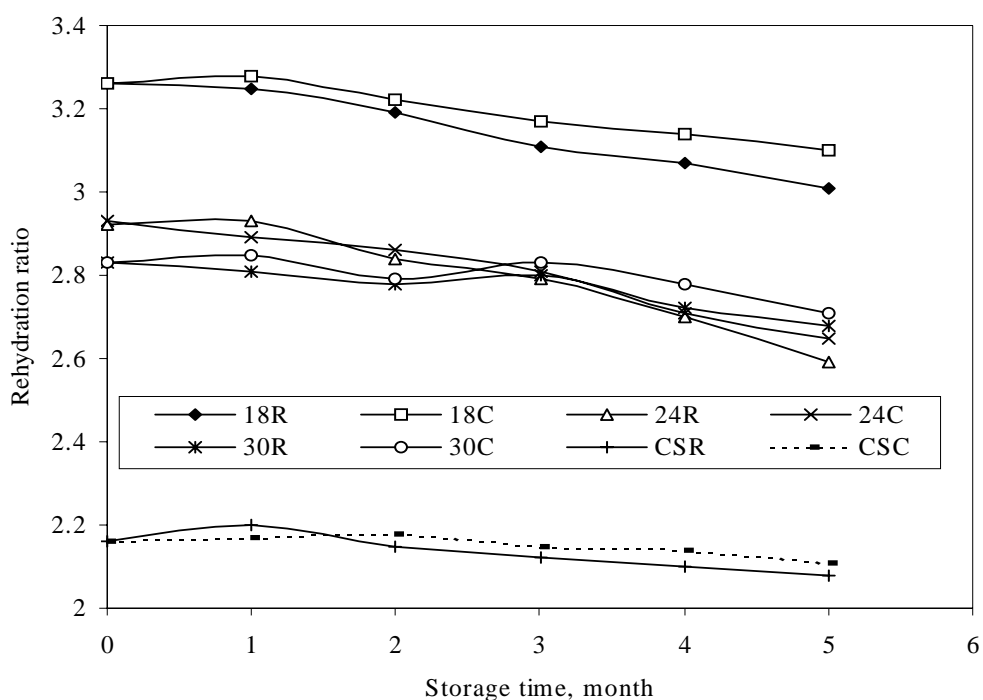


Figure 5.17: Changes of rehydration ratio of different dried tomato samples with storage time at two storage environments (18, 24, 30 are initial storage moisture content % (wb) of solar dried samples, CS=commercial sample, R=room and C=cool chamber)

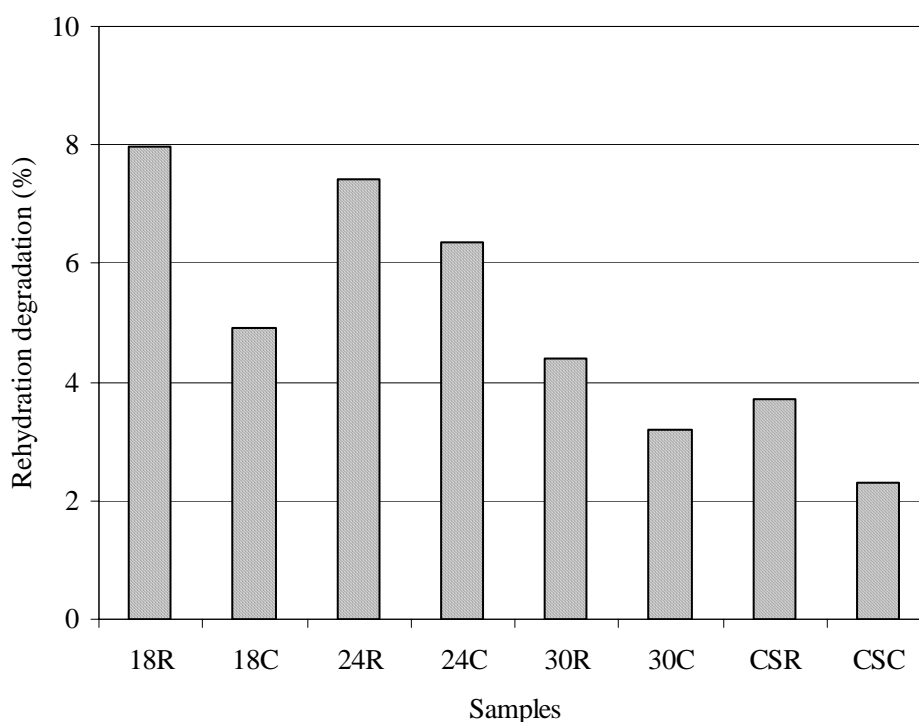


Figure 5.18: Comparison of rehydration ratio reduction after five months of storage of different dried tomato samples (18, 24, 30 are initial storage moisture content % (wb) of solar dried samples, CS=commercial sample, R=room, C= cool chamber)

Effect of Storage Container

Colour

Effect of storage containers and environments on colour difference (ΔE) during storage of dried tomato at low moisture content (18%, wb) is shown in **Figure 5.19**. For all storage containers and environments colour differences increased with storage time. Colour differences were found to be higher in room environment than cool chamber environment for all storage containers. This may be due to higher temperature was in room (average 20°C) environment than the cool chamber environment (average 5°C) and more oxidation took place in room environment. Both for room and cool chamber environments, the lowest colour differences were found for glass container followed by plastic container and polyethylene bag. Similar pattern of results had been observed for medium (24%) and high (30%) moisture contents for both room and cool chamber environments as shown in **Figure 5.20** and **5.21** respectively. During storage, the containers were made air tight and continuously measured the temperature and relative humidity in the storage containers by inserting sensors in them. Variations of temperature and relative humidity in the storage containers for a typical month (December 2006-January 2007) are shown in **Figures 5.22** and **5.23** respectively. It is observed from the Figures that variation of temperatures for glass container, plastic container, and polyethylene bag were almost same. But the variation of relative humidity in polyethylene bag was found little higher than plastic and glass containers. This reason might be that polyethylene bag might have some micro pores that allowed a very little moisture transport. But the glass container had no such micro pores for moisture movement. It is reported that some thin polyethylene have micro pores and it is gas permeable (KOMATSU & TAKAHASHI 1987).

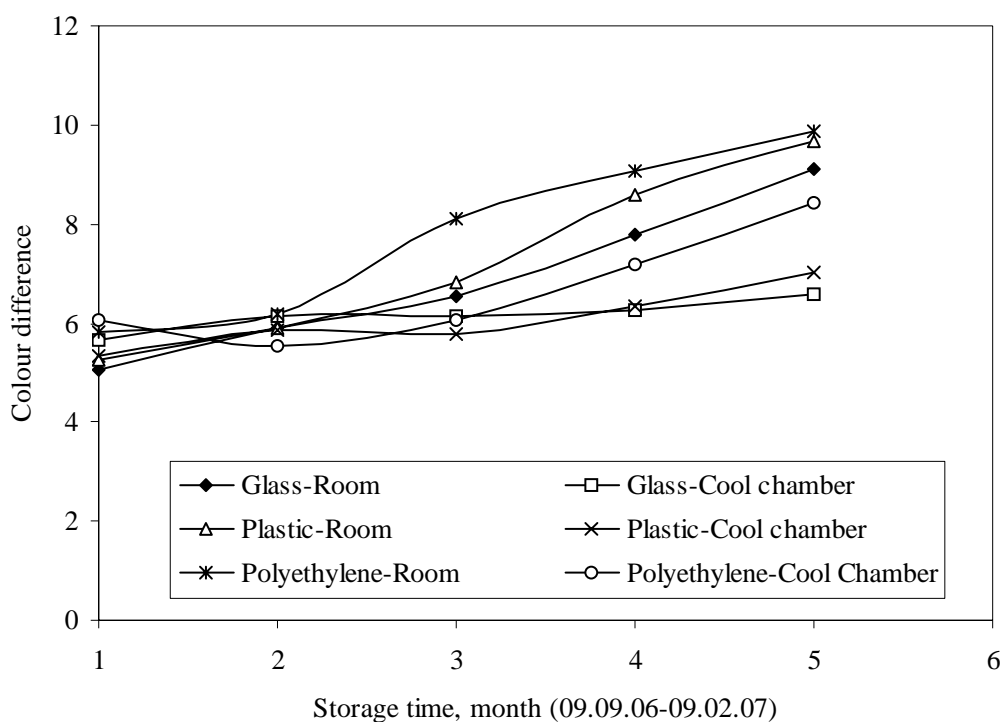


Figure 5.19: Effect of storage containers and environments on colour differences during storage of dried tomato at low moisture content (18%, wb)

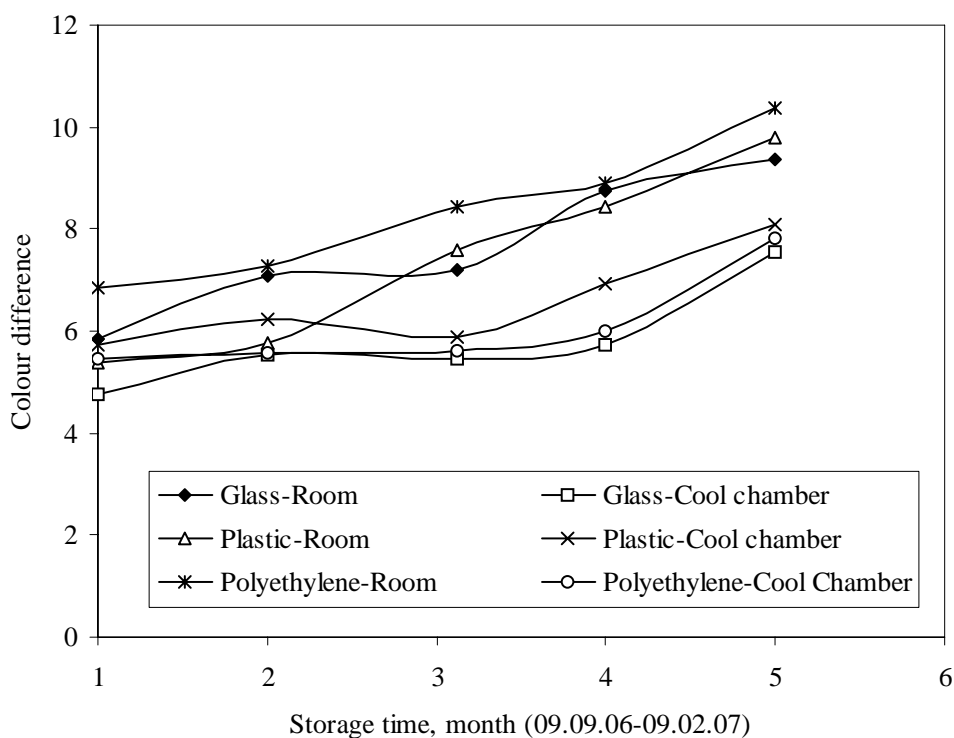


Figure 5.20: Effect of storage containers and environments on colour differences during storage of dried tomato at medium moisture content (24%, wb)

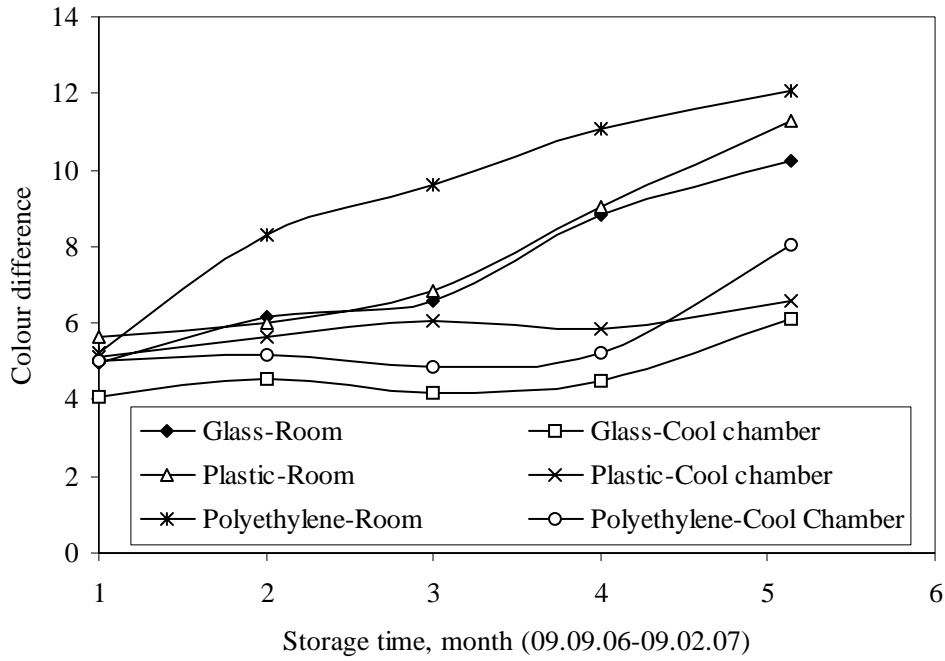


Figure 5.21: Effect of storage containers and environments on colour differences during storage of dried tomato at medium moisture content (30%, wb)

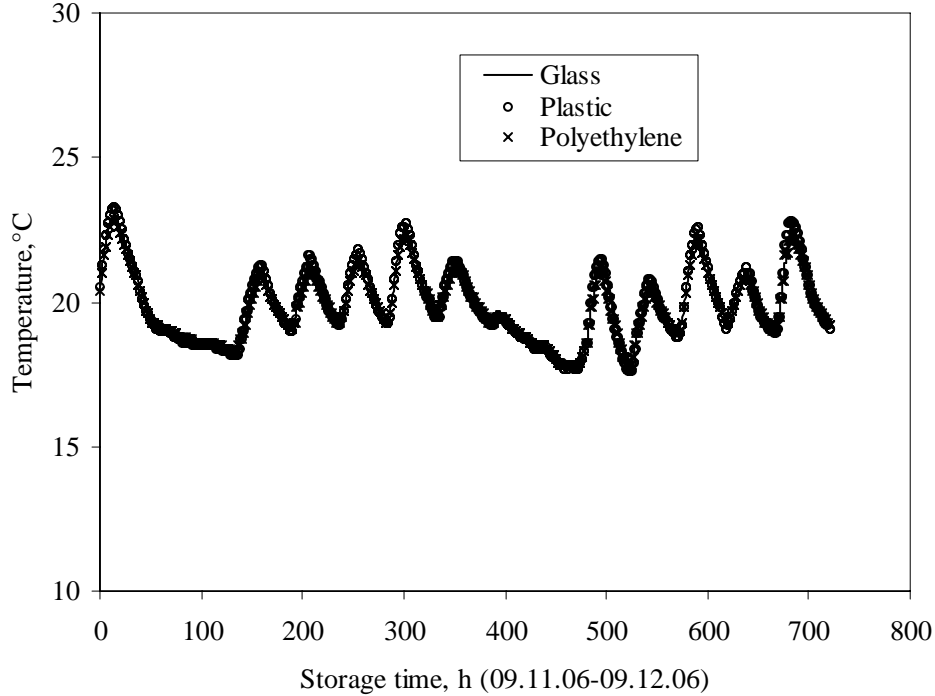


Figure 5.22: Variations of temperature in the storage containers in room environment for a typical month (9 November to 9 December 2006) (initial storage moisture content of all samples were about 24%, wb)

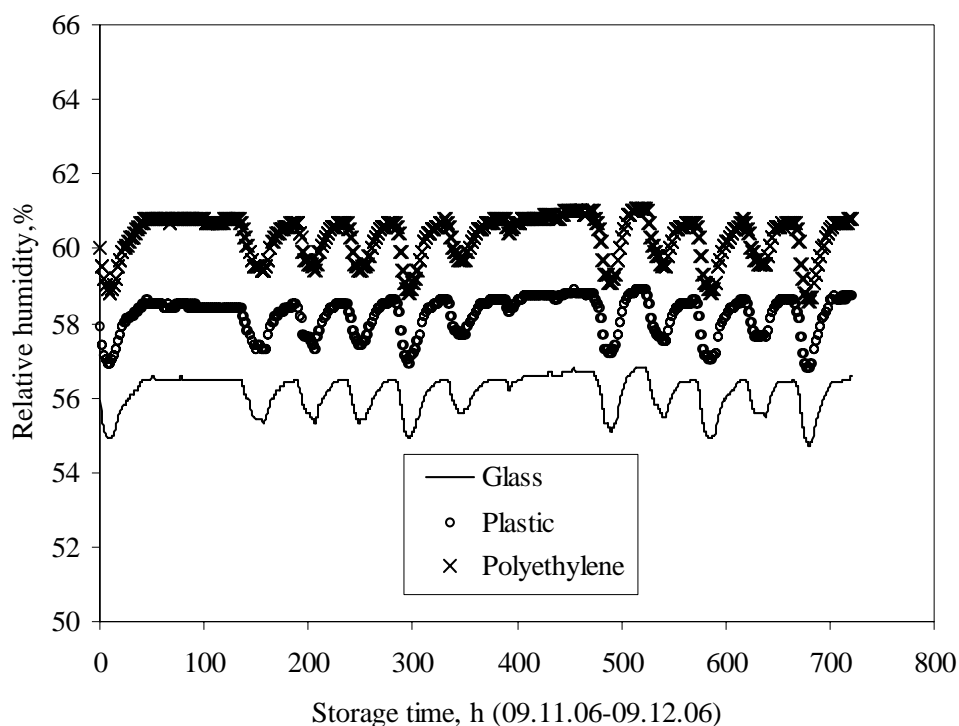


Figure 5.23: Variations of relative humidity in the storage containers in room environment for a typical month (9 November to 9 December 2006) (initial storage moisture content of all samples were about 24%, wb)

Moisture content

Variations of product moisture contents with storage containers during storage of dried tomato stored in room environment are shown in **Figure 5.24**. It is observed from the Figure that three levels of storage moisture contents (18, 24 and 20%, wb) remained almost flat during the storage period. Effects of storage containers on product moisture contents during the storage period were also insignificant. But for cool chamber storage, product moisture content little increased with the storage time (**Figure 5.25**). The increase of moisture content was higher in polyethylene bag and it was little higher than those of plastic and glass containers. The reason might that the sample stored in room temperatures were equilibrated during storage with the container environments (temperature and relative humidity) but in cool chamber environment, the temperature was low (5°C) and relative humidity was high (80%) in comparison to the room environment (average temperature 20°C and relative humidity 60%). Therefore, the samples absorbed more moisture from the container environment to become equilibrium state. Because, when the temperature decreases and relative humidity increases then, the equilibrium moisture content of the product also increases (HOSSAIN & BALA 2000). The comparisons of moisture content variations at low (18%, wb), medium (24%, wb) and high (30%, wb) are given in **Figures 5.26, 5.27 and 5.28** respectively. It is observed from the Figures that product moisture content remained almost flat with storage time for all the storage containers in the room environment. In

cool chamber environment, product moisture content in the glass container was flat but for plastic container and polyethylene bag, product moisture increased with storage time. This may due to the fact that glass container was completely air tight and no air entered or exhausted from or to the out side. As a result, product moisture content reached equilibrium with the glass container environment. In case of plastic containers and polyethylene bag it was not completely (possible) air tight. So the product might absorb moisture from the outside environment.

Growth of micro-organisms was examined during the storage period. No visible micro-organisms were observed in any samples during storage of dried tomato.

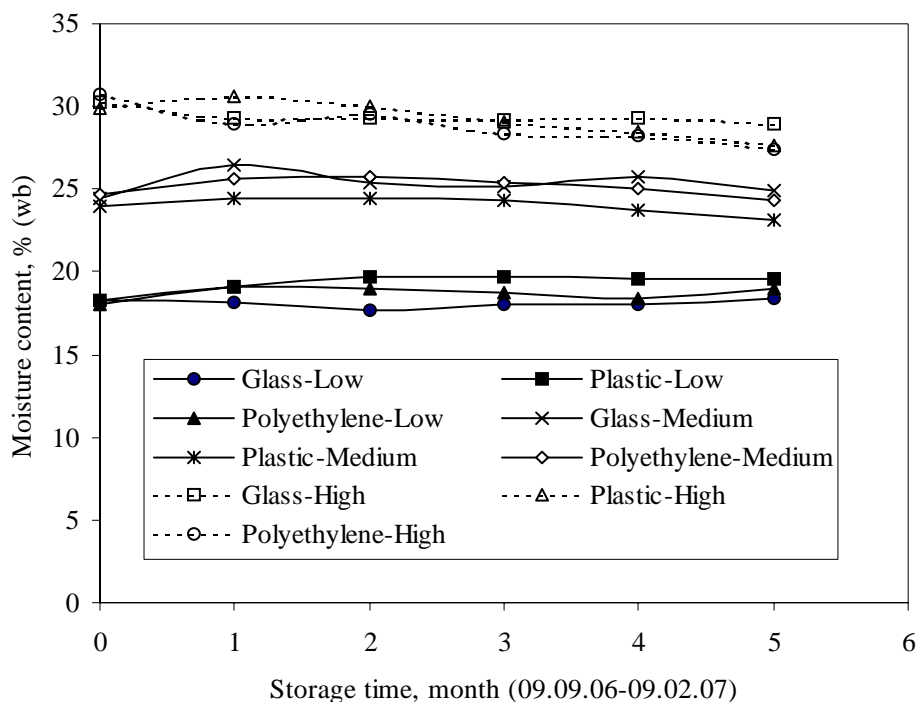


Figure 5.24: Variations of product moisture contents in the room environment with storage containers during storage of dried tomato (Low=18%, Medium=24% and High=30% product initial storage moisture content % in wet basic)

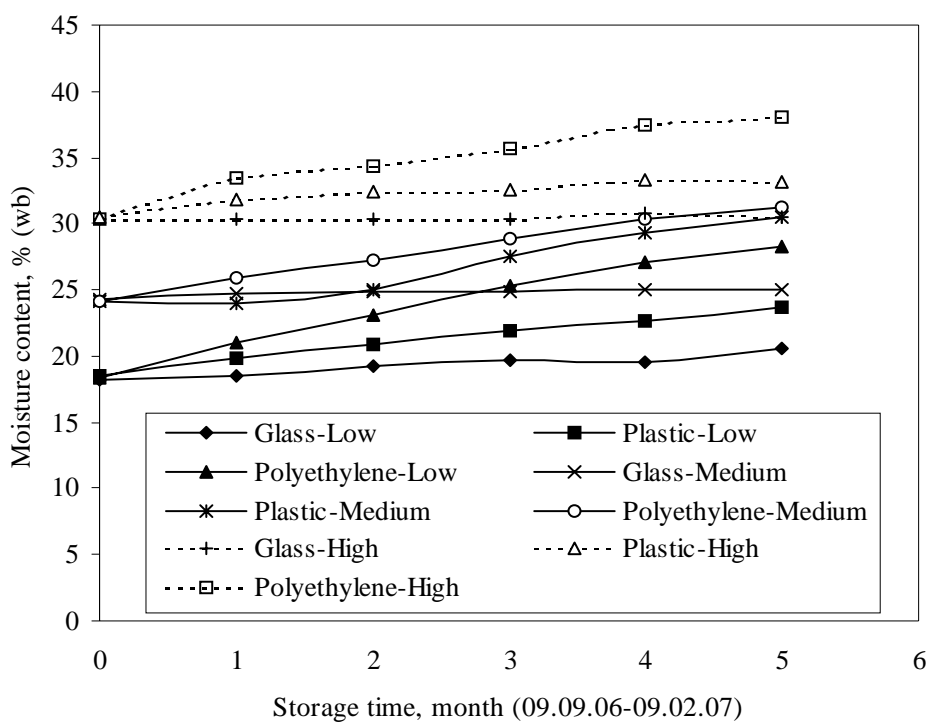


Figure 5.25: Variations of product moisture contents in the cool chamber environment with storage containers during storage of dried tomato (Low=18%, Medium=24% and High=30% product initial storage moisture content % in wet basic)

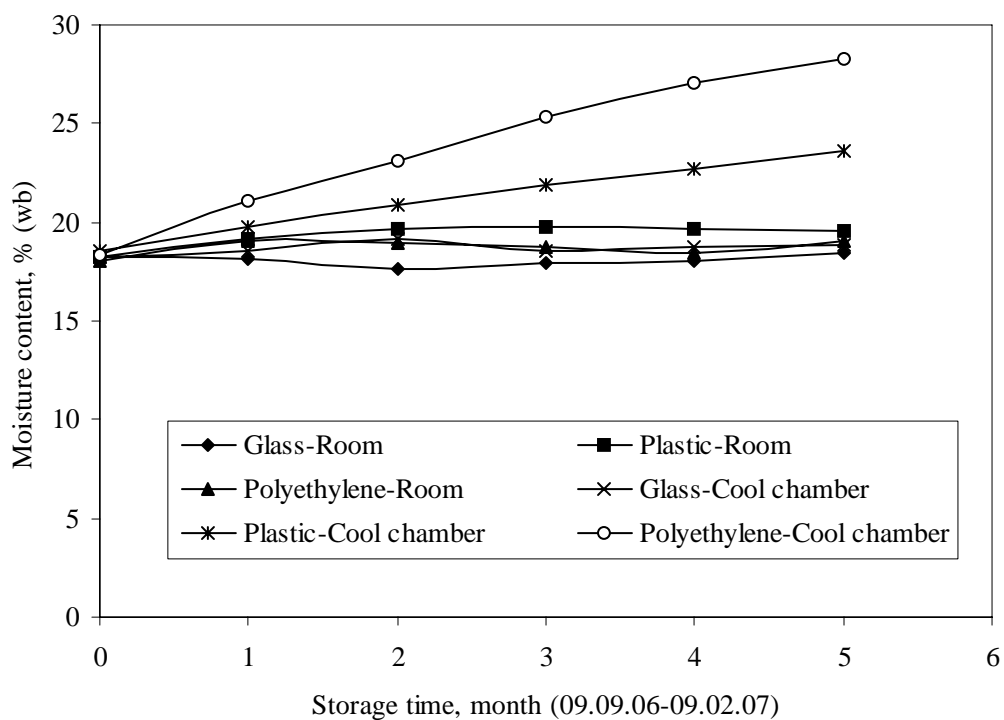


Figure 5.26: Comparisons of moisture content variations at low moisture level (18%, wb) in room and cool chamber environments

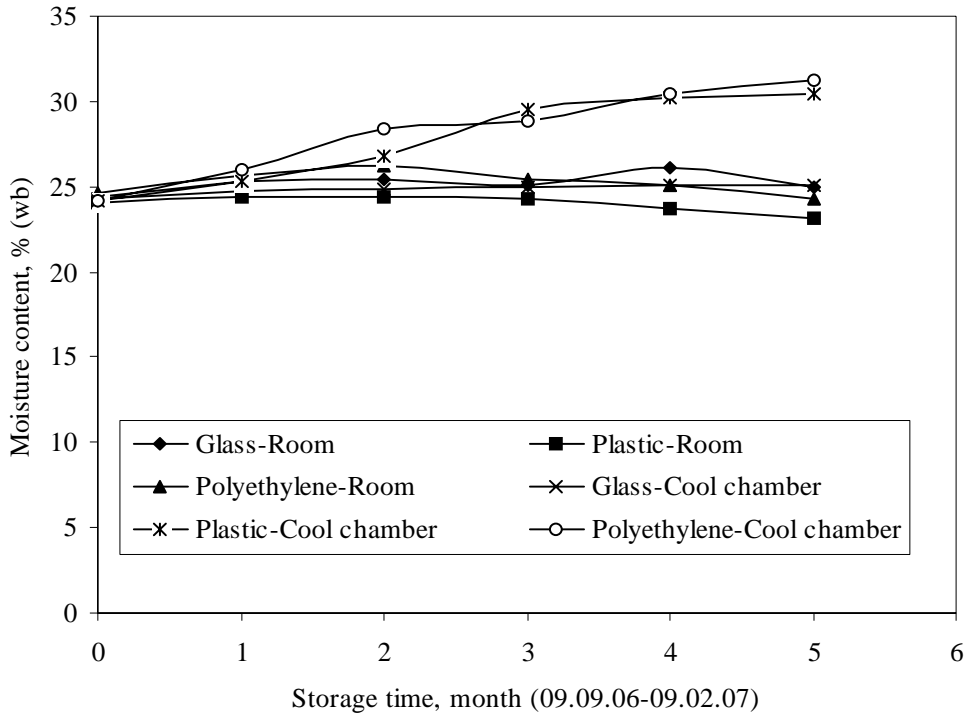


Figure 5.27: Comparisons of moisture content variations at medium moisture level (24%, wb) in room and cool chamber environments

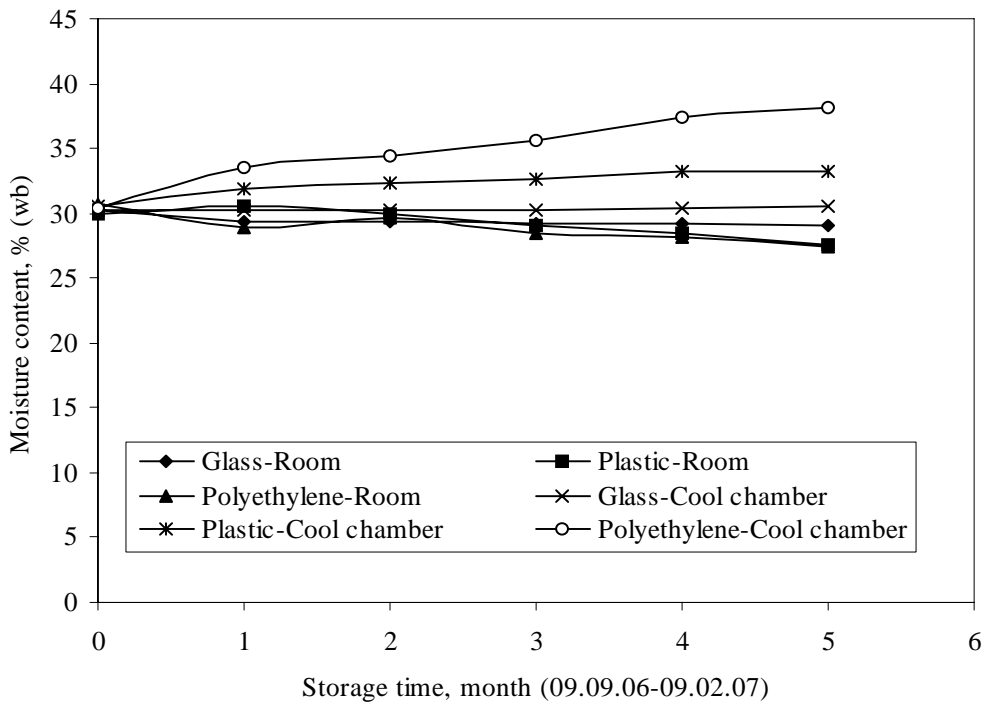


Figure 5.28: Comparisons of moisture content variations at high moisture level (18%, wb) in room and cool chamber environments

CONCLUSIONS

Significantly higher losses of colour, ascorbic acid, lycopene and total flavonoids were found for room environment than those of cool chamber environment. Significantly highest colour, ascorbic acid, lycopene and total flavonoids changes were observed for sodium chloride treated samples followed by control (non-treated), UV radiation and acetic acid pretreated samples. Colour, ascorbic acid, lycopene and total flavonoids changes of all samples were found significant between two subsequent months. Significantly lowest colour, ascorbic acid, lycopene and total flavonoids changes were found for sodium metabisulphite samples followed by ascorbic acid and citric acid treated samples. No significance effects of storage containers were observed during storage of dried tomato either room or cool chamber environments regarding the colour and nutrients. Effect of moisture contents in the room environments was insignificant but in cool chamber environment a little increase of moisture content were observed for plastic container and polyethylene bag. Colour, ascorbic acid, lycopene and total flavonoids decreased linearly with the product initial storage moisture content and storage time. No visible micro-organisms (moulds and fungus) were detected in any of the samples during the storage period. It may be recommended to dry tomato halves with sodium metabisulphite pre-treatment (8 g/l) and store them in cool chamber in glass container for better colour and antioxidants retention and maintenance of product moisture content.

NOMENCLATURE

a_0^*	From green to red colour at the beginning of storage (zero time)
a_t^*	From green to red colour at t time of storage
b_0^*	From blue to yellow colour at the beginning of storage (zero time)
b_t^*	From blue to yellow colour at t time of storage
L_0^*	From white to black colour at the beginning of storage (zero time)
L_t^*	From white to black colour at t time of storage
t_m	Storage time (month)
MC	Moisture content (% , wb)
wb	Wet basis

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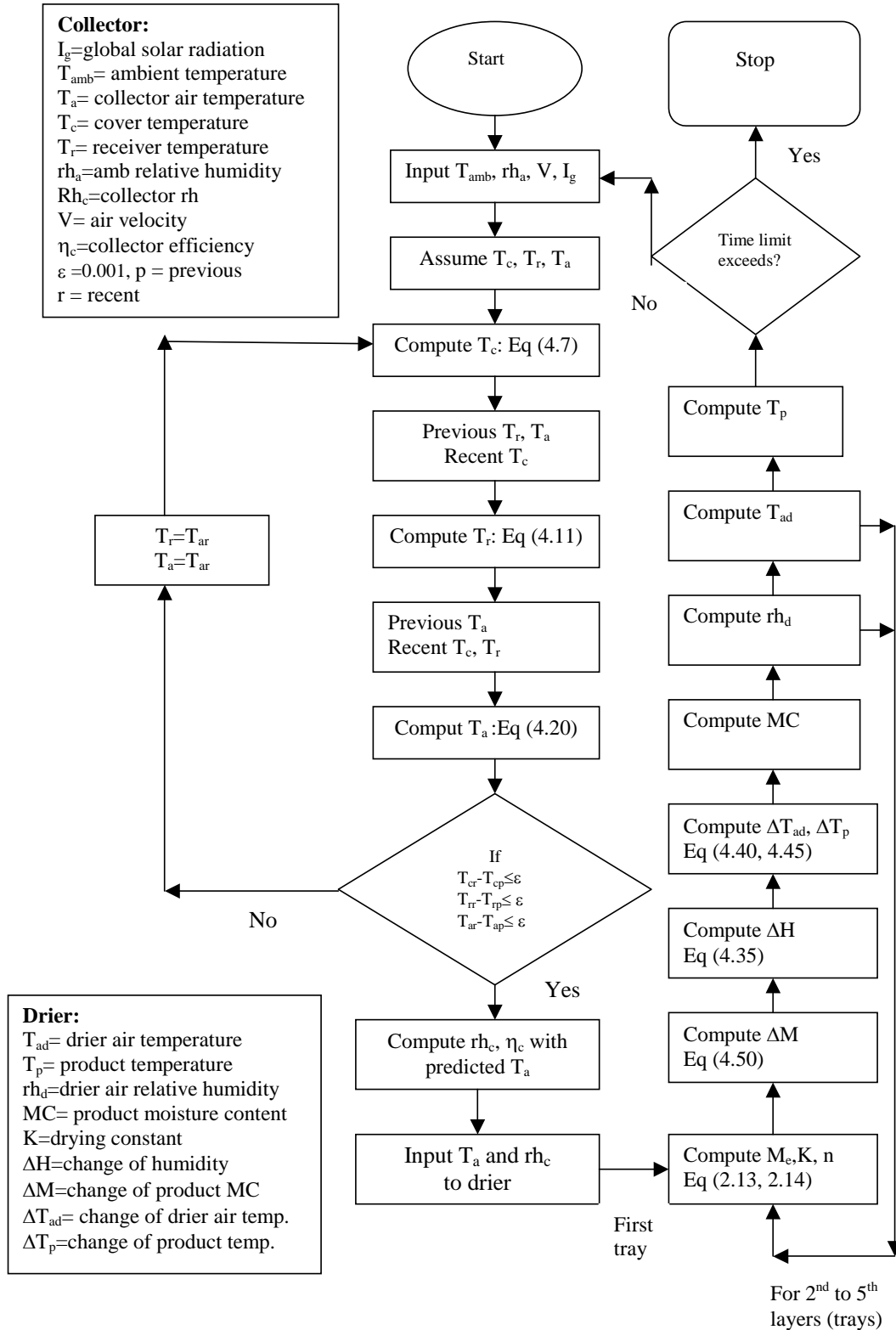
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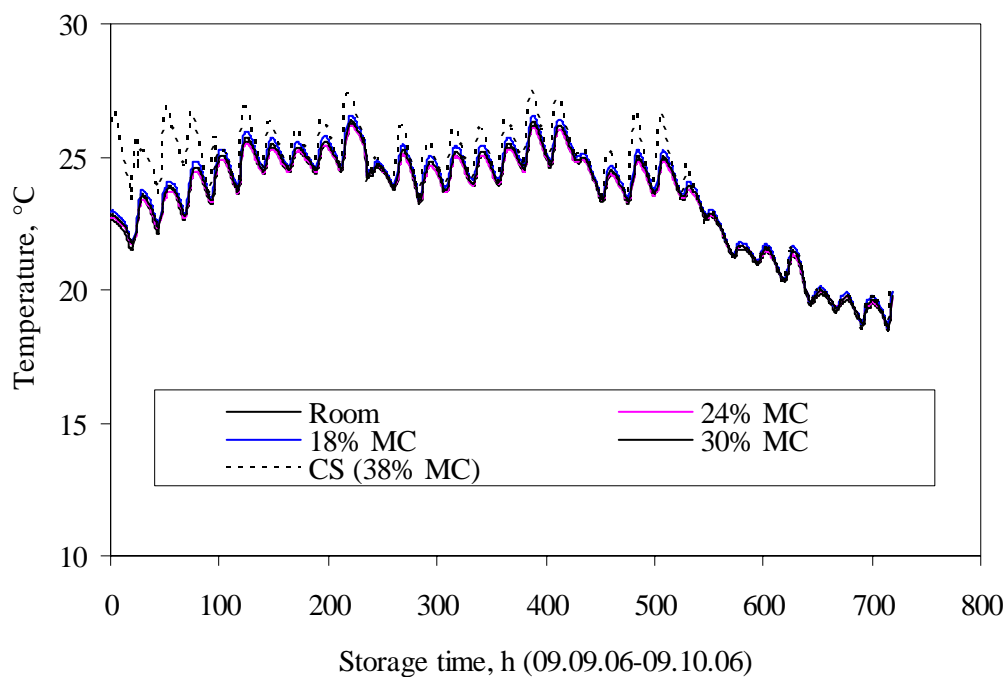
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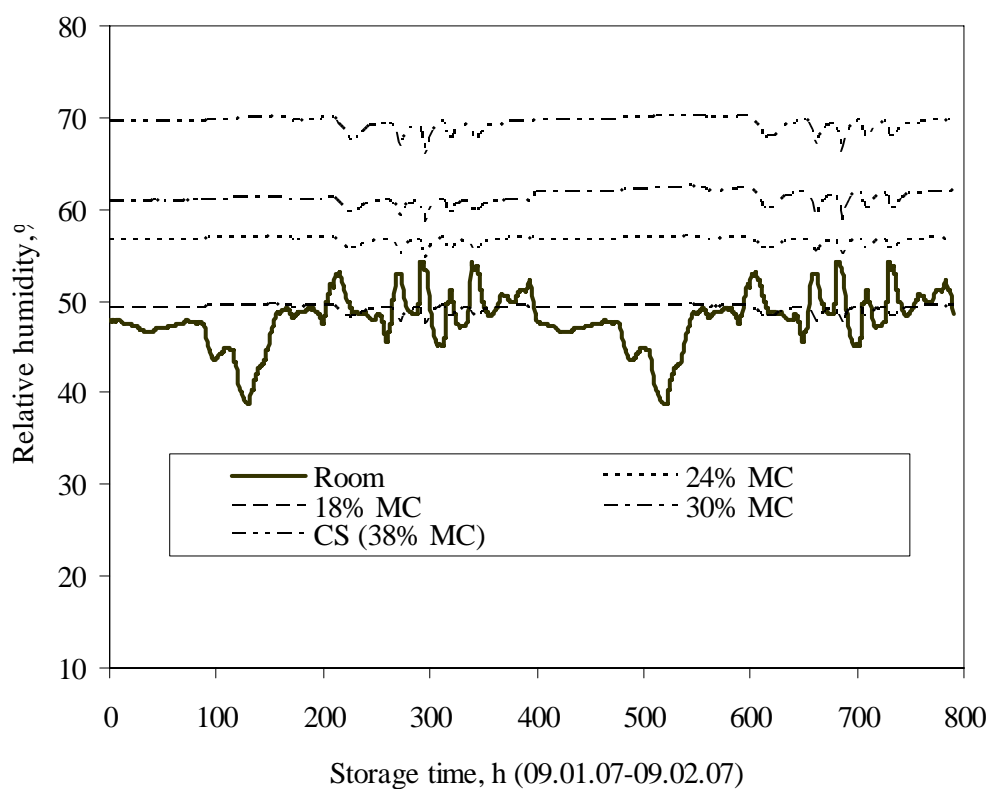
Appendix A: Flow chart of computer programme of mathematical model for solar drying of tomato



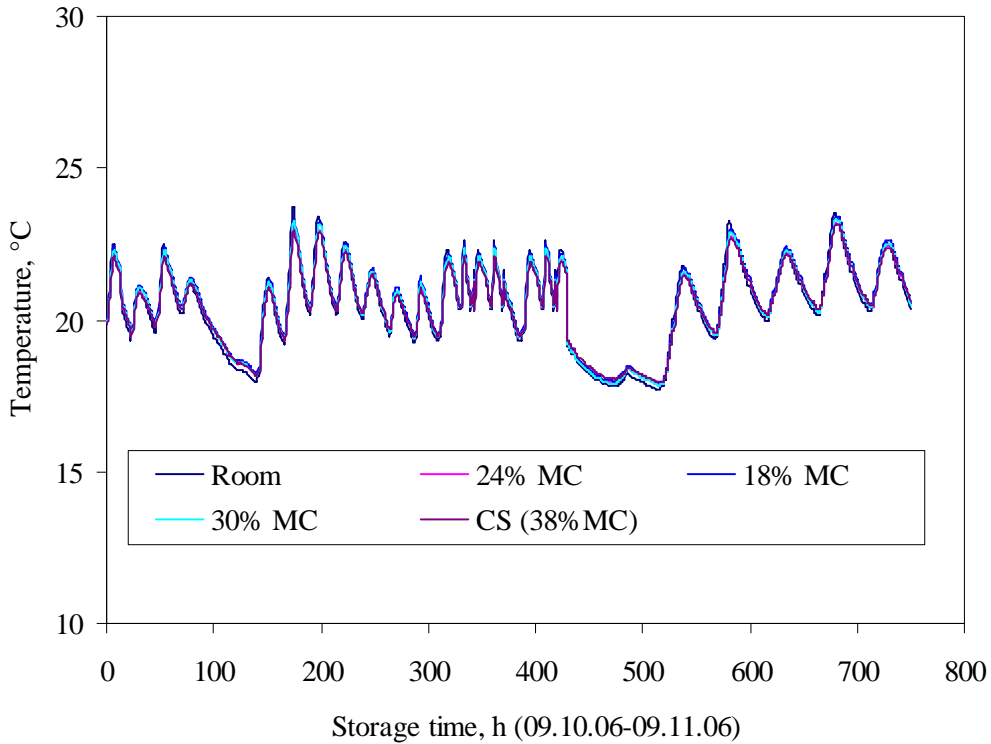
Appendix B: Variations of air temperatures in the room and in the glass containers with different product moisture contents of solar dried and commercial samples during the storage period of 09 September to 09 October 2006



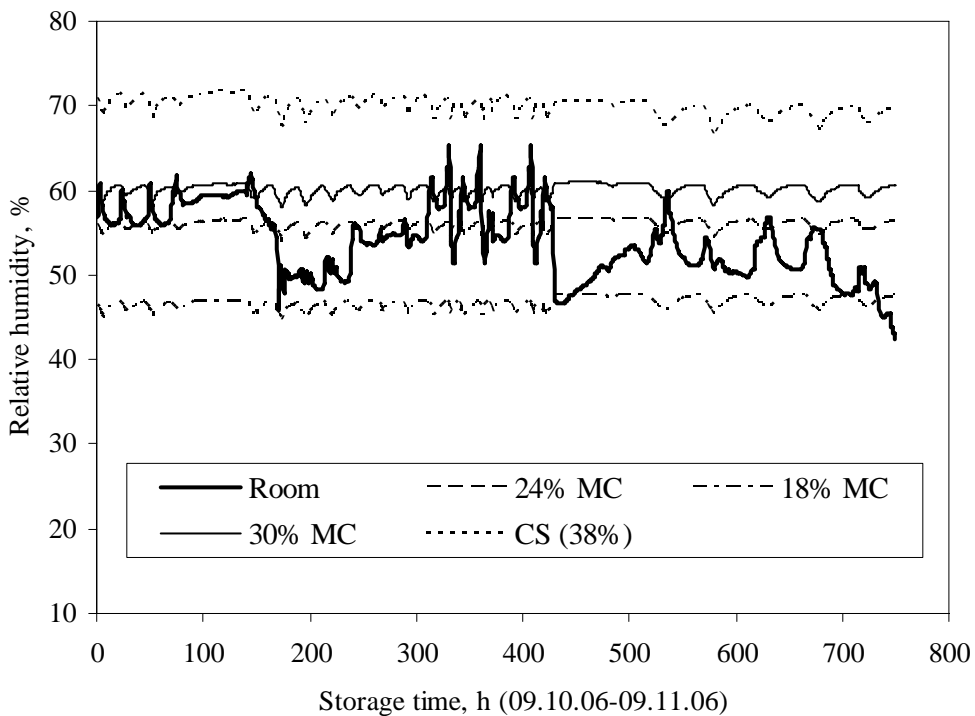
Appendix C: Variations of air relative humidity in the room and in the glass containers with different product moisture contents of solar dried and commercial samples during the storage period of 09 September to 09 October 2006



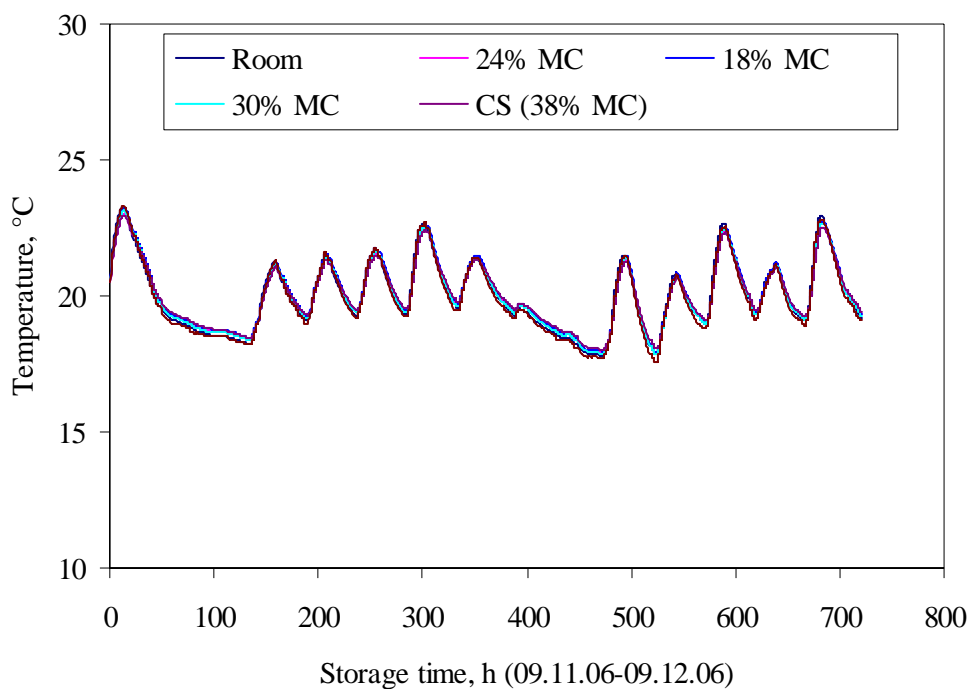
Appendix D: Variations of air temperatures in the room and in the glass containers with different product moisture contents of solar dried and commercial samples during the storage period of 09 October to 09 November 2006



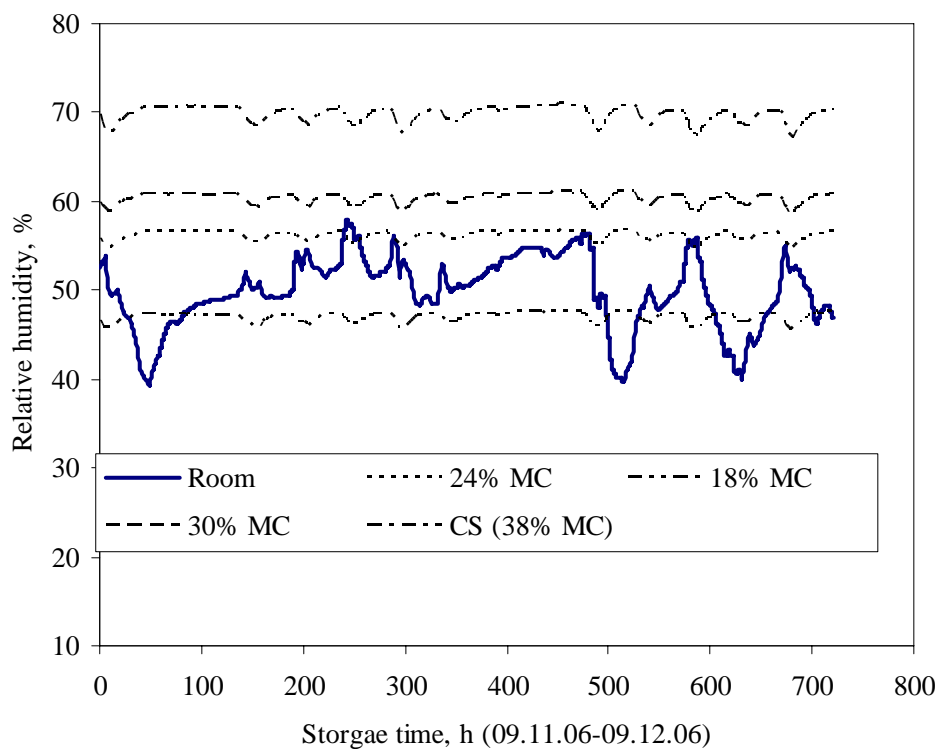
Appendix E: Variations of air relative humidity in the room and in the glass containers with different product moisture contents of solar dried and commercial samples during the storage period of 09 October to 09 November 2006



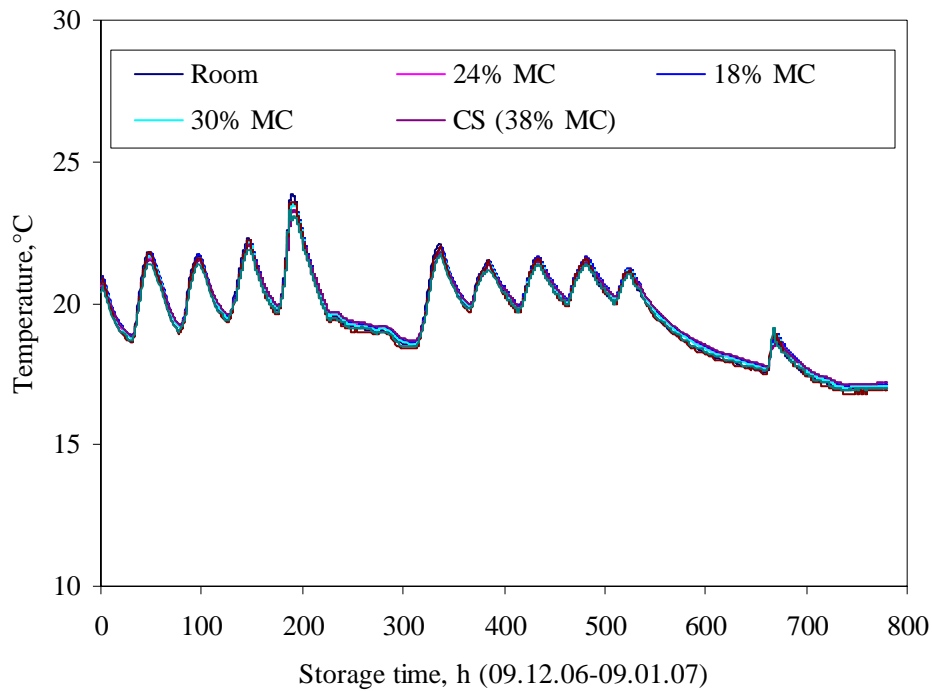
Appendix F: Variations of air temperatures in the room and in the glass containers with different product moisture contents of solar dried and commercial samples during the storage period of 09 November to 09 December 2006



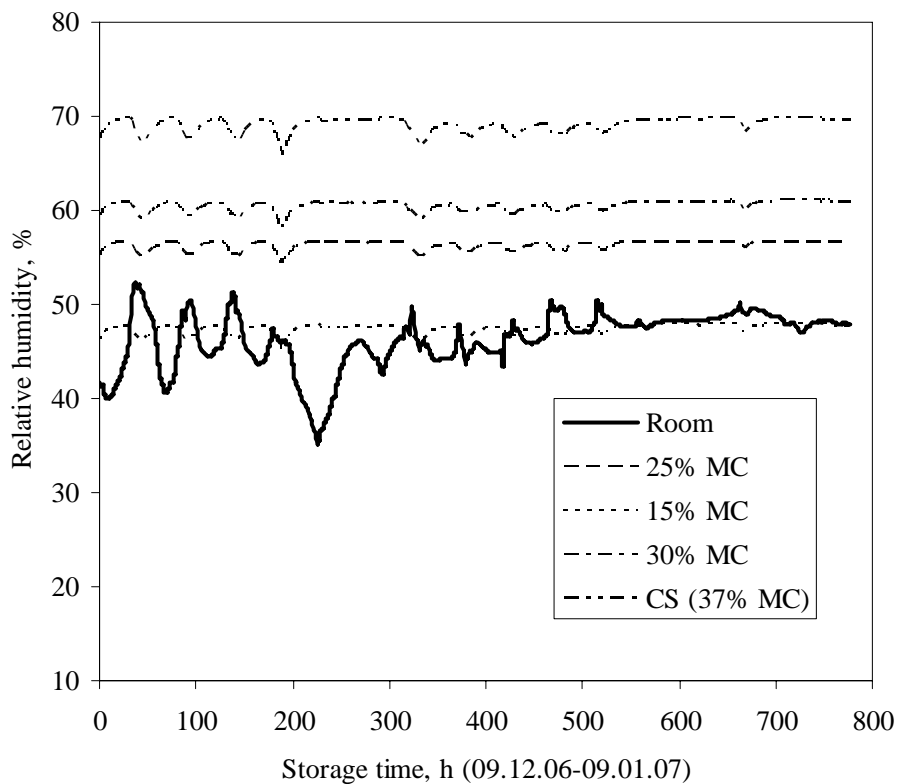
Appendix G: Variations of air relative humidity in the room and in the glass containers with different product moisture contents of solar dried and commercial samples during the storage period of 09 November to 09 December 2006



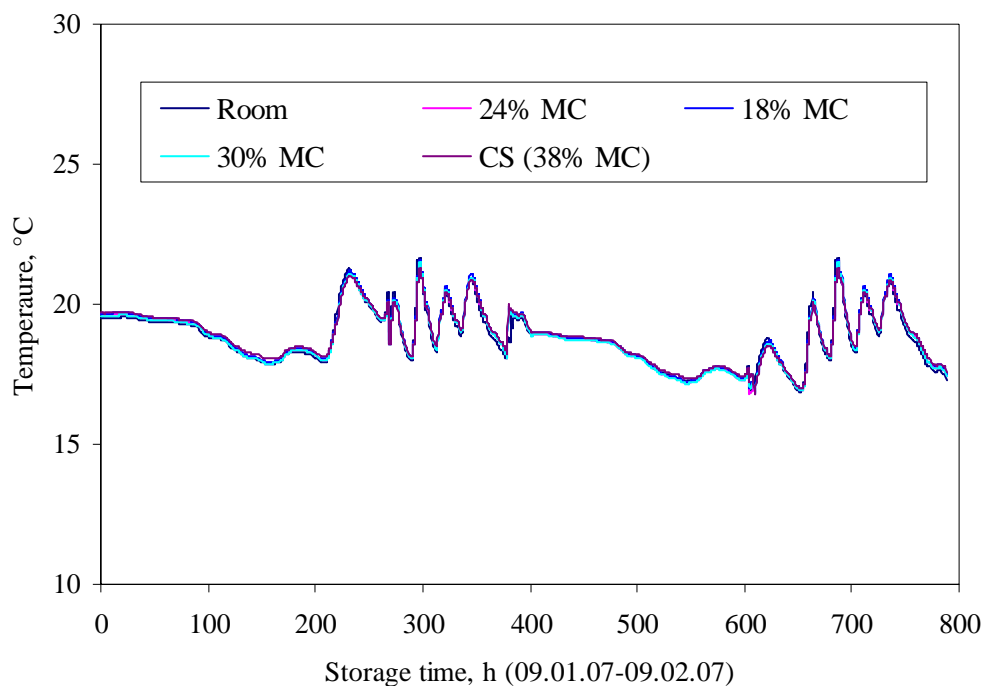
Appendix H: Variations of air temperatures in the room and in the glass containers with different product moisture contents of solar dried and commercial samples during the storage period of 09 December 2006 to 09 January 2007



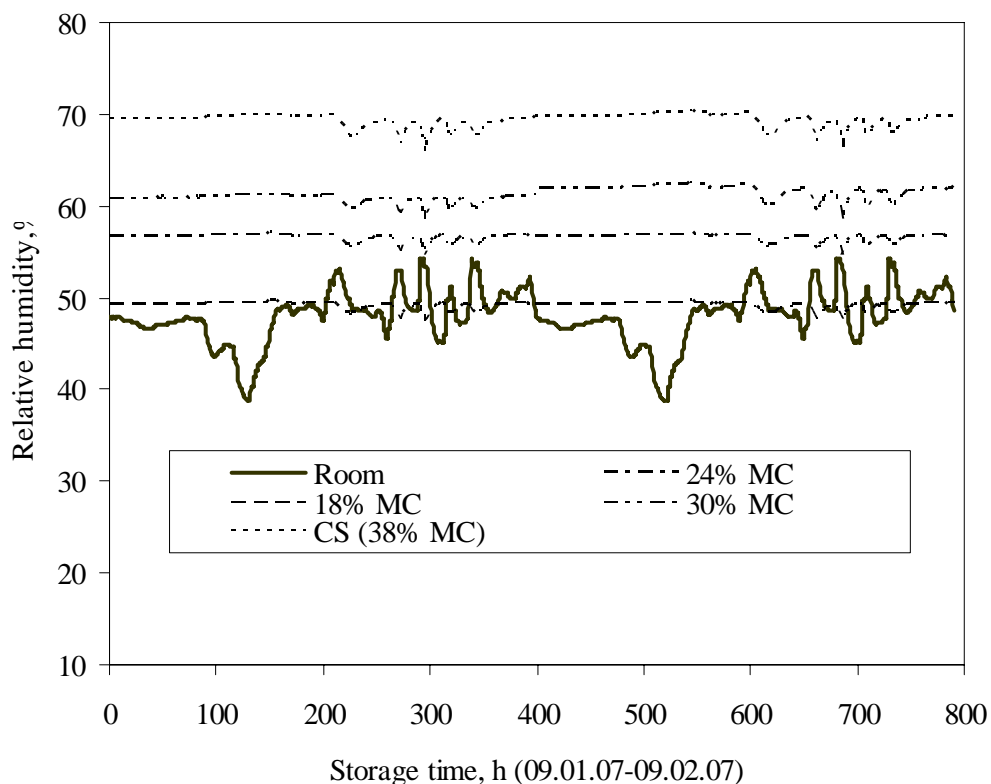
Appendix I: Variations of air relative humidity in the room and in the glass containers with different product moisture contents of solar dried and commercial samples during the storage period of 09 December 2006 to 09 January 2007



Appendix J: Variations of air temperatures in the room and in the glass containers with different product moisture contents of solar dried and commercial samples during the storage period of 09 January to 09 February 2007



Appendix K: Variations of air relative humidity in the room and in the glass containers with different product moisture contents of solar dried and commercial samples during the storage period of 09 January to 09 February 2007



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