CHAPTER 1

INTRODUCTION

1.1 GENERAL

The drying of fruits and vegetables is a subject of great importance. Dried fruits and vegetables have gained commercial importance and their growth on a commercial scale has become an important sector of the agro industry. Most of the fruits and vegetables contain more than 80% moisture and are therefore, highly perishable. Losses of fruits and vegetables in developing countries are estimated to be 30 to 40% of production and in India alone, the yearly losses are worth more than US$1.5 billion (Jayaraman et al 2000). It is necessary to remove the moisture content to a certain level after harvest to prevent the growth of mold and bacterial action. Prospect of solar drying applications in the tropical countries are enormous and it offers the advantages of faster drying than direct sun drying, greater retention of vitamins especially vitamins A and C, and minimizing the damage due to the rains.

Non-conventional sources of energy are capable of solving the twin problems of energy supply in a decentralized fashion and simultaneously help in achieving environmental sustainability. Patterns of total energy consumption in India show that there has been a steady growth in energy demand of about 6%, and there has been a gradual shift to commercial sources of energy though 45% of the primary energy contribution by the biomass (Bansal 1999).
Many of the third world countries produce large quantities of fruits and vegetables for local consumption and export. According to the Food and Agricultural Organization (FAO 1991), the estimates for the year 1990 were approximately 341.9 Million Metric Tons. In Asia, India produces 27.8 Million Metric Tons (8.1%) of the total world production, while China has a production capacity of 21.5 Million Metric Tons (6.3%). Many of these fruits and vegetables contain a large quantity of initial moisture content and are therefore, highly susceptible to rapid degradation of quality (Boxall and Gough 1993), even to the extent of spoilage, if not kept in thermally controlled storage facilities. Therefore, it is imperative that, besides employing reliable storage systems, post harvest methods such as drying be implemented hand in hand to convert these perishable products into more stabilized products that can be kept under minimal controlled environment for an extended period of time (Oguta et al. 1990). The basic essence of drying is to reduce the moisture content of the product to a level that prevents deterioration within a certain period of time, normally regarded as the “safe storage period”. Drying is a dual process of heat transfer to the product from the heating source and mass transfer of moisture from the interior of the product to its surface and from the surface to the surrounding air.

Drying involves the extraction of moisture from the product by heating and passing air mass around it to carry away the released vapor. Under ambient conditions, these processes continue until the vapor pressure of the moisture held in the product equals that present in the atmosphere. Thus, the rates of moisture desorption from the product to the environment and absorption from the environment is in equilibrium and the crop moisture content at this condition is known as the equilibrium moisture content.
In most industrialized countries, between 7 and 15% of the nations industrial energy is used in drying process (Dincer and Dost 1996). In India, some typical industries use energy in large quantities for drying tea, textiles, ceramics, milk powder, edible starch, baking powder, sugar, paper, raisins and pharmaceuticals. There are various drying technologies that are practically under use (Chua and Chou 2003) which includes fluidized bed, spouted bed, and infra-red radiation, solar, simple convective and desiccant drying. With the dwindling supply of fuel or energy resources, it is imperative that the world switches over to new and non-conventional alternatives to prevent from the energy crisis. Considerable efforts have been devoted to the use of renewable energy resources particularly in areas where low temperature applications are involved.

In recent years, some fruit drying methods have changed from sun drying to artificial hot air dehydration. Conventional, fuel-operated artificial dryers are more efficient, providing uniform high quality products, but in spite of all these favorable points, such units are beyond the reach of the farmers with limited crop volume and high requirements of financial resources with respect to the cost of equipment. Moreover, the increasing rate of fuel consumption in agriculture has made it necessary not only to save energy by intensifying the drying processes and improving their designs, but also by using renewable energy sources for drying processes. Solar energy shows promise of becoming a dependable energy source without new requirements of a highly technical and specialized nature for widespread utilization.

1.2 SOLAR DRYING

In solar drying, solar energy is used either as the sole source of the required heat or as the supplemental source. The airflow can be generated by either natural or forced convection. The heating procedure can involve the
passage of preheated air through the product by convective mode or by directly exposing the product to solar radiation or a combination of both. The major requirement is the transfer of heat to the moist product by convection and conduction from the surrounding air mass at temperatures above that of the product or by radiation. Absorption of heat by the product supplies the energy necessary for the vaporization of water from the product. Moisture starts to vaporize from the surface of the moist product when the absorbed energy has increased its temperature so that vapor pressure of the product exceeds the vapor pressure of the surrounding air. Moisture replenishment to the surface is by diffusion from the interior, and this process depends on the nature of the product, size and moisture content. Solar drying of agricultural products can be done when the product is abundantly available. The solar dried agricultural product provides the opportunity to sell in off-season period. Even during the season, the solar dried agricultural products will fetch higher price when compared to the traditional direct or open sun dried products.

There are numerous variations in the solar drying technology, each having its characteristic advantages and disadvantages with every drier being developed and tested for different applications. The feasibility of the dryer depends largely upon the crop to be dried as well as the climatic conditions. Climatic conditions have a great influence on the extent of crop losses and deterioration during sun drying. The most widely used method for drying crops all over the world, especially in developing countries, is open sun drying. However, considerable losses occur in open sun drying due to various reasons namely rodents, birds, insects, rains, storms and microorganisms. Thus, the quality of the dried product is lowered significantly. Long drying duration limits the use of open-air natural sun drying in large-scale production. Other factors such as the lack of ability to control the drying process properly, weather uncertainties, high labor costs, large area
requirements, mixing with dust, foreign materials etc., also limit the scope of open sun drying (Midilli 2001).

Solar drying offers the advantages of faster drying than regular sun drying, greater retention of vitamins especially vitamin A and C, and minimizing the damage from incessant rains. A systematic classification of solar dryers based on the design of system components and the mode of utilization of solar energy is shown in Figure 1.1 Green house driers have been the first series of solar drying innovations. They use regular structures where the product is placed in the trays receiving the solar radiation through the plastic cover, while the moisture is removed by natural or forced airflow (Condori and Saravia 1998).

Figure 1.1 Classification of Solar Dryers and drying modes
The earlier years of solar drying belonged to passive dryers. A passive dryer is one in which the food is directly exposed to sunrays and is best suited for drying small batches of fruits and vegetables such as banana, pine apple, mango, potato, carrots, green peas and French beans (Jayaraman 2000). To dry various agricultural products at farm level, natural circulation solar dryers are preferred because of non-availability or erratic power supply in villages. Natural convection-type dryers consist of a sloping collector, which is coupled to a drying chamber containing the trays to hold the crop. The ascending forces provide air circulation. However, forcing the air even through a thin layer results in relatively high air resistance, which cannot be overcome by natural convection. Therefore, chimneys or wind-powered ventilators have been installed to increase the airflow (Lutz et al. 1987). Natural convection-type solar dryer’s offer means for protecting the crop during the drying process. Also its drying time can be reduced when compared to natural sun drying. Some problems which prevented the dissemination is relatively small holding capacity of the dryer which causes productivity patterns and a high risk of air circulation to break down, causing spoilage of crop. Investigation showed that the required controlled removal of moist air only could be reached with forced ventilation using a fan or a blower.

For large scale drying applications, a number of direct and indirect, natural circulation solar dryers have been developed. Greenhouse solar dryer using fan for air flow (Zongnan et al. 1987), solar tunnel dryer with chimney for natural air flow (Norton et al. 1986), solar tunnel dryer with integrated collector for air heating and fan for air flow (Lutz and Muhlbauer 1987), solar tent dryer and solar dome dryer (Eechukwu and Norton 1997) have been reported in the literature. Most of these dryers have the drawback of absorbing solar radiation on horizontal surface, and at higher latitudes,
solar radiation input on horizontal surface is very low during winter. Besides, glazing area of these dryers is much more than the aperture area resulting in excessive heat losses. Hence, the temperature of the drying air remains low, resulting in higher equilibrium moisture content of the dried product.

Moreover, all these solar dryers are of direct-type and the product to be dried is exposed to solar radiation, resulting in discoloration and vitamin losses. To overcome these problems, a number of improved designs of direct, integral, natural circulation solar dryers have been developed. A dryer called multi-rack solar dryer (Sandhu et al 1979) which receives solar radiation on inclined surface, the product to be dried, is kept in a number of shallow perforated trays arranged one above the other, with space in between. The product is exposed to sunshine. The drying air is heated between the trays to reduce its relative humidity, thus increasing its drying capability. This results in uniform drying in all the trays. Loading of trays in the dryer is from the sides. Another similar design called staircase solar dryer has been reported (Hallak et al 1996). It has an openable glass cover at the top for loading. It also has a chimney for increasing the airflow. The disadvantages of these designs are that these are smaller in size and expensive.

Solar dryers having separate natural circulation air heater and drying chamber called indirect solar dryers have been reported (Khattab 1996). In these dryers, the product is placed in different trays and dried to different moisture content. Where, the product is not exposed to solar radiation. Mixed mode type with absorption on inclined surface using multi-rack reported by Majumdar (1986). In this dryer, air is heated in the natural circulation air heater and then allowed to pass over the product loaded in the trays. But it has the disadvantage since part of the product is exposed to solar radiation.
The absence of control over the drying air temperature was acutely felt in the passive dryer and later, research tended to have a proclivity towards the use of forced air circulation. Drying temperature and air velocity are the important parameters affecting the drying process. No doubt different mechanisms can be employed for using solar energy for reduction of the drying periods, but the multi-layer dryer with an air heating collector and a fan seems to be the most appropriate one, especially while handling a large quantity of products. Heating the drying air in the collector and with the dryer using solar energy increases the drying potential of the air as well as the drying rate. Several designs of forced convection solar dryers utilizing flat plate collector with auxiliary heating system have been proposed for drying applications (Tiris 1996, Midilli 2001 and Lachsasi et al 2004). A solar drying system coupled to biomass back-up heater (Jaishree and Vijay 2005) and LPG (Soponronnarit et al 1997) as supplementary heat sources has also been reported.

The solar drying however can be carried out only during the hours of daylight and to extend the periods of drying during off-sunshine hours, thermal storage systems are normally employed. Thermal energy storage using rock beds (Garg et al 1985, Chauhan et al 1996) and phase change materials (Enibe 2002) are successfully demonstrated. The recent trend for continuous solar drying during off-sunshine hours is to incorporate desiccants in the drying process.

1.3 **DESICCANT DRYING**

A desiccant displaying an affinity to hold moisture is generally classified as absorbents or adsorbents. Absorbents are altered physically or chemically during water sorption and are either a solid or a liquid. Adsorbents retain water vapor and other gases proportional to their surface area, while the remaining in the solid form. The inclusion of adsorbent desiccants continues
the drying process in the night and reduces the overall drying time. The desiccant drying involves forcing the air through a packed bed of solar regenerated desiccant to absorb moisture from the wet crop (Thoruwa et al 1996). Studies on flowers and herbs drying using silica gel, borax, corn meal or alum desiccants showed better product quality in terms of color, texture and durability characteristics (Chua and Chou 2003).

Commercial desiccants such as regenerative silica gel and molecular sieves have been applied to various grain drying systems with limited degrees of success. The main problems have been associated with high temperatures required for complete regeneration, typically 150°C and the high cost of desiccant. The molecular sieve method has been the least useful due to its low hygroscopic capacity, with activated alumina exhibiting less than 50% of the moisture sorption capacity of silica gel. Although silica gel is renowned for its high moisture sorption capacity up to 40% dwb, its dust particles have been shown to be carcinogenic to both humans and animals, making it unsuitable for direct food-processing applications (Collier 1989). However, solid clay, CaCl$_2$-based desiccants consisting of 60% bentonite, 10% calcium chloride, 20% vermiculite and 10% cement have given the maximum moisture sorption of 45% on dry weight basis with a regeneration temperature of less than 100°C (Thoruwa et al 2000). The major advantage of solid clay, CaCl$_2$ desiccant over commercial silica gel is its flexibility to be molded into different shapes (cylindrical, honey-comb structure etc.,) and sizes. Solid desiccant dehydration is an adsorption process, where forces on the desiccant agent bond the water molecules. These desiccants can easily be replaced inexpensively in the event of degradation of moisture sorption performance.
1.4 PERFORMANCE EVALUATION OF SOLAR DRYER

In the performance evaluation of solar dryers, the parameters generally measured and reported (Leon et al 2002) are:

1. Physical features of the dryer (type, size, shape, drying capacity/loading density, tray area and number of trays),

2. Thermal performance (drying time, drying rate, drying air temperature, relative humidity, airflow rate, dryer thermal efficiency),

3. Quality of dried product (sensory quality such as color, flavor, taste, texture, aroma, nutritional attributes, rehydration capacity), and

4. Cost of dryer and payback period.

The duration of the drying process is estimated from the time when the dryer is loaded with fresh product until the product dries to the required moisture level, and measured in hours or days. The time period when solar radiation is not available is also usually included in the drying time. Graphical representation of the product moisture content and the drying time indicates the drying rate. Garg and Prakash (1997) summarized the initial and final moisture content, and the maximum allowable drying temperatures for a variety of agricultural products. Li et al (2005) dried salted greengages using a forced convection solar dryer and have found that the drying time can be reduced from 48 days in natural sun drying to about 15 days. The average daily thermal efficiency of the system has been found to be 5.4%. Mohamed et al (2005) dried Citrus aurantium leaves on a forced convection solar dryer with an auxiliary heating system and concluded that the main factor influencing the drying kinetics has been the drying air temperature.
The highest airflow rate of 0.0556 m$^3$/s at 60°C, has the highest drying rate of 2.4 kg moisture/kg dry matter.min, and the moisture removal beyond this particular airflow rate is insignificant.

Airflow is another important parameter that influences the drying process. As the airflow rate increases, the conduction and radiation losses may be small due to smaller temperature rise. Drying efficiency may suffer at high airflow rates, since air may not have adequate contact time with the food product to increase its moisture content. Optimum airflow rate for solar dryers is 0.75 m$^3$/m$^2$.min of tray area (Leon et al 2002). Insufficient airflow can result in slow moisture removal as well as high dryer temperatures. However, the internal resistance to moisture movement in agricultural products is much greater when compared to the surface mass transfer resistance because airflow rate beyond certain levels has no significant effect on the drying rate (Handerson and Perry 1974).

Efficiency of the drying system includes dryer thermal efficiency, heat collection efficiency or collector efficiency, pickup efficiency and specific moisture extraction rate. Drying efficiency is commonly used to represent dryer performance. Specific Moisture Extraction Rate (SMER) is another performance index, which is used to describe the effectiveness of drying (Pengpad and Rakwichian 1998). Mumba (1996) dried 90 kg of maize with initial moisture content of 33.3% to 20% on dry basis in 7 h using photovoltaic-powered solar dryer. Its mean dryer thermal efficiency and pickup efficiency calculated is 58 and 77%, respectively. Tiris et al (1995) estimated the thermal efficiency of a collector and the pickup efficiency of a forced convection solar dryer, which varied from 18 to 78% and 28 to 90%, respectively at 0.042 kg/m$^2$.s. SMER is, in effect, the inverse of specific energy consumption, and it is the ratio of the total moisture removed to the total energy input.
Thoruwa et al (1996) dried maize using solid bentonite-CaCl₂ desiccant. 90 kg of wet maize is dried from 38% on dry weight basis to safe moisture level of 15% within 24 hours. In the total drying load, the solar heated air supported 75% and the desiccant supports the remaining 25%. However, solar drying of fruits and vegetables integrating solid bentonite-CaCl₂ desiccant has not been done to a large extent and the present study is aimed to dry fruits and vegetables by fabricating a system that operates under different modes of drying. In spite of the various efforts, the use of solar energy for crop drying as well as similar applications has not been taken to its shape as expected because of several factors like lack of awareness, non-availability of demonstrating unit, economic problems, etc., In view of the above facts, it is therefore necessary that, to minimize increasing demand for energy requirements for crop drying, simple, cheap but efficient solar driers supplied with fan ventilation and integrated supplementary heat sources should be developed. An attempt has been made to fabricate a drying system integrated with CaCl₂-based solid desiccant utilizing solar energy for the drying of fruits and vegetables with readily available indigenous materials. The concept of the design is to heat ambient air using flat plate collector and then, to let this air pass through a drying chamber. The desiccant material present in the drying chamber provides energy for drying during the off-sunshine hours. For performance evaluation of the solar drying system, out-door experiments have been performed.

1.5 MATHEMATICAL MODELING OF SOLAR DRYING CURVES

The use of a simulation model is a valuable tool for the prediction of the performance of solar drying systems and to study the drying characteristics of the particular material being dried (Steinfeld and Segal, 1986). Several thin layer models are available in the literature and they vary

Yaldiz et al (2001) dried sultana grapes in an indirect forced convection solar dryer and studied the effects of drying air temperature and velocity on the model coefficients and constants. Sacilik et al (2005) investigated the thin layer drying characteristics of tomatoes in a solar tunnel dryer and studied the effect of model coefficients and constants with the drying air temperature and relative humidity.

Togrul and Pehlivan (2002) dried apricots in a forced convection solar dryer so that model coefficients and constants were regressed with temperature, velocity and relative humidity of the drying air.

In this study, the thin layer mathematical models for the drying of green peas and pineapple slices are undertaken for studying the drying characteristics in a forced convection solar drying and forced convection solar dryer integrated with desiccant material, and to fit the experimental data to the considered mathematical models.