CHAPTER – II

REVIEW OF LITERATURE

In contrast, numerous investigations have shown that solar drying can be an effective method of drying since the product is completely protected during drying against rain, dust, insects and animals. These systems help in conserving nature and quality of products for long durations. A lot of research work has been carried out throughout the world to investigate and analyze the thermal performance of solar dryers.

This chapter deals with a review of research work carried out in utilizing solar energy for drying operation, design aspects of solar dryers, solar tunnel dryer for agriculture and industrial applications, techno-economics of solar tunnel dryers and modeling & simulation study of solar tunnel dryers.

A brief review of literature is presented here under the following headings.

1. Solar Drying
2. Forced Convection type Solar Dryers
3. Techno - Economics Analysis of Dryer
4. Solar Tunnel Dryer
5. Solar Tunnel Dryer for Industrial Products
6. Forced Convection Type Solar Tunnel Dryer

2.1 Solar Drying

Tiris et al. (1994) conducted a study on solar dryer which consists of a solar air heater and a drying chamber used for drying agricultural products. It was tested with sultana grapes, green beans, sweet peppers and chilli peppers and compared with traditional sun drying. The obtained drying curves indicated that use of the solar dryer reduced the drying time by a factor of 1.7, 2.2, 1.8 and 2.2 for grapes, beans and sweet and chilli peppers respectively. Mass losses were prevented and better product quality was achieved.

Chauhan et al. (1996) studied the drying characteristics of coriander in a stationary 0.5 ton/batch capacity, deep bed dryer coupled to a solar air heater and a rock bed storage unit
to receive hot air during sunshine and off-sunshine hours, respectively. The drying bed was assumed to consist of a number of thin layers of grain stacked upon each other. The theoretical investigation was made by writing the energy balance equations for different components of the dryer cum air heater cum storage and by adopting a finite difference approach for simulation. The results revealed that for reducing the moisture content from 28.26 to 11.4% (d.b.) the solar air heater takes 27 cumulative sunshine hours i.e. about 3 sunshine days, whereas the solar air heater and the rock bed storage combined take 31 cumulative hours i.e. about 2 days and 2 nights at an airflow velocity of 250 kg/h-m².

Ekechukwu and Norton (1997) reported the design and construction of a solar chimney for natural-circulation type solar dryers. The experimental solar chimney consists of a 5.3 m high and 1.64 m diameter cylindrical polyethylene-clad vertical chamber supported structurally by a steel framework and draped internally with a selectively absorbing surface. The performance of the chimney which was monitored extensively with and without the selective surface in place (to study the effectiveness of this design option) was also reported. The results obtained from the experimental solar chimney have illustrated that solar chimneys if designed properly can maintain air temperatures consistently above the ambient temperature which would chance the desired buoyancy-induced air flow though the chimney. The desired performance was achieved with the solar “greenhouse” chimney. Better performance was obtained with a solar radiation absorbing surface within the chimney.

Patil et al. (1997) developed a low cost polyethylene solar dryer for drying blanched soybean. A polyethylene based solar dryer costing about Rs.1000/- and having dimensions of drying surface of 2.5 × 1.25 m was fabricated. The frame was made of 10 mm diameter mild steel bar and bottom with rectangular base made from 25 mm × 25 mm × 3 mm angle iron. The black painted mild steel sheet was provided on the exhaust side to cover light energy to heat energy in addition to energy absorbed by the drying material. The structure was covered with flexible plastic of 200 gauges with the exhaust and inlet opening of 0.15 m × 2.5 m. The drying index was twice that of open sun drying and the cost of drying came to Rs.0.70 per kg compared to Rs.2 per kg in open sun drying.

Ambrose and Sreenarayanan (1998) studied dehydration of fresh and raw garlic under different drying methods viz., sun drying (27-33 °C), solar cabinet dryer (40-61 °C), thin layer drying at air temperatures of 40 °C, 50 °C, 60 °C and 65 °C, fluidized bed drying at air temperatures of 40 °C, 50 °C, 60 °C and 70 °C. Drying air temperatures and the drying method were optimized based on the organoleptic evaluation and browning index. Fluidized bed dried garlic sample at 60 °C with a browning index of 0.025 was adjudged to the best of
all other dried samples of garlic. All the organoleptic quality factors (flavour, colour, taste and texture) and acceptance to purchase were statically significant.

Ampratwum (1998) designed that a solar dryer for drying dates under controlled and protected conditions. A prototype of the dryer was constructed to be used in experimental drying tests. This paper described the design considerations followed and presents the results of calculations of design parameters. To dry a daily batch of 100 kg of dates from 49 to 21% wet basis in a drying time of 9.8 h under average ambient conditions of 32 °C air temperature and 65% relative humidity, with incident solar radiation 22.5 MJ/m²/day, a minimum of 16 m² solar collector area was required. The ambient conditions were for the month of July, August and September. The prototype dryer has a minimum collector area of 1.6 m².

Goyal and Bhargava (1999) compared three different types of dryer for potato chips drying. After giving various standardized pretreatments, potato slices were dried separately under open sun, in a solar tray dryer and in a mechanical tray dryer. The initial moisture content of potato (w.b.) was estimated as 78.9%. During drying, the total loss of moisture varied between 91.8 and 94.7%, resulting in 4.2 to 6.5% moisture content in dried potato chips. Results indicated that in relation to drying time and physiochemical quality of the product, the mechanical tray dryer stands first, followed by solar tray dryer and sun drying. But due to the frequent electricity failures and non-electrification of rural areas of our country, solar tray drying provides a suitable alternative for drying potato chips. Among the pretreatments, the use of common salt was observed to be the best.

Thanvi and Nahar (1999) developed a solar dryer for dehydrating fruits and vegetables either by exposing directly to solar radiation (direct mode) or in shade (indirect mode) as and when required. A solar dryer based on principle of natural circulation of air suitable for arid regions for dehydrating the produce in different modes was developed. A comparative study of performance of solar drying system, for drying tomatoes in direct and indirect mode at loading rate of 5 kg/m² was carried out. The study revealed that in indirect mode of drying, the moisture content of tomatoes was reduced from 95% to 3.8% within 1.8 days while in direct mode of drying, the drying time was reduced merely by 0.5 day. The efficiency of solar drying system in direct mode was 26.3%, while it was 21.5% in indirect mode. The colour of tomatoes dried in indirect mode was superior to that obtained with direct mode.

Supranto et al. (1999) designed an experimental solar assisted dryer for palm oil fronds. The size of the collector was 240 cm × 120 cm with upper and lower channels
adjustable for optimal operations. The size of dryer was 100 cm x 100 cm x 100 cm. The observed temperature rise was 25-30 °C with the collector thermal efficiency of 50-60%.

Rane et al. (2000) designed and developed a natural convection solar dryer for drying purposes. This dryer was designed to increase the moisture pick up per kg of air circulated. This achieved by heating the paddy bed with warm water. A plastic solar collector was used to heat the water. Water was heated up to the temperature of 45 °C and then passed though the grain bed. The chimney provided the draft to circulate the air required for moisture removal. This dryer provided an efficient and effective way of drying. Specific moisture evaporation rate for the proposed natural convection solar paddy dryer was estimated at 1.097 kg/kWh, which was 44% greater than the convectional non-solar batch in bin paddy dryer. A novel low temperature drying process was suggested which increased moisture pick up by air to 43%. A 50 kg/day paddy dryer having a 2 m² solar aperture, was expected to cost Rs.5000/-. 

Desai et al. (2001) studied a mini multi-rack solar dryer and its performance for drying sapota (*Manilkara zapota*) at the College of Agricultural Engineering, Raichur, Karnataka, India. The results indicated that the drying time for unpeeled full, half and quarter cut fruits was 60, 52 and 42 h, respectively for solar drying while the corresponding drying time for sun drying was 96, 76 and 64 h, respectively. These resulted in 37.5, 31.5 and 34.4% less in drying time, respectively for full, half and quarter cut fruits in solar drying over sun drying. For peeled sapota the drying time observed for full, half and quarter cut fruit was 48, 38 and 30 h, respectively for solar drying while the corresponding drying time for sun drying was 72, 60 and 46 h, respectively which resulted in 33.3, 36.7 and 34.8% less drying time, respectively over sun drying. The dehydration ratios calculated were 4:1 (unpeeled) and 4.2:1 (peeled) sapota. The total soluble solids was increased from 20° Brix in fresh fruits and 36° Brix in dried fruits.

Basunia and Abe (2001) described the design features of a three-shelf natural convection solar rough rice dryer of mixed mode type. A minimum of 17.4 m² solar collector area was required to dry a batch of 600 kg of rough rice in 17 h (two days drying period). The initial and final moisture contents considered were 25% and 15% wet basis, respectively. The average ambient conditions were 20 °C air temperature and 70% relative humidity with daily global solar radiation incident on a horizontal surface of 14 MJ/m². A prototype of the dryer was so designed and constructed that it had a minimum collector area of 1.74 m². This prototype of dryer was tested for different loading conditions of the thee shelves.

Thakur (2002) developed a collector type solar dryer for dehydrating fruits and vegetables. The dryer consists of solar collector, drying chamber, and sliding trays. A
convective air current passed through the passage between collector plate and glazing surface and then heated. The heated air flows across though the drying trays as a result of natural draught due to chimney effect. The dryer was tested for drying of fenugreek (*Trigonella foenum-graecum*) leaves and green pea. It was concluded that the overall performance of the dryer was quite satisfactory. It can be used for drying fruits and vegetables at farm level as well as at domestic level. It was inexpensive and easy to fabricate.

Pangavhane et al. (2002) developed a new natural convection solar dryer consisting of a solar air heater and a drying chamber. This system can be used for drying various agricultural products like fruits and vegetables. In this study, grapes were successfully dried in the developed solar dryer. The qualitative analysis showed that the traditional drying, i.e. shade drying and open sun drying, dried the grapes in 15 and 7 days respectively, while the solar dryer took only 4 days and produced better quality raisin.

Madhlopa et al. (2002) designed a solar air heater, comprising two absorber systems in a single-plate collector, on the principles of psychometry. The heater was integrated to a drying chamber for food dehydration. This collector design offered flexibility in manual adjustment of the thermal characteristics of the solar dryer. The performance of the dryer was evaluated by drying fresh samples of mango (*Mangifera indica*). Both fresh and dried mango samples were analyzed for moisture content (MC), pH and ascorbic acid. During dehydration period, meteorological measurements were made. The air heater converted 21.3% of incoming solar radiation to thermal power and raised the temperature of the drying air from about 31.7 °C to 40.1 °C around noon. The dryer reduced the moisture content of sliced fresh mangoes from about 85 to 13% on wet basis and retained 74% of ascorbic acid. It was found that the dryer was suitable for preservation of mangoes and other fresh foods.

Leon et al. (2002) reviewed of existing methods of evaluation and parameters used for the evaluation of solar dryer. Based on the review, a comprehensive procedure has been developed. Additional parameters have been included in the proposed procedure. The result of the observations could be reported using evaluation sheets, which together with the graphs representing the drying curves and cumulative drying energy consumption could provide a complete picture of the absolute and comparative performance of the dryers.

Prakash et al. (2004) studied the drying characteristics of carrots using a solar cabinet dryer, fluidized bed dryer and microwave oven dryer at temperatures 50, 60 and 70 °C (at power levels 2, 3 and 4). Drying occurred mainly in the falling rate period. In the case of fluidized bed drying and microwave oven drying after the initial falling rate period, temperature or power level number longer controlled the drying rate which was then
controlled by the moisture diffusion phenomenon. Carrots dried by fluidized bed drying showed better colour, rehydration properties, greater β-carotene retention and better overall sensory acceptability than those dried by microwave oven and solar cabinet dryer.

Chen et al. (2005) developed a closed-type solar dryer associated with a Photovoltaic system. The transparent drying cabinet was designed with high transmittance glass to decrease the reflection of direct sunlight and to offer extra direct solar heating on the raw material during drying. Parallel wiring with a local electrical grid was necessary for switching purposes, if there is insufficient battery backup during peak operation. Lemon slices were dried using the closed-type solar dryer and results were compared with hot air drying at 60 °C. The results indicated that the dried lemon slices using a closed-type solar dryer have better quality in terms of sensory parameters.

2.2 Forced Convection Type Solar Dryers

Soponromnarit et al. (1991) dried the bananas using a forced convection solar dryer. They found that the efficiency of the solar dryer was about 30% at average moisture content of 220% (d.b.) and dry mass of bananas 3.7 kg/m² solar receiving area. The moisture content of banana was 54% after drying (d.b) and drying time was found 7 days (6 h/day) for each batch.

Diamante and Munro (1993) used solar dryer for drying sweet potato slices with the loading intensity of 5 kg/m². The loaded tray was weighed every 15 minutes for the first two hours and then every 30 minutes until the end of the drying period. Potato slices of 3 mm and 6 mm thick were dried in a forced convection type solar dryer with loading density of 5 kg/m².

Pawar et al. (1995) designed and fabricated a large scale forced convection solar drying system comprising of an array of 40 solar collectors and thee drying cabinets with a blower to yield 300 kg of dry product of custard powder in a normal sunshine day in Pune. It was found that such a system is feasible and has an ability to save large amount of fuel. It was observed that forced convection solar drying systems were suitable in food and chemical industries where large scale drying is required.

Ong (1999) discussed about three types of solar dryers, natural convection cabinet type solar dryer, the forced convection indirect solar dryer, and the greenhouse type solar dryer, having the good potential for development in the Asia-Pacific Region. Also, he reported the traditional method of drying in the Asia Pacific Region was by open air drying where the product to be dried was exposed directly to the sun.
Philip (1999) designed a forced circulation type solar dryer for 100 kg of onion flakes and installed to demonstrate its technical feasibility in one of factory. The system consists of solar air heaters, blower, drying chamber and electrical back up. Experiments were conducted using the system to dry onion flakes and potatoes chips. The result indicated that onion flakes could be dried in the solar dryer in 6.5 to 7 h during the month of April-June. The cost of drying was estimated to be Rs. 5.00 per kg of dried onion flakes. The quality of the dried product was found to be acceptable.

Pande et al. (2000) performed studies on drying of methi (Fenugreek leaves) and coriander leaves in a forced circulation solar hot-air-dryer. Drying of methi was carried out at 40, 45, 50 and 60 °C, while coriander was dried at 40, 45 and 50 °C. Drying characteristic curves were drawn and drying equations were developed to understand the drying behaviour of these vegetables and to undertake appropriate solar dryer design. Organoleptic quality attributes like colour, appearance and taste of these dried samples were found acceptable to the respondents and solar-dried samples were appreciated for retaining fragrance and utility in off-seasons.

Yaldiz et al. (2001) conducted experiments on thin layer convective solar drying of Sultana grapes and examined the effect of drying air temperature and velocity on a thin layer drying of Sultana grapes. They found that these parameters were dominating the drying rate.

Rao (2003) designed and developed a forced circulation solar cabinet dryer by integration of solar thermal and solar photovoltaic technologies. This system eliminated the conventional energy for exhaust fan blowers. The system consists of cabinet, SPV fans and electrical back-up. The cabinet was made up of Al alloy with glass top tilled to 20° to horizontal and south oriented. The air inlet was provided at the bottom of the cabinet on three sides of the cabinet. Three fans were arranged in the cabinet to remove the moist air to the atmosphere. The dryer was made up of rainproof, dustproof material as well as insulated at the bottom of the cabinet from thermal losses. The solar dryer was tested for its uniformity of temperatures in the drying area in each row and bottom row with thermocouples. The temperature variation in the area was ± 5% and the variation in the top row and bottom row was 10% lower the temperature. The performance evaluation was carried out by collecting the drying data on 25 items of fruits and vegetables with necessary pretreatments.

Lahsasni et al. (2004) carried out experiments on thin layer convective solar drying of pear peel with an indirect convective dryer. They found that the prickly pear peel was sufficiently dried in the ranges of 32 to 36 °C of ambient air temperature, 50 to 60 °C of drying air temperature, 23 to 34% of relative humidity, 0.0277 to 0.0833 m³/s of drying air
flow rate and 200 to 950 W/m² of daily solar radiation. The experimental drying curves showed only a falling drying rate period. The main factor in controlling the drying rate was found to be the drying air temperature.

Mohamed et al. (2005) conducted the experiments on convective solar drying of citrus aurantium leaves in thin layer. An indirect forced convection solar dryer consisting of a solar air collector, an auxiliary heater, a circulation fan and a drying cabinet was used for the experiments. The air temperature, the relative humidity, and the drying air flow rate were varied from 50 to 60 °C, from 41% to 53% & from 0.0277 to 0.0833 m³/s respectively.

Janjai and Tung (2005) developed a solar dryer for drying herbs and spices using hot air from roof integrated solar collectors. The dryer was a bin type (1m × 2m × 0.7m) with a rectangular perforated floor. Hot air was supplied to the dryer from fiberglass-covered solar collectors, which also work as the roof of a farmhouse. The total area of the solar collectors was 72 m². The dryer can be used to dry 200 kg of rosella flowers and lemon-grasses within four and three days respectively. The products being dried in the dryer were completely protected from rains & insects and were of high quality. The solar air heater had an average daily efficiency of 35% and it performed well both as a solar collector and as a roof of a farmhouse.

Rathore et al. (2006) studied solar drying of Amla though solar tunnel dryer on commercial scale at M/s Shinath Amla Farm, Banswara. Design, development and performance evaluation of STD for drying pulp of amla were carried out. Amla can be dried from moisture content of 80% to 10% in two days when the STD temperature was 55-60 °C. The maximum drying rate of amla at economical cost was obtained though STD. The dried amla was also having high recovery of ascorbic acid.

Shanmugam and Natrajana (2006) designed, fabricated and evaluated the performance of an indirect forced convection type solar dryer for hot and humid condition of Chennai. The system consisted of a flat plate solar air collector, drying chamber and a desiccant unit. The desiccant unit was designed to hold 75 kg of CaCl₂-based solid desiccant. Drying experiments were performed for green peas at different air flow rate. The equilibrium moisture content (EMC) was reached in 14 h at an air flow rate of 0.03 kg/m² s. They also determined the system pickup efficiency, specific moisture extraction rate, mass shrinkage ratio and drying rate.

Bukola et al. (2008) designed, constructed and evaluated the performance of a mixed-mode solar dryer for food preservation. In this dryer, the heated air from a separate solar
collector was passed through a grain bed, and at the same time, the drying cabinet absorbs solar energy directly through the transparent walls and roof as well. The results revealed that the temperatures inside the dryer and solar collector were much higher than the ambient temperature during most hours of the day-light. The temperature rise inside the drying cabinet was up to 74% for about three hours immediately after 12.00h (noon). The drying rate and system efficiency were 0.62 kg/h and 57.5% respectively.

Folaranmi (2008) designed, constructed and tested a simple solar maize dryer, in such a way that solar radiation was not incident directly on the maize, but preheated air warmed during its flow through a collector made up of an insulating material (polystyrene) of size 100 mm x 50 mm x 25.4 mm, absorber plate (aluminium) sheet painted black of size 100 mm x 50 mm and a cover glass (5 mm thickness) measuring 100 mm x 50 mm all arranged in this order contributed to the heating. The test results gave temperature above 45 °C in the drying chamber, and the moisture content of 50 kg of maize reduced to about 12.5% in three days of 9 h each day of drying.

2.3 Techno - Economics Analysis of Dryer

Sodha et al. (1991) studied the techno-economic analysis of typical dryers with different kinds of energy sources. It was found that the plastic collectors, which last for 5-10 years, were the least cost among all the energy systems. The conventional collectors of lifetime equal to or more than 20 years were, however, economical when compared with other fuel systems.

Sattar (1994) studied that the economics of drying timber in the title kiln along with the conventional drying techniques. The operating and capital costs of the solar kiln were much lower than those of the steam kiln. Compared to air drying the solar drying was cheaper and cost less than half of the steam kilning. The payback period was approximately 1 year for the solar kiln against 31-45 years for the steam kiln.

Mumba (1995) conducted economic analysis on a dryer with passive drying-air temperature control for use on farms and obtained a payback period of less than 1 year and was cost-effective for a photovoltaic to solar air-heater area ratio of about 0.22.

Njomo (1995) analysed and compared the thermal performances of plastic cover and glass cover air collectors of the same dimensions under identical conditions of insolation and air flow rate. A simple expression taking into account the initial investment, the annual interest rate and the amount of energy which can be extracted from the collector was also developed to evaluate the cost of the energy produced by these collectors as a function of their
lifetime. It was concluded that the use of a plastic cover collector was feasible whenever the cost of the collector was an important factor in the solar application.

Palaniappan and Subramanian (1997) analysed the performance of two solar hot air drying units having 290 and 210 m² solar collector area for drying chilly and coriander respectively. The project site was a spice powder-making factory situated 80 km from Madurai. The factory processes 5.25 ton/day of chilly and 4 ton/day of coriander seed. The moisture content of chilly and coriander seeds when they arrived at the factory were around 14-18% (w.b.). The chilly have to be dried to a final moisture content of around 8% (w.b.) and coriander seeds to around 5% (w.b.). The study indicated that solar heating units for drying spices were technically and economically a viable option, offering a quality dried product and a payback period of less than 2 years. The fuel saving of 90% could be achieved. It was reported that 1 m² of solar collector saves 0.812 ton of fire wood.

Chauhan and Garg (1997) compared the cost and performance of a 20 m² solar air heater and 8.5 kW electric heaters to operate a 1.0 ton/batch capacity deep-bed dryer for coriander grains. Theoretical study was made using energy/mass balance equations and various cost parameters for different components of drying system. Finite difference method was adopted for the computer simulation. The drying cost of one ton coriander for electrical drying was observed to be higher. However, this difference in drying cost decreases with increased in air mass flow rate and decreased in annual utilization period.

Arinze et al. (1998) described the detail design, experimental performance and economic evaluation of an energy efficient solar dryer for commercial production of high-quality hay. The solar dryer consisted of an improved solar collector with selective coated aluminum absorber plate and spaced fins, and a drying shed connected to the collector by an insulated duct and having a perforated metal grate floor, swing-away plywood frames and polyethylene curtains for effectively sealing the haystack, and a crawl space below the floor where a 3 hp in-line centrifugal fan was housed for air circulation by suction. In late August and in early September, 1996, 160 small rectangular bales of Lucerne hay with about 25% brome grass were successfully dried from 33% initial moisture content to 13%, and from 25 to 11% in 4 and 3 days, respectively, under average weather conditions in Saskatoon, Saskatchewan, Canada. With about 18 m³/min per ton air flow, 10-15 °C temperature rises above ambient was obtained during peak bright sunshine hours. Relatively high daily average collector efficiency of 76%, high drying effectiveness, drying uniformity, uniform air distribution and tight sealing of the stack were achieved which resulted in an attractive green colour of hay, no mould growth on hay, and an overall system drying efficiency of about 79%. Compared to a conventional natural gas drying system or field-drying method, the
payback period on extra investment costs recovered though drying cost savings of $3 to $6 per ton or though higher prices for the high-quality hay produced can be as little as 1-2 years.

Jannot and Coulibaly (1998) presented a new index, called the evaporative capacity for rating the performance of the solar air heater in a solar dryer consisting of solar air heater and a drying chamber in series. The proposed index complements the widely used ‘collector efficiency’ as a performance indicator of the solar collector, by taking into account the specific use that was to be made with the heated air, presented in a detailed method for calculating the evaporative capacity, and a comparison of this new index with the thermal efficiency index, demonstrating its superiority. General charts for a rapid determination of the evaporative capacity were presented, and some possible applications of these charts were also described.

Hollick (1999) studied the commercial scale drying and concluded that a tremendous amount of energy to heat air was required when drying various food products and there was ample opportunity to utilize solar energy in this drying process. Commercial drying was different from the small scale traditional sun drying practiced by farmers. A feasibility study conducted by the Spices Board of India and US/ECRE using the transpired solar collector and ends with other similar drying opportunities, showed that commercial drying operations can switch to solar energy with minimal change in the operation and with payback periods of two years.

Rane et al. (2000) presented the economics of a novel low temperature solar dryer along with performance characteristics of the low cost plastic solar collector. Onion drying has been taken up as a case study to illustrate the economic viability of the dryer. A typical dryer with 2 m² solar aperture was in position to deliver 24 MJ of heat per day in the form of hot water. Water heated from 43 to 48 °C will then circulate through the plastic dryer. About 7.5 kg onion can be dried from an initial moisture content of 86.5 to 8% (w.b.) final value. Economic analysis for the low cost dryer indicated a payback period of less than 120 solar days (one solar day is equivalent to eight hours of sun shine). The novel solar dryer, without any moving parts, can increase the earning potential of the farmers and rural people at the village level by reducing wastage and by value addition.

Kumar and Garg (2000) developed and numerically evaluated a techno-economic analysis of natural convection type solar tunnel dryer for Indian climatic conditions. Proposed design of solar tunnel dryer was a mixed mode type solar drying system, in which the air heater and drying chamber were coupled together in series combination. The dryer has semi-cylindrical shaped cover of UV stabilized polythene sheet of 200 micron-meter thickness. The
solar tunnel dryer was given a small tilt for the development of natural convection flow rate on the basis of thermo syphon principle. For the estimation of annual drying yield of dryer, the analysis had included the design, operational and climatic parameters explicitly. The economic analysis was made taken into account the initial capital investment, maintenance and salvage cost and life of the dryer, which can be evaluated from the life cycle costing of the system. The estimation had been made for unit cost of the drying product and cost of unit mass of energy for different values of life expectancy of dryer and prevailing interest rate. The developed design has potential utility for drying low and high moisture crops with low initial investment and with very little operation cost.

Jain et al. (2004) worked out the techno-economic evaluation of a forced convection solar dryer. A forced convection type solar dryer consisted of a flat plate collector panel and a drying chamber. Two blowers were used for drying of groundnut, ginger and garlic in comparison to an electrically operated tray type mechanical dryer. The experiment and economic analysis of solar dryer has revealed that the solar dryer could be used effectively for drying of ginger, garlic and ground nut and has better economics than mechanical drying system. It saved considerable electrical energy over mechanical drying system. It was recommended that construction and use of solar drying system be encouraged for obtaining high value dried products and for generating additional income for the farmers/entrepreneurs. The benefit cost ratio for the solar dryer and mechanical dryer was found to be 1.56 and 1.18.

Sevda et al. (2004) evaluated a solar tunnel dryer in terms of its techno-economic analysis, which was carried out by using different economic indicators such as Net Present Worth (NPW), Benefit cost ratio and Payback period and compared with electrical drying system. The net present worth for commercial solar tunnel dryer was Rs. 78,74,500/- whereas for diesel fired electrical dryer it was Rs. 36,52,500/-. The benefit cost ratio for solar tunnel dryer and for the diesel fired electrical dryer was 7.08 and 2.56 respectively. The total payback period for commercial solar tunnel dryer was 10 months, whereas it was 2.9 years for diesel fired electrical dryer. The economics of solar tunnel dryer was made in comparison with diesel fired electrical dryer. It was observed that commercial solar tunnel dryer was a good proposition for drying of all kind of material and was techno-economically better than electrical drying system. Significant saving in electrical energy could be achieved through its use.

Hossain et al. (2005) optimized a solar tunnel dryer for drying of chilly in Bangladesh. The simulation model was combined with the economic model of the solar tunnel dryer and adaptive pattern search was used to find the optimum dimensions of the collector and the drying unit. Two optimum designs were obtained. For design-1, both
collector and drying unit were 14.0 m long and 1.9 m wide and for design-2, both collector and drying unit were 13.0 m long and 2.0 m wide. Both the collector and drying unit of basic mode dryer were 10.0 m long and 1.8 m wide. The capacity of optimum mode dryer was higher than the basic mode dryer and achieved a cost saving of 15.9%. The payback period of the basic mode dryer was 4 years and optimum mode dryer was about 3 years. Sensitivity analysis showed that the design geometry was quite sensitive to costs of major construction materials of the collector and air temperature in the dryer.

2.4 Solar Tunnel Dryer

Amir et al. (1991) developed a multipurpose solar tunnel dryer for the use in humid tropics. Open-air sun drying and smoke drying, which were traditional drying methods in these regions, lead to insufficient final product quality. A multipurpose solar tunnel dryer, originally developed for the use in arid zones, was modified to enable operation under tropical weather conditions. This type of dryer consisted of a small centrifugal blower, a collector and a tunnel drying chamber. To heat the drying air during cloudy and rainy days, particularly during the rainy season, a biomass furnace with heat exchanger was integrated into the solar drying system. Result showed that compare to natural sun drying, the drying time of coca; coffee and coconut could be reduced up to 40%.

Fuller (1995) conducted a simulation and experimental study of a small solar tunnel dryer to determine its performance compared to a conventional dehydrator for drying horticultural crops on-farm. Over a three-day drying period, the solar tunnel dryer was predicted to reduce energy consumption by 29% and achieve a 16% reduction in drying time. The load ratio in the solar tunnel dryer was inferior to the dehydrators surveyed, but the capital and recurrent costs were less. Variations in drying rate and product quality due to uneven levels of solar radiation and temperature gradients within the solar dryer have been overcome by the use of a rotating tray system, which also simplified the on and off loading of fruit. Sultana grapes, apricots and tomatoes were particularly suitable crops for drying in solar tunnel dryers because their final product quality was enhanced by the direct exposure to solar radiation.

Schirmer et al. (1996) investigated the performance of multi-purpose solar tunnel dryer for drying of bananas under the hot and humid weather conditions of Thailand. The dryer comprised a plastic sheet-covered flat plate collector and a drying tunnel. The dryer was arranged to supply hot air directly to the drying tunnel using three fans powered by a 53 W solar cell module. The products to be dried were spread in one layer on a plastic net in the drying tunnel to receive energy from both the hot air supplied by the collector and incident
solar radiation. This dryer can be used to dry up to 300 kg of ripe bananas in each drying batch. In investigating the performance of the dryer, seven drying tests were conducted at the Royal Chitralada Projects in Bangkok during March–May 1995. The temperature of the drying air from the collector varied between 40 and 65 °C during drying and the bananas could be dried within 3–5 days, compared to the 5–7 days needed for natural Sun drying. In addition, the bananas being dried in the solar tunnel dryer were completely protected from rain, insects and dust, and the dried bananas were of high quality in terms of flavour, colour and texture. As the fans were powered by the solar module, the dryer could be used in rural areas where there was no supply of electricity from grid. The pay-back period of the dryer was estimated to be about 3 years when the dryer was locally produced.

Garg and Kumar (1998) carried out a detailed analysis of solar irradiance estimation for the general orientation of the Solar Tunnel Dryer (STD) with respect to reference positions (N-S, E-W). It was found that if the STD axis was in the E-W, the absorber plate received more solar radiation as compared to the other reference position N-S. The amount of solar irradiation absorbed by the cover was also calculated and found very small compared to the absorber. All calculations were made for Delhi (28.58°N latitude) climate. The analysis presented for solar irradiance estimation over the absorber plate and cover of the STD was very general and it can be used for any location and for any day of the year.

Rachmat and Horibe (1999) designed a fibre reinforced plastic (FRP) house for drying of brown rice. They reported that the temperature raised shown an exponential relationship with global solar radiation and the values of temperature raised higher when using a collector (5-10 °C) than when not using one (4-11 °C). The installation of FRP inside house increased heat collection efficiency of the house around 23-23%.

Kumar and Mathur (2000) designed and fabricated a solar-biomass hybrid tunnel dryer. A biomass stove-heat exchanger- chimney using briquetted rice husk as fuel, complements the solar tunnel dryer and thus extended the working time of the dryer. Experiments have been conducted to test the performance of the dryer, on chili and mushroom drying. During the load test conducted for chili, 19.5 kg of ripe, fresh chilli, with a initial moisture content of 76% (w.b.) was dried to a final moisture content of 6.6% (w.b.) within 12 hours. Similarly, the moisture content of 21 kg of fresh harvested mushroom was reduced from 91.4 to 9.8% during 12 h of drying. The results indicated that for both the products, drying was faster, and was within 12 h in normal sunny weather, against 2-3 days in ‘solar-only’ operation of a tunnel dryer and 3-5 days in open sun drying. This paper evaluated the performance of the hybrid tunnel dryer against ‘solar-only’ operation of the same dryer.
and open sun drying. Efficiency of the dryer during its two mode of operation has been estimated and compared with other similar dryers.

Singh et al. (2000) conducted experiment investigation to determine temperatures available inside the solar tunnel dryer for drying crop produce. The air temperature in solar tunnel dryer was also calculated using a steady-state model. The maximum temperature gain of about 24 °C was obtained. The maximum temperature inside solar tunnel dryer enclosure reached about 64 °C when outside temperature was about 40 °C. The optimum temperature for drying vegetable falls in the range of 50-65 °C. The model can also predicted the relative humidity inside the solar tunnel dryer enclosure if outside relative humidity was known. The inside relative humidity varied from 14-21%. The model can also be used to modify the design of the solar tunnel dryer according to the optimum temperature required.

Joy et al. (2001) conducted studies on drying of red chillies using a solar tunnel dryer. Improvement in overall quality parameters, cleanliness and texture were noticed in tunnel-dried chilli samples compared to conventionally dried samples. Considerable reduction in drying time was noticed for solar tunnel drying compared to traditional drying.

Abello (2002) determinate the adaptability of the multi-purpose solar tunnel dryer (MPSTD) at the farmer-cooperative level of operation efficiently in drying perishable crops. Results showed that the traditional sun drying method incurred the longest drying time of 30 h to effectively reduce the moisture content level of the mango. On the other hand, solar tunnel and mechanical dryer had a total drying time of 19 h and 18 h, respectively. The drying capacity of the solar tunnel (162 kg) was higher than mechanical dryer (120 kg) which meant that more mangoes can effectively dried using this technology. The solar tunnel dryer reduced the total drying time by 57.9%, compared to the traditional sun drying method. This significant reduction of the total drying time using the solar tunnel dryer indicated that the said dryer improved the traditional sun drying operation. There was no significant difference between the observed quality of mangoes dried in the thee drying systems. It was also concluded that MPSTD was economically viable, ultimately increasing the income of the technology adopters.

Kamel and K holy (2002) developed a greenhouse type solar dryer at the experimental farm of Rice Mechanization Center, Meet El-Dyba, Kafer El-Sheikh Governorate, Egypt. The dryer was tested and evaluated for drying high moisture ear and shelled maize variety (thee way-cross 310) and compared with natural sun drying method. Results showed that the developed dryer was able to dry ear maize from an initial level of 29.85% to a final level of 14.26% in 84 h as compared to 187 h for natural sun drying method. The corresponding
drying times for shelled maize from an initial grain moisture level of 19.87% to a final level of 14.13% were 18 and 34 h, respectively. Quality evaluation tests of the dried ear and shelled maize showed a lower percentage of kernels stress cracks for the solar dried kernels compared with natural sun drying of ear maize giving the lowest percentage of stress cracks (SC) kernels (9.10%). While the natural sun drying produced the highest percentage of SC kernels (23.1%). However, the grain germination tests showed an average percentage of over 90% for both solar and natural sun drying methods of ear and shelled maize. Cost analysis of the solar dryer showed a total cost of 28.76 LE/tonne for drying ear maize from an initial grain moisture level of 29.85% to a final moisture level of 14.26% and 8.00 LE/tonne for drying shelled maize from an initial level of 19.87% to a final level of 14.13%. For the two stage drying system reduction the estimated drying cost from initial moisture level of 29.85% to a final level of 19.87% for ear maize and from initial level of 19.87 to a final level of 14.13% for shelled maize was approximately 20.68 LE/tonne.

Bala et al. (2003) conducted full-scale field level drying experiments for pineapple slices using solar tunnel dryer at Bangladesh. They reported that this dryer can be used to dry upto 150 kg of fresh pineapple and the temperature of the drying air at the collector outlet varied from 34.1 to 64.0 °C. The pineapple dried in the solar tunnel dryer was completely protected from rain, insects and dust and the dried pineapple were having a high quality. Compared open sun dried sample, the moisture content of sulphur treated pineapple of a typical experimental run reached to 14.13% (w.b.) from 87.32% (w.b.) in 3 days of drying to bring down the moisture content of a similar to 21.52% (w.b.) in the traditional method compared to open sun dried sample

Condori and Saravia (2003) analysed the performance of a tunnel type greenhouse dryer. Considering the greenhouse as a solar collector, a linear function between the incident solar radiation and the greenhouse output temperature was obtained. Using the dryer characteristic function, the dryer performance was evaluated as a function of the drying potentials. The results showed that an almost constant production was obtained each day. The generalized drying curve concept was applied to the first tunnel cart, obtaining a result that was similar to the single chamber dryer case. The simulation tests with red sweet pepper show an improvement of 160% in the production, compared with the single chamber dryer case, and an improvement around 40%, if the double chamber dryer was considered.

Sevda (2003) evaluated refinement and agro-industrial application of natural convection type solar tunnel dryer. A walk in type, semi-cylindrical poly house for drying di-basic calcium phosphate to 1.5 ton capacity per batch has been commissioned at the M/s Phosphate India Pvt. Ltd., Udaipur. It has been observed that performance of north wall made
up of glass wool sandwiched in metallic cover gives better performance in terms of maximum temperature attended. Computer programme for ready availability of tips of design parameters of a solar tunnel dryer for drying any other materials has been developed.

2.5 Solar Tunnel Dryer for Industrial Products

Gnanaranjan et al. (1997) studied field performance of a solar tunnel dryer, at Hohenheim University. From this investigation, it was concluded that solar tunnel dryer is better in eliminating some of the problems related to conventional solar dryer. The authors ascertained that as compared to other solar dryers, the capacity of the tunnel dryer was much higher. Adding that significant reduction in drying time, high quality of the dried material and complete protection from rain, dust and insects were the main advantages of the solar tunnel dryer.

Husni et al. (1999) studied the optimum temperature suitable for the drying of Stolephorus at the Department of Agricultural Technology, Faculty of Agriculture, Andalas University. Result indicated that it can prevent the case hardening, analysis was also conducted to increase its capacity. The results showed that drying period for this fish was 5 hours with the respective initial and final moisture content of 63.8% and 26.8% w.b. The drying rate was 1.01 kg of water per hour. Efficiency of the heating and drying of this system were 75.46 and 30.9% respectively. The total efficiency of this system was only 23.32%. This low efficiency was due to the high heat loss though the wall and outlet. The operating cost of the drying was Rs. 969.17/kg.

Bala and Mondol (2001) studied the field level performance of the solar tunnel dryer for drying of fish. The dryer consisted of a transparent plastic covered flat plate collector and a drying tunnel connected in series to supply hot air directly into the drying tunnel using four d.c. fans, operated by two 40 watt solar modules. This dryer can be used to dry up to 150 kg of fish per batch and three sets of full scale field level drying runs for drying silver jew (Johnius argentatus) fish were conducted in February-March, 1999. The temperature of the drying air at the collector outlet varied from 35.1 °C to 52.2 °C during drying. The fish was initially treated with dry salt and stacked for about 16 hours before drying. The salt treated fish was dried to a moisture content of 16.78% (w.b.) from 67% (w.b.) in 5 days of drying in solar tunnel dryer as compared to 5 days of drying in the traditional method for comparable samples to a final moisture content of 32.84%. In addition, the fish dried in the solar tunnel dryer was completely protected from rain, insects and dust, and the dried fish was a high quality product.
Kurklu et al. (2002) conducted experiment to store solar energy in an underground rock-bed for greenhouse heating. Experiments were carried out in two identical polyethylene tunnel type greenhouses, each with 15 m² ground area. Rocks were filled in two canals excavated and insulated in the soil of one of the greenhouses. Greenhouse air was pushed though the rock-bed by a centrifugal fan with 1100 m³/h air flow rate and controlled by two thermostats when the energy storage or release was required. No crops were grown in the greenhouses and the vents were kept closed unless excessive condensation occurrence inside the greenhouses. The results of this study showed that the rock-bed system created an air temperature difference of about 10 °C at night, between the two greenhouses, the control one having the lower temperature. Furthermore, the rock-bed system kept the inside air temperature higher than that of outside air at night, even in an overcast day following a clear day. While solar energy collection efficiency of the system was 34%, its energy recovery or release efficiency was higher than 80%. A numerical mathematical model was also developed and used for prediction of its efficiency. An economic analysis indicated that the rock-bed system was more economical than the LPG or petroleum-based fuel burning heating systems widely used in Turkish greenhouses.

Prasad (2002) designed and studied performance of solar tunnel dryer for drying industrial products. A semi-cylindrical solar tunnel dryer with appropriate chimney with ultraviolet protected plastic sheet was constructed and the performance of the dryer was evaluated at different condition with an industrial product viz. for drying Di-basic Calcium Phosphate. A humidity sensor was installed for automatically control and the on/off operation of the exhaust fan to maintain relative humidity of the inside air in the range of 50-55%. A wall in northern side i.e. north-wall with black coating was used to reduce heat loss and temperature enhancement inside the solar tunnel dryer especially for winter months. During winter season, the temperature inside solar tunnel dryer without north-wall under no load condition, with north-wall under no load condition and with north-wall under full load condition was recorded 14.65 °C, 18.50 °C and 16.25 °C more compared to ambient temperature, respectively. During summer season the temperature inside the solar tunnel dryer without north-wall under no load condition, with north-wall under no load condition and with north-wall under full load condition was recorded 17.20 °C, 20.25 °C and 17.35 °C more compared to ambient temperature, respectively. During winter season the initial moisture content of DCP was 38.50% (w.b.) and it was reduced to constant value of 9.4% (w.b.) inside the solar tunnel dryer, while in open air it was reduced to constant value of 9.7% (w.b.) inside the solar tunnel dryer while in open air it was reduced to 20.1%. Drying of 1.5 MT DCP from initial moisture content to a constant value was achieved in 16 and 12 sunshine hours during winter and summer months respectively. Economic analysis of solar tunnel dryer was carried
out by using different economic indicators and compared with electrical drying system. It was observed that commercial solar tunnel dryer was a good proposition for drying of all kind of material and was techno-economically better than mechanical drying system. Significant savings in electrical energy could also be achieved through its use.

Rathore (2004) designed and developed a solar tunnel dryer for drying Di-basic Calcium Phosphate (DCP) and evaluated its performance at the factory site, Udaipur. The evaluation of the dryer was conducted during the month of December and May. It was reported that during drying of DCP the maximum mean temperature inside the solar tunnel dryer under no load condition was 42.6 °C and 53.4 °C during winter and summer day respectively. Under full load condition the maximum mean temperature inside solar tunnel dryer was 42 °C and 52.7 °C during winter and summer day, respectively when the maximum ambient temperature during the winter and summer days were 24 °C and 34.7 °C, respectively. Drying of 1.5 MT DCP of 38.31% (w.b.) initial moisture content reduced to a constant value of 9.7% (w.b.) inside the solar tunnel dryer was achieved in 16 sunshine hours during winter month, while 12 hours were required during summer month.

Bala et al. (2005) studied the field performance of a solar tunnel dryer for drying jackfruit bulbs and leather. The dryer consisted of a transparent plastic-covered flat-plate collector and a drying tunnel connected in series to supply hot air directly into the drying tunnel using two direct-current fans operated by a photovoltaic module. The dryer was having a loading capacity of 120–150 kg of fruits. Sixteen experimental runs were conducted for drying jackfruit bulbs and leather (eight runs each). The use of a solar tunnel dryer led to a considerable reduction in drying time and dried products of better quality in comparison to products dried under the sun. A multilayered neutral network approach was used to predict the performance of the solar tunnel dryer. Using solar drying data of jackfruit bulbs and leather, the model has been trained using back propagation algorithm. The prediction of the performance of the dryer was found excellent after it was adequately trained. It can be used to predict the potential of the dryer for different locations, and can also be used in a predictive optimal control algorithm.

Rathore and Panwar (2010) natural convection poly house walk-in type solar tunnel dryer was designed and used for drying surgical cotton on industrial scale. A batch of surgical cotton of 600 kg by mass, having an initial moisture content of 40% wet basis from which 210 kg of water removed to got a desired moisture content of about 5% wet basis. Drying time was 7–8 h for the test location (Udaipur, 27° 42′ N, 75° 33′ E) with an expected average solar irradiance of 5.5 kW m⁻². Average cost of drying one batch of surgical cotton in a solar
tunnel dryer has been worked out to be approximately 4.63 USD as compared to 30.00 USD in the existing diesel fired dryer.

2.6 Forced Convection Type Solar Tunnel Dryer

Bala et al. (1997) conducted an experiment to investigate the performance of the solar tunnel dryer for drying of pineapple. The solar tunnel dryer consisted of a plastic foil covered on flat plate air heating collector and a drying tunnel. The dryer was arranged to supply hot air directly into the drying tunnel using two DC fans powered by a 40 W photovoltaic module. The products to be dried were spreading in one layer on a wire mesh in the drying tunnel to receive energy from both way i.e. hot air supplied by the collector and incident solar radiation on products. A batch of up to 120 kg of pineapple could be dried in three sets of drying runs. The temperature of drying air at the collector outlet varied from 20 to 35 °C and the pineapple could be dried within 3 to 4 days in the tunnel dryer compared to 4 to 5 days needed for natural sun drying. In addition, the pineapples being dried in the solar tunnel dryer were completely protected from rain, insects and dust and the dried pineapples were having high quality in nutrients wise.

Fuller and Charters (1997) investigated the performance of solar tunnel dryer with microcomputer control and tested in the Sunraysia district of Northern Victoria, Australia. A novel feature of the dryer was the microprocessor system used to control the exhaust fan. A tray containing a small sample of the crop was suspended from a load cell, and the output from this was used to continuously calculate the current moisture content of the crop. Using this estimation and inputs from sensors measuring the relative humidity of the air inside and outside the dryer, an appropriate decision was made on whether to activate the exhaust fan or not. The dryer was used to dry two loads of untreated grapes in the summer of 1992. Drying time was reduced by approximately 40% compared to sun drying in both trials. Using a two stage control algorithm, fan operating time was reduced by 67% compared to continuous fan operation and by 34% if a light sensitive switch had been used to control the fan.

Condori and Saravia (1998) presented an analytical study of the evaporation rate in two types of forced convection greenhouse dryers, the single and the double chamber system. A performance parameter defined to compare both dryers and its dependence on the operational variables were studied introducing the concept of the characteristics function simulation tests for red pepper. It was conducted that a higher production rate can be obtained improving the use of the drying potentials. Particularly, productivity of the double chamber greenhouse dryer as compared to the single type was increased by 87% for the drying area 50
m². The necessary charges needed to implement the double chamber dryer were simple and inexpensive reducing significantly the drying cost.

Garg and Kumar (2000) studied the modeling and thermal performance of the collector of a semi-cylindrical solar tunnel dryer (STD). The performance has been estimated under natural circulation as well as under forced circulation mode. The volume flow rate and the rise in the inlet air temperature have been optimized for natural circulation mode with respect to the design parameters, viz., length and radius of the collector. The performance of the collector was also calculated for different tilt of the STD. All calculations were made for Delhi climate (28.58 N Latitude). The development of the natural circulation type STD was very significant because it had certain advantages over the existing forced circulation type STD.

Manohar and Chandra (2000) conducted studies to characterize the drying process in a greenhouse type solar dryer using either natural or forced ventilation. A 4 m high circular black polyethylene stack attached to the dryer produced an air flow rate of 0.1 m³/s in the experimental dryer. A three-tier drying rack (1m x 1m x 2.5m) was installed in the greenhouse type solar dryer for multi-tiered drying of agricultural produce. Rewetted mustard were dried, both in the solar dryer and in the open sun. Drying of mustard under natural ventilation and forced ventilation was faster than that in the open sun by about 20 and 45% respectively. The drying data were well represented by Page's drying equation \( r^2 = 0.6 \) to 0.93. The drying coefficients 'k' and 'n' in the equation could not be correlated well with drying environmental parameters in this field study. The capacity of the greenhouse type solar dryer varied between 391 (natural ventilation) to 4861 kg/day (forced ventilation).

Condori et al. (2001) designed and tested a new low cost design for a forced convection greenhouse dryer i.e. the tunnel greenhouse dryer. Its main parts were, a plastic greenhouse cover containing a drying tunnel made up with transparent plastic walls; a line of carts with several stacked trays containing the product and moved manually inside the tunnel and an electrical fan that moves the hot air from the greenhouse into the tunnel. The trays receive solar radiation through the transparent walls, increasing the product temperature. Heat losses from the tunnel were low since greenhouse temperatures were higher than ambient temperature. The main advantages of this dryer were, (a) an almost continuous production since some carts with dried product come out of the tunnel every day, while the same amount of fresh product was introduced by the other tunnel extreme, (b) lower labor cost since the product handling was partly mechanized, (c) a conventional heater can be easily installed to keep a constant production rate, (d) the energy consumption was lower than as compared to other dryer types, (e) the installation can be used as a greenhouse for small production when it
was not used as a dryer. The prototype was built in the North of Argentina and red sweet pepper and garlic were used as load. The dryer thermal efficiency was calculated using the measured experimental data and a linear relation between the dryer temperature and the solar radiation were obtained.

Mangaraj et al. (2001) conducted a study to evaluate the performance of different drying methods, namely open sun drying on cemented floor, greenhouse type solar drying (natural ventilation system), solar cabinet drying (natural convection type) and mechanical drying for both unpunched and punched fresh red chillies of “Jwala” variety. Both unpunched and punched chillies of 2 kg each were taken for all the drying methods. The ripened red chillies with an initial moisture content of 300% (d.b.) were dried to the final moisture content of 8 to 9% (d.b.). The quality parameters like pungency and colour were estimated. It was also observed that the time taken for drying was minimum for mechanical drying, followed by solar cabinet drying, greenhouse type solar drying and open sun drying. The overall quality was found to be better in mechanical drying, followed by greenhouse type solar drying, solar cabinet drying and open sun drying. The greenhouse solar drying was most economical, followed by solar cabinet drying, mechanical drying and open sun drying respectively.

Jain and Tiwari (2004) developed a thermal model for thermal behavior of crops (cabbage and peas) for open sun drying (natural convection) and inside the greenhouse under both natural and forced convection. The predictions of crop temperature, greenhouse room air temperature and rate of moisture evaporation (crop mass during drying) have been computed in Mat lab software on the basis of solar intensity and ambient temperature. The models have been experimentally validated. The predicted crop temperature and crop mass during drying showed fair agreement with experimental values within the root mean square of % error of 2.98 and 16.55, respectively.

Singh et al. (2005) developed and studied the performance of solar tunnel dryer under no-load and for drying unripe peeled mango at Bhopal. It was batch type dryer (about 80-90 kg wet product/batch) were placed. The batch dryer consisted of 2.0 m wide, with a 4.5 m solar air heater and a drying tunnel of 8.0 m. The heater and dryer were covered with U-V stabilized polyethylene film. Solar photo-voltaic (9 SPV) operated axial flow fans have been provided at one end to push fresh air in to the dryer. An exhaust fan was provided at the other end to evacuate hot air and to control the air temperature, with the help of an electronic temperature controller automatically. Air temperature inside the dryer could be maintained in the range of 50-75 °C on typical sunny days. Cut mango pieces were uniformly spread over the drying trays at the rate of 4.5 kg/m². Initial moisture content of mango was around 79% and dried in the solar dryer in four and half days to a moisture level of 42% as compared to
ten days in open drying to moisture content of 4.7%. The average drying temperature in the tunnel was 60 °C. Quality of the product dried in the tunnel dryer was found to be superior as compared to the sun-dried product in terms of microbial load, appearance and acceptability.

Hossain and Bala (2007) reported that mixed mode type forced convection solar tunnel dryer was used to dry hot red and green chillies under the tropical weather conditions of Bangladesh. The dryer consisted of transparent plastic covered on flat-plate collector and a drying tunnel connected in series to supply hot air directly into the drying tunnel using two fans operated by a photovoltaic module. The dryer had a loading capacity of 80 kg of fresh chillies. Moisture content of red chilli was reduced from 2.85 to 0.05 kg kg\(^{-1}\) (d.b.) in 20 h in solar tunnel dryer and it took 32 h to reduce the moisture content to 0.09 and 0.40 kg kg\(^{-1}\) (d.b.) in improved and conventional sun drying methods, respectively. In case of green chilli, about 0.06 kg kg\(^{-1}\) (d.b.) moisture content was obtained from an initial moisture content of 7.6 kg kg\(^{-1}\) (d.b.) in 22 h in solar tunnel dryer and 35 h to reach the moisture content to 0.10 and 0.70 kg kg\(^{-1}\) (d.b.) in improved and conventional sun drying methods, respectively. The use of a solar tunnel dryer and blanching of sample led to a considerable reduction in drying time and dried products of better quality in terms of colour and pungency in comparison to products dried under the sun. The solar tunnel dryer and blanching of chilli were recommended for drying of both red and green chillies.