CHAPTER 2

REVIEW OF LITERATURE

Solar collectors are important components for solar energy utilization. Development of appropriate technologies for conversion of solar radiation to thermal energy is essential for food preservation. A review of various designs, construction, operational principles and various aspects of solar air heaters with and without thermal storage for drying applications is presented in this chapter. The chapter concludes with the scope of the work.

2.1 Solar air collector

Amir et al. (2012) developed a flat plat solar air collector with steel plate absorber with an area of 2×1 m² and thickness of 0.5mm in the form of window shade for increasing the air contact area. The surface of absorbent plate was covered by black paint. To insulate the collector, glass wool with the thickness of 5cm was used. The experiments on the efficiency were conducted for a week during which the atmospheric conditions were almost uniform and data was collected from the collector. The results showed that the collector efficiency in forced convection was lower, but the low temperature difference between inlet and outlet of the collector decreased its heat loss. In addition, the average air speed in forced convection was about 21% higher than the natural convection.

A double pass solar air heater was fabricated and integrated with thermal storage system. Paraffin wax was used as a thermal storage medium. Krishnananth et al. (2012) studied the performance of this heater for different configurations. The solar heater integrated with thermal storage delivered comparatively high temperature. The efficiency of the air heater integrated with thermal storage was also higher than the air heater without thermal storage system. It was concluded that the presence of the thermal storage medium at the absorber plate was the best configuration.
Rajendra et al. (2010) presented results of a study on the performance of solar air heaters with 60° v-down discrete rectangular cross-section repeated rib roughness on the air flow side of the absorber plate. The study showed that, at air mass flow rates less than about 0.04 kg s\(^{-1}\) per m\(^2\) of the absorber plate, roughened duct solar air heaters provided significant performance advantage over the smooth duct air heater. At the mass flow rate of about 0.045 kg s\(^{-1}\) m\(^{-2}\), the effective efficiencies of the roughened and smooth duct solar air heaters were practically the same.

Deniz et al.(2010) designed and compared three different types of designed flat-plate solar air heaters, two having fins (Type II and Type III) and the other without fins (Type I). One of the heaters with a fin had single glass cover (Type III) and the others had double glass covers (Type I and Type II). The energy and exergy output rates of the solar air heaters were evaluated for various air flow rates (25, 50 and 100 m\(^3\)/m\(^2\) h), tilt angle (0°C, 15°C and 30°C) and temperature conditions versus time. Based on the energy and exergy output rates, heater with double glass covers and fins (Type II) was found to be more effective and the difference between the input and output air temperature was higher than that of the others. The highest temperature difference was obtained with the heater (Type II) at air flow rate of 25 m\(^3\)/m\(^2\) h and 0° tilt angle, whereas the lowest value was obtained for the heater without fins (Type I) at air flow rate of 100 m\(^3\)/m\(^2\) h and 15° tilt angle. Besides, it was found that the circulation time of air inside the heater played a role more important than that of the number of transparent sheets.

An exergetic optimization of flat plate solar collectors was developed by Farahat et al. (2009) to determine the optimal performance and design parameters of the solar to thermal energy conversion systems. A detailed energy and exergy analysis was carried out for evaluating the thermal and optical performance, exergy flows and losses as well as exergetic efficiency for a typical flat plate solar collector under given operating conditions. In this analysis, the following geometric and operating parameters were considered as variables. The absorber plate area, dimensions of solar collector, mass flow rate, fluid inlet, outlet temperature, the overall loss coefficient, etc. A simulation program was developed for the thermal and exergetic calculations.
The results of this computational program were in good agreement with the experimental measurements noted in the previous literature.

Franz et al. (2009) gave a simulation program for a flat-plate solar air heater, used to estimate the potential to preheat drying air, given the conditions of several drying facilities. Results showed that solar collectors could replace up to 19.6% of the thermal energy demand during the drying season. It was found that bigger collectors and smaller air channels resulted in more useful heat, but attention had to be paid to costs and pressure drop respectively.

Natural convection heat transfer in a vertical flat-plate solar air heater of 2.5m height and 1m width with one and two-glass covers were studied experimentally. Hatami et al. (2008) considered totally six cases of airflow (two for air heater with one glass cover and four for air heater with two-glass covers). These cases included states that air could flow within spaces between absorber plate and glass covers or air was enclosed in such spaces.

Suleyman (2007) presented a performance analysis of four types of air heating flat plate solar collectors: a finned collector with an angle of 75°, a finned collector with an angle of 70°, a collector with tubes and a base collector. The first and second laws of efficiencies were determined for the collectors and comparisons were made among them. The results showed that the efficiency depended on the solar radiation and the construction of the solar air collectors. The temperature rise varied almost linearly with the incident radiation. The first law of efficiency changed between 26% and 80% for collector-I, between 26% and 42% for collector-II, between 70% and 60% for collector-III and between 26% and 64% for collector-IV. The values of second law efficiency varied from 0.27 to 0.64 for all collectors. The highest collector efficiency and air temperature rise were achieved by the finned collector with angle of 75°, whereas the lowest values were obtained for the base collector.
A parametric study on the thermal performance of a solar air collector with a v-groove absorber was investigated. To quantify the achievable improvements with the v-groove absorber, a flat-plate solar air collector where both the absorbing plate and the bottom plate are flat was also considered. The thermal performance of these two types of solar air collectors was analyzed and compared under various configurations and operating conditions. The results obtained by Tao et al. (2007) showed that the v-groove collector had considerably superior thermal performance to the flat-plate collector. It was also found that, to achieve better thermal performance, it was essential to use a small size of the v-groove absorber for the v-groove absorber collector and to maintain a small gap between the absorber and the bottom plate for the flat-plate collector to use selected coatings that have a very high absorptivity of solar radiation but a very small emissivity of thermal radiation on the absorber and glass cover to maintain an air mass flow rate above 0.1 kg/m²s and to operate the collectors with the inlet fluid temperature close to that of the ambient fluid.

A comprehensive parametric study was carried out by Wenxian et al. (2006) on the thermal performance of cross-corrugated solar air collectors. For the Type 1 collector, the wavelike shape of the absorbing plate was along the flow direction and that of the bottom plate was perpendicular to the flow direction, while for the Type 2 collector, it was the wavelike shape of the bottom plate that was along the flow direction and that of the absorbing plate was perpendicular to the flow direction. The aim of using the cross-corrugated absorbing plate and bottom plate was to enhance the turbulence and the heat transfer rate inside the air flow channel which were crucial to the improvement of efficiencies of solar air collectors. The thermal performance of these three types of solar air collector was analyzed and compared under various configurations and operating conditions. The results showed that, although the thermal performance of the Type 2 collector was just slightly superior to that of the Type 1 collector, both of these cross-corrugated solar air collectors had a significantly superior thermal performance to that of the flat-plate one.
Karim et al. (2006) reported the results of a performance study on v-groove solar air collector for drying applications. Experimental results indicated better thermal efficiency for a v-corrugated collector compared to a flat plate collector. Effects of operating variables on the thermal performance were investigated. The results showed that the temperature of the fluid at the exit of the collector decreased with flow rate resulting in an increase of efficiency due to decreased thermal losses to the environment. After a certain flow rate, these changes became less significant. Flow rate of 0.035 kg/m$^2$/s was recommended for most drying purposes in consideration of collector efficiency and outlet temperature. Efficiency increased from 0.41 at flow rate of 0.01 kg/m$^2$/s to 0.71 at flow rate of 0.054 kg/m$^2$/s.

A solar dryer for drying herbs and spices using hot air from roof-integrated solar collectors was developed by Janjai et al. (2005). The dryer was bin type with a rectangular perforated floor. The bin had a dimension of 1.0 m×2.0 m×0.7 m. Hot air was supplied to the dryer from fiber glass-covered solar collectors, which also functioned as the roof of a farmhouse. The total area of the solar collectors was 72 m$^2$. To investigate its performance, the dryer was used to dry four batches of rosella flowers and three batches of lemon-grasses during the year 2002–2003. The dryer could be used to dry 200 kg of rosella flowers and lemon-grasses within 4 and 3 days, respectively. The products dried in the dryer were completely protected from rains and insects and the dried products 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 a roof of a farmhouse.

Solar air collectors are important components for solar energy utilization in green houses. Zhai et al. (2005) carried out experimental studies on a solar air collector (SAC), for which the length of air channel was 1500 mm, the width was 500 mm, with a variable air channel gap ranges from 100 to 500 mm. In the experiment, the uniform heat flux along the air channel was affected by three electric heating plates, which played an important role as solar radiation. It was found that the temperature distribution of air and the induced natural air-flow rate were highly dependent on heat input, inclination angle, channel gap, etc. Experimental results
indicated that the optimum inclination angle for the SAC was 45°, under which a maximum natural ventilation rate could be created. Also it was found that there existed an appropriate channel length, about 1 m in this study, beyond which the obtained heat and the natural ventilation rate could not be increased drastically. Higher the volume of air-flow rate through the SAC, lower the temperature difference between inlet and outlet. Consequently, it should be balanced between the air temperature rise and a suitable mechanical air-flow rate in order to obtain maximum heat. Additionally, theoretical analysis based on heat balance equations was testified to agree well with experimental results.

Dilip (2005) presented a periodical analysis of multi-tray crop drying attached to an inclined multi-pass solar air heater with in-built thermal storage. It was observed that the crop moisture content decreased with the drying time of the day. Different drying rates were observed in different drying trays due to the variation in crop temperatures. The thermal efficiency of the drying increased with increase in mass of the crop. The maximum drying rate was obtained as 0.0158kg water/kg of dry matter per hour in tray-1 after 6 to 8 hours of drying. The crop temperature decreased significantly beyond a mass flow rate of 0.028kgs⁻¹.

Karim et al. (2004) presented an experimental study of three types of solar air collectors, namely flat plate, finned and v-corrugated, towards achieving an efficient design of air collector suitable for a solar dryer. A series of experiments were conducted, based on the ASHRAE standard, under Singapore climatic conditions. The performance of all three collectors was examined over a wide range of operating and design conditions. Results showed that the v-corrugated collector had 7–12% higher efficiency than flat plate collectors. The v-corrugated collector was found to be the most efficient collector, and the flat plate collector the least efficient. The collectors were also studied in double pass mode to investigate the extent of improvement in efficiency that could be achieved without increasing the collector size or cost. Double pass operation of the collector led to further improvement of the efficiency compared to the single pass of operation. The improvement in efficiency for the double pass
mode was most significant in the flat plate collector and least in the v-groove collector.

Irfan et al. (2004) studied five solar collectors with dimensions of 0.9×0.4 m and the flow line increased where it had narrowed and expanded geometrically in shape. These collectors were set to four different cases with dimensions of 1×2 m. Therefore, heating fluids exit the solar collector after at least 4.5 m displacement. The results of the experiments were evaluated on the days with the same radiation. The efficiencies of these four collectors were compared to conventional flat-plate collectors.

A solar air heater, comprising two absorber systems in a single flat-plate collector was designed by Madhlopa.et al. (2002) on the principles of psychrometry. 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. The air heater converted up to 21.3% of 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 MC of sliced fresh mangoes from about 85% (w/w) to 13% (w/w) 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.

The efficient design and construction of solar energy air heating collectors are critical to the overall performance of the distributed (indirect mode) and mixed-mode designs of either active or passive solar-energy crop dryers. A review of the various designs and the performance evaluation technique of flat-plate solar-energy air-heating collectors for low temperature (i.e. temperature elevations between 10°C–35°C above ambient) solar-energy crop drying applications were presented by Ekechukwu.et al. (1999).
Solar air heaters of many types had been developed in India and their performance studied in detail. The applications of these air heaters were limited to a few demonstration projects for food dehydration, and space heating. Some of these case studies were described by Bansal (1999). For a few cash crops, the potential of solar air heaters for the drying process were assessed in detail. Space heating by solar air heaters and their use for natural ventilation were discussed and results of a theoretical study presented to make out a case for more intensive research in the fields of solar air heater applications in India.

An integrated rock bed and solar collector system was investigated both experimentally and theoretically by Mohammed (1998). The system consisted of an insulated galvanized iron box containing rocks. It might act as both a solar collector and as a storage system. The measured parameters were the inlet and outlet air temperatures, the bed temperature, the ambient temperature and the solar insolation. Further, the measurements were performed at different values of tilt angle and mass flow rate of air. It was found that the bed had a maximum storage efficiency of 46% when it was tilted at an angle of 47°. Finally, the agreement between the experimental results and theoretical predictions was rather a good one.

Tea processing is an energy intensive operation requiring both thermal and electrical energy. Hot air at a temperature of 100°C –130°C for tea drying and withering had been obtained in the past by burning coal or firewood. Over the last four years, roof integrated solar air heating systems had been introduced in some of the tea factories of south India as a partial energy source. Palaniappan et al. (1998) presented the economic analysis of one such system of 212 m² collector area system that had been in operation for quarter to three years. The system had reduced specific fuel consumption for tea production from (0.932 to 0.71) kg/kg dmt (drier mouth tea), which represented a fuel savings of approximately 25%. The economic analysis considered the annual investment cost and returns cost and included concessions offered by the Government. It showed a payback period of two to four years, depending upon whether the company was profit making or non-profit making.
Dursun et al. (1998) presented a new index, called the “evaporative capacity”, for rating the performance of the solar air heater in a solar drier consisting of solar air heater and a drying chamber in series. The proposed index complemented 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. They presented 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.

A solar collector in the form of a prototype solar cabinet dryer was evaluated at no load as an air-heating system by David et al. (1998). The dryer was operated for 28 days from mid-April to the end of May 1996. For the period of operation, the dryer attained an average temperature of 81.3°C with a standard deviation of 8.6°C within a 7-hr period from 8:00 hr. to 15:00 hr. From hourly temperature considerations, it was determined that the rate of solar energy absorbed by the dryer ranged from 0.51 kW/m² to 0.93 kW/m². The peak was reached at 11:00 hr. and high solar-energy rate of capture of 0.90 kW/m² was maintained for about 6 hr.

Taki et al. (1997) presented experimental and theoretical studies of a flat plate solar air heater. The single pass heater was constructed locally and tested in southern Iraq. The upper face of the rear plate was then painted matt black and tests were repeated to investigate the influence of thermal radiative exchanges inside the air channel. Various parameters, such as temperature, solar intensity, and air flow rate were recorded and used to plot performance curves. A heat transfer model based on the subdivision concept was developed and solved by computer. The predicted transient variation of outlet air temperature compared reasonably well with measured values.

Yousif et al. (1996) described the development and testing of an educational solar air heater. The flat-plate solar air heater was used as a teaching rig for undergraduate students in measurements laboratory sessions, during which the
collector efficiency was determined. The results of indoor testing of the solar collector were presented together with some details of the test facility.

A solar air heater with a build-in-net was proposed and the collection characteristics were experimentally investigated. Eight kinds of metallic nets which had different transmissivity and opening fraction were configured parallel in the space between the transparent cover plate and absorber. The temperature distribution within the air layer and pressure drop were measured and the effects of the net transmissivity and opening fraction on the temperature distribution, collection efficiency and pressure drop were examined by Edmond et al. (1995).

The thermal performances of plastic cover and glass cover air collectors of the same dimensions under identical conditions of insolation and air flow rate were compared. A simple expression taking into account the initial investment, the annual interest rate and the amount of energy which could be extracted from the collector was also developed by Donatien (1995) to evaluate the cost of the energy produced by these collectors as a function of their lifetime. The result from this techno-economic analysis was that the use of a plastic cover collector was recommended whenever the cost of the collector was an important factor in the solar application considered.

Pawar et al. (1994) analysed the performance of a suspended plate solar air heater working at low and moderate temperatures with a fluid flow on both sides of the absorber plate. A theoretical model for the system and subsequent numerical analysis of the system was presented in steady state. Some experimental measurements of the fabricated collector under realistic parameters were made and an optimal design was given.

Al-Nimr (1993) described the transient behavior of a matrix solar air heater. The transient behavior of the heater resulted from sudden changes in the intensity of the incident solar radiation and the inlet fluid temperature. Axial conduction in both the fluid and solid matrix were neglected. The temperature distribution in both the
fluid and solid matrix domains were given exactly and then the performance of the solar heater was evaluated.

An experimental investigation of the enhancement of thermal performance of solar air heater having its duct packed with blackened wire-screen matrices were presented by Sharma et al. (1991). Tests were conducted to cover wide range of influencing parameters including geometry of wire screens, mass flow rates and input solar energy fluxes under actual outdoor conditions. Effect of these parameters on the thermal performance was investigated and results were compared with those of plane (flat-plate) collectors. These tests provided useful data for rating wire-screen matrices packed-bed collectors based on thermal performance. It was observed that the performance of plane collector improved appreciably by packing its duct with blackened wire-screen matrices and this improvement was a strong function of bed and operating parameters.

A new type of solar collector was designed and tested by Ezeike (1986). The design was compact, sufficiently simple and gave high thermal performance. Author deals with the design of a modular drying system consisting of three functional units namely, a triple pass flat plate air collector, a drying cabinet, and a dehumidification chamber. The flat plat collector was 190 cm long, 122.5 cm wide and 23.5 cm deep externally and incorporated two absorbers separated by about 6 cm. The results showed that the outlet temperatures ranged from 90°C to 101°C on clear days and at velocities of up to 3.5 ms^{-1}. Thermal analysis of the collector yielded average efficiencies of 73–81%. There was a steep temperature gradient between the top compartment where temperatures were quite high and the bottom compartment where temperatures were only 2°C–6°C above ambient. Results of the drying tests with rice paddy and yam slices showed that the system dried rice paddy at a layer density of 7.4 kg m^{-2} from 25.93% (wet basis) to 5.31% (w.b.) in 10 hr. and yam slices at a layer density of 5 kg m^{-2} from 64.90% (w.b.) to 10.66% (w.b.) in 31 hr.

The effect of the dimensions of rectangular ducts through which air flows in solar air heaters on the air heater performance was studied by Garg et al. (1984) for
laminar, transitional and turbulent flows. The collector performance and required pumping power to maintain the flow were assessed from a simple mathematical model. The effective energy collected was determined for different case studies and the duct depth was optimized with respect to this effective energy. An optimum duct depth was determined for different flow rates for collecting maximum energy at minimum pumping cost.

An analytical model to study the performance of a two channel suspended flat plate air heater was presented by Dhiman et al. (1984). The effect of different parameters, e.g. spacing between the plates, plate length, same and different flow rates of air in the two channels of the air heater on the air temperature was studied. A comparison of single channel and two channel air heaters was made.

A simple analytical model to investigate the effect of increased heat transfer area on a conventional type air heater was developed by Garg et al. (1983). This was done by incorporating rectangular fins or by vee-corrugating the absorber plate of a conventional type air heater. However, the heat transfer coefficient was assumed to be constant in their analysis. Performance curves were found for different collector configurations and a marked increase in efficiency was noticed with the increase in number of fins. The fluid temperature was also found to increase with the addition of fins, the effect being more at lower flow rates. The effect of vee-corrugating was found to be less promising than addition of fins.

A temperature rise of only 3°C to 6°C above ambient was recommended for drying cereal grains. Such temperatures could be attained in a simple unglazed solar air heater. However, the plate efficiency factor was low. Prasad et al. (1983) work involved the provision of protruding wires on the underside of the absorber plate to improve the heat transfer characteristics and hence the plate efficiency factor. The agreement of the measured heat transfer coefficients with theoretical predictions was found to be satisfactory. The improvements in the plate efficiency factor of the
unglazed collector with a corrugated galvanized iron absorber were considerable, i.e. from 0.63 to 0.72 for a Reynolds number of 40 000.

A theoretical analysis along with the experimental validation study of a solar air heater of the second kind was done by Garg et al. (1982). The heater consists of a flat passage between two metallic plates through which the heat transfer fluid air was made to pass by some auxiliary means. Study of the periodic response of different parameters of this solar air heater was attempted. The heat balance equations governing the behavior of the system were solved explicitly. The results obtained from the analytical expressions for the transient variation of outlet air temperature compared well with experimental data. Predictions were also made regarding effects of different performance parameters of the air heater with variations of air mass flow rate and plate emissivity with the hope of optimizing the collector configuration.

Gupta et al. (1967) reported an experimental study on the performance characteristics of four solar air heaters. Two were of a corrugated type and two were of a mesh type. All used ordinary black-painted surfaces. Instead of comparing the efficiencies at the same rate of discharge, the same amount of pumping power was employed so that the unequal frictional losses were also taken into account in the comparison of over-all heater efficiency. The rating parameters, such as plate efficiency factor, heat-removal efficiency factor, over-all heat-loss coefficient and the effective absorption coefficient were reported for average winter conditions for these heaters at Roorkee, India. The air-heater performance could be computed from these parameters for any other usual range of operating conditions.

2.2 Solar energy storage

Modeling of packed-bed heat transfer could be a problem of immense complexity in some cases requiring the use of 3-D finite element techniques to understand the dynamics of stratification and fluid-solid interaction during different modes of operations. The analytical solution to the packed bed heat transfer was identified by Adeyanju (2009). A set of governing equations that economically and accurately characterize the dominant energy transfer mechanisms in a charging or
discharging packed bed storage tank over a long time periods that include multiple cycles were analyzed.

An indirect forced convection solar drier integrated with heat storage material was developed to test its performance for copra drying. The dryer consisted of a flat plate air heater integrated with a sensible heat storage unit, a drying chamber and a centrifugal blower. The experiments were carried out with and without the integration of heat storage materials. Mohanraj et al. (2009) used sand mixed with aluminium scrap as a heat storage material in solar air heater. The moisture of copra was reduced from about 52% to about 8% in 80 and 104 hrs. respectively for drier integrated with and without heat storage materials. The specific Moisture Extraction Rate was estimated to be about 0.81 and 0.94 kg KW hour⁻¹ for drier integrated with and without heat storage materials respectively. The average solar drier thermal efficiency was estimated to be about 23% in both the drying modes.

A small scale solar agricultural dryer with a simple biomass burner and heat storage back-up heater was described by Elieser et al. (2009). The key design features of the dryer were the combination of direct and indirect type solar dryer, the jacket and gap enclosing the drying chamber as a hot gas passage and the arrangement of the real bricks in the heat storage system. The overall thermal efficiency of the dryer, tested for drying of some different agricultural products, was found to be in the range of 3%-13%. The overall thermal efficiency of the biomass back-up heater was found to be about 20%.

Dilip (2007) presented a transient analytical model to study the new concept of a solar crop dryer having reversed absorber plate type collector and thermal storage with natural airflow. The performance of (1 × 1) m² area of crop dryer with packed bed and airflow channel was evaluated for drying of onions. A 30° inclined absorber plate with in-built thermal storage and 0.12 m width of airflow channel induced the mass flow rate in the range of (0.032–0.046) kg s⁻¹ during the drying process. A reversed absorber plate of 1 m length and 1 m breadth with 0.15 m packed bed could
dry 95 kg of onion from a moisture content of (6.14–0.27) kg water/kg of dry matter in a 24 h drying period.

A transient analytical model for an inclined multi-pass solar air heater with in-built thermal storage and attached with the deep-bed dryer was presented. A parametric study was done by Dilip et al. (2004) for a day of the month of October for the climatic condition of Delhi (India). The rate of moisture evaporation and humidity of the drying air were analyzed with the drying time for different depth of the grain bed. It was observed that the bed moisture content decreased with the time of the day. The humidity of the air and the drying rate increased with the increase in the depth of drying bed.

The periodic analysis of a ground air collector with reflector and crop drying chamber was presented by Goyal et al. (1998). The effects of thermal storage, collector length, depth of the plane of heat retrieval, the flow rate on the useful energy gain and crop temperature were studied. Numerical computation was carried out for the typical day of month of June and December for Delhi climatic conditions. It was observed that there was a significant phase shift 10-12 hr. due to storage effect.

Chauhan et al. (1996) made efforts to study the drying characteristics of coriander in a stationary 0.5 tonne/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 grains stacked upon each other. The theoretical investigation was made by writing the energy and mass balance equations for different components of the dryer-cum-air-heater-cum-storage and by adopting a finite different approach for simulation. The results revealed that for reducing the moisture content from 28.2% (db) to 11.4% (db) the solar air heater took 27 cumulative sunshine hours, i.e. about 3 sunshine days; whereas the solar air heater and the rock bed storage combination took 31 cumulative hours, i.e. about 2 days and 2 nights at an air flow velocity of 250 kg/h m².
The thermal performance of a simple design solar air heater was presented by Hassan (1995). The conventional flat plate absorber was replaced by a set of tubes filled with a thermal energy storage material. The proposed integrated system heat transfer area and heat transfer coefficient were increased and the heat loss was reduced. Based on a simple transient analysis explicit expressions for the heater absorber and glass cover temperatures, effective heat gained outlet air temperature and the heater efficiency were developed as a function of time. The integrated system performance curves were presented and a marked improvement on the system performance was noticed over the conventional flat plate heater system.

An inexpensive augmented integrated solar collector cum storage system using rocks as a sensible heat storage medium was designed and fabricated by Sharma et al. (1991) to provide low grade heat to suit the needs for space heating and agricultural applications. Experimental observations of fluid temperature, energy storage and other measures of system performance were also presented in detail.

A non-mechanical solar dryer based on convective heat and mass transfer, and with energy storage was constructed by Ayensue et al. (1986) and tested to investigate the drying characteristics of various tropical products. Constructed a dryer using material that was available locally. The solar collector was capable of transferring 118 W m$^{-2}$ to the drying air at a temperature of 32°C. The drying constants $k_1$ and $k_2$, the constant and falling rate periods were calculated.

A performance study of three packed-bed solar collectors for air-heating was presented. Iron chips, aluminium chips and pebbles were used as packing materials. Mishra et al. (1981) observed that the performance of plane collectors improves appreciably by packing with blackened metallic materials. Moreover, the packed-bed collector also worked nicely as a thermal storage system. Iron-chips packed-bed collectors showed the best performance.
2.3 Solar drying

Historical highlights of food preserving technology are from 20,000 BC to 1775 AD. This period is broken down into nine epochs. The first food-drying methods used fire, but problems with pretreatment and drying conditions delayed the appearance of dried foods of superior quality until the 19th century.

Based on preliminary investigations under controlled condition of drying experiments, a mixed-mode solar dryer with forced convection using smooth and rough plate solar collector was constructed by Chandrakumar et al. (2013). The thermal performance of solar collector was found to be poorer because of low convective heat transfer from the absorber plate to air. Artificial rib roughness on the underside of the absorber plate was found to considerably enhance the heat transfer coefficient. The absorber plate of the dryer attained a temperature of 69.2°C when it was studied under no-load conditions. The maximum air temperature in the dryer under this condition was 64.1°C. The dryer was loaded with 3 kg of grapes having an initial moisture content of 81.4% and the final desired moisture content of 18.6% was achieved within 4 days, while it was 8 days for open sun drying. This prototype dryer was designed and constructed to have a maximum collector area of 1.03 m².

Drying for agricultural and marine products are one of the most attractive and cost-effective application of solar energy. Numerous types of solar dryers were designed and developed in various parts of the world, yielding varying degrees of technical performance. Basically, there are four types of solar dryers; (1) direct solar dryers, (2) indirect solar dryers, (3) mixed-mode dryers and (4) hybrid solar dryers. This paper by Fudholi et al. (2010) is a review of these types of solar dryers with respect to the product dried and also technical and economic aspects. The technical directions in the development of solar-assisted drying systems for agricultural produce are compact collector design, high efficiency, integrated storage and long-life drying system. Air-based solar collectors are not the only available systems. Water-based collectors can also be used whereby water to air heat exchanger can be used. The hot air for drying of agricultural produce could be forced to flow in the water to air heat exchanger. The hot water tank acted as heat storage of the solar drying system.
A solar drying system was constructed consisting of three parts (solar collector, drying chamber and air blower). Solar collector having v-corrugated absorption plate of two air passes, a single glass cover was used. The total area of the collectors was 2.04 m². The dimension of the drying chamber was 1.06 m, 0.66 m and 0.56 m for width, depth and height respectively. 38 kg of corn was dried. The moisture content was reduced from 21 to 13% within four hours of drying. The drying air temperatures at the inlet of the dryer were found in the range of 30°C to 45°C when the range of ambient air temperature was from 8.5 °C to 20°C and total solar radiation intensity was from (270 to 560)W/m². Increasing volumetric air flow rate from (0.025 to 0.030)m³/s raises the daily solar collector efficiency by 3.25%, while increasing volumetric air flow rate from (0.030 to 0.035)m³/s raises the solar daily collector efficiency by 11.11%. Kareem et al (2011) noticed that the drying rate was reduced when moisture content decreases. Efficiency of the collector was very much dependent on air flow rate. At the lower flow rate (0.025 m³/s), the collector efficiency was found to be 38.7%, at 0.03 m³/s the collector efficiency was found to be 40%, and at 0.035 m³/s the collector efficiency was found to be 45%.

Ahmed et al. (2010) presented the design, construction and performance evaluation of solar drying for maize, the solar drying system consisted of v-groove collector of 2.04 m² area, drying chamber and blower. It was designed in such a way that solar radiation was not incident directly on the maize. K-type thermocouples were used for temperature measurement, while solar radiation was measured. The thermal energy and heat losses from solar collector were calculated for each three tilt angles (30º, 45º, 60º). The results obtained during the test period denoted that the maximum gained energy occurred at 11 O'clock hour and then gradually declined since the maximum solar radiation occurred at this time. The performance of the solar drying system was highly dependent on the solar radiation, tilt angle and ambient temperature. The total loss factor of the collector increases with the increase in the intensity of solar radiation. The theoretical thermal energy, the experimental actual heats gain increase by increasing radiation intensity.
In the study by Tripathy et al. (2009), the application of artificial neural network (ANN) for prediction of temperature variation of food product during solar drying was investigated. The important climatic variables namely solar radiation intensity and ambient air temperature were considered as the input parameters for ANN modeling. Experimental data on potato cylinders and slices obtained with mixed mode solar dryer for 9 typical days of different months of the year were used for training and testing the neural network. A methodology was proposed for development of optimal neural network. In order to test the worthiness of ANN model for prediction of food temperature variation, the analytical heat diffusion model with appropriate boundary conditions and statistical model were also proposed. Based on error analysis results, the prediction capability of ANN model was found to be the best of all the prediction models investigated, irrespective of food sample geometry.

Developments and potentials of solar drying technologies for drying of grains, fruits, vegetables, spices, medical plants and fish were presented by Arun et al. (2009). Previous efforts on solar drying of grains, fruits, vegetables, spices, medical plants and fish using natural convection and forced convection solar dryers were critically examined. Recent developments of forced convection solar dryers such as solar tunnel dryer, improved version of solar dryer, roof integrated solar dryer, greenhouse type solar dryer for their use in rural areas for drying of grains, fruits, vegetables, spices, medical plants and fish were also critically examined in terms of technology and economics in rural areas of tropic and subtropics. A new forced flow type dryer, which consisted of air heater and drying chamber was developed for drying food products. The present drying system was successfully tested. Experiments were performed to test the performance evaluation and drying behavior of the food products and found that in this PV based solar dryer the outlet temperature was about –9°C higher than that of the ambient temperature which was more effective or favorable for drying of agricultural products as compared to traditional drying methods.

An attempt was made by Ramana (2009) to review various aspects of solar driers applied to drying of food products at small scale. Popular types of driers in
Asia-Pacific region and new types of driers with improved technologies were discussed. The open sun drying and some alternate solutions were presented. The various aspects considered for modeling and experimental investigations carried out on various food products were also presented.

An indirect forced convection solar drier integrated with different sensible heat storage maternal was developed and tested its performance for drying chili under the meteorological conditions in Pollachi, India. The system consisted of a flat plate solar air heater with heat storage unit, a drying chamber and a centrifugal blower. Drying experiments were performed by Mohanraj et al. (2009) at an air flow rate of 0.25 kg/s. Drying of chili in a forced convection solar drier reduced the moisture content from around 72.8% (wet basis) to the final moisture content about 9.1% in 24 h. Average drier efficiency was estimated to be about 21%. The specific moisture extraction rate was estimated to be about 0.87 kg/kWh.

A modular solar cabinet dryer equipped with an air collector including a drying chamber with different tray arrangements was developed to determine moisture changes in different sizes and forms (slices and cubes) of apple and carrot pieces and to carry out serial measurements of temperatures, solar radiation and air humidity distributions during the drying process. The initial and final moisture contents (w.b.) of fresh products were 88 and 26% for apple, 71 and 13% for carrot with initial weights of 1.56 Kg and 3 kg respectively. Romano et al. (2009) revealed that the temperature inside the chamber was strongly negatively correlated with air humidity ($R^2 = 0.91$) and that the length of the drying period was influenced by the weather conditions as the cloudy weather retarded drying of carrots. It was possible to reach an air drying temperature over 41°C with a daily total solar energy incident on the collector’s surface of 857.2 kJ/ (m$^2$·day) for apples and 753.20 kJ/ (m$^2$·day) for carrots. The analysis of energy requirements to remove moisture from apples and carrots during the total drying period showed values of 3300.19 kJ/kg and 7428.28 kJ/kg respectively. The amount of air to remove water from the samples was also determined as 126.93m$^3$ for apples and 928.56m$^3$ for carrots.
A forced convection solar drier was designed, fabricated and tested for the drying copra under Indian climatic conditions. Drying copra in the drier reduced its moisture content from about 51.8% to 7.8% and 9.7% in 82 h for trays at the bottom and top, respectively. The copra obtained was graded as 76% milling grade copra (MCG1), 18% (MCG2) and 6% (MCG3) according to Bureau of Indian standards (BIS: 6220-1971). The thermal efficiency of the solar drier was estimated to be about 24% by Mohanraj et al. (2008).

Ajadi et al. (2007) presented the effect of dust on the performance of a solar dryer. Two similar solar dryers were constructed with the same dimensions and materials. The effect of dust on both the absorber temperature $T_a$ and the oven temperature $T_o$ of each dryer was determined for the two experimental setups. The daily absorber temperature $T_a$ and oven temperature $T_o$ were recorded for a period of 25 days for both dryers simultaneously. The daily maximum temperature of the absorber $T_a$ and the oven temperature $T_o$ of each dryer were obtained. The results showed that the values of the oven temperature of the control dryer were always higher and approximately constant in magnitudes between 42°C and 45°C compared with the oven temperature of the test dryer, while the value of the absorber temperatures of the control dryer were between 55°C and 65°C. The maximum temperatures of the absorber and the oven of the test dryer were observed to fluctuate in magnitude.

The performance of the drying chamber of a solar assisted drying system was analyzed. The solar assisted drying system consisted of drying chamber, v-groove collector of 13.8 m$^2$ area, the auxiliary heater and two variable speed centrifugal fans. K-type thermocouples were used for temperature measurement, while solar radiation was measured by Eppley Pyranometer. Drying temperature was considered the most important factor in the drying operation. Salah et al. (2007) used standard equations under steady state condition to calculate the drying chamber efficiency and the heat losses from the chamber room.
A mixed mode type forced convection solar tunnel drier was used by Hossain et al. (2007) to dry hot red and green chillies under the tropical weather conditions of Bangladesh. The drier consisted of transparent plastic covered 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 drier 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\(^{-1}\) (dry basis) in 20 h in solar tunnel drier and it took 32 h to reduce the moisture content to 0.09 and 0.40 kg kg\(^{-1}\) in improved and conventional sun drying methods respectively. In case of green chilli about 0.06 kg kg\(^{-1}\) moisture content was obtained from an initial moisture content of 7.6 kg kg\(^{-1}\) in 22 h in solar tunnel drier and 35 h to reach the moisture content to 0.10 and 0.70 kg kg\(^{-1}\) in improved and conventional sun drying methods respectively. The use of a solar tunnel drier 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 drier and blanching of chilli were recommended for drying of both red and green chillies.

A drying system was constructed, consisting of three parts (solar collector, solar drying cabinet, and air blower). Two identical air solar collectors having V-corrugated absorption plates of two air passes, a single glass cover was used by Khalil et al. (2007). The total area of the collectors is 2.4 m\(^2\). The dimensions of the drying cabinet were (1×0.33×2) m (width, depth, and height). The cabinet was divided into six divisions separated by five shelves. The distance between the shelves was 0.3 m except the upper one, which was 0.5 m from the roof. Each shelf was (0.95 × 0.3) m and is made of metallic mesh. The drying chamber walls were made of aluminum plate except the southern side, which was fixed with glass plate having the dimensions (1 × 2 × 0.002) m. Two types of fruit and one type of vegetables were dried during the present work. These were grapes, apricots, and beans. The moisture content of apricot was reduced from 80% to 13% within one day and a half of drying. Moisture content of grapes was reduced from 80% to 18% in two and a half days of drying, while that of beans was reduced from 65% to 18% in one day only. The results showed that the most effective factor on the drying rate was the temperature of
the air inside the cabinet. The effect variation of speed of air inside the drying cabinet was small and could be neglected. The relative humidity of air exit from the cabinet was small between (25–30%) and therefore there was no need for high velocity air inside the cabinet.

A direct passive solar dryer was designed, constructed and tested using local available materials by Alonge et.al.(2007). Certain theoretical and design considerations such as volumetric air flow, wind speed, weight of moisture removed, daylight hour, declination angle and the time of drying were considered. The dryer was tested under no load and load conditions. The result of no load conditions gave the maximum of 59°C inside the dryer while outside the dryer was 38°C. The solar dryer was used to 2160 g of yam chips with initial moisture content 62 % to final moisture content of 11.11%. The drying time of yam chips during the test was 26 sunshine hours as compared as 36 hours as open air. The percentage moisture loss inside the dryer was higher.

The utilization of energy in a Mixed Mode Solar Dryer was evaluated by Akinola et.al (2006). Exergetic analysis of the dryer revealed that drying in a cabinet other than direct sun drying made drying more attractive and as well conserve energy. It had also an overall exergetic efficiency of 56 % and thermal efficiency of 66.95%.

The objective of Fadhel et al. (2005) was to analyse the drying of the Sultanine grape variety by three different solar processes. Three drying kinetics were established in a natural convection solar drier under a tunnel greenhouse and in open sun. These tests showed that the solar tunnel greenhouse drying was satisfactory and competitive to a natural convection solar drying process.

The solar dryer reported here was developed by Sukhmeet et al. (2004) to enable farmers to add value to their produce by drying it at farm itself. The dryer had a multi-shelf design with intermediate heating, passive, integral, direct/indirect and portable solar dryer. Intermediate heating of air in-between trays resulted in uniform drying in all the trays. Since the dryer at the farm was not likely to be used throughout
the year it was made portable. A novel feature of this dryer was that the product could be dried under shade or otherwise as per requirement. The design was low cost to make it economically viable. The maximum stagnation temperature was 75°C in the month of November at Ludhiana (31°N). During experiments on drying of fenugreek leaves the moisture evaporation on first, second and third drying day was (1.4, 0.9 and 0.4) kg/m² of aperture area. To overcome the problem of reduction in efficiency on second and third drying day, a semi-continuous mode of loading was investigated in which the efficiency remained almost the same on all drying days. The shelf life of the dried product was more than one year.

A solar collector, part of a drying system using solar energy as a heat source, was developed and reported previously and used in product-drying applications by Cigdem et al. (1998). In this study, energy efficiency analysis of the drying system in terms of the collector efficiency was investigated.

A flat plate and offset plate fin absorber-plate collectors were used by A. Hachemi et al. (1998), as a heat source and were linked to the forced dryer. The performance of the solar dryer improved remarkably, in relation to the use of the solar dryer with a flat-plate collector and the drying time was consequently reduced. A summary of theoretical analysis was given and experimental results were established in the study.

A detailed description of a novel direct-mode solar dryer with a staircase design was presented by Hallak et al.(1996). The temperature variation of the dryer compartments with time of day was plotted. Its efficiency values as a solar collector ranged between 0.26 and 0.65.

A solar dryer, which consisted of a solar air heater and a drying chamber, was developed for drying food products. The present drying system was successfully tested using sultana grapes, green beans, sweet peppers and chilli peppers. The traditional sun-drying experiments were employed and compared with the solar-drying experiments. Cigdem et al. (1996) showed that the use of this type of solar
dryer reduced the drying time significantly and essentially provided better product quality.

Cigdem et al. (1995) dealt with the construction and performance of a solar powered drying system consisting of a solar air heater and a drying chamber. The thermal efficiencies of both the solar air heater and the drying section as a function of typical physical parameters and the experimental results for different food products at different air flow rates were discussed. The results of this study indicated that the present drying system had thermal efficiencies between 0.3 and 0.8 during drying experiments and that the higher flow rates increased the overall drying performance and especially efficiency.

A new solar dryer, which consisted of a solar air heater and a drying chamber, was developed and used for drying agricultural products. The present drying system was successfully tested using sultana grapes, green beans, sweet peppers, and chilli peppers. Traditional sun drying experiments were employed by Cigdem et al. (1994). The drying curves of the solar dried products were compared with traditional sun-drying results. Use of the solar dryer reduced the drying time by factors of 1.7, 2.2, 1.8, and 2.2, respectively, for sultana grapes, green beans, sweet and chilli peppers prevented mass losses and provided better product quality.

Diamante et al. (1993) used an indirect solar dryer to study the drying of sweet potato slices. The solar drying rates of sweet potato slices were affected by the fluctuating chamber temperature over the drying period. Solar drying rate curves exhibited a constant rate period and one linear falling rate period. A mathematical model for solar drying of sweet potato slices was derived based on the simplified form of the Fick's diffusion equation. The mathematical model could satisfactorily describe the solar drying of sweet potato slices to moisture content below 20% dry basis. The mean effective drying chamber temperature and sample thickness were the main factors that affected the solar drying process for sweet potato slices.
Sharma et al (1991) discussed the design methodology, performance studies and analytical solution of a cabinet type solar dryer. Experimental results of different experiments conducted with different products in a New Delhi climate were included in the study.

A small solar dryer consisting of a drying unit, thermal storage and solar collector was designed for the climatic conditions of Papua New Guinea, constructed and tested at the Energy research site of the University of Papua New Guinea. Detailed experimental studies were carried out by Lawrence et al. (1990) for drying of tapioca as well as the testing of the drying unit with and without thermal storage.

Thanvi et al. (1987) gave reports on the designing details and performance of a low cost solar dryer. The dryer was effectively used for drying (10-15) kg of fruits and vegetables. The experimental trial showed that the drying time in solar dryer was 50% less than that of open courtyard drying.

A simple shelf type drier was described and test results were outlined by Kudret et al. (1974). The mathematical model of the multi-shelf type drier was developed and its solution using a digital computer was compared with test results to verify the mathematical formulation. Theoretical values of temperatures and drying rates were presented. Extension of the analysis for the refinement of the shelf type driers was discussed.

A prototype solar fruit and vegetable drier was developed by Akyurt et al. (1973). This comprised a glass covered flat plate collector containing metal chips, a drier with translucent walls and an insulated tunnel joining the two. Bell peppers and sultana grapes were dried to commercially acceptable moisture levels in various kinds of weather conditions and at various air velocities. The qualities of the dried product as well as the drying times were found to be in favor of the solar drier as compared with open-air drying. Likewise an economic analysis was undertaken to investigate the possibility of using various heat sources for an auxiliary heating system. Such a system was developed and coupled to the prototype to enable all-weather operation.
2.4 Scope of the work

Extensive work on solar air heaters has been reported in the literature. Various geometries have been proposed and their theoretical investigations are carried out. In this work an attempt has been made to design and fabricate solar dryer with a thermal storage unit with three different solar air heater designs.

Type I : Flat plate absorber collector with thermal storage and solar dryer.
Type II : Parallel plate absorber collector with thermal storage and solar dryer. This is the first attempt as review of literature does not show any evidence of such parallel plate absorber collector used as solar air heater.
Type III : v-groove absorber collector with thermal storage and solar dryer.

The scope of the project is to improve the thermal performance of the solar air heater and to use the same for off sunshine hours using thermal storage unit and also for possible drying applications.