CHAPTER 2
LITERATURE REVIEW

This chapter presents a review of literature on the developments in the area of harnessing solar energy for various applications, with a special focus on utilization of solar energy by employing parabolic concentrators for purposes of heating, cooking and use in water desalination systems. Since the present study has been carried out for design and fabrication of water desalination system for a rural household, work done in this area by researchers have been thoroughly reviewed with regards to approaches used and tools and techniques employed. Thrust of the ongoing research and limitations of existing approaches are highlighted. The review of literature has been categorized as under:

1. Solar energy and its applications
2. Water desalination systems and use of solar energy
3. Developments in analysis, design and fabrication of parabolic concentrators
4. Developments in analysis, design and fabrication of heat absorbers
5. Developments in analysis, design and fabrication of steam condensers
6. Mathematical modeling of solar heating systems

2.1 Solar Energy and its Applications

Solar energy is considered to be the most promising source of energy. Solar energy can be utilized for many thermal applications such as heating, deformation of metals, power generation, refrigeration and many more. Now a day, sun power has provided the most efficient and most reliable solar products available in the market. Different industries and researchers are actively engaged in research in the area of solar energy.

Badran and Hamdam (1997) have described a process of utilization of solar energy for preheating fuel oil. In countries like Jordan, where fuel oil is used as a major source of energy, a large amount of fuel was used for heating it to the required temperature. They used solar energy as an alternative source to heat the fuel oil to a temperature of about 50°C. In this work, the performance of a conventional flat-plate collector filled with fuel oil was studied theoretically and experimentally. The performance was also compared with that of an identical collector filled
with water. It was observed that the exit temperature from the fuel oil collector for the same incident solar radiations was higher than that at the exit of the solar collector. Efficiency was determined using heat balance equations. The deviations of experimental and theoretical observations were attributed to various factors like uncertainty regarding bond conductance, experimental error and manufacturing discrepancies of the collectors.

Lytvynenko and Schur (1999) have explained utilization of the concentrated solar energy for process of deformation of sheet metals. Importance of super plastic forming (SPF) was explained in this work, most important part that with the utilization of the concentrated solar energy, the operation can be made simpler and cheaper. Deformation experiments were performed for forming with a punch and negative forming. Several sheets made of aluminum alloys, brass and iron alloy were employed. The mirror dish concentrators with diameters of 1500 mm and of 5000 mm were used for heating the metals by solar energy. Solar tracking system was automatic. Results showed uniform deformations in almost all the experiments. Thus utilization of the concentrated solar energy for heating during forming of sheet metals was justified for the places which are located away from conventional power sources.

Badran (2001) has discussed industrial applications of solar energy and the range of their utilization in Jordan which does not have enough amounts of oil and natural gas but has a huge amount of solar energy available for most part of the year. This research was mainly a review of the industrial applications of solar energy, which may be useful for the development of military equipment and for energy economy. He explained a study of various solar thermal applications and found that solar water heating, space heating, photovoltaic-pumping systems and solar desalination have already made a small but encouraging impact on the Jordanian energy scene. It was shown that other applications using heat directly, like power generation and refrigeration, have not been evolved yet. This study also recommended that the Jordanian government should encourage research centers to take more serious steps towards the utilization of industrial solar energy.

Karagiorgas et al. (2001) explored the potential for application of solar thermal systems in sectors such as food industry, agro-industries, textiles and chemical industry. In this paper, these systems were evaluated in economic terms in comparison with energy equivalent systems.
Design and material quality requirements for solar systems in these industrial applications were studied. Design for collectors, absorbers and storage tanks were studied. Various current applications were reviewed and their inadequacies were also explained. After the review it was observed that installation of different solar harvesting devices such as solar dryer, parabolic through system and flat plate collectors for different applications can be economically attractive for the users. He also proved that use of such systems offer significant energy savings and provides environmental benefits to the society.

Kalogirou (2003) has explained the potential of solar industrial process heat applications. The range of temperature requirements of solar industrial process heat applications was determined. The characteristics of medium to medium-high temperature solar collectors were given. An overview of efficiency and cost of existing technologies was presented. Five collector types were studied varying from the simple stationary flat-plate to movable parabolic trough ones. Transient simulation program TRNSYS was developed for such systems. Based on TRNSYS simulations, an estimation of the system efficiency of solar heat plants operating in the Mediterranean climate were given for different collector technologies. The annual energy gains of using such systems were determined. The resulting energy costs obtained for solar heaters were estimated depending on the collector type applied. Dependency of the costs on international market trends and oil production rates was stressed. It was explained that costs will turn out to be more favorable when the solar collectors become cheaper and subsidization of fuel is removed. An optimization procedure was suggested in this paper to select the most appropriate system in each case.

Kalogirou (2004) conducted a survey of various types of solar thermal collectors and their applications and was presented in his work. Initially, an analysis of the environmental problems related to the use of conventional sources of energy was presented and the benefits offered by renewable energy systems were outlined. Various types of collectors like flat-plate, compound parabolic, evacuated tube, parabolic trough, Fresnel lens, parabolic dish and heliostat field collectors were explained. Optical, thermal and thermodynamic analysis of the collectors and a description of the methods used to evaluate their performance were described. Typical applications of various types of collectors were presented. These include solar water heating, space heating and cooling, heat pumps, refrigeration. Focus was also given on industrial process heat, which comprises air and water systems, steam generation systems, water desalination and
thermal power systems. Application of various devices such as the parabolic trough, power tower dish systems and solar furnaces were explained. The application areas described in this paper show that solar energy collectors can be used in a wide variety of systems and can provide significant environmental and financial benefits and should be used whenever possible.

Arulkumaran and Chirstraj (2012) performed experimental analysis of solar parabolic dish concentrating system which was used for steam generation. The evaporation part setup included a solar parabolic dish system and absorber. A galvanized steel pipe was used to carry water from a tank to the coiled absorber tube made up of copper and located in the focal point. The performance of the concentrator was studied experimentally with the water circulated as heat transfer fluid. Highly reflective aluminium foil sheet was used for fabrication. The experimental setup was placed in open, where tests were carried out. Heat transfer analysis was carried out to obtain its efficiency. The designed system eliminates tracking the sun in the east west direction and optimal tracking of the sun in the north-south to obtain maximum solar energy. The experimental results were taken on summer and cloud free days. The maximum temperature achieved was 215°C with solar steam conversion efficiency of 60-70%.

2.2 Water Desalination Systems and Use of Solar Energy

Desalination, in general means to remove salt from seawater or generally saline water. Desalination can be achieved by using a number of techniques. Different desalination systems have been studied and analyzed by the researchers.

Rheinlander and Grater (2001) discussed the application of desalination process for the supply of potable water to villages located in remote areas or having no back-up of reliable public water services by local means. Data pertaining to source data on the local climatic, technical and socio-economic conditions were collected. A computational tool was developed to achieve a pre-selection of appropriate systems from the wide range of technologies available in those days, including those suitable for the use of energy from renewable sources. Excel workbook DESAL including information and performance characteristics for most technologies were compiled. The results were used to lay a ground for the detailed decisions on the feasibility and the concept for the project development. The results of the evaluation of key data on design and economics can easily be used for a pre-feasibility analysis.
Rodriguez et al. (2001) explained indirect desalination systems with various technologies including distillation and its applications for future. The steam generated by solar energy is used to drive a reverse osmosis plant with parabolic trough collector. A solar distillation system consisting of two separate devices—the solar collector and the distiller as well as an integrated system were considered. They were classified as indirect solar desalination process and the direct solar desalination process, respectively. This paper dealt with indirect solar desalination and its perspectives in the future. First, a summary of existing plants was given followed by the different technologies were compared. Finally, the possible improvements of thermal solar and seawater distillation technologies were considered in order to analyze the perspectives of the competitiveness of solar vs. conventional energy in seawater desalination. The use of solar energy in thermal desalination processes was found to be one of the most promising applications of renewable energies to seawater desalination.

Rodriguez et al. (2002) carried out global analysis of the use of solar energy in seawater distillation under Spanish climatic conditions. Static solar technologies as well as one-axis sun tracking were compared. Flat-plate Collector (FPC), Evacuated Tube Collectors (ETC), Compound Parabolic Collectors (CPC) and Parabolic Trough Collectors (PTC) were compared. Different temperature ranges of the thermal energy supply required for a desalination process were considered. Parameters like fresh water production capacity and collector area required were analysed at all the temperatures. The performance ratio (PR) of the solar multi-effect distillation (MED) and multi-stage flash (MSF) plant was studied. Concept of Direct Steam Generation (DSG) in parabolic troughs was introduced. It was found that the DSG increases the fresh water production of conventional PTC between 18-32%. Considering all these factors and also the cost of desalination plant, parabolic trough systems with one axis tracking were found to be more efficient.

Fath and Ghazy (2002) carried out a numerical study to investigate the performance of a simple solar desalination system using humidification-dehumidification processes. The components of desalination system were listed as solar air heater, humidifier, dehumidifier and a circulating air-driving component. Effects of environmental, design and operational parameters on the desalination system productivity were studied. Environmental parameters include solar intensity,
ambient temperature and wind speed. Design parameters include the solar heater base insulation, humidifier and dehumidifier effectiveness. Operational parameters include air circulation flow rate, feed water rate and temperature. The results indicated that the solar air heater (energy source) efficiency significantly influences system productivity. By increasing the solar intensity, ambient temperature and reducing wind velocity, system productivity increases. The feed water flow rate has an insignificant influence on system productivity. The surprising result was that the dehumidifier effectiveness has an insignificant influence on system productivity, which has a very important implication for the system's economy.

Joseph et al. (2004) studied desalination with flash distillation process using vacuum pumps and condensers driven by electricity. In this paper, an attempt has been made to study a single stage solar desalination system to get a specific output of potable water. The components of experimental setup were flat plate collector, an evaporator, a single stage vacuum pump and a condenser. The effect of variation of input parameters such as solar irradiance and vacuum pressure in the flash evaporator were studied. Efficiency of this plant was measured for different solar radiations. A maximum distillate yield of 5 liters per day was obtained with collector area of 2 m². The frequency of operation of the vacuum pump and the yield of desalinated water for various beam solar radiations was carried out from which the cost of water was determined. The desalinated water was tested for various parameters required to make it potable. The quality of water was found satisfactory and the impurities well below the permissible limits.

Kalogirou (2005) explained various techniques of seawater desalination using renewable energy sources. The paper explained evolution of desalination followed by emergence of the need of desalination systems in the present situation of energy crisis. A large variety of systems used in industry to convert seawater into fresh water were discussed. Different types of desalination systems like MED, MSF, vapor compression process, reverse osmosis, electro-dialysis and solar stills were discussed along with their working and energy analysis. It was shown that renewable energy system produces energy from environment friendly sources freely available in nature. Review of renewable energy desalination systems was carried out. Solar ponds, photovoltaic and wind energy systems were discussed in detail. The factors that affect selection of correct renewable energy desalination system were explained. Factors like plant size, feed water salinity, remoteness, availability of grid electricity, technical infrastructure and the type and potential of
the local renewable energy resource were considered. It was found that solar thermal energy is one of the most promising applications of renewable energy to seawater desalination (Kalogirou, 2011).

Safwatnafey et al. (2006) conducted theoretical and experimental study on a small unit for water desalination using solar energy and flashing process. In this work, the system was investigated theoretically and experimentally at different real environmental conditions along Julian days of one year. A mathematical model was developed to calculate the productivity of the system under different operating conditions. The system consisted of a solar water heater with a flat plate solar collector working as a brine heater, and a vertical flash unit which was attached with a condenser unit. The feed water from preheater entered in the solar collector to raise the temperature of brine solution before entering the flash chamber. Then hot seawater entered the flash chamber by passing through a brine injector. The seawater injector was operated at maximum flow rate equal to 1.4 liter/min and minimum flow rate equal to 0.8 liter/min. The wasted brine then exited after releasing its vapor that condensed on the condenser tubes to produce fresh water. The average production of pure water in November, December and January was between 2.5 to 3.5 kg/day whereas, the average summer productivity was in the range of 10 to 12 kg/day.

Gálvez et al. (2008) designed innovative yet technically simple solar-powered membrane distillation system for seawater desalination. The paper deals with the MEDESOL (Seawater Desalination by Innovative Solar-Powered Membrane Distillation System) project. The main objective of the project was the development and experimental analysis of solar multi-stage MD system for increasing efficiency and reducing cost. Simplicity, low maintenance and high quality were the given priority areas in the design. The compound parabolic solar concentrator, developed for the specific concentration ratio, acted as heat source, to achieve the specific needed range of temperatures, and the advanced non-fouling surface coatings were used in seawater heater to avoid scaling. Scenarios in two countries, Spain and Mexico were discussed. RO and a multistage MD system were compared and was found that they withstand fouling and scaling better than RO systems. Five different configurations of MD systems were studied. The three systems were theoretically analysed, constructed and tested within MEDESOL. Finally cost-effective, efficient systems were developed within the framework of MEDESOL project which would work even in the remote areas where the electric grid is not available.
Zhao (2008) developed a combined desalination and power generation system using solar energy. The work forced a novel concept for a system powered entirely by renewable energy to produce both fresh water and electrical power from saline groundwater or seawater. The system was entirely based on solar thermal energy, with particular emphasis on lower-temperature solar thermal collectors and storages such as solar ponds. The system was designed primarily for operation at input brine temperatures in the range of 50 – 80°C, but consideration was also given to the potential for operation at higher temperatures up to 100°C obtained from other types of solar collectors. Salty groundwater was heated to a temperature of between 50°C and 95°C by a solar-thermal collector and introduced through a hollow shaft to a nozzle exhausting out into an evacuated chamber. The quality of the fresh water produced by the system was very high. It was found that residual salt concentration can be as low as 10 and the cost of operating a RO desalination system will increase together with the salt concentration of input brine.

Amos (2009) developed an advanced passive solar still with separate condenser. The work was done to improve the efficiency of solar still. A model was developed for calculating the distribution of solar radiation in a single-slope solar still. This model was applied to advanced solar still with a separate condenser. Numerical results were then used to design and fabricate prototype stills which were tested outdoors at the University of Strathclyde. The system consisted of separate evaporator and condenser. Results have shown that the new solar still gave a higher distillate output than a conventional type because of the integrated heat recovery unit. The daily productivity of the system was about 3-4 kg/m² with a maximum thermal efficiency of 35%.

Gude et al. (2011) discussed desalination using solar collectors augmented by thermal energy storage to run the desalination process round the clock without contributing to greenhouse gases. In this research, an innovative low temperature desalination system has been developed to utilize low grade heat sources such as waste heat releases, solar or geothermal energy sources. Low operation temperature minimised energy losses and hence energy requirements for desalination. Variations in solar radiations were considered to estimate the requirements for solar collector area as well as thermal energy storage volume. Mass and heat balance equations were developed. Results obtained from the modeling studies were validated experimentally. The study confirmed
the vital role played by thermal energy in managing the variable energy resource to maintain the performance of the desalination system during non-sunlight hours and cloudy days. Low temperature desalination process capable of producing 100 liter per day freshwater was designed to utilize solar energy harvested from flat plate solar collectors.

Elkader et al. (2013) developed a solar desalination unit based on a humidification-dehumidification process which has been proved to be suitable to provide fresh water for population in remote areas. The desalination chamber was divided into humidification and dehumidification towers. The circulation of air was maintained by forced convection between the two towers. Theoretical and experimental studies were carried out at different environmental conditions. A mathematical model was formulated in which the thermodynamic relations were used to study the flow, heat and mass transfer inside the humidifier and dehumidifier to increase the unit performance. Finite difference technique was employed to solve governing equations, based on heat and mass balance. The solar intensity was measured along the working day during the summer and winter months. The theoretical and experimental results were compared. The average accumulative productivity of the system in November, December and January ranged between 2 to 3.5 kg/m²/day while the average summer productivity was found between 6 to 8 kg/m²/day.

Agboola et al. (2014) investigated four configurations of an inclined solar still for solar desalination system. Experimental and economic analysis of various factors like daily production, efficiency, system cost, and distilled water production cost were discussed. Different configurations were shown to be the best for a specific parameter. The improved designs were tested with bare absorber plate, wick on absorber plate, and wire mesh on absorber plate. Also the different spray jet arrangements were tested on the designs for optimum performance. Payback periods were calculated in each case. All these systems were found economically and technically feasible as solar desalination systems for potable water.

2.3 Developments in Analysis, Design and Fabrication of Parabolic Concentrators

Parabolic concentrators play an important role for focusing solar energy on to a heating area. Various types of concentrators are used for heating applications. Utilization of solar energy largely depends upon the construction and the tracking mechanism of the concentrator. Analysis
on different types of concentrators have been made as per the desired application and few of them are disused below.

Rubio et al. (2007) in their paper presented a control application that performs solar tracking for concentrator with high accuracy without the necessity of recalibration. Performance of a solar concentrator can decrease due to errors in alignments and tracking. This paper explained the need and presented a control strategy for two axes trackers executed using microprocessor. In summary, there were three main aspects concerned with this control strategy, a new sun tracking strategy for low cost position with two degrees of freedom, a simulator that allows to evaluate how the tracking strategy is working and a mechanical structure that acts as a solar tracker. Simulation and experimental results were compared between a classical open loop tracking strategy and the proposed hybrid one. Simulation and experimental results have shown that new strategy gives more benefits than classical open loop strategy.

Dascomb (2009) in his thesis explained the concept of low-cost concentrating solar collectors for steam generation. The work presented the use of concentrating solar power to provide electricity, refrigeration and water purification in one unit. An economic parabolic dish concentrating system was built at the Sustainable Energy Science and Engineering Center at Florida State University. The aim of the project was to provide 6.67 kW of thermal energy using a conventional micro steam turbine. The concentrator was coated with a highly reflective polymer film. Sodium nitrate was filled in the cavity type receiver which acts as a heat storage and transfer medium. Thermal losses were determined for each component and the losses from the absorber were also calculated. Other losses were considered due to mirror reflectivity, mirror wear, absorptive, imperfect insulation and receiver conduction to the support arm. The gross thermal conversion efficiency of the system was calculated and found to be 39%.

Chong and Wong (2009) derived a general formula for on-axis sun-tracking system using coordinate transformation method. Two most commonly used configurations in two-axis sun-tracking system were azimuth-elevation and polar tracking system which have their own application domains. Azimuth-elevation system was based on ordinary optical mirror mount while tilt-roll polar tracking system drives the collector to follow the sun-rising and sun-set. The change of the tilting angle of the collector due to the yearly change of sun path was also
discussed in the work. Accuracy of both systems was based on alignment of the concentrator. But, the general sun-tracking formula in the paper was derived using matrix method. It not only provided a general mathematical solution, but more significantly, it improved the sun-tracking accuracy by tackling the misalignment of solar collector during installation.

Ying Yeha et al. (2011) in his paper proposed a novel concentration solar collector and developed the focal point tracking system for it. Instead of rotating a heavy concentrating lens, the proposed system moves the photo transducer. It was observed that the design required no exposed moving parts that were difficult to maintain and consumed less power to move the lightweight solar transducer. The design was also found suitable for vertical applications like building walls. This paper explained the procedure to calculate the trajectory and then built an experimental setup to verify the concept. The experimental results proved that the proposed focal tracking system consumes less power and achieves solar energy conversion efficiency as comparable to the conventional systems.

Mohamed et al. (2012) designed and fabricated solar dish concentrator with 1.6 meters diameter for water heating application and for generation of steam. The dish was fabricated using galvanized steel and its interior surface was covered with a reflecting layer of reflectivity up to 76%. The system was equipped with a receiver (boiler) located in the focal position. The heat receiver was made of stainless steel cylindrical tube, coated with a thin layer of black paint as antireflection coating and was located in the focal zone of the solar dish concentrator. Water heating was done by passing water through helical wrapped copper tubes inside the receiver cavity. It was observed that the inlet and outlet water temperatures increased during daytime between 9:30 A.M. to 1:30 P.M. because of high solar intensity. The dish was equipped with the tracking system and the temperature of water was measured and found to be in the range of 80°C and the system efficiency was found to be 30%.

Garcia et al. (2012) developed an efficient parabolic dish engine based on Rankine cycle. They carried out a case study to evaluate the technical viability of a parabolic dish concentrator to convert solar energy into electric power. This was done by means of a high performance Rankine cycle operating with ethane, ammonia or water. Thermal efficiency and net developed work were compared. Parabolic Dish Concentrator was used to convert the solar energy to mechanical
energy and then to electrical power. System used a mirror array to reflect and concentrate incoming solar radiations to a receiver using dual axis tracking. Among all concentrated solar energy technologies, parabolic dish based systems have demonstrated the highest efficiency, approaching 30%. The receiver was designed to absorb the concentrated solar radiations and to transfer as much energy as possible to a high transfer fluid. Results obtained show that Rankine efficiency was greater than that of the Stirling cycle under the same operating temperatures with Stirling engine conversion efficiencies of around 30% to 40%. Thermal losses were determined for each component. The losses from the absorber were also calculated. Other losses were considered due to mirror reflectivity, mirror wear, imperfect insulation and receiver conduction to the support arm. The gross thermal conversion efficiency of the system was calculated and found to be 39%.

Mohammed (2012) designed and developed a parabolic dish solar water heater for domestic hot water application. The concentrator acted as a water heater and was used to provide 40 liters of hot water a day for a family of four. To improve the efficiency of the system, an automatic electronic control circuit was designed and developed for automatic tracking. Experimental test showed that the thermal efficiency of the system was in the range of 50%. The diameter can be decided as per the requirements.

2.4 Developments in Analysis, Design and Fabrication of Heat Absorbers

The reflected heat energy from the concentrator in a solar heating system is focused on the absorber. For maximum utilization of focused heat, the absorber has to be designed optimally by considering all relevant parameters. A large number of studies have appeared in the literature related to different types of absorbers. Parameters considered are material used, size and the type of analysis carried out. A brief account of these studies is given below.

Bonometti and Hawk (2001) developed a new approach to evaluate the material properties of a solar absorber wall and experimentally tested the method using sample coupons. They measured the reflectivity, both at ambient and elevated temperatures over a range of angles from $0^\circ$ to $90^\circ$. The same experimental data set was used to calculate the sample’s total reflectivity by uniquely integrating the recorded intensities over a hemisphere. The test methodology used the incident solar energy as the heating source. The reflected light was measured directly and was found
suitable for test samples over temperature of 3,000 K. Temperature dependence was analysed as an important factor influencing the reflectivity measurement. The identical, reflective raw test data was used to approximate the sample’s total reflectivity and investigate its temperature dependence. New experimental measurement methodology developed was found to be excellent. This new methodology was used to conduct measurements with the sample at 1000 K and under a vacuum. It was concluded that the new analytical approach was seen as a valid method to estimate total reflectivity.

Wazwaz et al. (2002) explained the solar thermal performance of a nickel pigmented aluminum oxide absorber by using an experimental model (prototype model). The effect of the optical properties of the selective absorber nickel-pigmented anodized aluminium on calculating the conversion efficiency and effect of environment conditions and the configuration of the system (prototype) on the heating power of the selective absorber were discussed. Prototypes of different volumes were used. The thermodynamic characteristics of each flat-plate collector were determined and conduction and convection losses were studied. The constructed models were tested outdoors during daylight under a clear sky. The solar radiation flux was measured at a fixed time during the day. The effects of absorptivity, emissivity and prototype volume on the collective flux and conversion efficiency were discussed. The relationship between the parameters was explained.

StankoShtrakov et al. (2006) described an application of the finite element method for thermal analysis of concentrating solar receivers. Heat conductivity transfer model was used for calculation of temperature distribution in the receiver for Dish Sterling concentrating solar system. The method yields local geometric flexible discretized equations which are then solved by a computer program. They performed a large number of numerical experiments to validate these results.

Bellel (2011) studied two types of cylindrical steel absorbers of a spherical concentrator. One absorber was closed type and the other coiled type. The first was filled with water and the second contained a copper coil open at the bottom, containing a coolant (water) whose energy supply was provided by a spherical concentrator. Determination of operating characteristics, the temperature of the absorber, the power and the efficiency were the main objectives of research.
The thermal characteristics of the absorber were determined using energy balance equations. Convection and radiation losses were considered and effect of wind on the losses was analyzed. They were used to calculate the temperature concentrated at the surface in the first absorber. Implicit finite difference method was used to solve the heat equation. The numerical results by computer code showed good agreement with those obtained through an experimental study conducted in parallel. Various suggestions were made to improve the efficiency.

Wang et al. (2012) investigated the temperature field and thermal stress of dish solar concentrator’s focal region. With finite element method, they used a modified radiant heat flux function dependent on the solar radiant flux and velocity, to calculate the temperature field of a plate on the focal region of a dish solar concentrator. There was a good accordance when these results were compared with picture taken by an infrared camera.

Gómez et al. (2012) simulated a solar radiation absorber with CFD techniques and the results were compared with experimental data. A solar furnace was used as the concentrator. The porous medium was modeled with a dispersed particle approach. Heat transfer of the media was calculated separately for a non-equilibrium approach and was simulated using ANSYS fluent. Discrete ordinates model was used for radiation. Heat balance analysis was carried out theoretically. It was found that the CFD results were in reasonably close agreement.

2.5 Developments in Analysis, Design and Fabrication of Steam Condensers

Condensation of steam is an important process in a desalination system. Condensation of steam is possible by using different types of heat exchangers. The mass flow rate and properties of the fluid are the major concern while designing a heat exchanger. All heat exchangers needs external source for circulations of fluids. One of the major difficulties in modeling of a two phase flow is determining the distribution of the liquid and the vapor phase in the flow channel. As the performance parameters such as heat transfer and pressure drop are closely related to this distribution, the calculation of the two phase flow pattern by means of computational fluid dynamics (CFD) can be very useful. However, there is not much work reported in the literature on the CFD analysis of multi-phase flows. An account of work reported in the literature regarding these aspects is briefly presented below.
Sparrow and Gregg (1969) carried out boundary-layer analysis of condensation on a single horizontal cylinder. Their study extended Nusselt’s simple theory by including the inertia forces and energy convection terms. The starting point of their study was the boundary layer equations appropriate to the horizontal cylinder. They transformed partial differential equations of the boundary layer equations to ordinary differential equations which are valid over a major portion of the cylinder. The transformation they made coincides with those for condensation on a vertical flat plate. Utilizing numerical solutions of the transformed equations, heat transfer results were presented for the horizontal cylinder over the Prandtl number range from 0.003 to 100.

Makas (2004) has investigated the problem of condensation of steam on a vertical tier of horizontal tubes by both analytical and experimental methods. Initially, fundamentals of flow regimes have been discussed. A computer program, written in Mathcad, has been implemented for the analysis of film condensation. The program was capable to calculate condensate film thickness and velocity distribution, as well as the heat transfer coefficient within the condensate. An experimental setup was also fabricated to observe the condensation phenomenon. Effects of tube diameter and temperature difference between steam and the tube wall on condensation heat transfer were analytically investigated with a computer program. Experiments were carried out at different inclinations of the tier of horizontal tubes. Effects of the steam velocity and the distance between the horizontal tubes were also experimentally investigated. It was concluded from the experiments of the first stage that the heat transfer rate slightly increased at the middle and the bottom tubes by inclining the test section and no significant change in the heat transfer coefficient of the upper tube was observed. It was concluded from the experiments of the second stage that the rate of heat transfer significantly increased due to the sweep effect of steam on the condensate. Results of the experiments are compared with those of the studies of earlier work as well as with the analytical results of the present study.

Karkoszka (2007) in his work discussed the analytical and numerical analysis of the water vapour condensation from the multi component mixture of condensable and non-condensable gases in the area of the nuclear reactor thermal-hydraulic safety. An extensive literature review of surface condensation, liquid condensate interaction with gaseous mixtures and spontaneous condensation in supersaturated mixtures was carried out. Simplified physical and mathematical models were formulated in order to analyze the multi component mixture distribution in the
above-mentioned conditions. Two mixture compositions have been taken into account viz. a binary mixture of water vapour with heavy non condensable gas and a mixture with two non-condensable gases with different molecular weights. The analytical part has been performed by applying the boundary layer approximation and the similarity method to the system of film and mixture conservation equations. The numerical analysis was performed with the code developed in-house and with commercial CFD software. By performing analytical and CFD calculations, it was found that the most important processes which govern the multi component gas distribution and condensation heat transfer degradation were directly related to the interaction between interface mass balances and buoyancy forces. It was concluded that degradation of the condensation heat transfer rate, which is a consequence of degradation of the convective mass flux, should be taken into account for highly supersaturated gaseous mixtures. It was also shown that this phenomenon can be captured successfully by a combination with the mechanistic CFD surface condensation model.

Nabati (2012) in his thesis has explained the use of numerical approaches to analyze and optimize heat transfer for single and multiphase fluid flow, carried out by heat exchangers in power generation industry. Numerical modeling was performed using commercial CFD software. Heat transfer characteristics in surfaces with pin fin and numerical modeling approaches for condensation were reviewed. Investigations of different pin fin shapes with various flow boundaries were studied and thermal and hydraulic performances were calculated. The effect of inlet boundary conditions, pin fin shapes, and duct cross-section characteristics were studied. Two important applications in power generation industry viz. power transformer cooling and condenser for CO₂ capturing application in oxy-fuel power plants were examined. Available experimental data and correlations in the literature were used for validating models. The analysis results showed that the drop-shaped pin fin configuration has heat transfer rates approximately equal to the circular pin configuration, and the drop-shaped pressure losses are less than one third of those of the circular. Results for the power transformer cooling system showed that geometrical defects in the existing system could be easily discovered using modeling. It was shown that a condensation model based on boundary layer theory gives a close value to experimental correlations. Also it was shown that sensitivity of heat transfer rate to inlet temperatures and velocity values decreased when these parameters increased. It was also found
that data validation for the CO₂/H₂O condenser was challenging since this was quite a new application and less experimental and theoretical correlations are available in literature.

Aslambhutta et al. (2012) have reviewed and analyzed the applications of CFD in various heat exchanger designs. The concepts of fluid flow maldistribution, fouling, pressure drop and thermal analysis in the design and optimization of heat exchangers were discussed followed by review of application of CFD for the study of these parameters. It was observed that CFD has proven to be an effective tool in the design, optimization of heat exchangers by studying thermal properties. Conventional methods used for the design and development of heat exchangers were shown to be tedious and expensive. CFD has shown to be a cost effective and speedy solution to heat exchanger design and optimization. Dependability and reliability of CFD results make it an integral part of all design processes, leading towards eliminating the need of prototyping. The simulations generally yield results within good agreement with the experimental studies ranging from 2% to 10% while in some exceptional cases, vary up to 36%. The quality of the solutions obtained from these simulations were largely within the acceptable range proving that CFD is an effective tool for predicting the behavior and performance of a wide variety of heat exchangers.

Tay et al. (2012) have experimentally validated a CFD model for tubes in a phase change thermal energy storage system. The paper showed comparison between the results obtained from CFD model and those from experimentation. The heat transfer fluid (HTF) flows in tubes which were configured in a unique arrangement during the charging and discharging processes. Water contained in a cylindrical tank with four tubes coiled inside it was used as the phase change material (PCM). Experiments were conducted for both freezing and melting processes. A three-dimensional CFD model using ANSYS code was developed and validated with experimental results. From this study, it was found that the CFD model can accurately predict the behavior of the thermal storage system during the charging and discharging processes. This model endeavored to describe both the freezing and melting processes of the PCM. The inlet and outlet HTF temperatures as well as nine temperature locations in the PCM were compared with the CFD results. It was observed that without the effect of natural convection, the thermal behavior of the freezing and melting processes of the PCM were different as compared to the experimental results. The phase change duration between the CFD model and the experimental results were
also compared. It was found that the CFD melting models phase change duration was generally longer than the experimental results.

Hamlin (2012) has performed CFD analysis and modeling of generation and distribution of steam in an autoclave. Theoretical and numerical analysis of the generation of steam in the steam generator and distribution of steam in the sterilization chamber is performed. An extensive literature review was conducted regarding the droplet boiling mechanisms, nucleate boiling and droplet-wall interaction in the steam generator. Suitable computational models were selected and analyzed with the help of theoretical framework and key parameters. In general, realistic results were obtained but complete validation was not possible due to lack of detailed experimental data. A droplet boiling model framework was presented for future modeling of nucleate boiling with the discrete particle method. The general trends of steam distribution inside the sterilization chamber were analyzed in multi component single phase simulations. The feasibility of modeling high rates of condensation was successfully shown with regard to simplified simulations. The fundamental problems of modeling high rates of condensation were identified and partly solved in this study.

Waiker et al. (2013) analyzed the performance of a set of multiple horizontal tubes for steam condensation. The effect of tube inclination of steam tube on steam condensation was investigated. The steam condensation problem on a vertical tier of horizontal tubes was studied by both analytical and experimental methods. The laminar film condensation on the horizontal tubes was analyzed theoretically. Condensate film thickness, velocity distribution and the heat transfer coefficient within the condensate were calculated. The principles of conservation of mass and conservation of momentum on the condensate layer were used to develop two equations, which were transformed into the finite difference forms. A computer program, using Newton-Raphson method, was applied in order to analyze the problem. An experimental setup was also fabricated to observe the condensation phenomenon on horizontal tubes. In this investigation, possibility of transfer of the latent heat from steam to get a condensate was raised. The heat transfer coefficients of condensation tubes obtained experimentally conducted at the vertical position were compared with the analytical investigation. It was shown that though the heat transfer coefficients obtained by the analytical method agree with the Nusselt’s analysis, they were less than those of the experimental results. It was observed from the third stage
experiments that the distance between the condensation tubes did not have a considerable effect on condensation. The steam condensation on vertical tier of horizontal tube was shown to be dependent on diameter of horizontal tube, temperature difference between the steam and the tube wall, angle of inclination of the tube and the condensation surface.

2.6 Mathematical Modeling of Solar Heating Systems

Mathematical modeling translates beliefs about how the world functions into the language of mathematics. This includes the formulae of mathematics and also the computers for numerical calculations. There is a large element of compromise in mathematical modeling. The majority of systems in the real world are too complicated to model in their entirety. Hence the first level of compromise is to identify the most important parts of the system.

The second level of compromise is the mathematical manipulation. Modeling involves various stages like formulation, analysis, testing and use. Each stage is important and necessary to minimise the compromise factors. In the literature, researchers have used mathematical models in various fields like solar energy and other thermal applications. Viorel Badescuis stated in the book “Solar Energy Conversion and Photoenergy Systems Desware – encyclopedia of desalination and water resources” the elementary concept about modeling thermal radiations (with solar radiations as a particular case). General aspects concerning the mathematical description of solar radiation concentration are treated. Examples are given for models based on spectrally integrated energy fluxes or on detailed balance equations. The ways of improving the model’s accuracy are emphasized.

Moodaly (2008) has discussed how basic solar design principles like sun and earth geometry, energy wavelengths, intermittent cloudiness, concentrator configurations, optics, incident angles and efficiency can be used in design and fabrication of a prototype of a solar concentrator. Mathematical models for optimization are generated using the present literature. The models produce data in terms of energy available on an arbitrary tilted surface. Design, fabrication, testing and optimization of orientation of collectors were done. Tracking was used to obtain higher concentration.
Bojic et al. (2009) presented a mathematical model for stationary asymmetric solar concentrators that would use solar energy to generate electricity and heat. Its objective was to find the economically optimum design of the solar concentrator with parabolic and cylindrical reflector. Basic geometric analysis of the concentrator was done followed by economic analysis. Simulation was performed for seven concentrators that had different aperture angle $\delta$ and the same absorber size. The meteorological data for the given place was taken into account. It was then concluded that, the concentrator with the minimum payback had 200 aperture angles.

Grigoniene et al. (2009) presented the possibility to calculate the optimal angles of tilt of a solar collector and a solar collector with a sunray reflector in a selected geographical position, the sun position, and sunlight duration per day and per year. The geographical position and geometrical parameters were estimated. The total cross-section area, $A$ of sunrays falling on the surface was calculated. The absorbed quantity of solar radiation energy was determined with various angles of tilt and a mathematical model was developed for each case. Various statistical and mathematical software were used for the purpose. The models were validated using experimental analysis. Comparison of the results showed a 16% difference between experimental and mathematical results. It was concluded that the results of mathematical modeling quite well correspond to experimental data and could be applied as a tool for finding the optimal angles.

Albahloul et al. (2010) developed mathematical model of the compound parabolic concentrator for use in a solar cooling system with the aid of numerical method and simulation. The mathematical model included all equations and necessary correlations to predict the terms in the energy balance with certain assumptions for simplification. The model was implemented using computer program whose input was a set of values, including collector dimensions, concentration ratio, flow rate and optical and radiative properties. Simulation was done for different concentration ratios but continuous tracking was neglected. The simulation results of the system showed acceptable values of system efficiency, approximately in the range of 35-40%.

Patil et al. (2011) studied the performance of Scheffler reflector in which storage reservoir was installed at the focal point. A generalized seasonal model was formulated using the experimental database from the tests carried out over a period of time. The variables affecting like generated
water temperature, incident rays, dish position, water quantity, dish area, operation time, wind speed, temperature, and acceleration due to gravity were considered. The water temperature was identified as dependent variable and others as independent variables. Using Buckingham’s $\pi$ theorem the system was analyzed.

Beltran et al. (2012) developed a mathematical model that allows representing the optical behavior of a solar parabolic dish concentrator and the thermal performance of a cavity receiver. A graphical method for the design of dish and cavity systems was proposed. The model considers influence of climate, errors of solar collector, intercept factor, reflected and emitted radiation, conduction, and convection heat losses. Theoretical and experimental results were used for the validation of the model. The highest concentration was observed at a rim angle of 45°. It was observed that the maximum temperature reached in the absorber was limited mainly by heat losses. So it was recommended to optimize the aperture diameter of the cavity for reducing such losses.

Sotte et al. (2012) developed a mathematical model to predict optical efficiency and thermal losses for any parabolic trough collector (PTC). The model was validated through comparison with the experimental results on the prototypes. It was included in a custom built simulation environment to predict yearly performances of a PTC field coupled with an industrial process heat demand. Encouraging results were shown and final considerations were drawn for this application. The mathematical model developed for a PTC was composed of two different parts, an optical model and a thermal model. They carried out annual simulation for the performance of the developed model.

Kaddour and Benyoucef (2012) simulated the operation of the Stirling dish concentrator using Greenius software. This simulation allowed the use of the correct value to predict the influence of meteorological parameters (direct normal isolation, ambient temperature, air density (altitude), the angle of elevation of the sun, and wind speed) on the system performance and the net power produced. The Dish Stirling systems were anticipated for producing power at more economical rates and higher efficiencies by converting nearly 31.25% of direct normal incident solar radiation into electricity after accounting for power losses. The developed Stirling dish power systems model was validated.
2.7 Present Status and Limitations of Existing Approaches

Most of the existing systems have used flat plate collectors and parabolic trough concentrators for desalination. Complex mechanisms have been used for solar tracking. Finite element analysis is used to determine temperature stress and temperature distribution but costly instruments like infrared cameras are used. Mathematical model have been developed for solar dishes. Although a great deal of work has been carried out in many individual areas of solar systems like design of concentrators or absorbers or the components of condensers in case of desalination system, yet a comprehensive integrated work on complete design of desalination systems and their optimization, particularly for rural household use with the required economy, has not been seen in the literature. Very few attempts have been made by using CFD software to study condensation of steam.

Today the world is facing a problem of providing safe drinking water. High initial cost and dependency on conventional sources make the installation of desalination plants difficult. Unavailability of skilled workers in rural areas poses another problem. Researchers have not paid adequate attention to a solar based desalination plant for rural families. Various studies appearing in the literature, however, definitely cover the areas like energy scarcity, design of concentrators, absorbers and condensers. Studies also cover the conditions in rural areas and the unavailability of drinking water.

2.8 Need for Research

Numerous studies have appeared in the literature on desalination using different techniques. Use of solar harvesting devices for water desalination has also been reported in the literature but at least some use of electricity is required to run those plants. A small solar desalination system for a family without use of electricity is not yet fully developed. Thus research must be carried out to design, fabricate, install, use and optimize a solar desalination system which provides sufficient water for drinking without using electricity and also is trouble free and requires negligible maintenance.
2.9 Concluding Remarks

A selective review of available literature in the field brings out an important considerations related to different technique used for solar desalination techniques and the use of software to perform different FE and CFD analysis. The gaps in the literature with regard to developing small solar desalination systems have also come to the fore. The present work is an attempt in the direction of providing sufficient drinking water for rural families by utilizing solar energy.