CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The use of solar energy is receiving more attention in the recent years due to the depletion of fossil fuels on one side and environmental degradation, due to the use of conventional energy sources, on the other side. The present chapter reviews various studies carried out in the field of solar hot water systems, in particular natural and forced circulation mode of operation in the past and the present. Performance of solar hot water system can be improved in any one of the following methods: (i) by the use of various selective coatings in the absorber plate of the collector; (ii) improving the mass flow rate by optimizing the size of various components of the system; (iii) incorporating Photovoltaic (PV) cells in the case of forced circulation mode; and (iv) usage of phase change material in the storage tank.

2.2 STUDIES ON OPTIMIZATION OF VARIOUS PARAMETERS OF THE SYSTEM

Kulkarni et al (2008) have discussed the design of solar thermal systems utilized for storage of pressurized hot water for industrial applications. In this research work the authors have developed a design space methodology procedure for component sizing of concentrating collectors, pressurized hot water storage and a load heat exchanger by considering the design variables as collector area, storage volume, solar fraction, storage mass
flow rate and heat exchanger size. Zerrouki et al (2002) have analysed the natural circulation of thermosyphon domestic solar water heater in Algeria and found that the flow rate of such water heaters can be increased by increasing the relative height between the collector and storage tank but it does not have much effect in the system efficiency.

Shariah and Lof (1996) have analysed the optimum values for storage tank height and volume of thermosyphon type solar hot water system for the operating range of 50 to 80°C. Shariah and Shalabi (1997) have recommended the optimum design parameters for a thermosyphon solar water heater through the use of TRNSYS, a transient simulation programme, for two regions in Jordan, namely Amman and Aqaba. The study reveals that by proper choice of the parameters solar fraction of the system can be improved by 10-25%. Ammar et al (1989) have optimized the system parameters of solar hot water system of Egypt with the help of f-chart and TRANSYS models.

Hussein (2003) has investigated the two phase natural circulation thermosyphon flat plate solar water heater and predicated that storage tank volume to collector area ratio and storage tank dimensions ratios have significant effects on the heater performance, while the height between the heater tank and collector has little effect and optimum values are suggested for the same. Cadafalch (2009) has devised a one dimensional transient numerical model for flat plate solar thermal devices and described the fundamentals of a model for the design and optimization of flat plate collectors. This model can be utilized to analyze different components such as multiple glazing, transparent insulation, air-gaps, surface coatings, opaque insulation and energy accumulation in water.

Badescu (2006) has conducted a study on optimization of size and structure for solar energy collection system by considering three solar energy applications and economical indices like net present value and internal return
rate. The author has suggested that best performance is obtained with the use of unglazed, single and double glazed collectors. Nand Kishor et al (2010) have established a fuzzy model to predict the output temperature with respect to inlet water temperature, ambient temperature and solar radiation in thermosyphon solar water heating system and this in turn can be used to evaluate the performance of the same. Chuawittayawuth and Kumar (2002) have carried out an experimental investigation to predict the temperature and flow distribution in a natural circulation solar water heating system and the same was compared with the theoretical models.

Dagdougui et al (2011) have analysed the performance optimization of solar water heater flat plate collector based on the impact of number and type of cover plate on top heat loss and tests were conducted in Morocco. The experiments were conducted with single glass cover plate, double glass cover plate, plastic cover and plexigal. The authors have found that top heat loss is reduced by the use of double cover plate than single and by combining glass and plexigal cover gives better performance of flat plate solar collector. Shariah et al (2002) have evaluated the optimum tilt angle of solar collectors installed in northern and southern region of Jordan and recommended that tilt angle (\(\phi\)) range of \(\phi\) to \(\phi+10^\circ\) for northern region and \(\phi\) to \(\phi+20^\circ\) for southern region will give better performance based on high solar fraction. Also this tilt angle needs to be increased by 5-8° to achieve maximum solar radiation on the top of the collector.

Holck et al (2003) have emphasized on the design of collectors to solve the moisture problems. Humidity existing inside collector will lead to the decrease in service life time of absorber coating. The authors have developed a simulation program to take care of micro climatic condition existing inside the collector by considering various configuration of the collector like location and size of the ventilation hole, etc. This model gives
an idea about design optimization of the collector based on the micro climatic conditions.

2.3 STUDIES ON SPECIAL TYPE OF SOLAR HOT WATER SYSTEMS

Abdel Rehim (1998) has proposed a new design of solar hot water system of pyramid shaped frustrum in which collectors and a water storage tank are integrated together as one unit. Ammari and Nimir (2003) have developed and tested the performance of tar solar water heater and the same was compared with the conventional solar water heater and revealed that tar collector had better conservation of energy in late afternoon and evening, as a result, warmer water outlet is possible late in the day.

Nayak et al (1989) have studied the performance of solar concrete collectors and such collectors are integrated with the building structures. The collectors are made up of thin concrete slabs with a network of PVC tube embedded inside the concrete and top of the slab is painted black and glazed. Daily efficiency of 37% is achieved with such collector for an inlet temperature of 34 °C. Kang et al (2006) have analysed the thermal performance of a roof integrated flat plate solar collector assembly. A network of riser tubes and headers of flat plate collectors are connected in series to form a large flat plate collector and the same is made as integral part of the roof of the building. The results show that the collector efficiency increases in proportion to the increase in number of riser tubes, aspect ratio (H/W), mass flow rate, thickness and conductivity of the absorber plate. Fernandez-Garcia et al (2010) have described the use of parabolic trough solar collectors in various solar applications like space heating, desalination etc. and pointed out that in order to utilize the solar energy effectively trough type collector is the right choice of the engineers.
Esen and Esen (2005) have developed an experimental setup to investigate the performance of two phase closed thermosyphon solar water heater. In this system the collector tubes are filled with refrigerants R134a, R407C and R410A and experiments are conducted separately. The experimental results show that R410A gives highest solar thermal energy collection among the three refrigerants. Solar radiation falling on the collector plate was transferred to the refrigerant which in turn transfer the heat to the water sink, fitted separately. Mathioulakis and Belessiotis (2002) conducted the same type of experiments by using ethanol as heat transfer fluid in the absorber tubes of the collector.

Kumar and Rosen (2011) have designed an integrated collector storage solar water heater with extended storage unit. In this design the storage unit available below the collector is extended to top and is insulated all around the surface. Experiments are conducted by varying the configuration of collector storage volume \(V_A\) and extended storage volume \(V_B\), \(V_A/V_B\) from \((10/90)\), \((30/70)\), \((50/50)\), \((70/30)\) and \((80/20)\). It has been determined that volume ratio 70/30 gives higher efficiency and higher water temperature. Assari et al (2011) have analysed the performance of dual purpose solar collector. In this, collector plate of solar hot water system is attached with V shape air duct just below the absorber tubes and heat energy is transmitted simultaneously to the collector fluid and air. The experimental result shows that dual purpose collector is more efficient than single water heater or air heater. Also, energy which is not transferred to the water due to higher inlet temperature can be utilized for air heating.

Alvarez et al (2010) have designed and tested a new corrugated channel type flat plate collector which gives higher surface area of contact than the tube and fin type collector. The same was analysed with the help of numerical model and the results were compared with the commercial model.
The results show that corrugated model performance is better than the existing conventional model in terms of mean tank water temperature. Al-Madani (2006) has designed and fabricated a special type of water heater namely cylindrical solar water heater. It consists of a cylindrical glass tube with spiral tube painted black which acts as collector, is fitted inside the cylinder. The experiments were conducted for two months and it was noticed that a temperature difference of 27.8°C is achieved between the inlet and outlet temperature of the collector tube with mass flow rate of 9 kg/h and an efficiency of 41.8% during that particular period. Also, cylindrical heater is cheaper than flat plate collector and hence it is cost effective.

Siqueira et al (2011) have analysed the performance of low cost solar heater. In this model, the collector is made of uncovered flat panels of rigid PVC and the storage tank is made of polyethylene coated with polystyrene. This low cost solar heater was tested and the results reveal that global heat transfer coefficient of storage tank is satisfactory eventhough the thermal efficiency is less compared to the conventional solar heaters. Sopian et al (2002) have analysed the thermal performance of solar collectors where thermoplastic natural rubber tubes have been used as absorber plate. It is claimed to be of low weight, cheap, maintenance free and resistance to corrosion. Temperature output upto 65°C is reported with rubber absorber plate, and natural rubber products are recommended as an alternative to others in the conventional hot water systems.

2.4 STUDIES ON INTRODUCTION OF PERFORMANCE ENHANCEMENT EQUIPMENT AND TECHNIQUES

Koffi et al (2008) have conducted the theoretical and experimental analysis of the thermosyphon solar hot water system with heat exchanger fitted inside the storage tank and found that collector outlet water temperature rises upto 85.5 °C and maximum thermal efficiency of 58% is arrived with
such a system. Lu et al (2003) have applied Taguchi method to arrive at the optimum design of natural-circulation solar water heater and suggested that the collector must be surface coated with black chrome plating instead of painting and low density PU foam is recommended as an insulating material for storage tank because of its higher heat preservation capacity and low cost in comparison with higher density foam insulation.

Chen et al (2009) have carried out experimental analysis of long term thermal performance of two-phase thermosyphon solar water heater and predicted that efficiency of the system is 18% higher than conventional systems. Kumar and Prasad (2000) have carried out the experimental investigations of solar hot water system with twisted tape inserted inside the fluid flow tubes. The results reveal that twisted tape will induce swirl flow and act as turbulence promoters which lead to the increase in heat transfer by 18 - 70% and pressure drop is increased by 87 - 132% as compared to plain collectors.

Hobbi and Siddiqui (2009) have studied the effect of various heat transfer enhancement devices in flat plate solar collectors. The experiments are conducted in the laboratory by inserting twisted tape, coil spring wire and conical ridges inside the collector tubes, one at a time. The comparison of various results shows that heat transfer enhancement devices do not have any influence in improving the heat transfer rate in the studied range and geometry.

Heat transfer and friction factor characteristics of thermosyphon solar water heater system fitted with full length twisted tape, twisted tape with rod and twisted tape with spacer in the trailing edge was investigated by Jaisankar et al (2009). It was predicted that twist fitted with rod and spacer have reduced the heat transfer by 17% and 29% respectively in comparison with twisted tape. Twist fitted with rod has greater advantage in terms of
friction factor even though it has less impact on heat transfer enhancement. Also tube fitted with full length twisted tape with twist ratio of 3 has greater heat transfer characteristic than plain tube collector.

Al Shamaileh (2010) has suggested a new solar coating comprising of NiAl alloy particle embedded in black paint. The test was carried out by considering two solar domestic water heating systems, one painted with conventional black paint and the other with NiAl alloy coating. It was depicted that new coating absorbs more thermal energy than the conventional black paint collector and also metallic particles increases the corrosion resistance of the paint. Zambolin and Del Col (2010) have compared the thermal performance of conventional glazed flat plate collector with evacuated tube solar collectors under the same working conditions and predicted that because of the geometry, most of the absorber area is exposed to solar radiation to the maximum period of sunshine hours, evacuated tube collector gives higher efficiency than the conventional one.

2.5 STUDIES ON COMBINATION OF PHOTOVOLTOIC AND THERMAL MODULES

Dubey and Tiwari (2008) have designed and tested an integrated combined system of a photovoltaic (glass-glass) thermal (PV/T) water heater of capacity 200 litre and observed that the photovoltaic thermal (PV/T) flat plate collector partially with PV module gives better thermal and average cell efficiency. Grassie et al (2002) have designed a PV driven low flow solar domestic hot water system and an algorithm was developed for calculating the collector outlet temperature with respect to peak PV output. In this system, a 12 Volts DC pump driven directly by the PV module is connected to provide variable low flow which keeps the output temperature relatively constant and hence thermal stratification in the storage tank.
Chow (2010) has reviewed various applications of combining photovoltaic and thermal solar technologies and suggested to apply the concept in domestic hot water systems, space heating and heat pumps, etc. since the hybrid system performs better than conventional systems. Al-Ibrahim et al (1998) have suggested the design procedure for selecting an optimum photovoltaic pumping system in a solar domestic hot water system (PV-SDHW) and pointed out that 3 Wh energy have been saved for every hour of pumping operation by the use of PV-SDHW system over the conventional one.

Tripanagnostopoulos (2007) has designed hybrid photovoltaic/thermal solar energy systems and recommended that PV/T system with dual heat extraction operation can be utilized in hotels, hospitals and residential buildings where space heating and hot water requirements are fulfilled along with providing electricity. Kalogirou and Tripanagnostopoulos (2006) have designed and tested PV/T solar systems for domestic hot water and electricity production with the use of polycrystalline silicon (pc-Si) and amorphous silicon (a-Si) PV panels and found that considerable amount of electrical and thermal energy is produced in PV/T systems.

2.6 STUDIES ON SMALL SCALE WINDENERGY USE

Muller et al (2009) have analysed the sistan type vertical axis windmill integrated with building and revealed that design improvements of the sistan type wind turbine can increase the theoretical efficiency of rotor to about 48%. Saha et al (2008) have carried out the experiments in savonius rotor wind turbine with the help of wind tunnel to optimize the configuration of the wind turbine. He conducted the experiments with different blade geometry, number of blades and number of stages. The final conclusion of the tests states that two stage, two bladed and twisted blade geometry had good performance as compared to other configurations, single and three stage
rotors. Menet (2004) has designed and tested a prototype of double step savonius rotor for local production of electricity. The axis of the rotor was directly coupled with the rewound conventional car alternator. This system can be used in sailing applications, to generate electricity on a sail boat.

Gupta et al (2008) have conducted a comparative study on a three bucket Savonius rotor with a combined three bucket-three bladed Darrieus rotor. The tests were carried out in a subsonic wind tunnel and various parameters like power coefficient and torque coefficient were calculated. Power coefficient of combined Savonius and Darries rotor is higher than the power coefficient of savonius rotor and also the combined rotor model gives higher efficiency than the savonius rotor model.

Pope et al (2010) have compared the horizontal and vertical axis wind turbines based on energy and exergy efficiency. Two commonly used airfoils in horizontal axis wind turbine NACA 63(2)-215 and FX63-131 are compared with Savonius and Zephyr type vertical axis wind turbine. Analysis of the above four types of rotors, based on first and second law of thermodynamics, was carried out numerically and with the help of FLUENT software. The result states that a difference in first and second law efficiencies of between 50-53% is noticed for airfoil systems whereas 44-55% difference was reported for vertical axis wind turbines.

Reupke and Probert (1991) have designed and analysed the performance of slatted blade savonius wind rotors. The solid S type rotor available in conventional savonius turbine was replaced with the array of 8 flaps and 16 flap rotors and flaps are hinged properly. These flaps open and close automatically according to the wind direction and hence reduce the flow resistance. Modified rotors were tested in wind tunnel and their performance were compared with the solid rotor model. Experimental result shows that
traditional rotor has developed a peak power co-efficient of 18% whereas slatted rotor only 5%.

Eriksson et al (2008) have compared the horizontal axis wind turbine with vertical axis wind turbine of Darrieus model and H rotor model. By considering the structural dynamic, control systems, stability, maintenance and manufacturing, vertical axis wind turbine performs better than horizontal axis wind turbine. Also, H type rotor does not require any yaw mechanism and pitch regulation and hence, it is advantageous over Darrieus rotor in particular for off shore applications.

Al-Karaghouli et al (2009) have discussed about the various opportunities of utilizing solar and wind energy for solar desalination in Arab countries. The authors have investigated the renewable/conventional hybrid systems such as solar/Multi Stage Flash (MSF), Solar /Multi Effect Distillation (MED) and solar-wind / RO and summarize that solar desalination systems working in renewable energy sources can compete with conventional systems under certain circumstances. Mahmoudi et al (2009) have conducted a case study in Algeria for the utilization of wind energy to power solar brackish water greenhouse desalination units. The authors have selected five locations in Sahara which are potential places for agriculture and wind data were evaluated for 10 years, the result depicts that the available wind energy is sufficient to provide electricity to power the brackish water greenhouse desalination plants and the units can be installed in those regions.

Eltawil and Zhengming (2009) have introduced a wind turbine and Inclined Solar Water Distillation (ISWD) unit with the existing Main Solar Still (MSS) to produce distilled and hot water. The new hybrid system was tested under actual environmental conditions in Beijing, China and it has been observed that the average daily efficiency of MSS and ISWD ranged from 67.21 to 69.59% and 57.77 to 62.01% when the system was due south, while
it ranged from 66.81 to 69.01 % and 57.08 to 62.38 % when the system was tracking the sun respectively. The annual saving of electricity of the hybrid system is found to be 101.52 RMB/kWh.

2.7 RECENT STUDIES ON FORCED CIRCULATION SOLAR HOT WATERSYSTEM

Large number of studies using forced circulation has been reported during 1970 – 1990. Few of the recent studies are presented here. Hobbi and Siddique (2009) have derived the optimal design of a forced circulation solar water heating system for a residential unit in cold climate using TRNSYS. In this analysis, a flat collector is modeled for domestic hot water requirements of a single family in Canada. All the design parameters like collector area, fluid type, collector mass flow rate, storage tank volume and height, etc. are studied and optimum values are obtained using TRNSYS. The result shows that the designed system can fulfill 83-97% and 30-62% of hot water requirements in summer and winter seasons respectively.

Jaisankar et al (2009) have studied the heat transfer and friction factor characteristic of forced circulation solar hot water system fitted with helical twisted tapes. The experiments were conducted with various twist ratios of 3, 4, 5 and 6 and the results are compared with the plain tube collector. The result shows that twist ratio of 3 gives higher heat transfer and pressure drop due swirl generation and hence thermal performance of twisted tapes collector with minimum twist ratio is better than the conventional flat plate collectors. Also, due to increased heat transfer, a reduction in collector area of 8-24% is observed for the same output.

Lee and Sharma (2007) have studied the thermal performance of active and passive water heating system with ethylene glycol as heat transfer fluid. The experimental setup consisting of three flat plate collectors filled
with ethylene glycol as heat transfer fluid (HTF) and a pump is fitted between the collector and storage tank in active heating and no pump is used in passive heating. The experiment was conducted in South Korea for one year and the results depict that due to the existence of cold climate use of active hot water system is suitable for that region. The value of $F_R$ ($\tau_0$) is 0.69 and 0.61 in active and passive water heating systems respectively. Also to get higher performance of the system, water should be drawn off only once in the evening.

Lambert et al (2006) have demonstrated a new concept of oscillatory flows in solar collectors to enhance the heat transfer rate. A reciprocating pump is used to produce oscillatory motion of the fluid and the experiment is conducted with Newtonian and visco elastic fluids. As the thermal diffusivity of fluid in oscillatory motion is several orders of magnitude higher than the fluid molecular diffusivity, this type of flow enhances the heat transfer rate in comparison with the conventional forced circulation mode with unidirectional flow.

2.8 STUDIES ON EFFECT OF PHASE CHANGE MATERIALS IN SOLAR HOT WATER SYSTEMS

Shukla et al (2009) have emphasized the use of phase change material (PCM) as thermal energy storage medium in solar water heaters. The authors have suggested that the use of PCM with high latent is one of the most efficient ways to store thermal energy for heating water by the energy received from the Sun. Al-Hintiet al (2010) have investigated the use of phase change material in the storage tanks of conventional solar water heating systems. Cylindrical containers filled with paraffin wax as PCM was placed in two rows in commercially available storage tank and the tests were conducted. It was noticed that PCM keeps the storage tank water temperature of 45°C under all climatic conditions.
Mazman et al (2009) have analysed the effect of various phase change materials in solar domestic hot water system. Experiments were conducted with three different combinations of phase change materials in the storage tank. PCM mixtures such as paraffin and stearic acid (PS), paraffin and palmitic acid (PP) and stearic and myristic acid (SM) in the ratio of 80:20 by weight was tested separately in cooling and reheating modes of test. It was suggested that PS gave the best results in thermal performance enhancement of solar hot water system. A simulation model was constructed by Talmatsky and Kribus (2008) to evaluate the effect of phase change material in domestic hot water system storage tank. Simulation result shows that PCM does not yield any favorable result. An increased heat loss during nighttime due to reheating of water by PCM is the cause for this unexpected result.

Canbazoglu et al (2006) have studied the effect of using sodium thiosulfate pentahydrate as phase change material, in thermal energy storage, in a conventional solar water heating system and found that usage of this particular PCM, the storage time of hot water, mass of hot water produced and total heat accumulated in the storage tank was improved by 2.59 – 3.45 times than that of conventional solar water heating system.

2.9 OTHER STUDIES RELATED TO SOLAR HOT WATER SYSTEMS

Thirugnanasambandam et al (2010) have reviewed various solar technologies available, related to the existing designs, mathematical simulation and fabrication of new design concepts and their improvement. Michaelides and Eleftheriou (2011) have carried out the experimental investigation of the performance boundaries of a solar water heating system. The experiment was conducted with 3 m² flat plate collector with 68 litre tank for two years. It was revealed that flow rate variations from 0.07 -0.25 lit/sec did not produce any noticeable effect on the energy collected in the storage
Tang et al (2008) have investigated the thermal performance of flat plate collectors at night and predicted that if thermosyphonic reverse flow is not allowed, the stagnant temperature of the collectors were 6-8 °C and about 1 °C lower than the ambient temperature at clear nights. Also, if reverse flow is allowed then the absorber temperature of the collector is stable even higher than ambient temperature which results in anti freezing of the collector fluid. Furbo et al (2005) have emphasized that discharge from different levels in solar storage tanks will improve the performance of the system. The experiments are conducted by considering two hot water system with same configuration and one with single draw off at the top of the storage tank and other with two draw off points. The second draw off is located at the middle or just above the midpoint of the tank. Through the experiments, it was depicted that with the introduction of second draw off, the thermal performance of the system increases by 6 %.

Kalogirou (2009) has analysed the thermal performance, economic and environmental life cycle of thermosyphon solar water heaters. The result shows that the payback period of 2.7 years and life cycle saving of €2240 with electricity backup and it is 4.5 years with diesel pack up and life cycle savings of €1056. Also the system will not emit any polluting gases which spoil the green house effect of the earth. An integrated appraisal of a solar hot water (SHW) system in the UK residential sector was carried out by Allen et al (2010) to assess its overall energetic, environmental and economic performance. The study estimates that the SHW system would breakeven with its embodied energy ‘debt’ in 0.7–2.4 years, and that it will payback its embodied carbon debt within 2 years. These results indicate that the SHW
system will provide a net energy and carbon benefit for the majority of its estimated 25 year lifetime.

Tsilingiris (1996) has developed a computer simulation model suitable for the design of large solar water-heating system by incorporating hourly demand profiles, solar system design configuration and heat losses from various system components. Xu et al (2006) have carried out a simulation study on the operating performance of solar-air source heat pump water heater (SAS-HPWH) and observed that by utilizing both solar energy and heat pump technology SAS-HPWH can effectively heat water upto 55°C at all weather conditions. Roonprasang et al (2008) have studied the performance of new solar water heater system that used solar water pump instead of electric pump and predicted that the daily thermal efficiency of the system as 7-13%.

2.10 CONCLUSIONS FROM THE LITERATURE REVIEW

In general, various methods of enhancing NCS type SHW have been attempted and reasonable improvements are reported. The following are the major conclusions arrived out of the review:

(i) As solar hot water systems are most promising and found wide spread commercial use, considerable number of optimization studies have been carried out to optimize various components for better overall system performance.

(ii) Attempts have been made with alternate system components either to reduce cost or to improve the system performance.

(iii) To solve freezing problems, refrigerants and ethylene glycol as collector fluids are attempted.
(iv) Techniques like inserting twisted tapes, coil spring wires in the collector tubes and pulsating flow using reciprocating pumps are attempted and its impact on system performance and friction loss are presented.

(v) Combined photovoltaic and thermal energy recovery systems are built and are studied to a considerable extent.

(vi) Phase change materials are used for better heat storage and to keep collector tank temperature rise within limit. It is found to improve system efficiency by about 5 – 8%.

(vii) Various types of wind mill rotors are developed for small scale power generation and water pumping.

(viii) One study has attempted wind driven pump circulation to enhance the solar distillation system performance.

In the present research work, it has been decided to introduce a wind mill driven pump in an existing 200 litre natural circulation solar hot water system with a view to enhance its overall system efficiency. The system is tested in natural circulation mode, wind driven circulation mode and forced circulation mode with two flow rates to make the performance comparisons. The details are presented in the following chapters.