CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Solar Hot Water Systems (SHWS) are widely used in domestic as well as industrial applications. SHWS of 200 litre capacity are most suited for a family with two adults and two children. The performance of SHWS is a widely researched area. A brief review of research on SHWS is presented and discussed in this chapter. A review of 50 years of research work on solar energy has been discussed by Hottel (1989). The history of MIT, USA Solar House-I, MIT Solar House-II, MIT Solar House-III and MIT Solar House-IV are enumerated in detail. Useful heat gains ranging from 20 to 40% of the total incident solar radiation are reported. The relative performance of gray absorber, selective absorber and low-reflecting glasses are reported. Heller (2000) has reported 15 years of research and development on solar heating in Denmark.

Hrayshat and Mohammed (2004) have focused on the use of solar energy in Jordan and its current state and prospects. Mirza et al (2003) have presented the status and outlook of solar energy use in Pakistan. Lloyd (2001) has dealt with the renewable energy options for hot water systems in remote areas in Australia and pointed out that it is a most viable option. Headley (1998) has presented the solar thermal applications widely practiced in the West Indies. Al-Karaghouli et al (2009) have drawn attention to the various
opportunities of utilizing solar and wind energy for solar desalination in Arab countries. A low cost solar water heater suitable for rural, as well as urban areas of Vietnam has been put forth by Tiwari et al (1998). Voivontas et al (1998) have used geographic information system to explore the solar potential for water heating. Identification and assessment of environmental benefits of using solar hot water production has been presented by Haralambopoulos and Spilanis (1997). This study especially gains significance in the light of emerging global warming and other environmental issues.

Renewable energy development, resource assessment, technology status and greenhouse gas mitigation potential are widely delineated by Junfeng et al (1997) for China and for the Caribbean region by Headley (1997). Reddy (1995) has compared the use of solar water heater against electrical heater for Indian conditions using a case study. The author suggested that when the monthly installment for SHWS loan is lower than the monthly electricity bill, it is better to use SHWS. Nahar (2003) studied the natural circulation system extensively at Jodhpur, India and developed a model. Using the model, the author presented the year round performance and potential of a natural circulation type of solar water heater in various locations of India. Abdul-Jabbar (1998) investigated and compared the performance of natural and forced circulation solar water heaters.

Chang et al (2006, 2008) have reported the promotion and growth of solar water heaters in Taiwan and their contribution in the reduction of conventional energy use, since 1986. Smyth et al (2006) have reviewed the developments in integrated collector storage solar water heaters. Houri (2006) has stressed similar aspects with respect to Lebanon. Pope et al (2010) have compared the horizontal and vertical axis wind turbines based on energy and exergy efficiency. Mahamoudi 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 use of present solar thermal technologies was reviewed in detail by Thirugnanasambandam et al (2010). All these studies have widely demonstrated the need and potential for using solar energy in general and SHWS in particular in various parts of the world.

2.2 STUDIES ON MODELLING AND ANALYSIS

In the recent decades, attempts have been made by Hussain and Urmee (1996) to design and fabricate low cost solar water heaters. Hasan (1997) studied the effects of storage tank volume and configuration on efficiency of thermosyphon solar water heaters. Whereas Shariah and Löf (1997) presented the effects of auxiliary heater on annual performance of thermosyphon solar water heater simulated under variable operating conditions. The effects of system configuration and load pattern on the performance of thermosyphon solar heaters were analyzed by Morrison and Sapsford (1983). Plastic film liquid layer solar water heaters are developed by the authors. The optical performance and directional characteristics of such plastic film liquid layer solar water heaters have been reported by Tsilingiris (1998). The effect of thermal conductivity of absorber plate on the performance of a solar water heater has been reported by Shariah et al (1999). The natural circulation solar water heater has been modeled with a linear temperature distribution approach by Zerrouki et al (2002). An equation for mass flow rate through the collector circuit has been developed by the authors and it has been verified with the experimental data.

Kalogirou and Papamarcou (2000) have modelled the thermosyphon solar water heating system and validated the model with experimental data. An analytical approach has been employed by Belessiotis
and Mathioulakis (2002) to analyze the performance of thermosyphon solar domestic hot water system. An alternative approach to thermosyphon solar energy water heater performance analysis and characterization has been put forth by Norton et al (2001). Modelling the performance of a large area plastic solar collector has been carried out by Janjai et al (2000). Artificial neural networks have been used by Kalogirou et al (1999) for the performance prediction of a thermosyphon solar water heater. Four types of system data are used to train the network. Prediction accuracy within 2.2 °C is obtained. These studies have demonstrated that Domestic Solar Hot Water System (DSHWS) performance can be modelled with good accuracy.

Degelman (2008) has reported the measurement of residential SHWS performance over a period of 22 years and proposed methods for simulation. Upto 63% reductions in glass cover transmissivity were reported over the years due to fogging. Tsilingiris (1996) developed a computer simulation model suitable for the design of a large solar water heating system by incorporating hourly demand profiles, solar system design configuration and heat losses from various system components.

Various system configurations were investigated by Abd-al Zahra and Joudi (1984), Prapas (1995), Fanney and Klein (1988) to improve the performance of solar heaters. AlShamaileh (2010) attempted to improve the solar absorption efficiency by an affordable solar selection coating and observed the tank water temperature to increase by 5 °C when compared to commercial black paint coating. A 15 °C increase in tank water temperature over conventional ones was observed by Sopian et al (1994) using thermoplastic natural rubber tubing as absorber plate. 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 up to 55 °C at all weather conditions.

2.3 STUDIES ON OPTIMIZATION

In recent times, considerable efforts have been made to optimize the system performance of SHWS. Dagdougui et al (2011) have analyzed the performance optimization of solar water heater flat plate collector based on the impact of the number and type of cover plate on top heat loss and tests were conducted in Morocco. An optimum design of natural circulation solar water heater has been attempted by Lu et al (2003) using the Taguchi method. Collector surface coating (black paint, black chrome painting), PU form density (high, low) of the collector insulation and tank (with and without) insulation are used as control parameters. Daily average efficiency and average heat dissipation time constant are used as output responses. Black chrome coating, low density PU form insulation for collector and tank with insulation are obtained as optimum.

The economic optimization of low-flow solar domestic hot water plants has been attempted by Cardinale et al (2003). The flow has been provided by solar PV panels. Life cycle cost analysis has been carried out and the PV powered system is found to be economic when compared to direct electricity use. Saha et al (2008) have carried out experiments in Savonius rotor wind turbine with the help of wind tunnel to optimize the configuration of the wind turbine. Hussein (2003) has done the optimization of a natural circulation two phase closed thermosyphon flat plate solar water heater. Mills and Morrison (2003) have optimized the minimum backup required for the SHWS under varying load conditions. Optimization of tilt angles for the solar
collectors is attempted by Shariah et al (2002) and that for the low latitude countries is attempted by Bari (2001). Optimal design for a thermosyphon solar water heater is carried out by Shariah and Shalabi (1997). Shariah and Löf (1996) have attempted the optimization of tank-volume-to-collector-area ratio for a thermosyphon solar water heater. Capital cost and economic viability of thermosyphon solar water heaters manufactured from alternate materials in India have been analyzed by Nahar (2002).

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. Smyth et al (2004) have presented a detailed techno-economic appraisal of integrated collector cum storage water heating systems. Dharuman et al (2006) have made a performance evaluation of an integrated solar water heater as an option for building energy conservation. Daytime collection efficiencies of about 60% and overall efficiencies of about 40% are reported. 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.

Kulkarni et al (2008) have discussed the design of solar thermal systems utilized for storage of pressurized hot water for industrial applications, in which the authors developed a design space methodology procedure for component sizing of concentrating collectors, pressurized hot water storage and load heat exchanger by considering the design variables as collector area, storage volume, solar fraction, storage mass flow rate and heat exchanger size. Amar et al (1989) have optimized the system parameters of
solar hot water system of Egypt with the help of f-chart and TRANSYS models.

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 theoretical models. 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 systems with the same configuration and one with single draw off at the top of the storage tank and the 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 increased by 6%.

2.4 STUDIES ON NEW TYPES OF SHWS SYSTEMS AND COMPONENTS

Apart from regular natural circulation and forced circulation solar hot water systems, a variety of new systems have been attempted in recent times which are briefly discussed in this section. A comparative study between the forced and wind assisted domestic solar hot water systems was assessed by Tamilarasan et al (2008). A comparative study between the natural and wind assisted domestic solar hot water systems was studied by Tamilarasan et al (2008). Ramasamy and Srinivasan also studied the performance of natural circulation type domestic solar hot water system by using a wind turbine. Performance analysis of a solar-assisted heat pump water heater was carried out by Chyng et al (2003). 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 up to 85.5 °C and maximum thermal efficiency of 58% is arrived with that system. The long-term performance of solar-assisted heat pump water heater was assessed by Huang and Lee (2004). Chen et al (2009) have carried out experimental analysis of long thermal performance of two-phase thermosyphon solar water heater and predicted that the efficiency of the system is 18% higher than conventional systems. Agarwal and Garg (1994) have made a study of a photovoltaic-thermal system thermosyphonic solar water heater combined with solar cells and Garg et al (1994) have experimentally studied such a system and developed methods for its performance predictions. 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 PV/T flat plate collector partially with PV module gives better thermal and average cell efficiency. Abdel Rehim (1998) has proposed a new design of solar hot water system of pyramid shaped frustum in which collectors and water storage tank are integrated together as one unit. Experimental observations on a continuous flow type domestic solar water heater have been reported by Venkatesh (1994). Advanced control strategy of a solar domestic hot water system with a segmented auxiliary heater for better performance has been reported by Prud'homme and Gillet (2001).

Efforts have been made to improve the collector performance itself with new components or to minimize the cost by alternate materials. Water-in-glass evacuated tube solar water heaters approach has been reported by Morrison et al (2004). Razavi et al (2003) have used polypropylene tubes in solar water heaters and studied the rate of heat transfer with such tubes. Heat
transfer analysis of low thermal conductivity solar energy absorbers is carried out by Tsilingiris (2000). Efficiency can be improved by increasing the solar radiation absorption, minimizing the heat loss from the absorber plate to the surroundings. The use of selective coated absorber is a widely accepted concept. The use of solchrome solar selective coatings has been discussed in detail by Abbas (2000). 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. They predicted that because of the geometry, most of the absorber area is exposed to solar radiation to the maximum period of sunshine hours and that the evacuated tube collector gave higher efficiency than the conventional one.

Absorbed heat has to be effectively transported out for better efficiency. Kumar and Prasad (2000) have investigated the use of twisted tape inserts for solar water heaters and presented the heat transfer, friction factor and thermal performance results. The use of heat pipes for such effective heat transport has been attempted by Chun et al (1999) and Morrison et al (1999). Reducing the cost of domestic solar water heater without compromising on efficiency or with as little compromise on efficiency is always of interest to the scientific community in order to increase the use of such systems. One such attempt by using the locally available materials and manufacturing methods has been reported by Khalifa (1999). Collector cum storage type solar water heaters are attempted by a sizable number of investigators, viz. Kaptan and Kilic (1996), Mohamad (1997), Reddy and Kaushika (1999) and Chaurasia and Twidell (2001). 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.
A mobile water heater for rural heating in Africa has been attempted by Nieuwoudt and Mathews (2005). Tank water temperatures of 60 °C by mid-afternoon and 45 °C by 20 hours are reported by the authors. Morrison et al. (2005) have reported the measurement and simulation of flow rate in a water-in-glass evacuated tube solar water heater. Tarhan et al. (2006) have reported the study of storage type solar water heaters with and without phase change materials and found that the use of phase change materials results in advantageous control of rise and drop of water temperature during both day and night time, which in turn reduces system losses. Ho and Chen (2008) have reported marginal improvements in collector efficiency with the use of internal fins. Al-Hinti et al. (2010) have investigated the use of phase change material in the storage tanks of conventional solar water heating systems.

Al-Ibrahim et al. (1998) have suggested the design procedure for selecting an optimum Photo Voltaic pumping system in a Solar Domestic Hot Water (PV-SDHW) system and pointed out that 3 Wh energy has been saved for every hour of pumping operation by the use of PV-SDHW system over the conventional one. 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%. 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. 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, heat pumps, etc.
Reupke and Probert (1991) have designed and analysed the performance of slatted blade Savonius wind rotors. 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. 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. Hobbi and Siddiqui (2009) have studied the effect of various heat transfer enhancement devices in flat plate solar collectors. The experiments were 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.

Lee and Sharma (2007) have studied the thermal performance of active and passive water heating system with ethylene glycol as heat transfer fluid. Shukla et al (2009) have emphasized the use of Phase Change Material (PCM) as thermal energy storage medium in solar water heaters. Canbazoglu et al (2006) have studied the effect of using sodium thiosulfate pentahydrate as PCM, in thermal energy storage, in a conventional solar hot water heating system and found that the storage time of hot water, mass of hot water produced and total heat accumulated in the storage tank was improved by 2-3 times than that of the conventional solar water heating system.

Roonprasang et al (2008) have studied the performance of new solar hot water system that replaces electric pump by a solar water pump and predicted that the daily thermal efficiency of the system as 7 - 13%. Holck et al (2003) have emphasized on the design of collectors to solve the moisture problems. Michaelides and Eleftheriou (2011) have carried out the
experimental investigation of the performance boundaries of a solar water heating system.

2.5 CONCLUSIONS FROM THE LITERATURE REVIEW

From the review of Literature over the past 25 years, the following major conclusions emerged:

(i) The use of SHWS for domestic and industrial water heating is the most common factor. Such SHWS operate on FCS mode or on NCS mode.

(ii) Forced circulation systems are most widely used in larger and industrial applications due to higher efficiencies. However, FCS requires an electrically operated pump for the circulation of water.

(iii) Under the given conditions, the higher the flow rate of water through the collector, the higher the efficiency of the solar hot water system.

(iv) Natural circulation type domestic hot water systems are widely used. However, the efficiencies are relatively low due to lower circulation rate of water through the collector.

(v) Efforts are made to improve and optimize the performance of both FCS and NCS, by modelling, analyzing and by using newer materials and methodologies. Sizeable improvements have been reported, however, with sizeable increase in the cost of the system.
(vi) Efforts are needed to improve and optimize the performance of both FCS and NCS without increasing the cost of the system.

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

### 2.6 NEED AND OBJECTIVES OF THE PRESENT RESEARCH WORK

It was observed that any effort to increase the collector flow rate of NCS will improve the system efficiency. A comparative study between the forced and wind assisted domestic solar hot water systems was assessed by Tamilarasan et al (2008). A comparative study between the natural and wind assisted domestic solar hot water systems was studied by Tamilarasan et al (2008). Ramasamy and Srinivasan also studied the performance of natural circulation type domestic solar hot water system by using a wind turbine. Based on the concept of green house effect, it was intended to observe the role of CO$_2$ gas in improving the efficiency of all three types of solar hot water systems. A new concept of filling CO$_2$ gas in the collector panel has been thought of. Similar to NCS, FCS and WACS, NCS-CO$_2$, FCS-CO$_2$ and WACS-CO$_2$ has been thought of with CO$_2$ gas filled in the collector panel. Thus, a windmill driven pump was taken to a 200 litre capacity natural circulation type domestic solar hot water system along with CO$_2$ gas filled in the collector panel. It was termed as Windmill Assisted Circulation System with CO$_2$ gas filled in the collector panel (WACS-CO$_2$). If sufficient wind velocity exists, the WACS-CO$_2$ was expected to perform better than NCS. In order to compare the performance of such WACS-CO$_2$, two identical experimental facilities were utilized such that they can be operated in NCS.
mode, FCS mode and WACS mode with and without filling CO$_2$ gas in the collector panel. With these aspects, the objectives of the present research work are as follows:

(i) To utilize a research facility with necessary instrumentation and data logging that can be used to measure the performance of the domestic SHWS in NCS, Natural Circulation System with CO$_2$ gas filled in the collector panel (NCS-CO$_2$), FCS, Forced Circulation System with CO$_2$ gas filled in the collector panel (FCS-CO$_2$), WACS and WACS-CO$_2$ modes.

(ii) To carry out the experiments over a day in each mode, preferably spread over different periods of the year.

(iii) To compare the performance of the three modes with and without filling CO$_2$ gas in the solar collector panel in order to understand their relative performances.

With these objectives, two identical experimental facilities have been utilized. The details of the experimental facilities are presented in Chapter 3.