

Department of Mechanical Engineering

# **Thermal Modelling and Control of Domestic Hot Water Tank**

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Master of Science in Energy Systems and the Environment

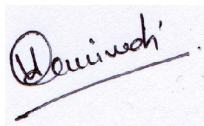
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आ नो भद्राः क्रतवो यन्तु विश्रतः ।

*Let noble thoughts come to us from every corner of the world.  
Rigveda 1.89.1*

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## ABSTRACT

A Solar Domestic Hot Water (SDHW) system recovers the energy from the solar collector panel and transfers it to the domestic hot water tank. Based on the location and the orientation of the solar collector panel, one could easily estimate that such systems can meet the hot water demand fully or partially and accordingly design the auxiliary heating system such as a gas or an electric heater, to supplement the hot water demand.

To meet the hot water demand in a colder climate such as the UK, primarily the gas or electric heater, is preferred over past decades due to its cheap and easy availability of the gas or electricity. As the UK is committed to Kyoto protocol, it has set a target of achieving 14% of heating requirements from the renewable heat sources, such as solar, by 2020. Therefore financial incentives and tax exemptions are available for the installation of the solar thermal systems. These incentives require that the existing hot water cylinder has to be retrofitted with the solar panel. By installation of a solar panel along with an auxiliary heating system, the required water would be heated by the solar energy and complemented by the auxiliary heater.

To design such a SDHW system from scratch and to meet the above criteria is an easy task. However, to retrofit the existing hot water cylinder in order to meet the tax benefit criteria is a challenge. The basic principle of solar energy is based on the concept of thermal storage. The existing hot water cylinder volume is of the order of 80 to 120 litres, which is close to the hot water required for a family of three to four persons. Standard SDHW system, available in the market, to meet the tax benefit criteria requires to opt for a 300 litre capacity hot water storage tank.

The objectives of this project are to understand the heat transfer characteristic of a SDHW system and to explore the fact that these modified hot water cylinder could be controlled in such a way that they operate efficiently. By controlling the auxiliary heating system, it is feasible that at certain times the solar energy would heat the water or may require additional energy from the auxiliary system.

In order to understand the physics of the problem, an existing hot water cylinder of 80 litres capacity with two hot water demand profiles and the weather data for London, UK is analysed. It is observed that the thermally stratified tank is able to meet the criteria for single hot water cylinder with retrofit of the solar panel. Thermal stratification inside the tank is not only influenced by the design parameters of the storage tank but also by the location of the auxiliary heater and its control strategy. To understand and further explore the tank's thermal behaviour, an experiment on actual system is proposed to substantiate the thermal stratification results.

It is feasible to predict the solar energy output from the panel by means of a neural network. So a simplified neural network is developed based on the function approximation technique. Once the experimental data is available, it is proposed to train the network with experimental data. It would be helpful in assessing the thermal stratification inside the tank as calculated by a dynamic SIMULINK model.

Solar thermal hot water systems are amongst the easiest and most cost effective renewable energy systems to install, which makes them one of the most popular systems amongst consumers and developers. Should the modified solar thermal hot water systems be found to operate effectively with existing hot water cylinders then the cost of installing a new solar hot water system is likely to be reduced. This will stimulate and contribute to the carbon emission reductions required to meet UK 2020 carbon emission targets.



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## CHAPTER 1: INTRODUCTION

*“The Sun in the service of mankind”*

UNESCO conference in Paris, July 1973

One will appreciate the fact that Sun is the source of life and energy to all living creatures on the earth for millions of years. An attempt was made on a small scale to harness the solar potential in form of “burning mirrors” by English monk Roger Bacon in the 13<sup>th</sup> century and Bernard Foret Belidor (1697-1761) <sup>[1]</sup> invented solar operated pump. In 20<sup>th</sup> century, countries like Israel, USA, Japan, and UK took initiative to maximize the benefits incurring due to utilization of the solar energy in form of water heating, building heating, electricity production etc. The main impetus in utilization of the solar energy for any application is that fuel is free of cost and the solar technology is eco friendly. However, the high capital costs, intermittent solar radiation are some of the potential reasons, which hampered the solar technology to take the centre stage in human life.

Conventional fossil fuel reserve may last for few more centuries. The power generation technology based on fossil fuel, has serious implication on global warming. Currently the soaring price of fossil fuel does allow to countries to invest in non-polluting and inexhaustible solar technology. Moreover, the solar energy is also driving force behind other renewables such as biomass, wind, and hydropower.

### 1.1 The Solar Resource and Solar Domestic Hot Water (SDHW) system

The source of solar radiation is a fusion reaction-taking place inside the core of sun at a temperature of ~30,000 K. However, the sun’s surface temperature is ~5762 K. To calculate the amount of energy received by the earth outside the atmosphere, also called solar constant, one has to assume that the sun is a black body at 5762 K, the mean distance between the sun and the earth is  $1.5 \times 10^{11}$  m and the sun’s diameter is close to  $1.39 \times 10^9$  m <sup>[2]</sup>. By using Stefan-Boltzmann radiation law, the value of solar constant is close to  $1353 \text{ W/m}^2$ . However, the ‘*constant*’ is misnomer in term Solar Constant as it varies from day to day. The daily “solar constant” is calculated with the following formula <sup>[3]</sup>:

$$I_o = 1353 * \left[ 1 + 0.034 * \cos\left(\frac{2 * \pi * N}{365}\right) \right] \quad (1.1)$$

Where

N is day number of the year or Julian date (for example, January 1 is day 1; December 31 is day 365.)

Solar energy reaching a given location on the earth, called insolation, is attenuated as it travels through the atmosphere by means of reflection, absorption, scattering, before reaching the surface of the earth. For example, Ozone layer absorbs Ultra-Violet (UV) radiation while CO<sub>2</sub> and water vapours absorb infrared radiation. One can refer (table 1.0) tentative values of mean annual daily solar radiation reaching the earth's surface for various cities.

City	Solar Radiation, W/m <sup>2</sup>
Cairo	280
El Paso	240
Glasgow	100
Johannesburg	230
Mumbai	240
Naples	200
Rio de Janeiro	200
Seattle	125
Sydney	210
Tokyo	125

Table 1.0: Typical mean annual daily solar radiation for selected cities. <sup>[3]</sup>

Let us analyse some basic terms to understand the components of solar radiation such as direct beam, diffuse components. On a clear sky, it is possible that the solar radiation can reach the earth's surface directly, without any attenuation as explained above. This component is termed as direct solar radiation. On a cloudy day, the solar radiation gets scattered, refracted. This component is termed as diffuse solar radiation and it reaches the earth's surface at range of different angle. Sum of diffuse and direct component is called Global Insolation.

In summary, typical value of the global insolation varies, at particular location, as the condition in the sky changes with maximum in the range of 900-1000 W/m<sup>2</sup>. Figure 1.0 gives idea about variation in monthly global insolation at a particular location.

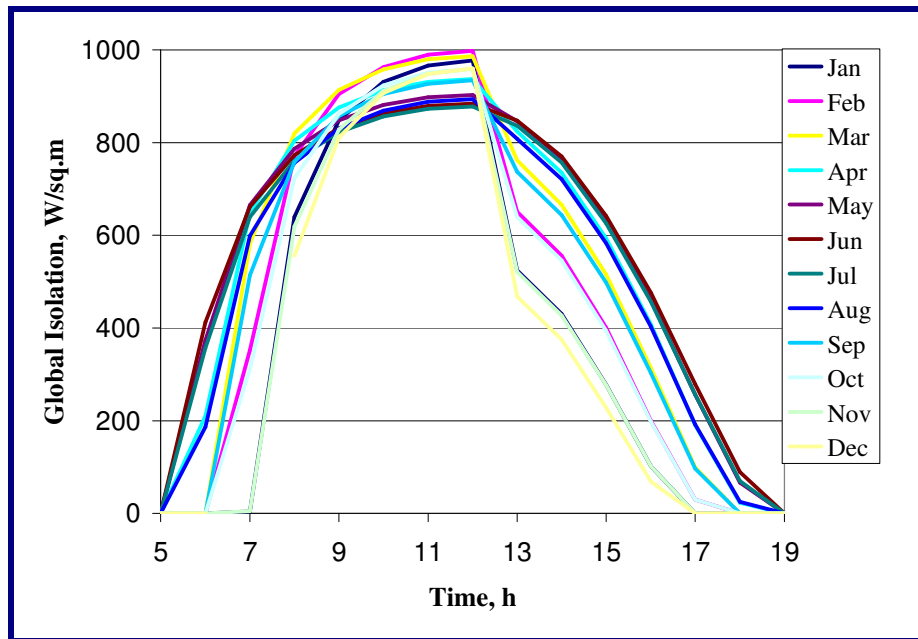


Figure 1.0: Monthly averaged global insolation at 32° N latitude <sup>[3]</sup>

When solar radiation falls on a surface, it can be converted in to electrical power or thermal energy. Photovoltaic or PV cell is one of the solar technologies used for the electrical power generation. Solar heating is used for many applications such as crop drying in field, producing salt from seawater; meeting hot water demand, space heating etc. Effective solar radiation must be collected at a high temperature and transported or stored for later use. Solar Domestic Hot Water (SDHW) system is one of the examples of it. It uses the solar energy available in the sunlight to heat the water for household purpose. It supplements the existing gas or electric water heating system and provides heat for all hot water needs including showers, dishwashing, and laundry, cooking and even for space heating.

Hot Water accounts for approximately 25% of the total energy used in a typical single-family home and can lead to savings of 85% on the utility bills over the costs of electric water heating <sup>[4]</sup>. Figure 1.1 <sup>[5]</sup> gives idea about the average annual solar radiation available in UK. By an estimate,

the average energy required is close to 3000-4000 kWh per year for domestic hot water purpose <sup>[5]</sup>. It follows to achieve this demand a moderate solar collector panel with an area of 4-5 m<sup>2</sup>.

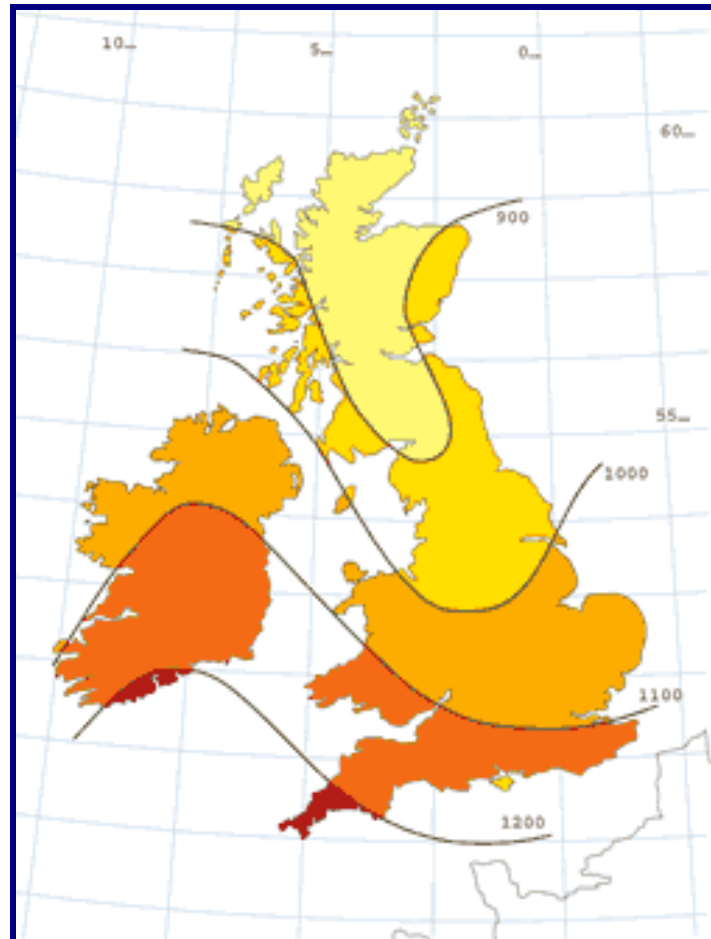


Figure 1.1: Map showing average annual solar radiation on a 30° inclined panel facing due south in kWh/m<sup>2</sup>

To meet the hot water demand in the colder climate such as UK, primarily an auxiliary system is preferred over past decades due to its cheap and easy availability of gas or electricity. As UK is committed to Kyoto protocol, it has set a target of achieving 14% of heating requirements from the renewable heat sources, such as solar, by 2020. Therefore financial incentives and tax exemptions are available for the installation of a solar thermal systems <sup>[6]</sup>. These incentives require that hot water cylinder has a 'dedicated solar volume' defined as a proportion of the volume of the hot water cylinder that can be heated only by the solar system and not by the auxiliary one.

To design such a SDHW system from scratch and to meet the above criterion is quite easy task. However, to retrofit or to modify the existing hot water cylinder in order to meet the above design criterion is a challenge to the designer. The basic principle of solar energy based heating system is based on the concept of thermal storage. The existing hot water cylinder volume is of the order of 80 to 120 litres, <sup>[6, 7, 50]</sup> which is close to the hot water required for a family of three to four person. Standard SDHW system, available in market, to meet the ‘ dedicated solar volume’ criterion requires to opt for 300 litre <sup>[6, 8, 50]</sup> capacity hot water storage tank.

## 1.2 Aim

Aim of the project is to study thermal behaviour of two basic configurations of SDHW tanks, for a generic hot water demand in UK and to investigate the efficacy of the thermal stratification on performance of the system as a whole. It also includes study of temperature control in the tank and the auxiliary heater control on the performance of the SDHW system.

The challenge in SDHW technology is to match the supply with demand. In this project, the study aims to understand the mismatch between supply and demand of hot water for the domestic application and to investigate the control strategies for the hot water storage tank in order to smoothen out the mismatch between supply and demand.

## 1.3 Project Objectives

The objectives of the project are to understand the heat transfer characteristic of SDHW system and to explore the fact that these modified hot water cylinder could be controlled in such a way that it operate efficiently. By controlling an auxiliary heating system, it is feasible that at certain times only the solar themal system would heat the water in the hot water tank, making the entire volume of the hot water cylinder the dedicated solar volume.

The objectives of the project are as follows.

- To better understand the physics behind the whole process of Solar Domestic Hot Water (SDHW) system.



- To develop a thermal model of active (direct and indirect) SDHW configuration in Simulink.
- To model the heat transfer phenomena in a solar collector panel and predict the heat input to the hot water storage tank.
- To model of an auxiliary heater in the hot water tank and carry out a control strategy modelling from demand side requirement.
- To better understand the thermal stratification concept in SDHW tank.
- To research and establish the number of days when a solar heating system can meet the hot water demand independently.

## **1.4 Thesis Organization**

Chapter 1 gives the detail about an introduction to the topic with relevance to the UK. It also lays down the objectives of the thesis and elaborates the present scenario existing hot water cylinder and its retrofit option. By retrofitting, the existing heating system means to add the solar collector panel with the existing hot water cylinder, which presently runs on electrical or gas heating.

Chapter 2 gives the necessary background information about the utilization of natural resources, its availability and a comparison with the solar energy potential. It also explains, in detail, about the various SDHW configurations and its main components.

Chapter 3 details the mathematical modelling of a solar collector panel, the water storage tank along with an auxiliary heater. This chapter starts with the explanation of basic term used in this project, the concept of thermal stratification, high vs. low flow SDHW system and the parameters, which have significant impact on stability of thermal stratification inside the tank. It also describes the various kinds of heat exchanger used in the SDHW systems.

Chapter 4 describe the two cases of SDHW under consideration, which are classified as single cylinder (retrofit option) and twin cylinders (retrofit option with two cylinders). These two classifications are used in the Standard Assessment Procedure (SAP) 2005. It also describes boundary conditions used in the analysis, the bird's eye view of the system performance.

**“SAP is the Government's Standard Assessment Procedure for Energy Rating of Dwellings. SAP 2005 is adopted by government as part of the UK national methodology for calculation of the energy performance of buildings”<sup>[9]</sup>.**

Chapter 5 deals with implementation of Artificial Neural Network techniques in predicting the energy output from a solar collector panel based on future weather data such as ambient temperature, direct and diffuse component of solar radiation. In this part, an attempt is carried out to simulate the calculated value of the heat output from the given three variables. However, once the network has been trained using an experimental data, it would help in the estimation of solar energy available for next couple of days.

Chapter 6 deals with conclusions and illustrates and the future works to be carried out in this project. It also explains the challenges associated with retrofit option to meet the “dedicated solar volume” requirement.

## CHAPTER 2: BACKGROUND & SDHW SYSTEM DESCRIPTION

*"I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait till oil and coal run out before we tackle that."*

Thomas Alva Edison

Growth and development are the key factors in human life and it always put challenges before him. Be in industry, agriculture, energy, space or environment, the options offered by engineers, academia or scientists are awesome such as cars, aeroplane, computers, roads, buildings, electricity for lighting, operating the home appliances and heating or cooling the residential, industrial or shopping mall. All these equipments require energy in the form of heat or electricity. To meet the energy demand, natural resources are utilised such as fossil fuels like coal, oil, natural gas, termed as non-renewable energy sources or nuclear fission based energy resources utilizing natural Uranium as fuel. One can easily infer from figure 2.0 <sup>[10]</sup> that there is continuous depletion of natural resources. The higher standards of living coupled with population explosion are the popular explanation of such pattern.

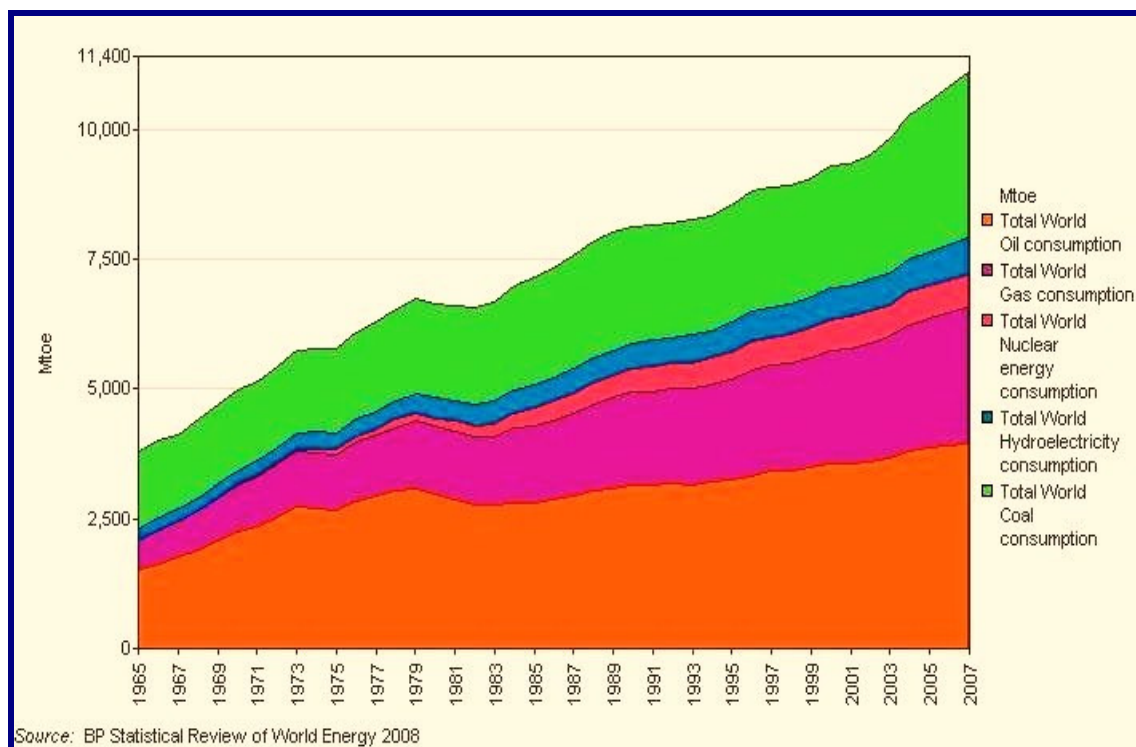


Figure 2.0: Consumption pattern of natural resources since 1965.

One can easily identify from figure 2.0 is that the major part of natural resources being utilized are oil, gas and coal. These resources are also responsible for the Green House Gases (GHG) emission, a potential source of global warming.

Let us get the idea about the supply or availability of natural resources and demand or present day consumption pattern. Figure 2.1 <sup>[11]</sup> gives a generic idea about the world energy resources, its comparison to present day consumption pattern. The natural resources are limited and will be exhausted in the future if we continue to exploit the natural resources in an unsustainable manner. Figure 2.1 also suggest that solar energy has good potential to play significant role in the energy carving society. Not only solar energy, wind energy, bio-fuels, tidal energy, wave energy etc termed as renewable energy, are better candidate for heat or electricity generation.

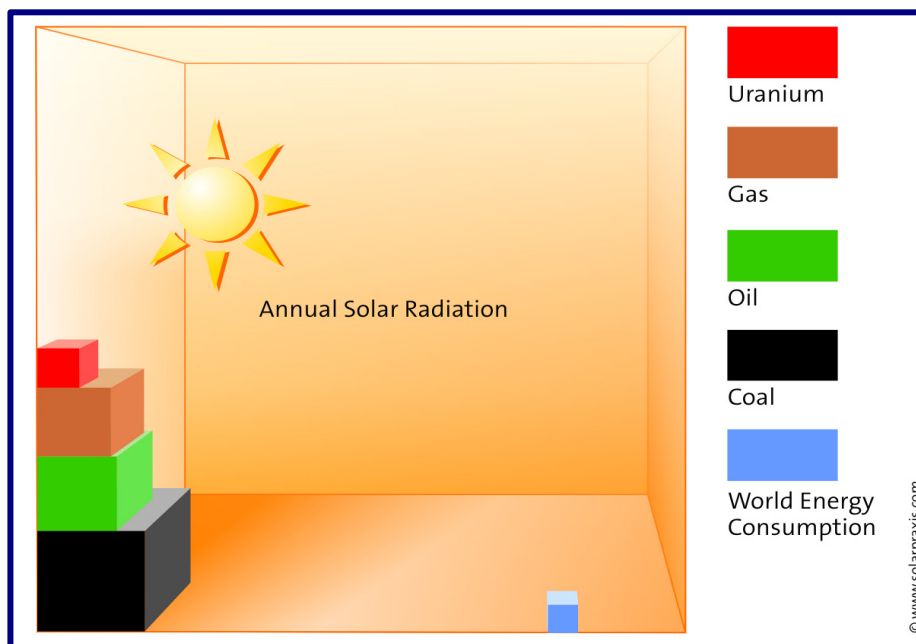


Figure 2.1: World Energy Reserve and Energy consumption

Figure 2.2 <sup>[12]</sup> shows the contribution of renewables in the global energy consumption. Although it is only at 18.3 % of the global energy consumption, its potential is very high and the basic fact is that it is non-emitter of GHGs.

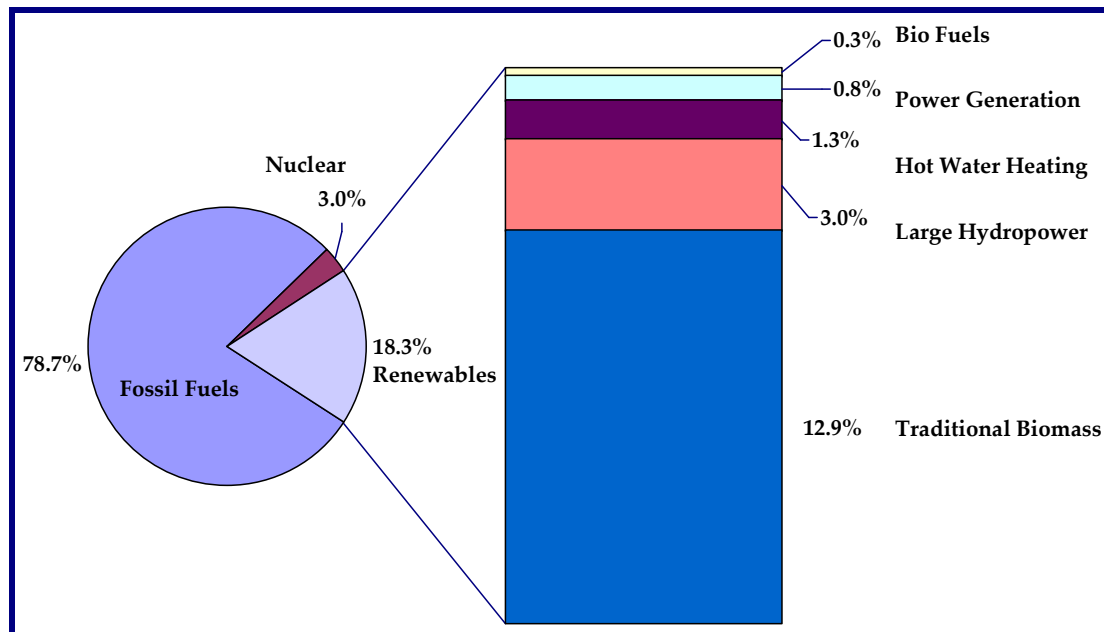


Figure 2.2: Renewable Energy share of Global Final Energy Consumption, 2006

Let us again look in to main components of the renewable energy and in particular to Hot water heating systems. In 2006, the hot water demand supplied by the renewable energy source was close to 1.3%. Traditional biomass such as wood, waste, alcohol etc contributes 13% of total renewable energy share. As we have seen that in the colder climate, the hot water accounts for approximately 25% of the total energy consumed. Therefore, a lot of scope exists in meeting the hot water demand by means of the renewable energy particularly by Solar Collector systems. Figure 2.3 <sup>[13]</sup> depicts the solar hot water / Heating capacity around the world in 2007. Although it is very small fraction of total energy share of energy share presently, yet it has great potential and have good competitor to other technology as it has least impact on the global warming and minimum impact on the GHG emission.

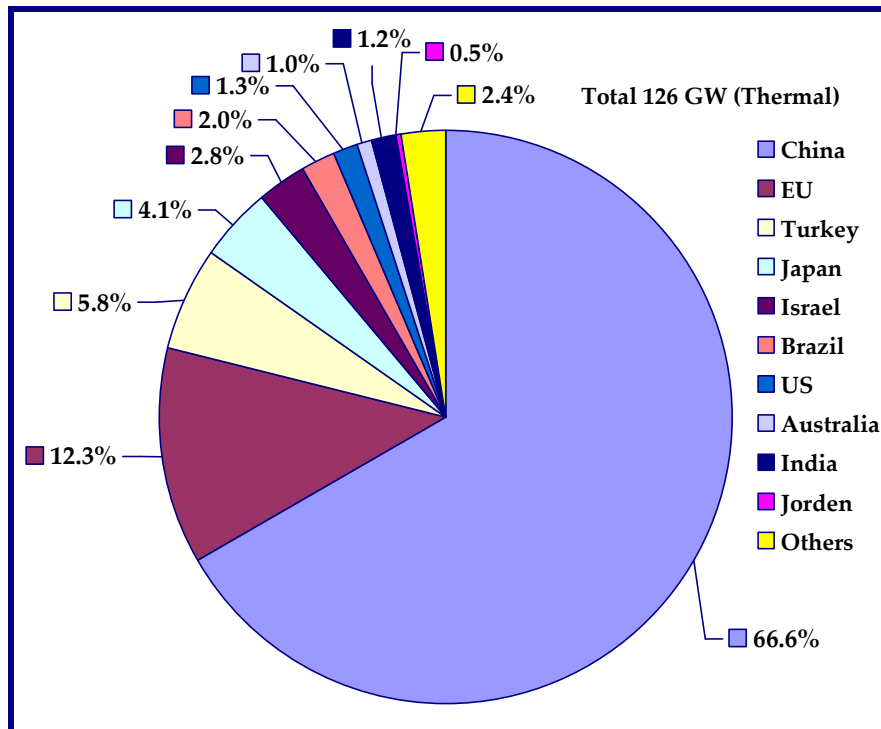


Figure 2.3: Solar Hot Water/Heating Capacity Existing, 2007

Let us study the UK, where hot water demand is sufficiently high. The main consumers of electricity are the domestic and industrial sectors. It is interesting to note that 33% of total power produced in the UK (close to 392979 GWh) is used for the domestic application <sup>[14]</sup>. In 2004, the percentage of coal, gas and oil in total electricity production is close to 74%. In the same year, power stations in the UK emitted 47 million tonnes of carbon. By an estimate, it accounts for 30% of the UK's total carbon dioxide emissions in that year.

Under Kyoto Protocol, the UK government is committed to reduce the carbon emission to 12.5% below 1990 levels by 2008 to 2012 <sup>[15]</sup> and 20% of electrical supply from the renewable energy resource by 2020 <sup>[16]</sup>. To meet the above-mentioned targets, it is pertinent to opt for the integration of renewable technology to the built environment and implement zero energy building design concept.

Wang (2009) describes the design concept of zero energy building as “**a building with a net energy consumption of zero over a typical year**”. He concludes that it is theoretically possible to design a building with the concept of zero energy consumption in the cold climate with the

integration of renewable energy systems such as photovoltaic, wind turbines, heat pump and solar hot water system <sup>[17]</sup>.

In order to reduce the carbon emission, one of the simple steps is to introduce the solar technology in domestic sector for fulfilling the hot water demand, space heating etc. Integration of the solar panel in existing hot water tank is one among the prominent options to tackle zero carbon policy.

## 2.1 SDHW System Description

A SDHW system uses the solar radiation to heat the water. It connects to a home's existing gas or electric water heating system, compliments the source of heat for all hot water needs including showers, dishwashing, clothes washing, cooking etc. It consists of a solar radiation collector panel, a storage tank, a pump, a heat exchanger, piping units, an auxiliary heating unit, a heater control panel. Figure-2.4 <sup>[18]</sup> gives classification of the SDHW system based on the solar collector panel type, auxiliary heater type and based on the principle of heat transfer.

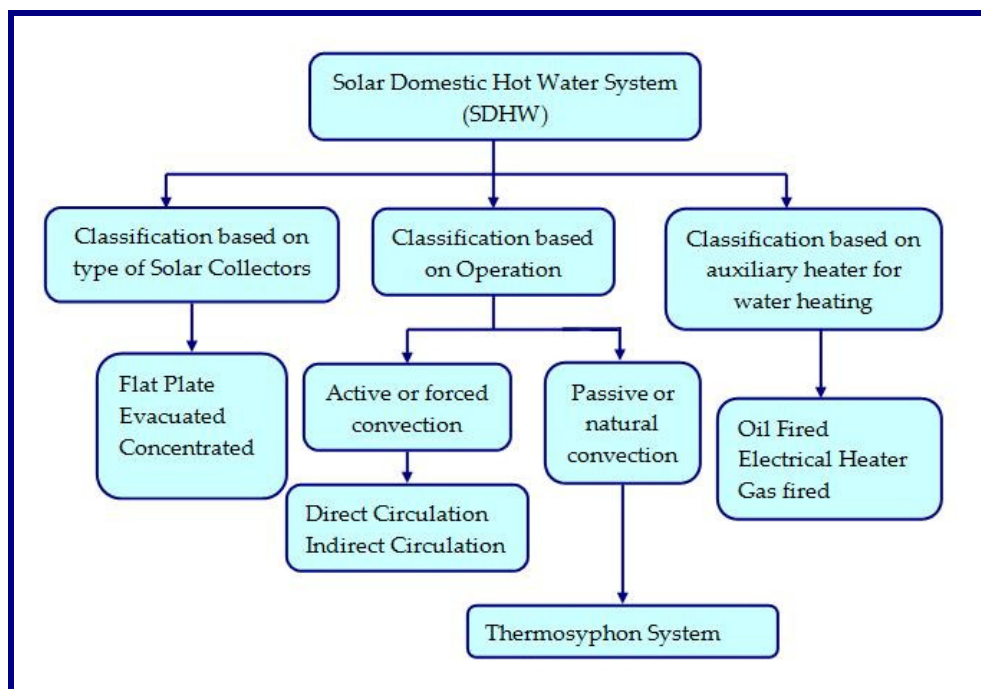


Figure 2.4: Classification of SDHW system



A basic flat plate solar collector is shown in figure 2.5. Although it looks a simple piece of equipment to absorb the solar radiation and transfer to the fluid flowing in the tubes, however the mechanism of heat transfer is quite involved. All modes of heat transfer, viz. conduction, convection and radiation needs attention in the thermal analysis. The absorber plate absorbs solar radiation and in turn transfers the heat to the fluid by means of conduction and convection. A fraction of absorbed heat would be conducted and convected to the ambient via thermal insulation and some would be irradiated back to the surrounding. Heat transfer mechanism is so involved that it is not amenable to the hand calculation. Chapter 3 presents a simplified mathematical model for the SDHW configuration.

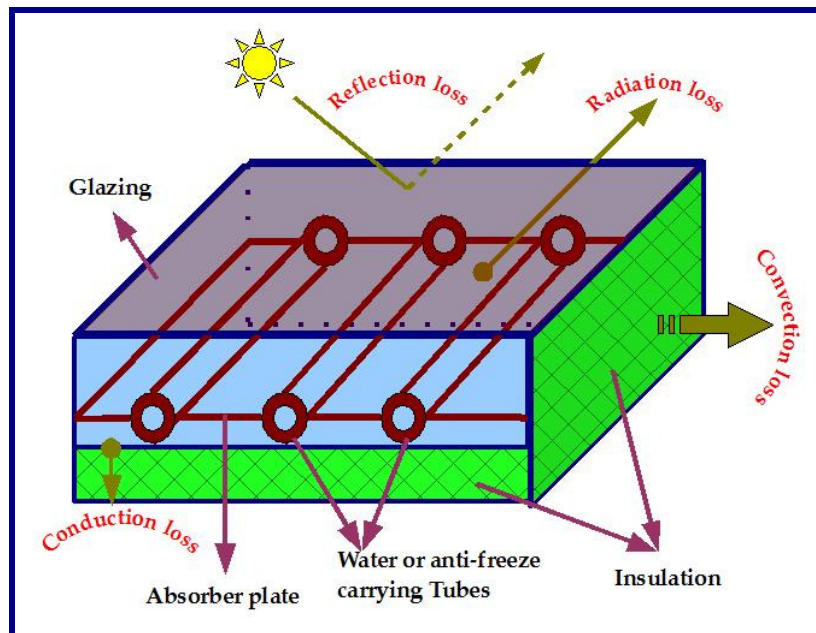


Figure 2.5: Basic components of flat plate collector along with heat loss mechanism.

To improve the heat transfer, the concentrating collectors are available which focus the solar radiation on the tube by means of a concave absorber plate. However, in tropic regions where diffuse radiation is higher, the flat plate collectors are considered thermally superior since it can make use of diffuse radiation as well as beam radiation <sup>[19]</sup>. Moreover, the flat plate collector operation and maintenance cost is lower in comparison to the concentrating collectors. In summary, the decision to use which type of solar collector is influenced by the heat transfer characteristics, the location and the application.



Figure 2.5 gives generic details of the SDHW system. The fluid in solar collector tubes absorb the heat of radiation from the Sun, transmits it the hot water tank with the help of a pump. This configuration is called an active-direct SDHW. If a heat exchanger is used for transferring the heat from the collector panel, it is termed as an active-indirect SDHW system. Advantage of heat-exchanger deployment is to avoid freezing of working fluid in the colder climate.

Instead of deploying a pump to collect the solar energy, the concept of density difference in working fluid or natural convection could also be employed. This class of SDHW systems are called Passive or Thermosyphon SDHW systems. It does not require any source of conventional power or electricity to aid the solar heat collection. Use of passive system is in no way precludes the use of back-up auxiliary system.

For detailed information about the SDHW system one can refer Duffie (2006). A brief description about the three configurations is given below. The configurations can be classified as indirect circulation (closed loop) or direct circulation (open loop) systems.

## **2.2 Active-Direct SDHW Configuration**

A direct (open) configuration are defined as systems in which the collector directly transfer the heat to hot cylinder without any intermediate heat exchanger and the heat transfer fluid is water. These systems require external supply of power to operate the pump for circulation of water through the solar collector. Cold Water enters at the bottom of the hot water cylinder and in turn passes through the solar collector, gets heated and delivers energy at the top portion of hot water cylinder. However, the hot water requirement is typical at constant temperature and sunshine's varies through out the day, so auxiliary heater, attached to the cylinder, is available to compliment the demand at constant temperature. Figure 2.6 depicts schematic of Active-direct SDHW configuration.

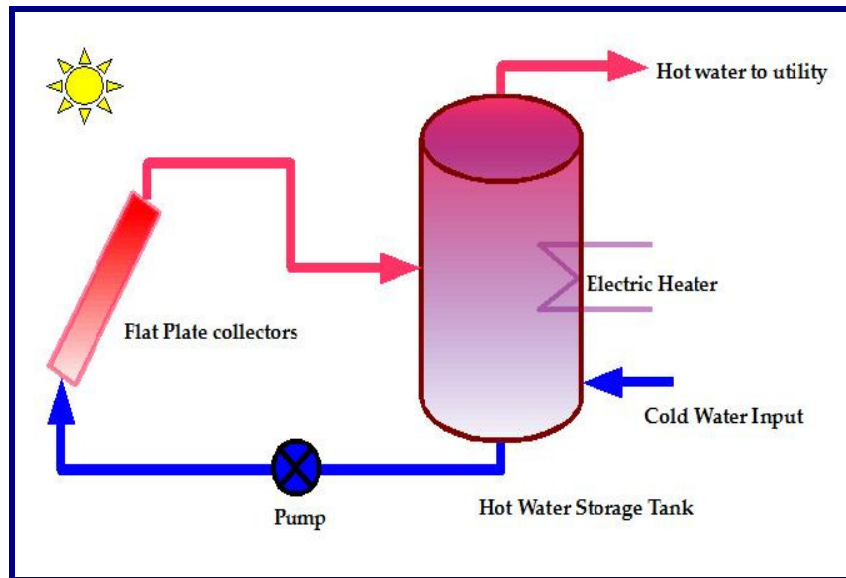


Figure 2.6: Schematic of active-direct SDHW system with electrical heater

## 2.3 Active-Indirect SDHW Configuration

An indirect (close loop) configuration is defined as a circuit in which the heat transfer fluid does not mix with the working fluid (water). Heat transfer fluid is antifreeze for example a mixture of water with ethylene or propylene glycol and these systems requires heat exchanger to transfer the useful solar energy to hot water cylinder. Figure 2.7 depicts the schematic of an active –indirect SDHW system with the electrical heater.

Active indirect SDHW configuration is prevalent in the cold climate like in Europe or the UK. It is because as the ambient temperature goes below  $0^{\circ}$  in winter, it leads to freezing of the water inside the tubes and leading to rupture of the tubes.

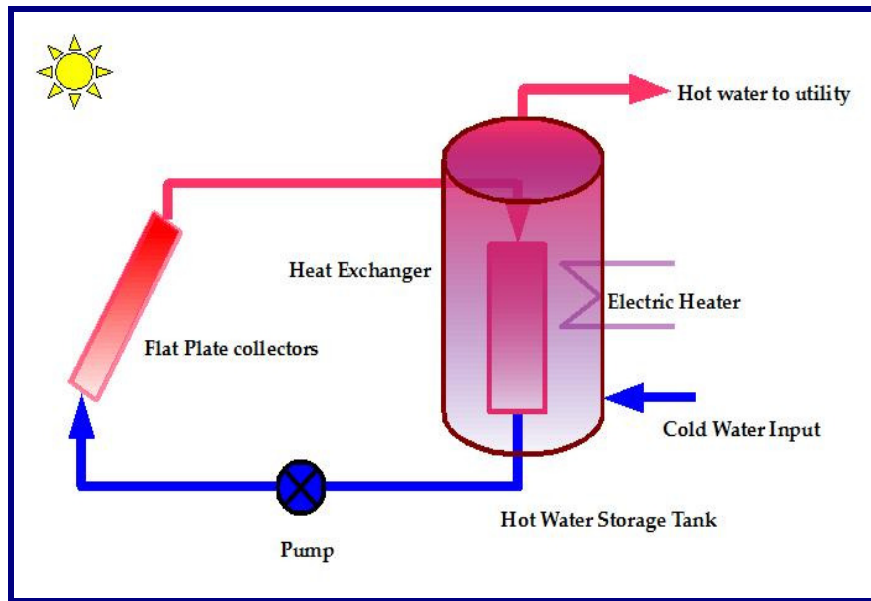


Figure 2.7: Schematic of an active-indirect SDHW system with the electrical heater

The distinguishing feature between an open and a close system is a heat exchanger. It is helically wound coil, having forced and natural convection heat transfer in and outside the coil <sup>[20]</sup>. One can refer Berkel (1991) for detailed information about the heat transfer coefficient used inside and outside the helical coil. He suggests that the **“Heat transfer coefficient of storage tank integrated heat exchanger vary considerably and can not be treated as constant.”** For detailed understanding about the heat exchanger classification, one can refer Sukhatme (1988) <sup>[21]</sup>.

## 2.4 Thermosyphon System

A SDHW configuration based on natural convection of water between the solar collector panel and the hot water tank, called thermosyphon system. During daytime, the water inside the collector loop is heated up by the solar radiation whilst the tank water would be relatively cold. Due to density difference, the hot water moves up and heats the water inside the tank. This continues until the fluid in both the components attains the same temperature. Thermosyphon system does not require any prime mover for water to circulate between the collector and the tank. However, to avoid reverse flow of water during night, the tank needs to be located sufficiently high above the collector panel. Figure 2.8 depicts a simplified model of thermosyphon configuration.

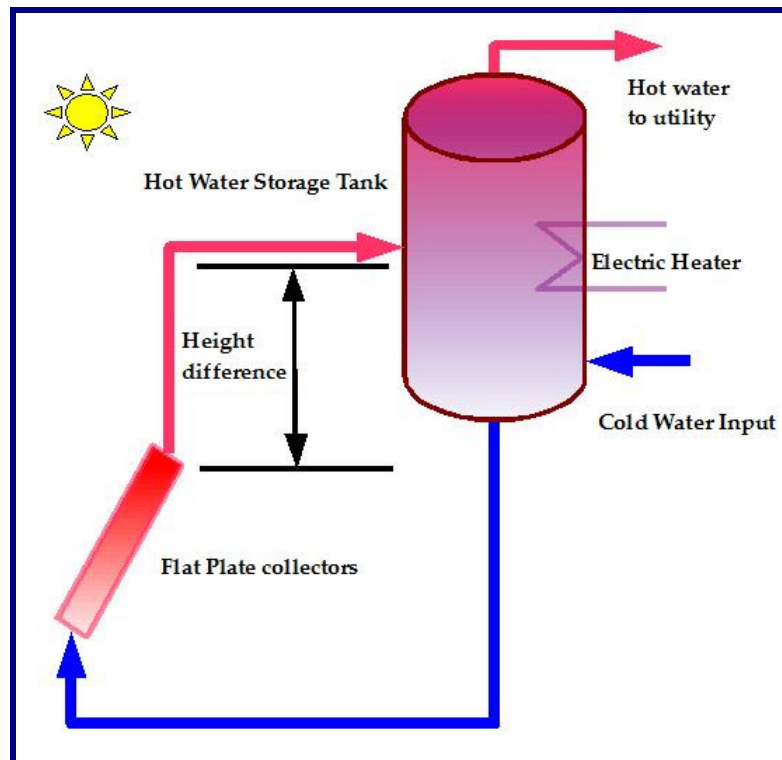
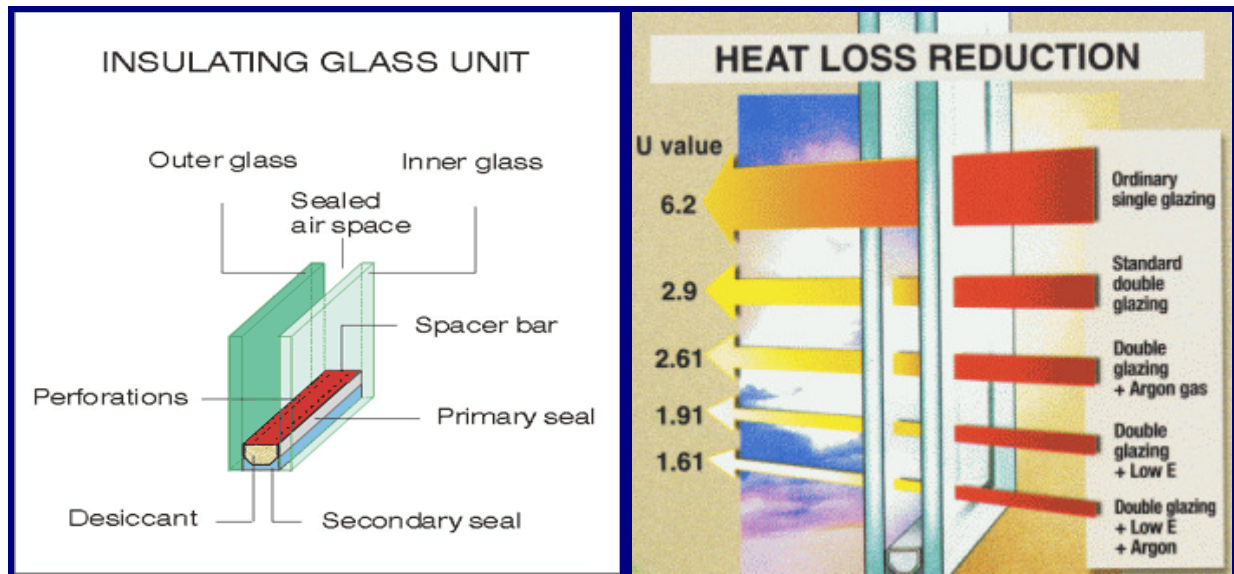


Figure 2.8: Schematic of thermosyphon SDHW system with the electrical heater

## 2.4 Glazing and Coating

Glazing is backbone of all solar energy application. Its function is to allow the short wave (0.3 to 3  $\mu\text{m}$ ) solar radiation to pass freely and restrain long wave (3 to 50  $\mu\text{m}$ ) radiation <sup>[22]</sup>. Incidentally, a simple glass pane has this property. As Stefan-Boltzmann, radiation law states that all body emits radiation (or energy) and is directly proportional to fourth power to absolute temperature. Thermal radiation falls under solar radiation spectrum and it consists of short wave radiation. However when a body gets heat up, it emits radiation, which falls under long wave category. Therefore, when solar radiation reaches the collector panel, whose cover sheet is made of a glass, (Figure 2.8), it allows to radiation to pass through and heats up the absorber plate. However, the same sheet of glass becomes opaque to radiation emitted by heated absorber plate.



(a) Geometric details of double-glazing<sup>[23]</sup> (b) Heat loss comparison for various<sup>[24]</sup> configurations

Figure 2.9: Typical Double-glazed insulation unit

A simple improvement to the single glass pane is to use two-glass panes separated by a thin air gap, called double-glazing. Figure 2.8 (a) shows the concept of double glazing unit. Heat transfer phenomena in the glazing unit are complex. As the glass heats up it also emits long wave radiation, and the air out side solar collector is responsible for heat transfer by other mode, namely conduction and convection.

As the output from the solar panel is dependant upon the over all heat transfer coefficient,  $U$ , of the panel, efforts are made to reduce value of  $U$  by filling the argon gas in place of air or by applying low emittance (Low-E) coating which reflects the long wave radiation but transparent to the short wave radiation or evacuated glazing. Figure 2.8 (b) shows some typical values of  $U$  with permutation and combination of option stated above to improve glazing.

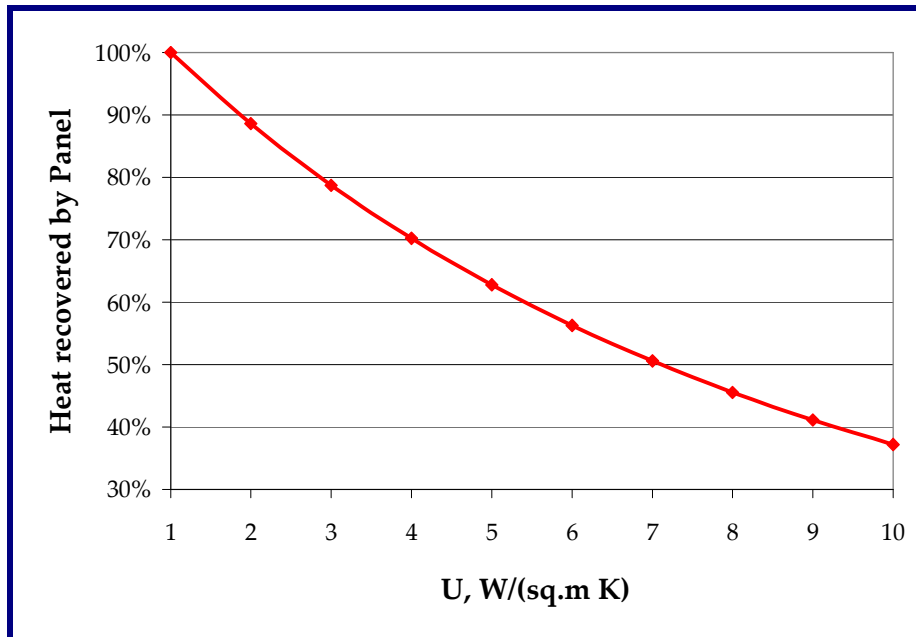


Figure 2.9: Variation in heat recovered by panel vs. over all heat transfer coefficient.

Let us analysis the impact of variation in  $U$  with respect to heat recovered from the panel. Equation 3.1 gives an idea that as the value of  $U$  increases, the amount of heat recovered from the panel will decrease. This is captured in Figure 2.9 assuming that the heat available in solar collector panel is 100% at  $U=1 \text{ W/(m}^2 \text{ K)}$ . On comparing the Figure 2.8 (b) and Figure 2.9, one would appreciate the increase in heat recovered from panel if one switches from single glazing to double-glazing. However, there is a substantial increase in the cost of SDHW if one switches from single glazing to double-glazing. In this study, the value of  $U$  turns out to be  $\sim 6 \text{ W/m}^2 \text{ K}$

## 2.5 Heat Transfer Fluids in SDHW System

A heat transfer fluid is used to collect the heat from solar panel transfer to the storage tank either directly or with the help of heat exchanger. In order to have an efficient SDHW configuration, the fluid should have high specific heat capacity, high thermal conductivity, low viscosity, and low thermal expansion coefficient, anti-corrosive property and above all low cost.

Among the common heat transfer fluids such as water, glycol, silicon oils and hydrocarbon oils, the water turns out to be the best among the fluids <sup>[25]</sup>. However, water changes its phase when temperature tends to  $0^\circ \text{C}$ . During this process, water becomes solid from liquid state and expands.

This phenomenon leads to increase in stress inside the pipe and can lead to pipe rupture. To circumvent this issue, one has to opt for a pre-heating system. It would not allow water to freeze in any condition.

Another way to overcome water-freezing issue is to use antifreeze. It is a mixture of glycol and water and a prominent candidate to act as heat transfer fluid. This is widely used in radiators of cars as heat transfer fluid and proved very efficient. To use glycol - water mixture as heat transfer fluid in SDHW, following points need attention <sup>[11]</sup>.

- Glycol content of 40% or less assures smooth operation until - 24 °C. However, glycol content in excess of 50% increases viscosity and lower heat capacity.
- Glycol is not compatible with Zinc. So, internally galvanized pipes should be avoided.
- Propylene glycol is more food compatible than ethylene glycol.

## CHAPTER 3: MATHEMATICAL MODEL OF SDHW SYSTEM

*"The amount of sunshine energy that hits the surface of the Earth every minute is greater than the total amount of energy that the world's human population consumes in a year!"*

Home Power Magazine

Broadly, there are two distinct components in SDHW systems, viz., solar collector panel and storage tank. Other components can be clubbed with above-mentioned components for purpose of developing a simple and concise thermal model. With information about load profile and weather data for a particular location, it is possible to solve the sets of equation simultaneously for the simplified model over an entire year and assess the thermal performance or contribution of the SDHW system in the hot water demand for given location such as Glasgow or London, UK.

The solar collector performance is function of inlet fluid temperature. If we assume that the heat losses from the connecting pipes between storage tank and the solar panel inlet are negligible, the final set of equations become simple to solve. The outlet temperature from the solar collector panel becomes the inlet temperature to the hot water cylinder.

The hot water cylinder supplies the hot water at desired temperature. It has two source of heat input, one from solar collector panel and other from electrical or gas heater. The cold water enters the cylinder at an average temperature of  $10 \pm 2.6$  °C over a year<sup>[26]</sup>.

### 3.1 Two Design Concepts – Low Flow and Thermal Stratification

Concept of low flow design in the collector panel and thermal stratification inside the storage tank are the two prominent research areas in SDHW system design. Relatively high collector flow rates are prevalent in the field for an active indirect SDHW configuration because a high collector flow rate improves the collector flow factor, which in turn improves collector efficiency by improving the heat removal factor<sup>[13]</sup>. Figure 3.4 supports this logical outcome for SDHW system.

Hollands (1989) suggested that **“By using low collector flow rates (roughly one-seventh of the standard value) with thermally stratified storage tanks, the calculated performance of solar**



hot water systems for domestic, commercial, and industrial use can be improved by as much as 38%, if one compares to a system having a fully mixed tank and a high flow rate [27].”

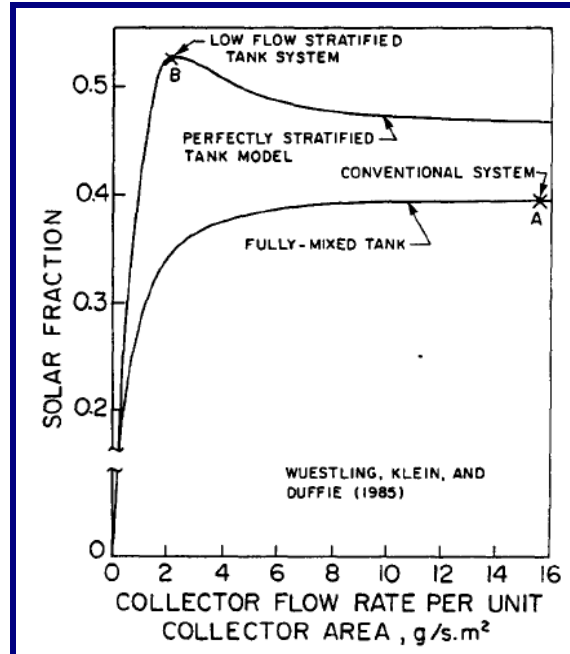


Figure 3.0: Annual solar fraction Vs collector flow rate per unit area [27, 28]

Wuestling et al., (1985) carried out the study for low flow SDHW configuration and showed that with a low flow configuration in SDHW, one could achieve the enhanced solar fraction available for heating the water.

### 3.2 High Flow Vs Low Flow Design of SDHW System

A high flow SDHW system refers to nominal flow rate of fluid in the primary loop (between solar collector and storage tank) and it is in the range of 10 to 20 g/s per m<sup>2</sup> of the collector area. Corresponding value for low flow SDHW system is 2 to 8 g/s per m<sup>2</sup> of the collector area [11, 27, and 28].

Let us analyse the both system from the thermal performance point of view. To simplify the calculation, let us assume that the solar radiation of 1000 W/m<sup>2</sup> with collector efficiency of 60% and specific heat capacity of antifreeze 3.8 kJ/kg K are the parameters for the analysis [3, 11]. By applying the heat balance across the solar collector, (equation 3.1), the temperature difference

across the collector panel for the high flow and low flow SDHW system would be 8-15 K and 20-80 K respectively.

For high flow system, lower the temperature difference enables the system to work efficiently as the losses through the panel would be low. However, the pumping requirement would be reasonable high. It is also advantageous when one decides to go for more number of panels connected in series or in parallel configuration or combination of series and parallel systems.

For low flow system, higher temperature difference would lead to higher losses. However, higher outlet temperature would enable to supply the hot water directly to utility with out significant addition of heat from auxiliary heater or in other words, the contribution of solar fraction would be higher in comparison to high flow system (Refer figure 3.0). So for domestic application, low flow system preferred not only from the thermal performance point of view but from pumping point of view also. In this project, low flow system is selected with a collector flow value in the range of 4-5 g/s per m<sup>2</sup> of collector area.

### 3.3 Thermal Stratification

Due to effect of gravity and the buoyant force, a high-density fluid or cold water will settle at the lower part of a tank and a low-density fluid or hot water at the upper part of the storage tank. Now one can imagine that a thermal barrier is available between a hot zone to a cold zone inside the tank and maintains the stable vertical temperature or density gradient. This part of tank mimics the concept of **Thermocline**. Figure 3.1 <sup>[29]</sup> elaborates the concept of stratification inside a tank with high value of thermal stratification to a fully mixed tank.

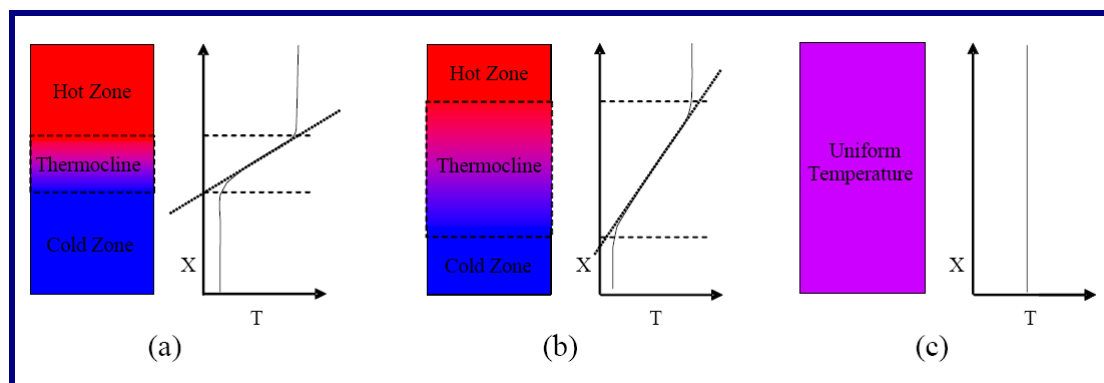


Figure 3.1: Different levels of stratification within storage tank with equivalent stored energy (a) highly stratified, (b) moderately stratified and (c) a fully mixed, unstratified storage

Thermal Stratification has impact on the thermal performance of SDHW systems also. Furbo (1993) explains, “**A high degree of thermal stratification increases the thermal performance of solar hot-water systems because the return temperature to the solar collector is lowered. A lower return temperature to the solar collector will increase the efficiency of the solar collector** <sup>[30]</sup>.”

Building of stable thermocline in time and space implies that the mixing should be minimised. Stable thermal stratification or thermocline within the tank can be achieved by various means. Following are typical three ways to achieve it <sup>[31]</sup>.

- (1) Heating of vertical walls, which results in the creation of hot thermal boundary layers drawing hot fluid into the upper part of the tank.**
- (2) Heat exchange between the fluid contained in the tank and that circulating in a heat exchanger carefully placed inside or outside the tank.**
- (3) Direct inlet into the tank of hot fluid at suitable heights.**

Thermal stratification in the storage tank is influenced by various parameters such as insulation thickness, flow rate at inlet and outlet, tank inlet and outlet geometry. Lavan and Thompson (1977) carries out an experimental investigation to investigate the effect of inlet and out geometry on the thermal stratification in the storage tank. They conclude that inlet location has a strong influence on thermal stratification while the location of the outlet is much less important <sup>[32]</sup>.

To illustrate the impact of a baffles plate at inlet to the storage tank, Shah and Furbo (2003) conducts a theoretical and experimental analysis on the impact of different baffle plate designs on the flow patterns. He has considered three different type of baffle plate: (a) a straight pipe, (b) hemispherical baffle plate and (c) a large plate. For low flow of water (~ 1 l/min, figure 3.3), the geometries have marginal impact on the thermal stratification. However, if the flow rate is high (~ 10 l/min, figure 3.2), the impact of geometry is significant. Figure 3.2 <sup>[30]</sup> shows how the quality of energy or the exergy in the hot water tank is changes with various inlet designs. The primary cause for such a pattern is that the baffles plate decreases the mixing at the inlet to the tank by redirecting the incoming fluid <sup>[30]</sup>.

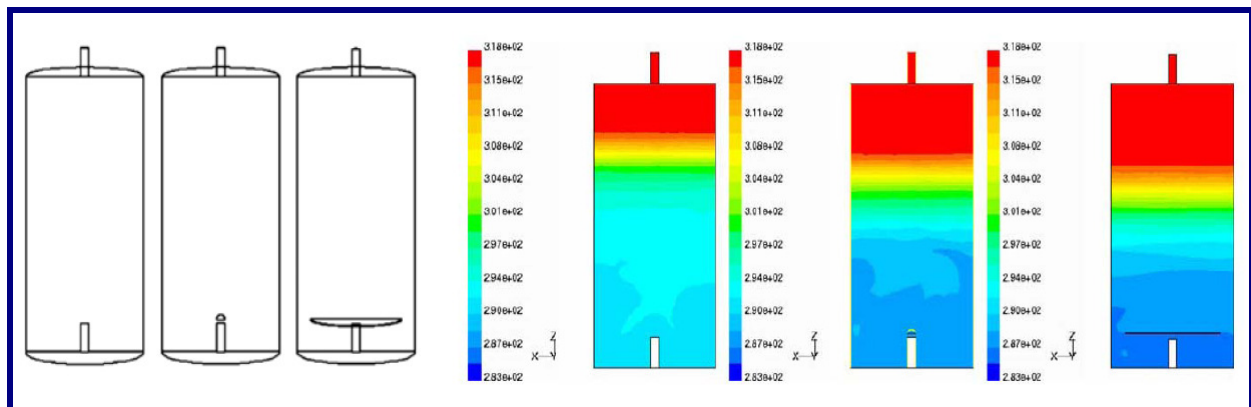


Figure 3.2: Baffle plate designs and temperature distribution (by CFD) in the tank at high flow rate (~10 l/min)

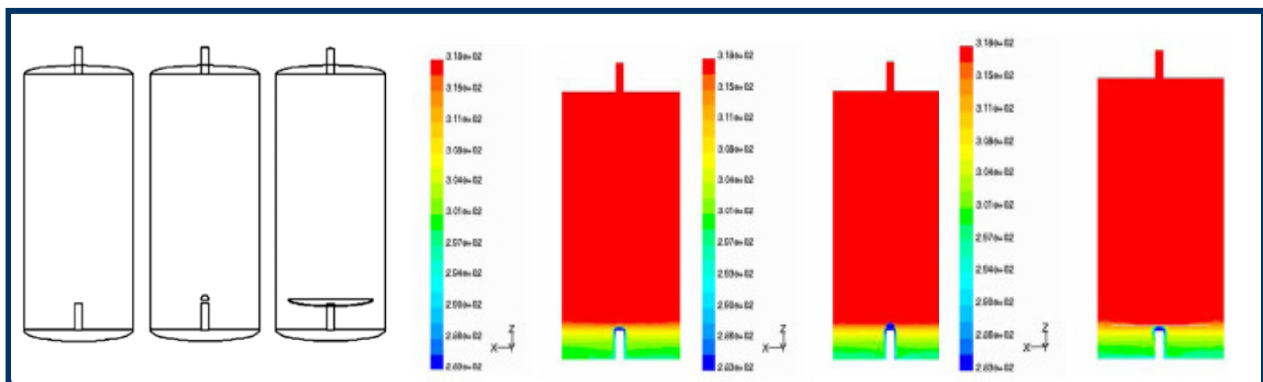


Figure 3.3: Baffle plate designs and temperature distribution (by CFD) in the tank at low flow rate (~1 l/min)

Let us explore the impact of outlet geometry on performance of SDHW tank. Furbo et. al., (2005) investigates the advantage of two outlets at different levels in the storage tanks; one at fixed level and other at just above the middle of the storage tank. It indicates an increase by 6% in thermal performance if one opts for “**two draw-off levels from the solar tanks instead of one draw-off level at a fixed position**” [33].

The degree of stratification in the storage tank depends on various parameters such as tank size, location, design of inlets and outlets, flow rates, heat exchanger type, and the design of internals of storage tank [18]. Ghaddar (1994) compares between a fully stratified and a fully mixed water tank

from the energy storage point of view. Ghaddar proposes that the energy storage efficiency might be increased up to 6% <sup>[34]</sup> for fully stratified tank.

### 3.4 Dimensional Analysis of Thermal Stratification

One would appreciate the complexity of the thermal stratification analysis in the hot water tank and number of parameters influencing it. As we can clubbed various parameter and termed it into dimensionless numbers such as inlet Reynolds ( $Re$ ) number, the Froude ( $Fr$ ) number or Richardson ( $Ri$ ) number.

Han et. al., (2009) prepares a table (Table 2 <sup>[31]</sup>) which details about the researchers efforts in understanding the impact of above-mentioned dimensionless number on stratification. It is interesting to note that the  $Ri$  plays significant role in characterising the mixing inside the tank. One could safely infer from the table 2 <sup>[31]</sup> is that if the “ **$Ri$  is greater than 0.2 inside the tank, “the mean temperature gradient is not influenced by the inlet flow”.**

### 3.5 Thermal Modelling of the Solar collector Panel

Before starting, the mathematical modelling of SDHW components, it would be wise to state the source of all set of equations. One can refer “**Solar Engineering of Thermal Processes**” by Duffie and Beckman <sup>[18]</sup> for detailed concept and modelling.

Figure 2.5 gives the details of all modes of heat transfer mechanism happening in a flat plate collector. Useful energy is given by: (Refer figure 3.3)

$$Q_C = A_C * F_R * [S - U * (T_{ci} - T_a)]^+ = \dot{m} * C_p * (T_{co} - T_{ci}) \quad (3.1)$$

Where

$Q_C$  is actual useful energy gain, W

$A_C$  is aperture area of the flat plate collector, m<sup>2</sup>

$F_R$  is equivalent to effectiveness of a conventional heat exchanger.

$S$  is absorbed solar radiation, W/m<sup>2</sup>

$\dot{m}$  is mass flow rate of antifreeze inside the collector loop, kg/s

$C_p$  is heat capacity of anti-freeze, J/kg K

$T_{co}$  is outlet temperature of solar plate collector, °C

$T_{ci}$  is inlet temperature of solar plate collector, °C

$U$  is overall heat transfer coefficient, W/m<sup>2</sup>K.

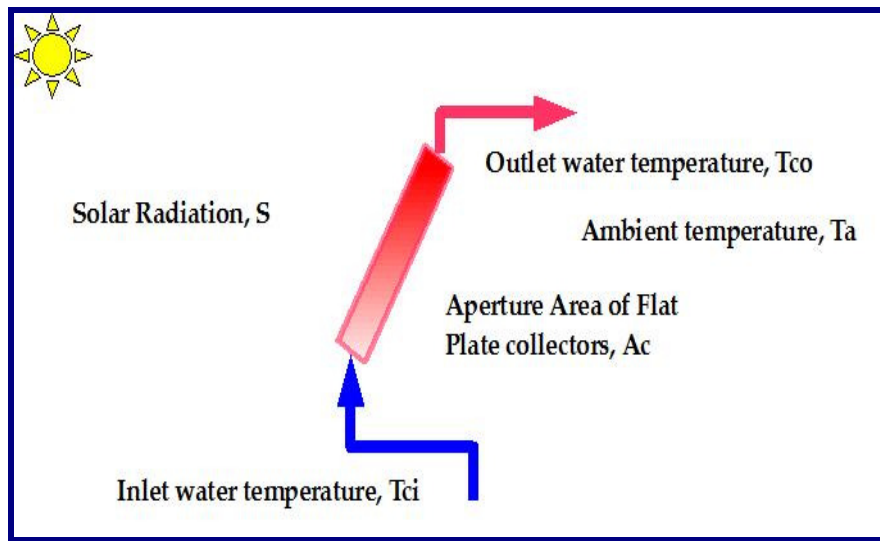


Figure 3.3: Thermal model of flat plate collector

One of the challenges is to estimate accurately the  $U$  for a given geometry. Klein (1979) developed an empirical equation for the heat transfer coefficient for the upper surface from the solar collector panel <sup>[35]</sup>.

$$U_t = \left[ \frac{N}{\frac{C}{T_{pm}} \left[ \frac{(T_{pm} - T_a)^e}{(N + f)} \right]} + \frac{1}{h_w} \right]^{-1} + \frac{\sigma(T_{pm} + T_a)(T_{pm}^2 + T_a^2)}{(\epsilon_p + 0.00591 * N h_w)^{-1} + \frac{2N + f - 1 + 0.133\epsilon_p}{\epsilon_g} - N} \quad (3.2)$$

Whereas

$U_t$  is overall heat transfer coefficient, W/m<sup>2</sup> K

$N$  is number of glass cover

$T_{pm}$  is mean plate temperature, K

$T_a$  is ambient temperature, K

$h_w$  is wind heat transfer coefficient,  $W/m^2 K$

$\epsilon_g$  is emittance of glass cover.

$\epsilon_p$  is emittance of plate

$$e = 0.43 * (1 - 1/T_{pm})$$

$$f = (1 + 0.089h_w - 0.116 * h_w * \epsilon_p) * (1 + 0.07866N)$$

$$C = 520 * (1 - 0.00005 * \beta^2) \text{ for } 0^\circ < \beta < 70^\circ. \text{ For } 70^\circ < \beta < 90^\circ, \text{ use } \beta = 70^\circ$$

There are two more terms in the equation 3.1,  $S$  and  $F_R$ , which need more elaboration.  $S$ , Solar absorbed radiation is a combination beam radiation, diffuse radiation and ground reflected radiation. Appendix-A elaborates the procedure to transfer the beam, diffuse and ground reflected radiation to a tilted solar panel at a given orientation and location.

$F_R$  is equivalent to effectiveness of a conventional heat exchanger as heat or heat removal factor, which is defined as follows.

$$F_R = F' * F'' \quad (3.3.1)$$

$$F'' = M_C * (1 - e^{(-1/M_C)}) \quad (3.3.2)$$

$$M_C = \frac{\dot{m} * C_p}{A_C * U * F'} \quad (3.3.3)$$

Where as

$F'$  is plate efficiency factor.

$M_C$  is dimensionless collector mass flow rate.

$F''$  is defined as collector flow rate.

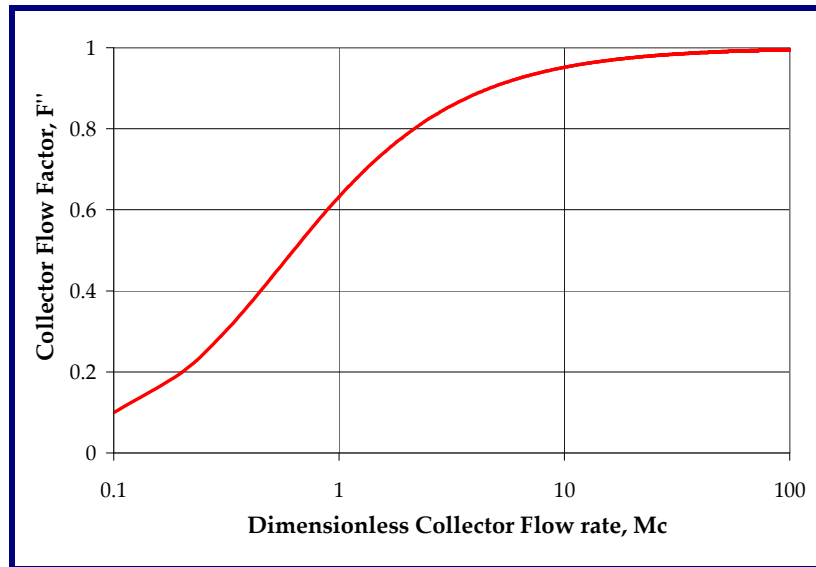


Figure 3.4: Variation of collector flow rate with collector flow factor

### 3.6 Thermal modelling of Hot Water Tank

To start the thermal modelling, a control volume approach is applied to the hot water tank. Energy balance is applied for the elemental volume i.e., rate of change of energy inside the elemental volume is equal to the net rate of input/output of energy to the elemental volume. As the total volume is divided into finite control volumes, so for each elemental volume the heat balance equation is to be written. Equation 3.4 represents the heat balance for a single node while equations 3.5, 3.6 and 3.7 represent the heat balance for finite number of nodes. Figure 3.5 depicts the heat balance in the control volume. One can refer either figure 2.6 or 2.7 for basic understanding about the heat input and the heat output from the control volume.



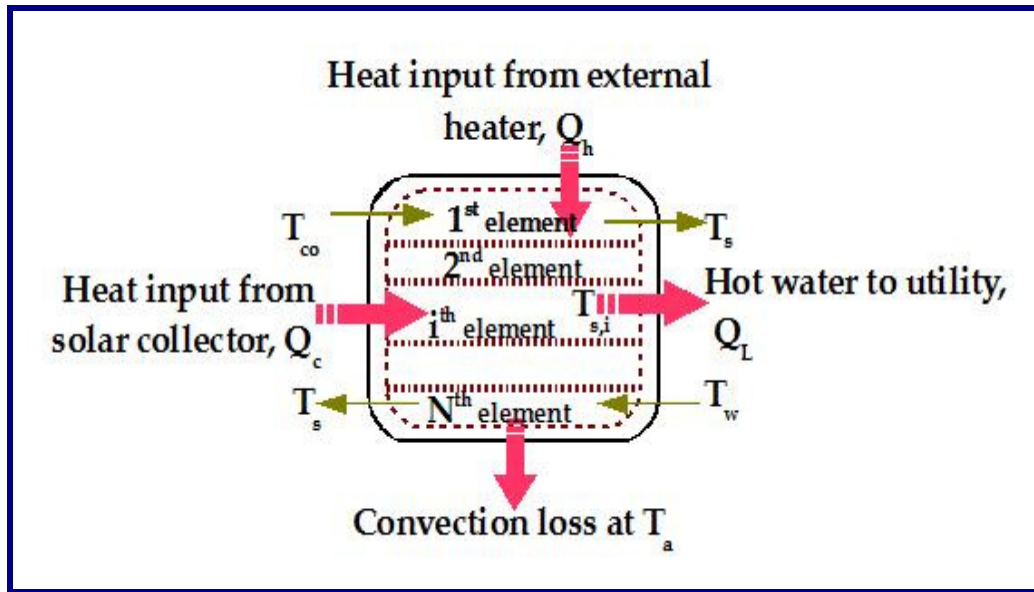


Figure 3.5: Heat balance for the hot water tank

On application of first law of Thermodynamics,

$$m_s * C_p * \frac{dT_s}{dt} = Q_c - Q_L - UA * (T_s - T_a) \quad (3.4)$$

Where,

$m_s$  is mass of water in the storage tank, kg

$C_p$  is heat capacity of water, J/ (kg K)

$T_s$  is the instantaneous tank temperature, K

$Q_c$  is heat addition from the solar collector panel, W

$Q_L$  is heat removal from the storage tank due to load to the utility, W

$U$  is overall heat transfer coefficient of the storage tank, W/ (m<sup>2</sup> K)

$A$  is the storage tank area, m<sup>2</sup>

$T_a$  is the ambient temperature, K

$T_w$  is water temperature at inlet to the storage tank, K

$T_c$  is outlet temperature from a flat plate collector, K

$T_i$  is inlet temperature to a flat plate collector, K

In Appendix-A, a detailed calculation procedure is presented for calculation of  $Q_C$  for the direct and the indirect SDHW configuration along with simplified modelling of the flat plate collector. MATLAB code is also written to optimize the tilt angle for the solar collector panel for maximum annual heat output from the collector for given location and a solar incident radiation.

Equation 3.4 talks about the single node model for the storage tank. To model the stratified tank, that is, with top of tank hotter than the bottom of the tank, a multi-node tank model or a plug flow approach is next step in the tank modelling. In multi-node modelling, the tank is divided into  $N$  nodes or sections, with energy balances written for each node. It results in  $N$  differential equations to be solved simultaneously to obtain the temperature of each node. While in a plug flow approach, each section of liquid is assumed to be moving through the tank with different temperature. Essentially, it is a bookkeeping method so as to track the size, temperature and the position of a section.

Following are the equations, which are essential to formulate the energy balance for  $i^{th}$  node of a multi-node tank model at time,  $t$ .

$$(m_s * C_p)_i * \frac{dT_{S,i}}{dt} = F_i * \dot{m}_c * C_{p,c} * (T_{co} - T_{S,i}) - L_i * \dot{m}_L * C_p * (T_{S,i} - T_L) - (UA)_i * (T_{S,i} - T_a) + \left\langle \begin{array}{ll} \dot{m}_{m,i} * (T_{S,i-1} - T_{S,i}) & \text{if } \dot{m}_{m,i} > 0 \\ \dot{m}_{m,i+1} * (T_{S,i} - T_{S,i+1}) & \text{if } \dot{m}_{m,i} < 0 \end{array} \right\rangle + Q_H \quad (3.5)$$

Where as,

$F_i$  and  $L_i$  are defined as a control function for the collector and load return in the multi-node model.

$$F_i = \begin{cases} 1 & \text{if } i = 1 \& T_{co} < T_{S,i} \\ 1 & \text{if } T_{S,i-1} \geq T_{co} > T_{S,i} \\ 0 & \text{if } i = 0 \quad \text{or} \quad \text{if } i = N + 1 \\ 0 & \text{otherwise} \end{cases} \quad (3.6)$$

$$L_i = \begin{cases} 1 & \text{if } i = N \text{ \& } T_L < T_{S,N} \\ 1 & \text{if } T_{S,i-1} \geq T_L > T_{S,i} \\ 0 & \text{if } i = 0 \quad \text{or} \quad \text{if } i = N + 1 \\ 0 & \text{otherwise} \end{cases} \quad (3.7)$$

$Q_H$  is defined electrical or gas heating values, W.

$\dot{m}_L$  is defined as the hot water demand, kg/s.

$U$  is defined as overall heat transfer coefficient of the storage tank at outer radius, W/m<sup>2</sup> K.

$A$  is defined as outer area of the storage tank including insulation, m<sup>2</sup>.

Subscripts

's' represents the storage tank.

'c'. represents the data related to the solar collector panel.

'N' represents total number of nodes in the storage tank.

These sets of equation are modelled in SIMULINK and solved by (ode45) or Runge-Kutta Method [36].

Before attempting to simplify the modification of the existing hot water cylinder study, let us discuss the concept of the “dedicated solar volume” requirement as mentioned in Domestic Heating Compliance Guide, table 31 (g) [37].

**Table 31 (continued)**

(g). Storage of solar pre-heated water	The ratio of solar heated water storage volume to collector area should be specified as follows:
	I. The dedicated solar storage volume, $V_s$ , should be at least 25 litres (or equivalent heat capacity) per net m <sup>2</sup> of the solar collector area.
	II. Alternatively, $V_s$ should be a volume (or equivalent heat capacity), which is equivalent to at least 80% of the daily hot water demand, $V_d$ , (as defined by SAP 2005).

With the above information, it is sufficient to divide modification of existing hot water cylinder into two different models captured in figure 3.6. [38]

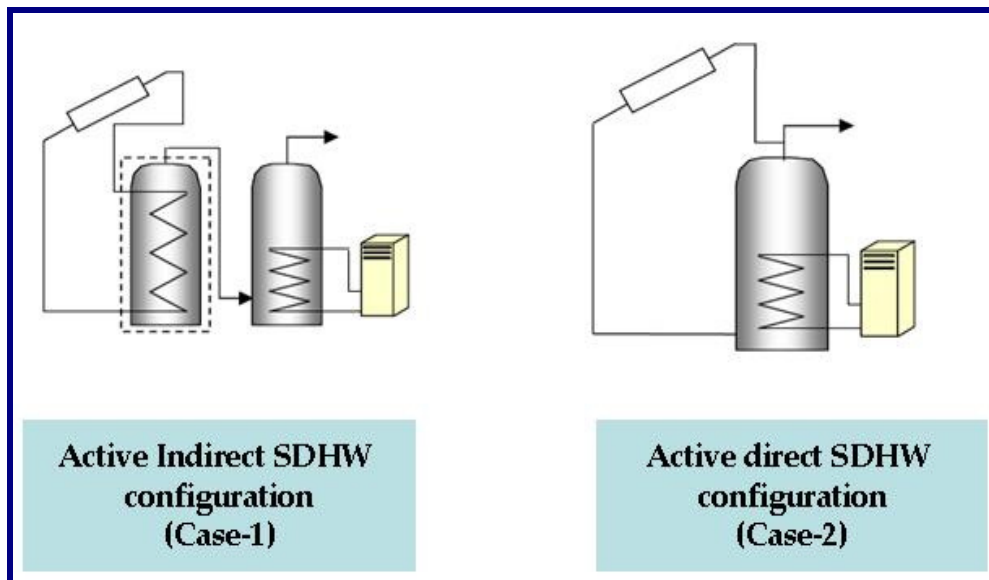


Figure 3.6: Two cases considered for analysis in the project.

For case-1, the storage is modelled as a two-nodded tank and an auxiliary vessel is as singled noded tank. For case-2, the storage is modelled as a two-nodded tank with the auxiliary heater in upper half.

Soo (2009) carried out the study of closely similar case as described above. However, in place of an internal helical coiled heat exchanger, he used a mantle heat exchanger with one hot water cylinder. He suggested that **"The performance simulation showed that the annual solar contribution for daily and seasonal load conditions in Sydney, as specified in the Australian Standard (AS4232) drops from 79% for a direct-coupled system (stratified routine) to 72% for a system with a mantle heat exchanger in the collector loop. The loss of performance may be acceptable given the advantage of freeze protection that the mantle heat exchanger provides, however, with improved heat exchanger design it may be possible to reduce the heat exchanger penalty by improving tank thermal stratification [39]."**

### 3.7 Heat Exchanger Modelling

There are three basic configurations, as shown in Figure 3.7 <sup>[31]</sup>. These are commonly employed in the storage tank such as (a) Immersed Helical coils in the Storage Tank, (b) External Shell and Tube Heat Exchanger, (c) Mantle Heat Exchanger with an annular Jacket <sup>[31]</sup>.

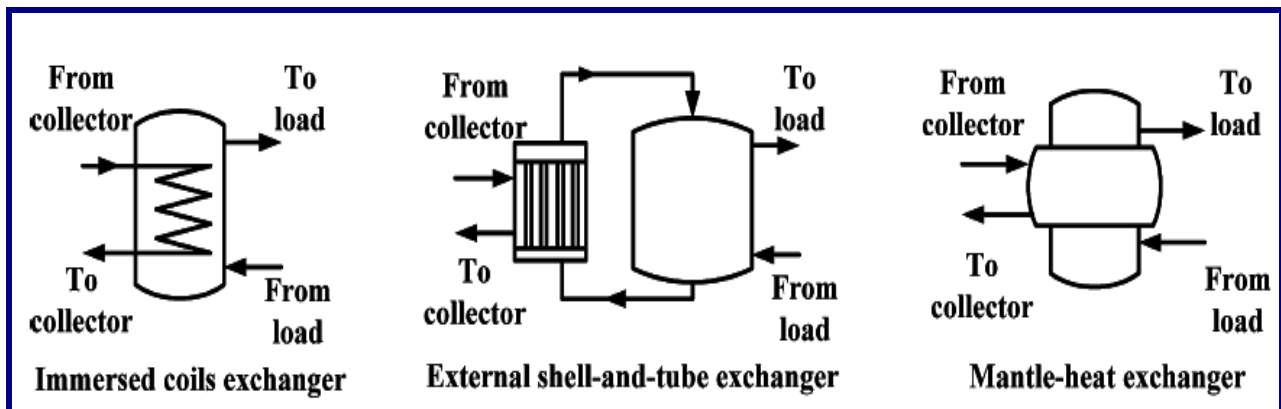


Figure 3.7: Schematic of three typical heat exchanger options for SDHW

### 3.7.1 Immersed Helical Coils in the Storage tank

In this type of heat exchanger, the helical coils are placed inside the storage tank in such a manner to improve and enhance the thermal stratification in the tank. Heat transfer in this configuration is function of various parameters such as mass flow rates, temperature differences, heat transfer area and geometric shape of coils, pitch of the coil etc.

Lou et. al., (1989) carries the parametric study of immersed coil heat exchanger. Lou concludes that performance of heat exchanger is more influenced by temperature difference and flow rate<sup>[40]</sup> in comparison to any other parameters. Out side area of these coil can be finned or have smooth surface. Farrington (1987) suggests that a smooth coil with only 70% of the surface area of a finned coil performed better than the finned one<sup>[41]</sup>.

### 3.7.2 External Shell and Tube Heat Exchanger

In this arrangement, the liquid flows in the solar collector panel in primary circuit and the liquid in secondary circuit heats the storage tank. As it is an external to storage tank, pipe losses could be one of the extra penalties on the heat exchanger performance. However, with the help of distribution of the hot water at different level in the storage tank, it has better chance of maintaining the thermal stratification.

### 3.7.3 Mantle Heat Exchanger with an Annular Jacket

In this configuration, the hot liquid flows around the storage tank as shown in figure 3.4. This configuration is amenable to desirable flow pattern in the collector, which increases its effectiveness and promotes the thermal stratification <sup>[31]</sup>. Its advantages are numerous such as simple design of storage tank with exchanger, large heat transfer area etc. A study is carried out for a low flow solar water heating system to get the performance of three type of heat exchanger. For the low flow water heating system, the vertical mantle type outperforms the immersion and external shell and tube types <sup>[42]</sup>.

In this project, an immersion type of heater is modelled for the analysis purpose. Mathematical model of the heat exchanger is lumped with the solar collector panel modelling as the heat exchanger penalty.  $F_R$  in equation 3.1 is replaced with  $F'_R$ , which is defined as follows.

$$\frac{F'_R}{F_R} = \left[ 1 + \frac{1}{M_C} \left( \frac{(\dot{m} * C_p)_C}{\varepsilon * (M_C C_p)_{\min}} - 1 \right) \right]^{-1} \quad (3.5)$$

Where

$F'_R / F_R$  could be thought of as a penalty in the solar collector performance. This is incurred because of the heat exchanger causes the collector to operate at higher temperature.  $\varepsilon$  is heat exchanger effectiveness as defined by the manufacturer.

## 3.8 Draw-off Profiles for Hot Water

Availability solar energy is dependant on many parameters such as an hour of day, year of a month, location etc and so does the energy demand. However, the supply of the solar energy varies in different fashion than that of energy demand. Generally, demand of the hot water is there in the morning and in the evening. However, the solar radiation available is in the daytime only. In summary, storage of the solar energy is necessary to meet the lag in supply and demand. In order to meet the challenges of matching supply and demand, it is necessary to have a vivid picture of demand profile.

Let us first analyse the total hot water required for a dwelling in a day. Hot water demand stands for the energy required at particular temperature. SAP elaborated that the demand of the hot water is correlated to the Total Floor Area (TFA) of a dwelling. It states that a dwelling with  $104\text{m}^2$  TFA would have a hot water usage of 119L per day <sup>[38]</sup>. In this analysis, a standard dwelling TFA is assumed as  $104\text{ m}^2$ .

In order to carry out a systematic analysis of the two cases, it is vital to use realistic profiles. Typically, two normalised hot water demand profiles <sup>[26, 43]</sup> are considered for the analysis purposes and captured in Figure 3.8.

Hot water demand profile-1 captures two bathing events, one in the morning and other in the evening. It also takes care of the hot water required for the washing and the cleaning purpose during noontime. Demand profile-2 is smoother way to the capture the concept of hot water demand as explained for the load profile-1.

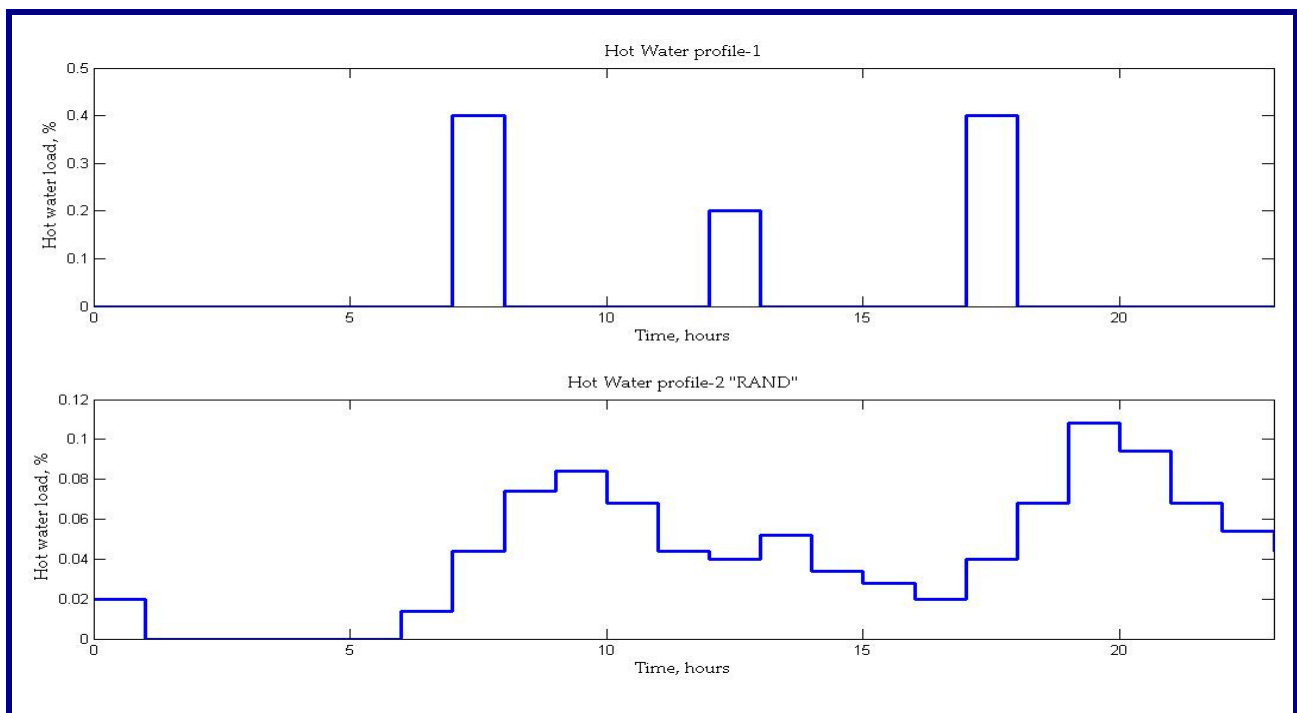


Figure 3.8: Two hot water demand profile used for analysis.

### 3.9 Control Strategy in SDHW

As explained earlier, there is an element of mismatch between the supply of energy by the solar panel and the demand of hot water to the utility. Therefore, the option available is to store the hot water during the daytime when sunshine is available and utilize it when it is required. Let us explore and formalise this concept. The above-mentioned situation could be tackled by segregating the whole process into two elements viz., **Storage** and **Direct Supply**. “Storage” implies the heating of water by the solar energy to a certain temperature. “Direct Supply” suggests the additional heat provided by the auxiliary heater to the heated water in order to meet the demand at required temperature.

By this concept, the heat from the solar panel could be maximized with minimum intervention of the auxiliary heater. To implement the above-mentioned concept, a proper control strategy is needed. Controls are also required for the pump and for the auxiliary heater.

In a SDHW design, two types of control schemes are commonly employed: ON/OFF and proportional or proportional plus integral control <sup>[44]</sup> for two components viz. the solar collector pump and the auxiliary heater. In ON/OFF scheme, the solar collector pump is switched either ON or OFF so that the significant amount of heat recovered from the panel could be transferred to the storage tank. With a proportional controller, the pump speed is controlled to maintain the collector out temperature at a specified level. The purpose of controls in an auxiliary heater is to maintain the constant temperature either by proportional or proportional plus integral control scheme.

#### 3.9.1 Control Scheme in Pump

Potential for heat transfer between the solar collector panel and the storage tank is higher temperature of water/fluid at the collector outlet than the storage tank temperature. Otherwise, reverse phenomena will happen. In other words, the equation (3.1) needs to be positive for the heat transfer to happen from the collector panel to the storage tank.



In order to implement the concept, two temperature sensors are needed, one at the outlet of the solar collector panel,  $T_{co}$  and other at the storage tank,  $T_s$ . So if the temperature difference ( $\Delta T = T_{co} - T_s$ ) is positive, pump will be ON. Otherwise, it will be OFF.

$$S - U * (T_{co} - T_a) = 0 \quad (3.8)$$

Or

$$S_{ON} = U * (T_s + \Delta T - T_a) \quad (3.9)$$

On substituting the values of  $S_{ON}$  in equation 3.1 and rearranging the terms,

$$\Delta T_{OFF} \leq \frac{A_C * F_R * U}{\dot{m} * C_p} \Delta T_{ON} \quad (3.10)$$

In the analysis, ON/OFF type of controller is implemented. Figure 3.9 depict it.

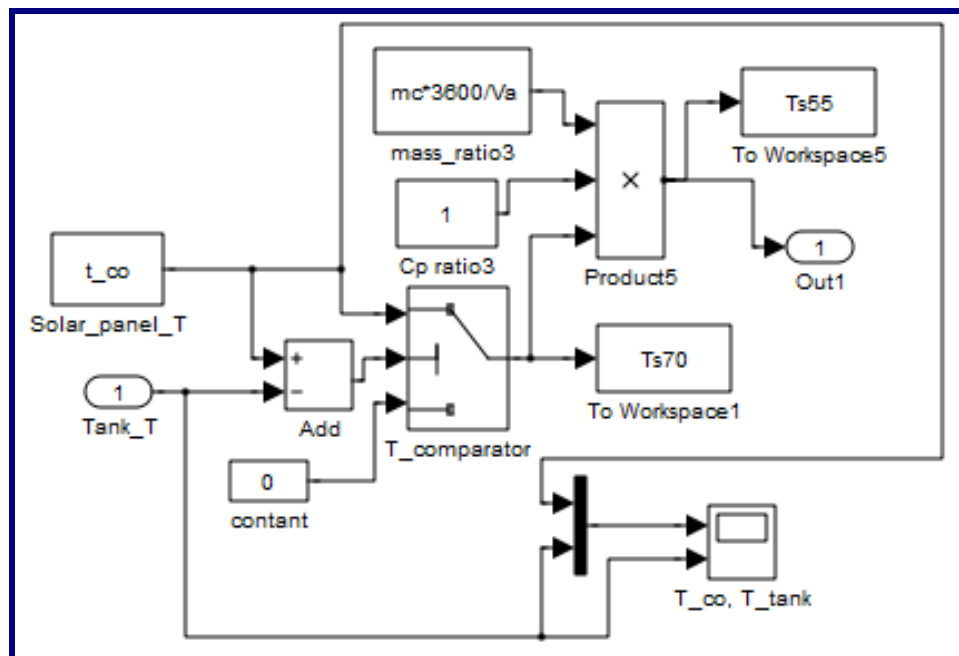


Figure 3.9: ON/OFF control logic implementation in SIMULINK

In actual practice, there will be a drop in temperature from the collector panel to the storage tank due to losses in the connecting piping between the two components. Therefore, it is recommended

to calculate the actual temperature drop for the installed system by a field measurement and set the  $\Delta T$  value.

### 3.9.2 Control Scheme in Auxiliary Heater

An auxiliary heater is either gas or electricity driven water heater. It also need control scheme for fulfilling the second element of the control strategy i.e., “**Direct supply**”. Ideally, the heater should be switched ON when the hot water demand is needed and switched OFF, when demand is not there. Moreover, the heater should maintain a constant temperature of 70 °C when the demand is there. It should also not allow the temperature to reach 100 °C from safety point of view. The auxiliary heater should be located, inside the tank, in such way that it does not increase the bulk temperature of the storage tank. It would be help in maintaining the thermal stratification inside the tank.

To meet the above-mentioned functions, the auxiliary heater is located in the upper most node in the multi-node model of the storage tank. For the auxiliary heater, the ON/OFF type of control is implemented. If water temperature were in the range of 0° - 70° C, it would be in ON condition. More than 70° C, otherwise it will be OFF condition. (300° C is taken as tentative value only. It can be any figure more than 100° C). Figure 3.10 shows the SIMULINK block for the auxiliary heater.

Once the heater is ON, it would maintain the requisite temperature for the demand duration. However, when the demand is zero, it should quickly switch off, irrespective of storage tank temperature. To implement this logic, the hot water demand profile is added as a driving function for the heater input.

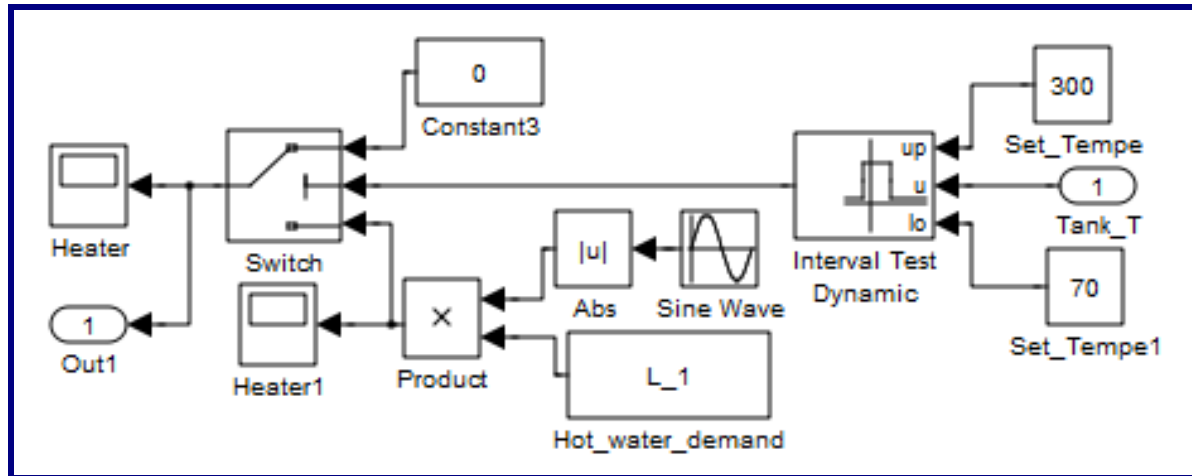


Figure 3.10: Auxiliary heater control box for both the cases (1&2) in SIMULINK

Ideally, the auxiliary heater should be separated from the storage tank so that the average temperature of the storage tank is not influenced by the auxiliary heating system. Segregation of auxiliary heater from the storage tank would help in maximizing the utilization of the solar energy for water heating purpose. Examples are a twin cylinder based SDHW system (case-1) or combi-boiler.

## CHAPTER 4: ANALYSIS OF TWO OPTIONS

*“Heat Transfer coefficients are small only if you do not want them to be.”*

*Murphy’s Law applied to solar collectors*

To analyse the two cases for comparison, one need to apply two boundary conditions: (a) The hot water demand profile as discussed in figure 3.8, (b) The weather data for location under consideration. For weather data, TRNSYS <sup>[45]</sup> database for London, UK is used in the analysis. It includes the direct and diffuse components of the solar radiation and the ambient temperature. Appendix A details about the systematic procedure to transform the weather data in useful energy output from the solar collector panel. Figure 4.0 captures the heat recovered by solar panel for four days in the year. These four days, considered in analysis, are assumed as the representative of a year for the energy output from the collector and for the SDHW system performance. From the system stabilization point of view, total six days are considered sandwiching the particular day (for example 12 Jan) under consideration.

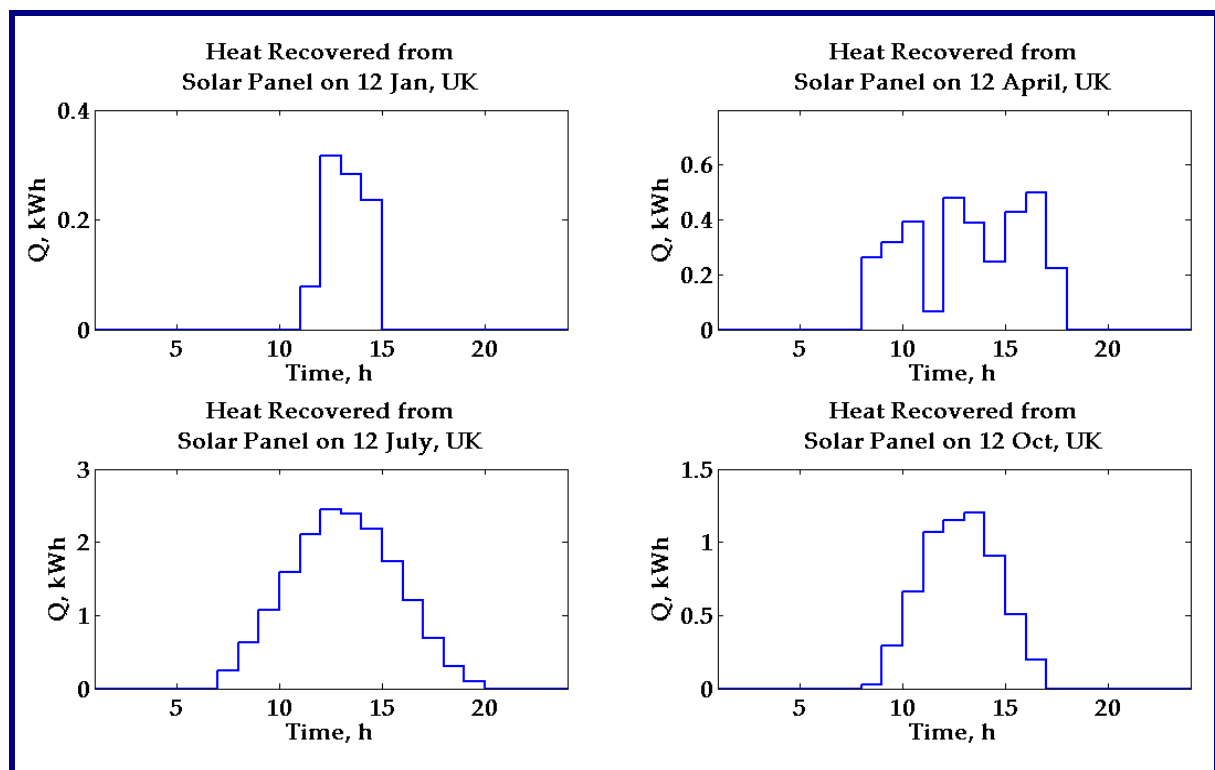


Figure 4.0: Heat recovered from the solar panel for four typical days in a year.

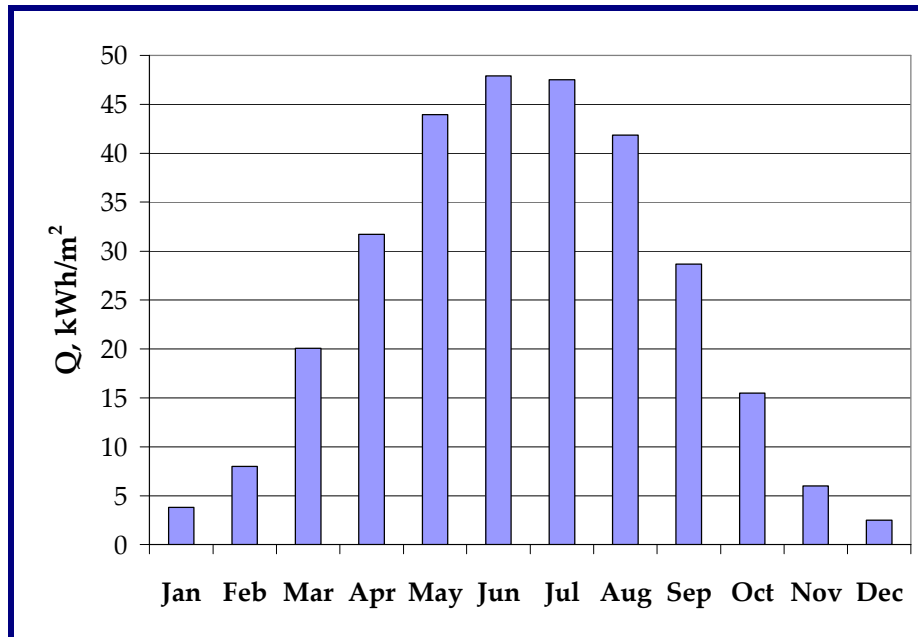


Figure 4.1: Total energy recovered by solar panel for London, UK

It would be interesting to start with the solar collector panel response for the location under consideration. Figure 4.1 represents the total energy recovered on monthly basis from the panel per  $\text{m}^2$  panel area. Now the output from the panel viz. heat and temperature are input to the SIMULINK model or the storage tank upper most node in case-1 and middle node to the case-2. As explained in the control logic section, the heat input to the corresponding node in the storage tank happens only when the incoming water temperature is higher than the node temperature inside the storage tank.

For case-1, the primary tank is divided into two nodes in case-1 and the secondary tank, where auxiliary heater is placed, as a single node. For case-2, as it has only one cylinder, it is divided into three nodes with an auxiliary heater at the upper node.

As the aim of the project revolves around storage tank, so the output of solar panel is adjusted in such a fashion that for both the cases, the output of the panel is same. It is a way to make same denominator for evaluating the storage tank performance for various cases under consideration.

The rating of the auxiliary heater is turned out to be 4-8 kW based on average input to the storage tank.

## 4.1 Parameters Used in Two Cases

To start the analysis of two cases, it is pertinent to summarise the various parameters assumed for the two cases. Table 4.0 gives a list of parameters.

Table: 4.0 List of parameters used in analysis of the two cases.

Parameters	Case-1 (Twin cylinders)	Case-2 (single Cylinder)	Reference
Solar Panel aperture area	2.8 m <sup>2</sup>	2.8 m <sup>2</sup>	46
Collector mass flow rate, g/s-m <sup>2</sup>	4.9	3.4	29, 30
Specific Heat of collector fluid, kJ/kg-K	3.800 <sup>47</sup>	4.184 <sup>48</sup>	47, 48
Tilt angle of solar panel, degree	45	45	
Orientation	South	South	
Latitude of location, radian	0.98	0.98	45
Longitude of location, radian	0.1	0.1	45
Glass emittance, $\epsilon$	0.88	0.88	18
Plate transmittance, $\tau$	0.95	0.95	45
Plate absorptance, $\alpha$	0.87	0.87	18
Plate efficiency	0.85	0.85	18
Ground reflectance	0.6	0.6	45
Heat Exchanger effectiveness	0.65		49
Water Inlet temperature, °C	10	10	26
Hot cylinder volume, m <sup>3</sup>	0.08 for each cylinder	0.08	50
Overall heat transfer, W/m <sup>2</sup> -K	0.764	0.764	49
Room Temperature, °C	20	20	26

Regarding variation of the specific heat capacity of the water, it is assumed a constant value averaged over temperature range. As seen in figure 4.2, variation in specific heat capacity of water is negligible for temperature range of 10 to 70 °C. Therefore, an average value of 4.184 kJ/ (kg K) is assumed for the analysis purpose.

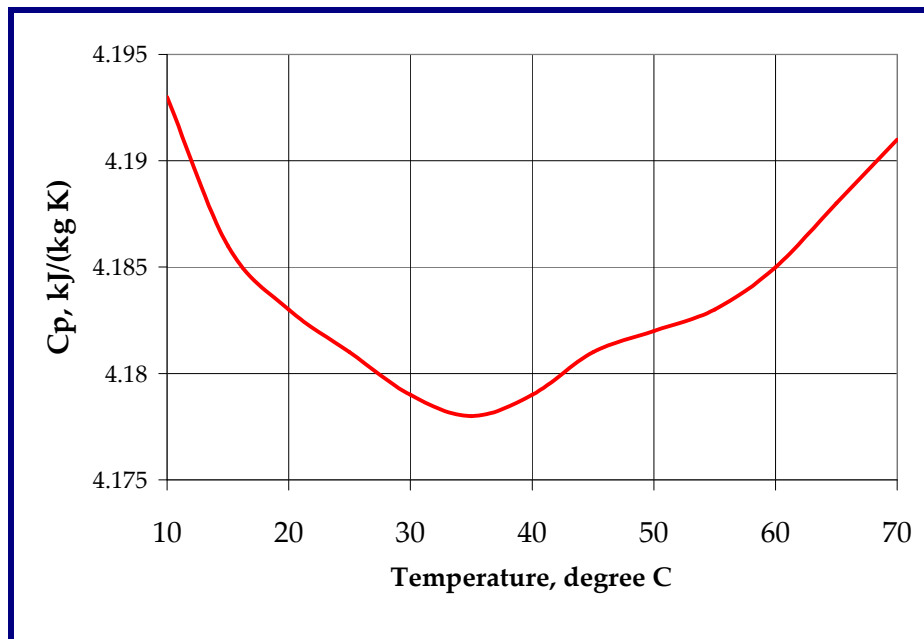


Figure 4.2: Variation of specific heat capacity of water with temperature

In this analysis, the solar panel inclination angle is assumed as 45° and its orientation towards south. The optimum tilt angle for maximum annual energy output from the panel is close to 51° with southward facing of the collector panel. As the common angle used in literature for analysis are 30°, 45°, or 60° <sup>[26]</sup>. Therefore, 45° with southward facing configuration of solar panel is assumed in the analysis. However, output from the solar panel is characterised by its orientation and inclination. Figure 4.3 <sup>[11]</sup> represents the impact of an orientation and an inclination of solar collector panel at a particular location with respect to the annual radiation absorbed by it. It is a handy chart for quick assessment of solar panel effectiveness with respect to an orientation and an inclination angle of the solar panel.

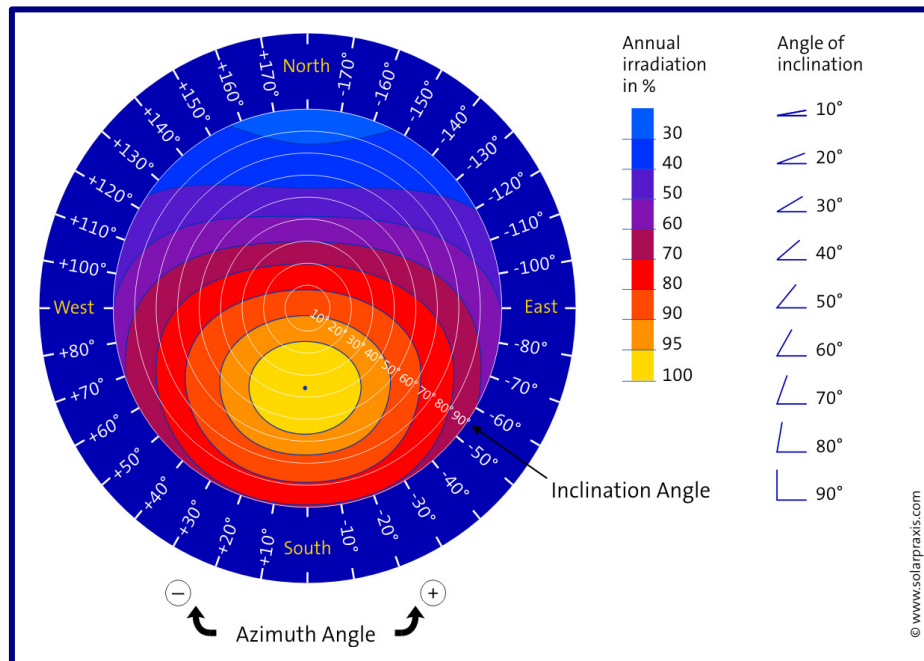


Figure 4.3: A chart showing impact of the orientation & the inclination angle on the solar panel on its output.

## 4.2 SIMULINK Models

Figure 4.4 and 4.5 shows the out line of the SIMULINK models for the two cases in consideration. The individual components of LHS of the equation (3.5) are used to form a SIMULINK block and than added to get complete LHS of the equation. All these input are than integrated by “**integrator**” block set, which makes the RHS of the equation. The time step set at “**0.001**” and “**ode45**” is used to solve the equation. “**ode45**” is a MATLAB function to solve the set of ordinary differential equations based on second order Runge-Kutta method <sup>[36]</sup>.

These SIMULINK models need the inputs such as the energy from the solar panel and the corresponding temperature value. These inputs are the output from the MATLAB code. Refer Appendix-A. Once these inputs are available, the SIMULINK model solves and gives the output as water temperature at two locations, before and after the auxiliary heater.



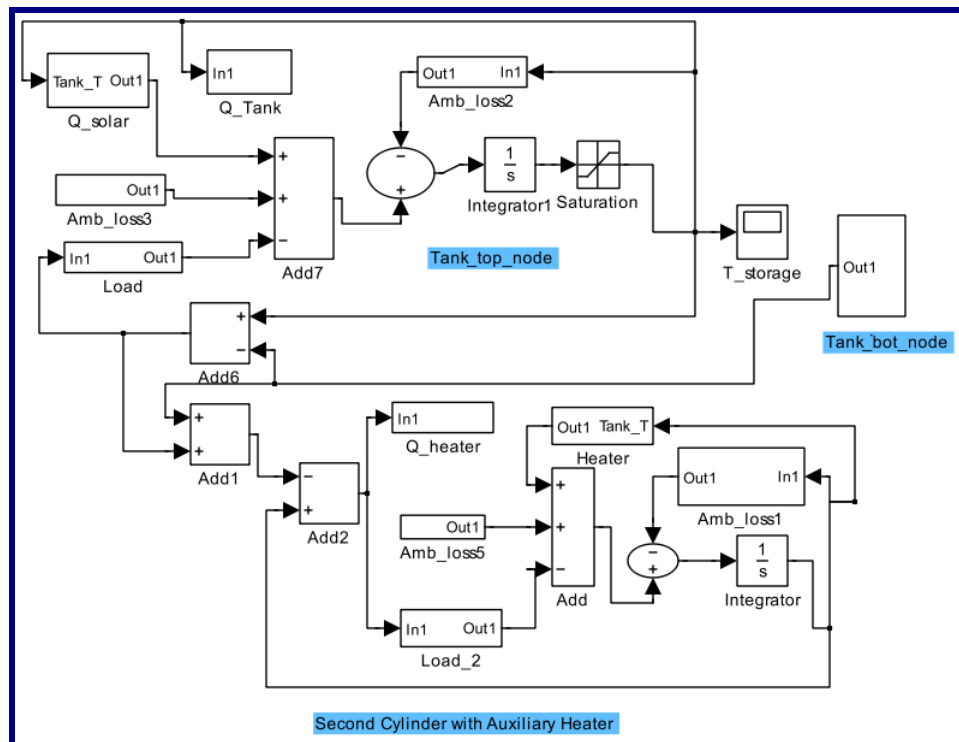


Figure 4.4: SIMULINK model for case-1

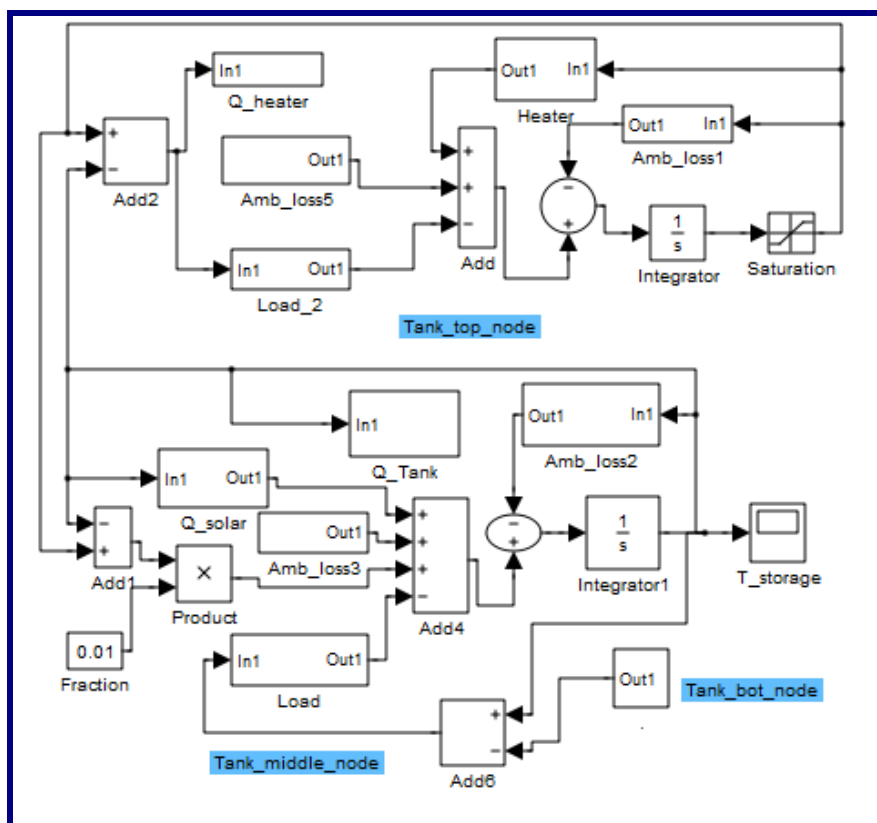


Figure 4.5: SIMULINK model for case-2

### 4.3 Results

Now we have two cases, four days and two hot water demand profiles. Therefore, one needs to run the SIMULINK model for 16 times. Water temperatures, before and after the auxiliary heater, are the prime parameters for understanding the thermal behaviour of the system. Therefore, these two temperatures are plotted against time for various cases. In the plots, “**Storage Tank**” refers to the temperature of water before the auxiliary heater. It (water) is heated by the solar energy alone. “**Heater**” refers to the water temperature after the auxiliary heater, which is supplemented by the additional energy to meet the designed temperature of the water for the utility. One can refer the complete list of these temperature plots in Appendix – C. Here the temperature results are listed for three cases out of 16 to support the observations.

- (a) Water temperature profiles for case-1, two days and two load profile (Figure 4.6)
- (b) Water temperature profiles for case-1&2, one-day (12 April) and two load profiles (Figure 4.7)
- (c) Water temperature profiles for case-1&2, one-day (12 July) and two load profiles (Figure 4.8)

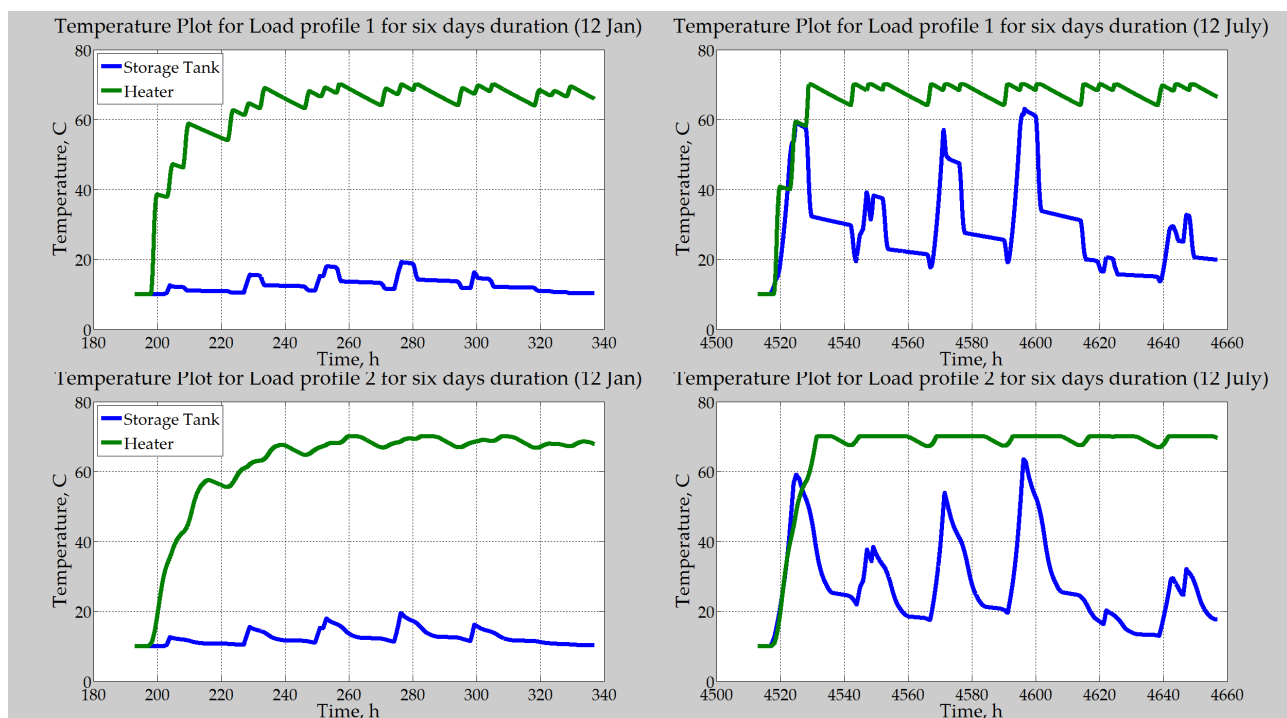


Figure 4.6: Temperature profiles for Case-1, two days, two-load histories

Following are the observation about the temperature profiles.

- The auxiliary heater maintains the temperature in the range of 60-70 as required.
- Solar heating does contribute to the hot water tank heating and its contribution increases as the solar radiation increases.
- The average temperature of the tank is higher in case-2.
- Hot water demand profile -2 is smoother than profile-1. Therefore, the temperatures profile inside the tank is smooth for case-2.

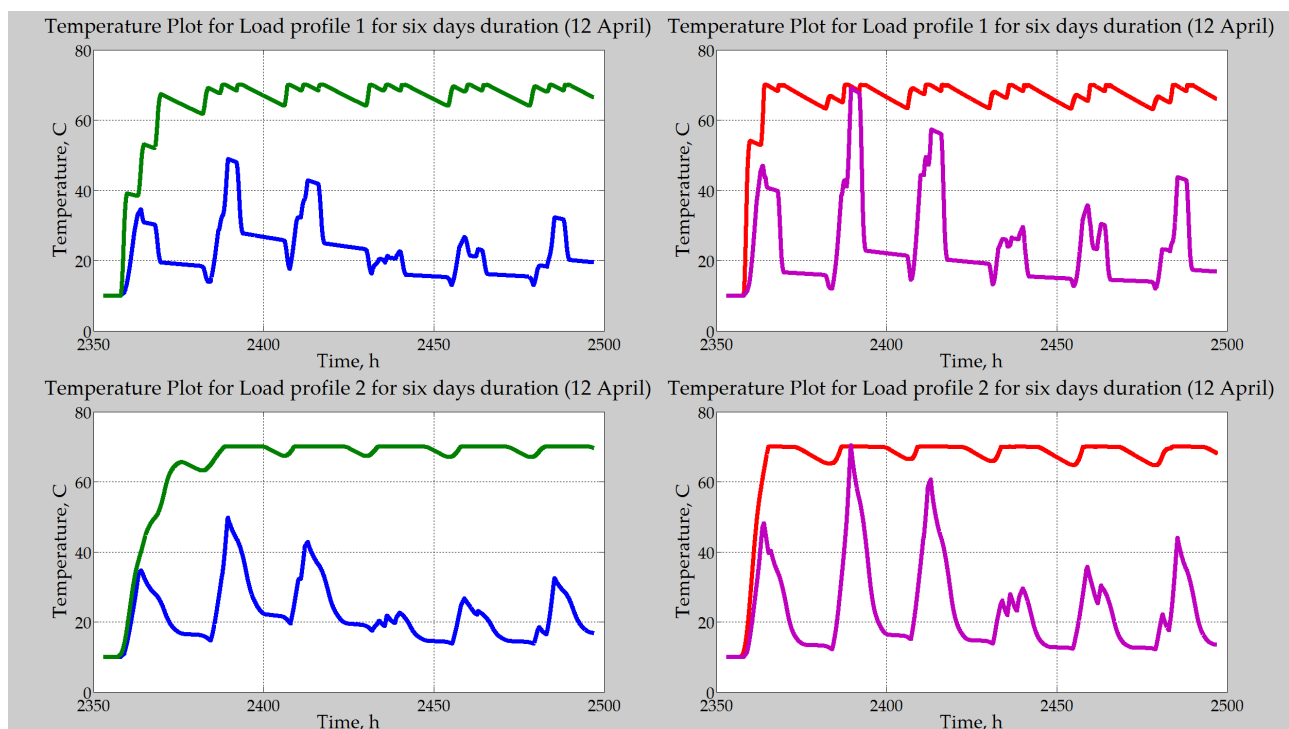


Figure 4.7: Temperature profiles for Case-1 & 2, one-day (12 April), two-load profiles

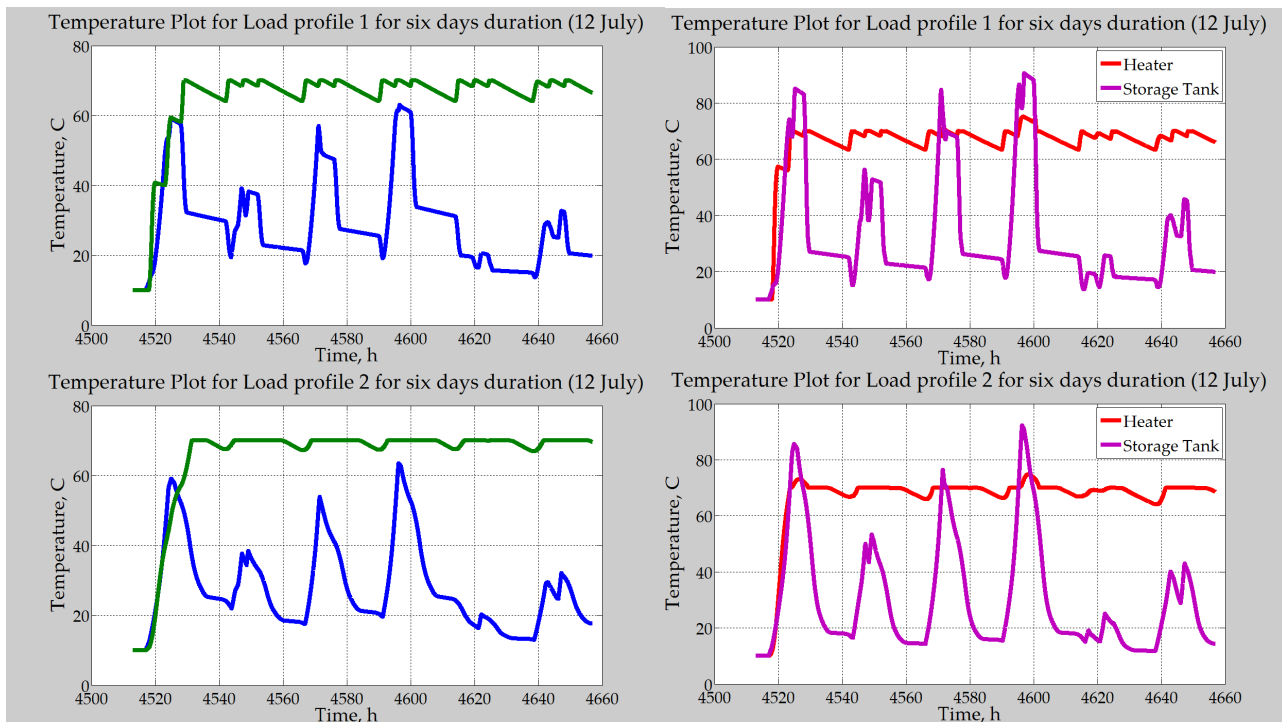


Figure 4.8: Temperature profiles for Case-1 & 2, one-day (12 July) two-load profiles

Two parameters, to be assessed in the analyses, are the contribution of the solar energy to the total hot water demand and understanding the phenomena of mixing in the single cylinder. Figure 4.9 and figure 4.10 show these parameters for two cases and for two load profiles.

Before discussing the results, let us understand the modelling of the mixing phenomena assumed in the analysis for case 2. For the case of single cylinder, the whole cylinder is modelled in to three nodes. The bottom node received the cold water at 10 °C. In this analysis, the mixing between upper two nodes is considered. As we know that, the potential for heat transfer is temperature gradient and the phenomena of heat transfer is quite complex inside the tank, so based on the temperature gradient magnitude, a fraction of it is assumed to be transferred to the middle node from the top node. These assumptions need verification either by an experiment or by the detailed CFD model. However, one would appreciate the quick understanding the complex mixing phenomena by simplified assumptions.

Following are the observation for the figure 4.9, figure 4.10 and figure 4.11

- The maximum and minimum value of solar energy contribution in meeting the hot water demand is 25% and 10 % respectively for case-1.
- The maximum and minimum value of solar energy contribution in meeting the hot water demand is 30% and 15 % respectively for case-2 with an assumption of no mixing between upper and middle nodes or with the thermal stratification built inside the tank.
- As mixing progresses inside the tank for case-2, the system performance moves towards the case-1 and deteriorates further.
- The assumed value of mixing parameter needs verification either by an experimental set-up or by CFD models.
- Fraction of solar energy utilized for heating the water inside the tank is high in April month. However, the magnitude is high for July months.
- Case-2 does meet the requirement of the “dedicated solar volume” partially in July for three days and in April for one day.
- For case-2, the “dedicated solar volume” requirement is met for close to 67 days in a year either partially or fully.
- Although the parameters calculated are typical four months in a year, yet it captures the phenomena in question.

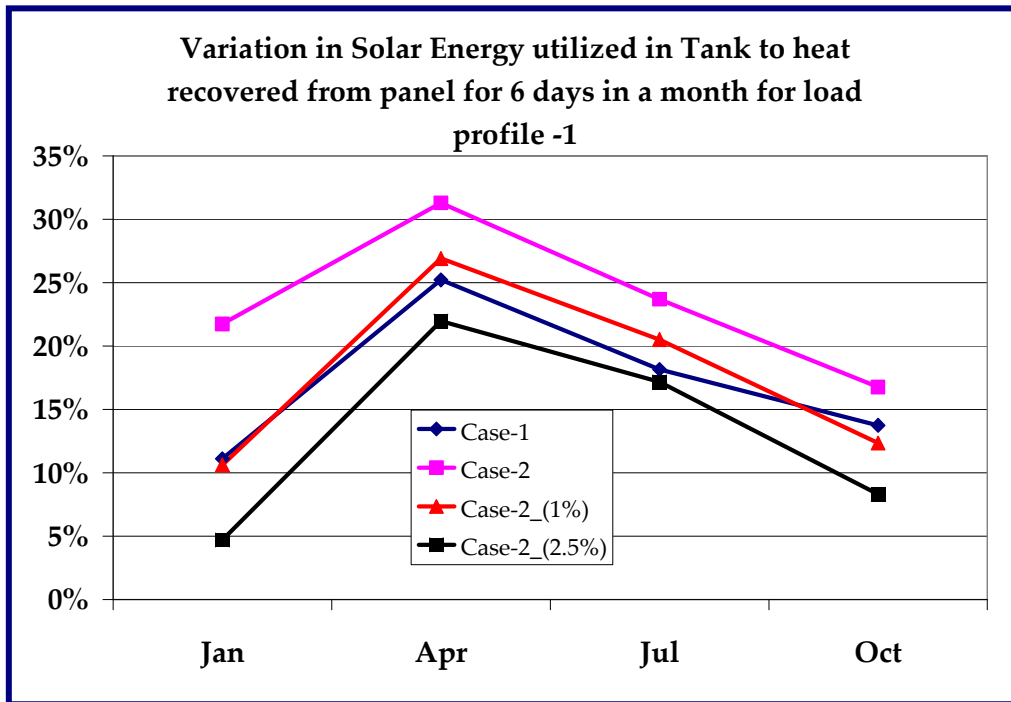


Figure 4.9: Variation in solar energy utilized in tank to heat recovered from panel for 6 days in a month for the hot water demand profile-1.

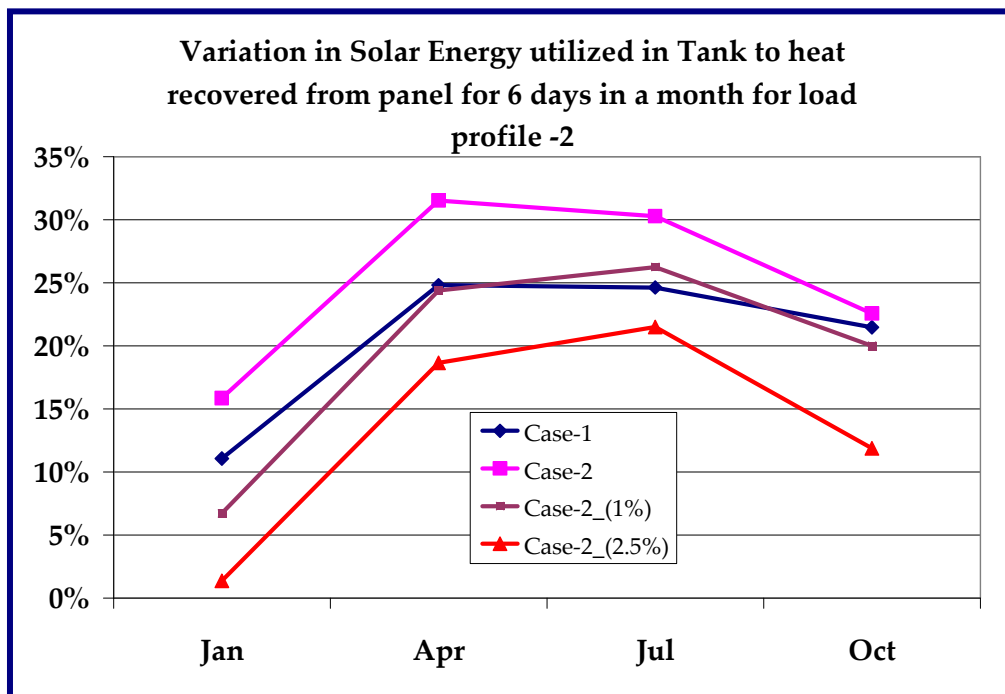


Figure 4.10: Variation in solar energy utilized in tank to heat recovered from panel for 6 days in a month for hot water demand profile-2.

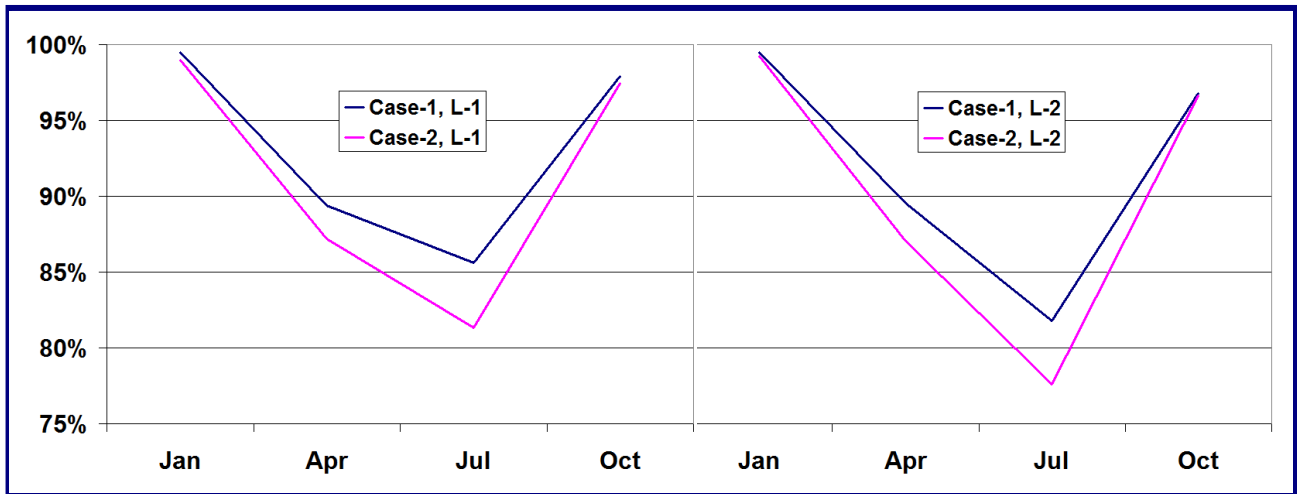


Figure 4.11: Auxiliary heater performance for two cases and two-load profiles.

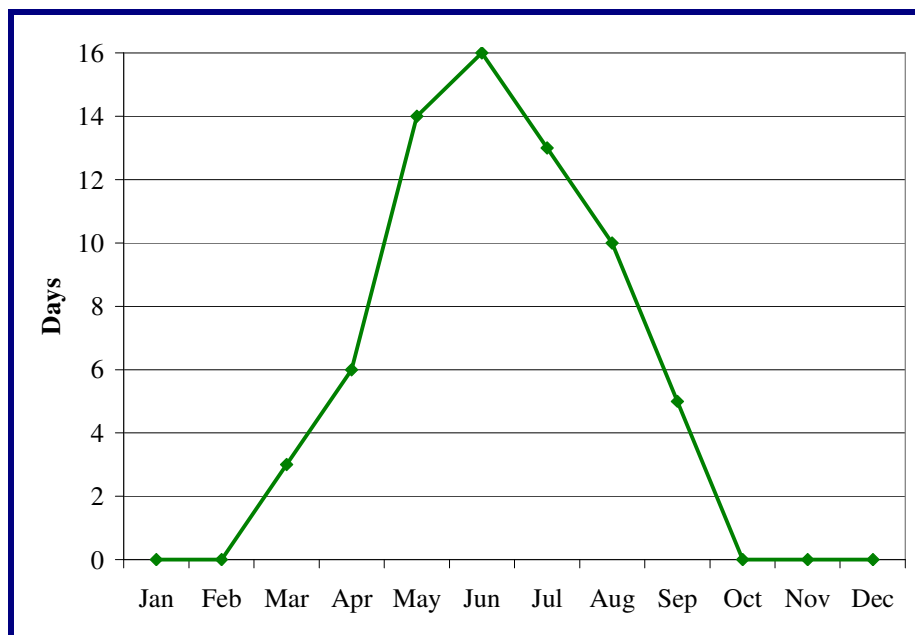


Figure 4.12: Number of days when the “dedicated Solar Volume” is achieved partially or completely for the case-2.

## CHAPTER 5: ARTIFICIAL NEURAL NETWORK – PREDECTIVE TOOL

*“One day there would be a machine that could duplicate human intelligence in every way”*

Alan Turing, British mathematician.

An Artificial Neural Network (ANN) or Neural Network (NN) is a mathematical model that simulates the functional or the structural aspects of a biological Neural Networks <sup>[51]</sup>. ANN architecture is built upon a simplified artificial neuron and does processing of the given information using a parallel computing approach in contrast to modern computer approach of series architecture. It has an adaptive concept that changes its structure based on the given information during the learning or the training phase. One can imagine ANN as a linear or non-linear data modelling tools in some sense. Primarily it is used to model the complex relationships between inputs and outputs.

Concept of NN is applied in various fields such as high performance aircraft autopilots, banking sector, weapon steering, target tracking, dynamic modelling of process and its control in chemical industry, market or weather forecasting and in quality control.

Kalogirou (2001) reviewed ANN application in renewable energy system such as modelling and design of a solar steam generating plant, estimation of a parabolic trough collector intercept factor and local concentration ratio, modelling and performance prediction of solar water heating systems. **“ANN also used for the estimation of heating loads of buildings, for the prediction of air flow in a naturally ventilated test room and for the prediction of the energy consumption of a passive solar building, solar radiation and wind speed prediction, photovoltaic systems, building services systems and load forecasting and prediction”** <sup>[52]</sup>.

One of the practical utilization of the ANN in the solar industry could be prediction of sunshine at given location based on the historical weather data. Probably it would help the customer to know the quantitatively solar energy availability in the hot water tank for the next few days based on the given weather forecasting. This concept is similar to wind speed prediction for the wind farm. An



attempt is made in this chapter, to predict the solar panel output to the storage tank by means of a function approximation technique.

## 5.1 Basics of Single Neuron Model <sup>[53]</sup>

Let us assume that a scalar  $p$  is an input and  $a$  is the out connected through a function  $f$ . Normally, the input is connected to the output by means of some physical set of equations. However, let us assume that we do not have any clue about that relationship explicitly. We will treat those set of equation as a black box and we would like to represent the relationship between the input and the output as follows:

$$a = f(w * p + b) \quad (5.1)$$

$$n = w * p + b \quad (5.2)$$

Where

$w$  is a weight function.

$b$  is defined as bias.

$f$  is transfer function for example Hardlim, which is defined as

$$\begin{aligned} a &= 0, n < 0 \\ a &= 1, n \geq 0 \end{aligned} \quad (5.3)$$

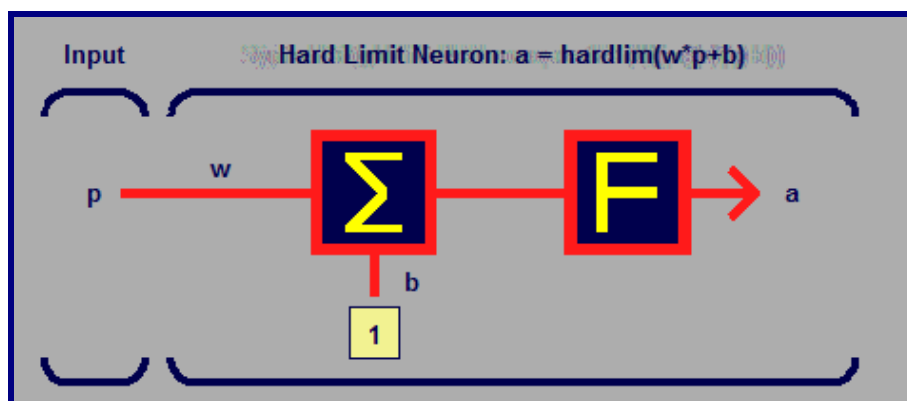


Figure 5.0: Basic single neuron mathematical model

A pictorial representation of single neuron is shown in figure 5.0. Here we can assume a random value of a weight  $w$  and a bias  $b$ . For a range of values of the weight  $[-2, 2]$  and the bias,  $[-2, 2]$  one can easily calculate the value of output variable,  $[0, 1]$  provided the transfer function is defined for example “**Hardlim**”. Total process of the above (concept) neuron is shown in figure 5.1.

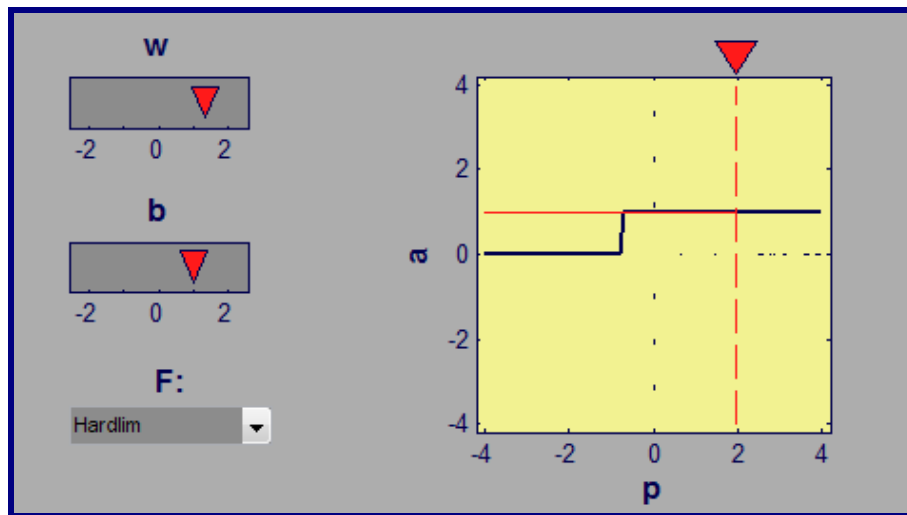


Figure 5.1: Capturing the various parameters in single neuron model

As we know the true value of the output variable and the calculated value of the output variable, we can apply the method of least square to optimise the value of weight function for minimum error in the output variable. Now one can use a set of neuron in place of a neuron. A set of neurons form a network for input to output variable. Therefore, it is possible to identify the set of new weight function by a process called minimization of error. This process is called training of the network and once the network is trained, it is now ready for carrying out the intended objective, “**Prediction**”.

## 5.2 Description of ANN model

There are various NNs available to perform the designated task such as Perceptron, Hamming, Hopfield network etc. Each network has its own characteristic in order to tackle the complexity in the problem. In the analysis, a Multi-layer Perceptron (MLP) network is selected to carry out the function approximation. Three inputs, horizontal direct solar beam radiation, diffuse solar

radiation and the ambient temperature for a year, are chosen to approximate the heat recovery from the panel. The heat from the panel is calculated as explained in section 3.1 and used as an output for the network. 80% of the input data is used for training purpose and 10% for the validation and the testing purpose respectively.

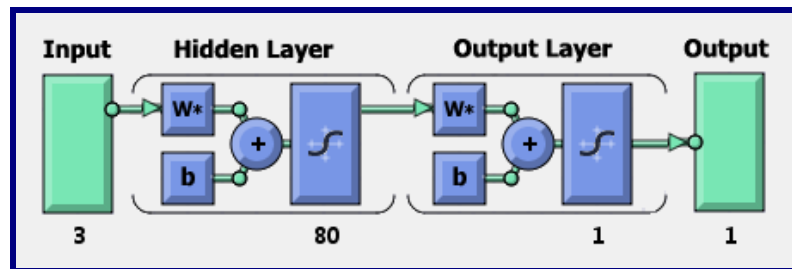


Figure 5.2: ANN used in solar heat recovery from the panel <sup>[41]</sup>

For training of the NN, Levenberg Marquardt optimization algorithm is selected. By setting these parameters, the performance of the network or Mean Squared Error (MSE) is 0.000983142 within 20 epochs. Results are shown in figure 5.3 and figure 5.4. Now with the available trained network, one can predict the Solar panel performance provided we have three inputs for the next day.

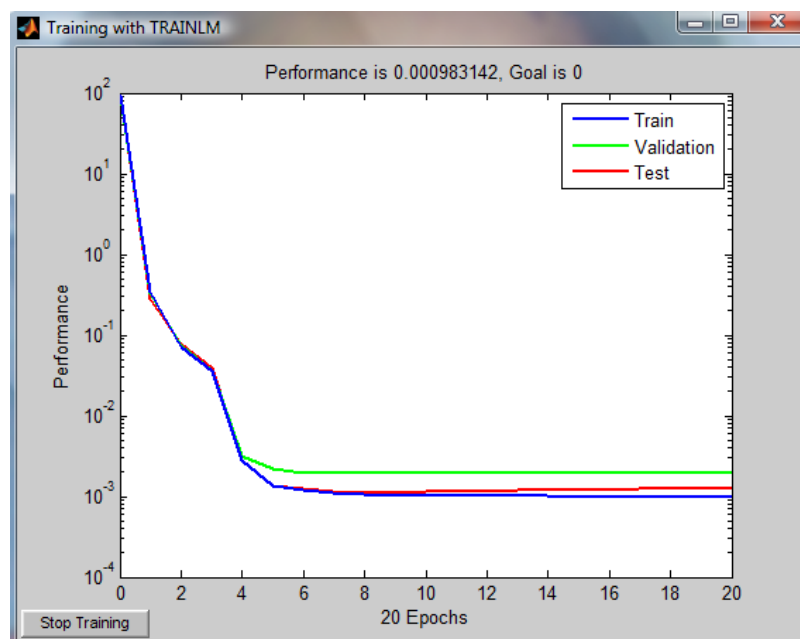


Figure 5.3: Performance of MLP network

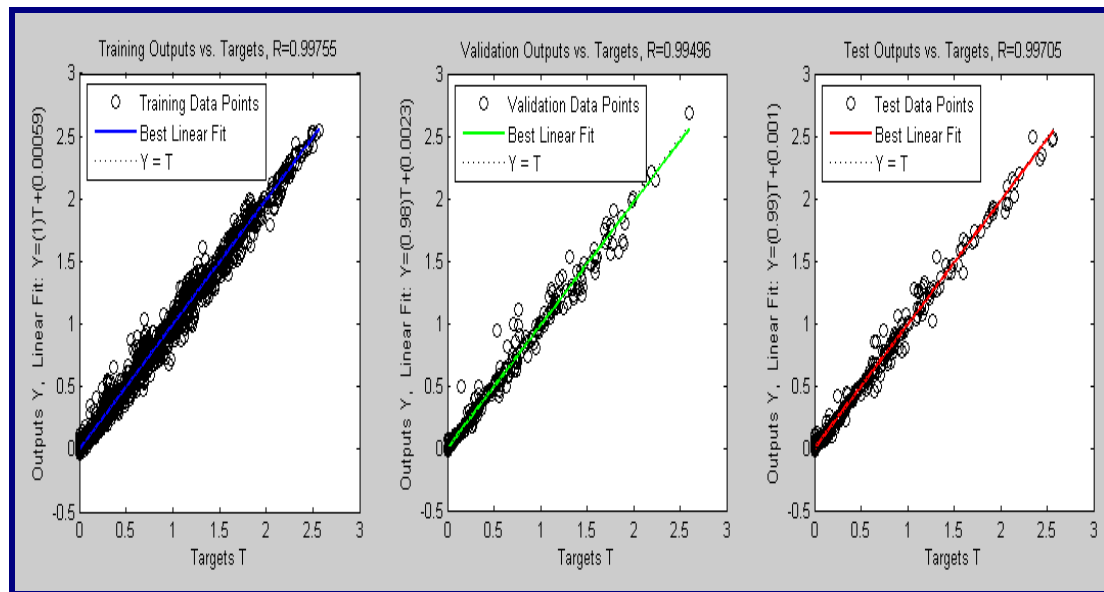


Figure 5.4: Detailed information about the network performance.

## CHAPTER 6: ENVIRONMENTAL, HEALTH & SAFETY ISSUES RELATED WITH SDHW SYSTEM

Every technology has its own pros and cons. The same principle is applicable in the case of solar energy based technology. Solar energy based technologies are considered as an environmental friendly and ‘clean’ or non-emitter of GHGs. However, there are key Environmental, Health and Safety (EHS) issues related with it. Primarily we will be discussing the EHS concerns associated with the solar energy relevant to the SDHW system.

### 6.1 Hot Water Contamination

As discussed previously, the active indirect SDHW configuration has antifreeze fluid in the primary loop. Rupture of the heat exchanger tube inside the water storage tank leads to contamination of water. A typical antifreeze fluid also has various additives such as a corrosion inhibitor, pH controller, bactericides etc <sup>[54]</sup>. These additives are toxic in nature. For example, **corrosion inhibitors includes chromate, borate, nitrate, sulphate, sulphite, arsenate and benzoate salt. The toxicities of these compounds range from the relatively benign to highly toxic and include such potential effects as cancer** <sup>[54]</sup>.

Number of measures could be initiated to avoid such contamination.

- 1 Use of a leak indicator dye in primary loop
- 2 A pressure differential between secondary and primary loop would not allow the mixing of antifreeze with the water.
- 3 A double walled heat exchanger.

### 6.2 Solar Collector overheating and Fire Hazard

An Active SDHW configuration has a pump to circulate the hot water inside the collector panel to the storage tank. Failure of pump operation may result in high temperature of the fluid, also called

stagnation temperature. A high temperature can cause the steam formation or high pressure inside the pipes. It would also overheat the insulation material, wrapped around the SDHW system to protect the heat loss. Poor design and improper selection of an insulation material may cause overheating or the burning of insulation material with release of potential toxic gases. Typical insulation materials (fibreglass / mineral wool) are used with binder such as a phenolic compound <sup>[47]</sup>. The phenolic substances fumes may prove harmful if inhaled in large quantity or for long periods.

Typical installation of a SDHW system is in open air or on terrace. Therefore, there is little or no impact of burning of insulation. However, it would become a major concern in case of fire. Fire would lead to very high temperature and may degrade the insulation, releasing irritating and highly hazardous fumes of cyanide, toluene di-isocyanurate (TDI), hydrogen chloride, ammonia, nitrogen oxide, etc <sup>[54]</sup>.

To avoid such situation, one can opt for proper system design along with suitable insulation material that reflect the thermal and chemical stability at higher temperature particularly stagnation temperature. Table 6.0 <sup>[54]</sup> gives the upper temperature limit for the insulation material.

Insulation Material	Upper Temperature limit, °C	Comments
Fiber Glass with binder	177	Generally non toxic, non hazardous. Handling of fibreglas is occupational concern.
Fiber Glass with no binder	454	
Mineral fiber blanket	649	Mineral fiber is non toxic, non irritating and will not burn.
Urea Formaldehyde foam	99	Irritation if subjected to higher temperature (93.5 °C) for extended period of time. At high temperature (650 °C), it will decompose to water vapours and carbon monoxide (highly toxic), formaldehyde (toxic), hydrogen cyanide (extremely toxic) and ammonia (toxic).
Polyurethane Foam	121-204	While blowing urethane foam, vapours of isocyanate, TDI are hazardous if inhaled. Complete combustion of polyurethane is clean. However, presence of fire retardant agents would result in acidic vapours of phosphorous oxide and hydrochloric acid or hydrobromic acid.

Table 6.0: Properties of potential insulation materials <sup>[54]</sup>

### 6.3 SDHW Flushing

An Active indirect SDHW configuration, as we know, has a primary fluid as antifreeze. As time goes, its heat transfer properties deteriorate and need replacement or the system needs to be decommissioned. Release of antifreeze in into local water bodies may affect the aquatic life and source of drinking water.

Commonly available antifreeze is a mixture of water and ethylene or propylene glycol with percentage of water in the range of 0 to 20%. With respect to time, antifreeze heat transfer properties deteriorate, so it needs to be replaced on regular basis <sup>[54]</sup>. The general tendency is to dispose it off by dumping in the ground or down the drain.

**“If dumped on the ground, the glycol solution could be an immediate but short-lived threat to the children, animals, and plant life. Disposal through the sewage system reduces the direct environmental dangers because of the large dilution factor, but the effects on the waterways or sewage treatment facility many be significant.”** <sup>[54]</sup>

Although anti-freeze is a concerned from the environmental or societal impact, yet it is biodegradable. Therefore, the approach to such an issue is dilution. By an estimate, a dilute solution of glycol – water mixture (approximately 190 litres) would not pose any threat to 40 kg child <sup>[54]</sup>.

Regarding the disposal through sewage system, data needs to be available to the city council or sewage treatment plant about it in order to design an adequate sewage facility to handle the anti-freeze.

## CHAPTER 7: CONCLUSIONS AND FUTURE WORKS

In this project, the thermal behaviour of two cases is studied; a retrofitted single and twin cylinders with two hot water demand profiles. A flat solar collector panel is used to collect the heat and transfer it to the storage tank. A simplified thermal model of the tank is created in SIMULINK to get the quick information about the thermal profile of hot water tank with two draw off profiles and a weather data of London, UK.

Single cylinder model is retrofit of the existing hot water cylinder. Retrofit is carried out by adding a solar collector panel loop with the existing cylinder. Basic configuration parameters of the solar collector panel have a close match with a solartwin configuration for single cylinder <sup>[46]</sup>. Technically twin cylinders configuration is an extension of a single cylinder system with higher capacity of hot water and a separated auxiliary heater from the main tank. Idea behind the two case studies is to understand the thermal behaviour of the SDHW configuration provided the capacity of system is the range of total hot water demand in a family of three or four persons in UK.

Dynamic models of the two cases are prepared in SIMULINK and solved for a typical year to understand the solar configuration performance from the ‘dedicated solar volume’ concept. In simple words, let us understand the typical number of days in a year during which the auxiliary heating system contribution in meeting the hot water demand is negligible. An attempt is also made to understand the concept of building thermal stratification inside the tank and the design parameters influencing it.

### 7.1 Conclusions

The objectives of the project are to evaluate the retrofitted or modified single hot water cylinder performance and its feasibility to meet the “dedicated solar volume” requirement. Therefore, the modified single hot water cylinder (case-2) is analysed and compared with the twin hot water tank (case-1) to assess the thermal performance.



It is observed that the modified single cylinder water tank meets the “dedicated solar volume” requirement partially at least three days in July and a day in April out of six days considered in a month for both the load cases with an assumption that the tank is thermally stratified. However, as the mixing of the fluid starts, its potential to meet the “dedicated solar volume” requirement deteriorates. For a year, it is observed that case-2 partially meets the criterion of the “dedicated solar volume” for close to 67 days.

The maximum and minimum value of solar energy contribution in meeting the hot water demand are 25% and 10 % respectively for case-1. For case-2, the maximum and minimum value of solar energy contribution are 30% and 15 % respectively. However, as mixing progresses inside the tank for case-2, the system performance moves towards the case-1 and deteriorates further.

Low flow SDHW configuration performs better for the SDHW configuration in terms of building thermal stratification and enhances solar fraction utilisation.

The influencing parameters for assessing the thermal performance are the thermal stratification in the tank and the hot water demand profile. These two factors determine the SDHW system performance. Optimum tank capacity is another factor, which needs attention in the design of SDHW system.

In summary, it is feasible to do suitable modifications in a single storage tank to attain thermal stratification inside the tank and achieve the objectives.

## **7.2 Out of the Box Solution**

Let us explore some other options briefly, which would help in maximising the utilization of solar energy. We have seen two main challenges before the retrofit option for the single cylinder.

- Building and maintenance of thermally stratified layer of hot water inside the cylinder.
- Control aspect of the auxiliary heater as higher bulk temperature of water inside the tank would hamper the heat transfer from solar panel.

As discussed in control strategies (section 3.9), it would be better to implement the two elements of control independently i.e., Storage and Direct Supply. Considering the challenges and the control aspect, following are the options, which can be explored further for their potential.

- Single cylinder with solar panel and auxiliary heater outside the hot water cylinder or a combi-boiler.
- Twin cylinder with second cylinder capacity much smaller than the main cylinder, where solar collector panel is fitted.

### **7.3 Future Works**

Although efforts are made to capture various parameters influencing the retrofitting of existing hot water cylinder, yet a good scope exist in further exploring and substantiating the outcome of this study presented in the project. Following areas are listed for quick reference for further exploring the thermal modelling and control of SDHW systems.

- Modelling of mixing phenomena inside the tank and its experimental validation would be next step in assessing the realistic behaviour of a retrofitted single cylinder water tank. It will not only boost the confidence in dynamic modelling but also help in exploring and substantiating the thermal mixing or diffusion of energy inside the tank.
- To understand the impact of geometric parameters on thermal stratification, the tank inlet or outlet, geometry needs attention. One could extend the better understanding of the subject by taking into account into the geometric factors in order to optimize the geometric parameters for a retrofit model.
- As the actual or experimental data for heat recovered from the solar panel are not available, neural network is trained based on the calculated values of solar panel output. However, once the actual data are available, the same network could be tested for its performance for the realistic input parameters. One could also test the correlations developed in the NN between input and output variables for accuracy.

- Neural Network formulated in this project is based on the function approximation techniques. NN based on the time series approximation would be a next step in the heat-recovery predictions from the panel.
- As hot water demand profile is available on an hourly basis, so the simulation is carried out over an hour. However, an instantaneous demand profile would be next step to get the better feel of the system performance. It will help in understanding the realistic control of an auxiliary heater.
- In this project, the weather data is considered for London, UK. One can take challenge in looking the system behaviour at various locations across UK. It will not only boost the confidence in the thermal model developed in for this project but also help in understanding the complete picture of a retrofit option implementation in UK.
- In this analysis, only two components in the solar collector panel are modelled. Other components such as pump, piping, could also be considered. Modelling of other components would help in calculation of pressure drop across the system in order to select the pump and optimize the piping size. Modelling of heat losses through piping would be step forward in actual modelling of the SDHW system and will help in the selection of insulation material.
- The retrofit system is analysed for southward orientation with tilt angle of  $45^\circ$ . However, this would not be always the case, as not all the houses would have provision to orient the solar panel southwardly. A study can be taken up to understand the impact of the orientation on SDHW performance. Likewise, the  $45^\circ$  may not be the optimise tilt angle for particular location in UK. It would be a good idea to understand the impact of both of these parameters in evaluating the retrofit option at particular location.
- In this analysis, the flat plate collector is considered for analysis purpose with 80-160 litres capacity of hot water tank. It would be a good initiative to explore the impact of other types of solar collector panels such as an evacuated tube or a concentrated collector on the the



SDHW performance or more than one panel. Same point is also applicable to higher capacity storage tank such 200-400 litres capacity water tanks.

## REFERENCE:

- [1] McVeigh, J. C., 1977, Sun Power-An Introduction to the applications of Solar Energy, Pergamon press Ltd, Oxford, UK
- [2] Jansen, T. J., Solar Engineering Technology, Prentice-Hall, USA
- [3] Vanek, F. M., Albright, L. D., (2008), Energy System Engineering, McGraw-Hill Companies, USA
- [4] [http://solarthermal.com/facts\\_about\\_solar\\_energy.asp](http://solarthermal.com/facts_about_solar_energy.asp), accessed on May 17, 2009.
- [5] <http://www.solar-trade.org.uk/solarenergy/ukresource.htm> accessed on July 29, 2009
- [6] Holden, J, BRE, personal communication, (23 June, 2009)
- [7] <http://heasn.manufacturer.globalsources.com/si/6008829764250/pdtl/Solar-water/1012794742/Solar-Hot-Water-Tank.htm> accessed on September 09, 2009
- [8] <http://tmcpet.manufacturer.globalsources.com/si/6008825116596/pdtl/Water-heater/1017631493/Split-Water-Tank.htm> accessed on September 09, 2009
- [9] <http://projects.bre.co.uk/sap2005/> accessed on September 09, 2009.
- [10] <http://www.bp.com/sectiongenericarticle.do?categoryId=9023753&contentId=7044109> accessed on August 11, 2009.
- [11] Peuser, F. A., 2002, Solar Thermal System, Solarpraxis AG, Berlin.
- [12] [http://www.ren21.net/pdf/RE2007\\_Global\\_Status\\_Report.pdf](http://www.ren21.net/pdf/RE2007_Global_Status_Report.pdf) accessed on August 11, 2009.
- [13] [http://www.ren21.net/pdf/RE\\_GSR\\_2009\\_Update.pdf](http://www.ren21.net/pdf/RE_GSR_2009_Update.pdf) accessed on August 11, 2009.
- [14] [http://www.aepuk.com/need\\_info.php](http://www.aepuk.com/need_info.php) accessed on July 20, 2009.
- [15] [http://en.wikipedia.org/wiki/Energy\\_in\\_the\\_United\\_Kingdom](http://en.wikipedia.org/wiki/Energy_in_the_United_Kingdom) accessed on July 20, 2009.
- [16] <http://www.climatechangecorp.com/content.asp?ContentID=5837#part4> accessed on July 20, 2009.
- [17] Wang, L., Gwilliam, J, Jones, P., 2009, Case Study of Zero Energy House design in UK, Energy and Building, article in Press.
- [18] Duffie J. A., Beckman W. A., 2006, Solar Engineering of Thermal Processes, John Wiley and Sons, USA.
- [19] Reddy, T. G., 1987, Design and Sizing of Active Solar Thermal Systems, Oxford University Press, UK.

- [20] Berkel, J. V., et al., 1991, Thermal Behaviour of a Heat Exchanger Coil in a Stratified Storage, Proceeding of the Biennial Congress of International Solar World Society, Colorado, USA.
- [21] Sukhatme, S. P., 1988, Classification of Heat Transfer Equipment, Hemisphere Publishing corporation, Taylor & Francis Group, USA.
- [22] Holland, K. G. T., Wright, J. L., Granqvist, C. G., 2001, Glazing and Coating, Solar Energy: The State of the Art, Edited by Gordon Jeffery, International Solar Energy Society, James & James, UK
- [23] <http://www.dg-c.com.au/doubleglazing.html> accessed on August 1, 2009.
- [24] <http://www.northcanterburyglass.co.nz/images/HeatLossReduction.gif> accessed on August 1, 2009.
- [25] Lenel, U. R., Mudd, P. R., 1984, A review of material for Solar Heating Systems for Domestic Hot water, Solar Energy, 32, pp 109-120
- [26] Murphy, G. B. et al., 2009, A comparison of the UK Standard Assessment Procedure (SAP) and Detailed Simulation of Building-Integrated Renewable Energy System, Build Simulation-2009, Glasgow. UK ([http://www.ibpsa.org/proceedings/BS2009/BS09\\_1177\\_1184.pdf](http://www.ibpsa.org/proceedings/BS2009/BS09_1177_1184.pdf) )
- [27] Hollands, K. G. T., Lightstone, M. F., 1989, A review of Low Flow, Stratified-Tank Solar water Heating System, Solar Energy, 43 (2), pp 97-105.
- [28] Wuestling, M. D., Klein, S. A., Duffie, J. A., 1985, Promising control alternatives for solar water heating systems, Journal of Solar Energy Engineering 107, pp 215-221.
- [29] Cruickshank, C. A., 2009, Evaluation of a Stratified Multi-Tank Thermal Storage for Solar Heating applications, Ph D Thesis, Queen's University, Ontario, Canada.
- [30] Shah, L.J., Furbo, S., 2003, Entrance Effects in Solar Storage Tanks. Solar Energy, 75, pp 337-348
- [31] Han, Y. M., Wang, R. Z., Dai, Y. J., 2009, Thermal Stratification within the Water Tank, Renewable and Sustainable Energy Reviews, 13, pp 1014-1026
- [32] Lavan Z., Thompson J., 1977, Experimental Study of Thermally Stratified Hot Water Storage Tanks, Solar Energy. 19-(5), pp 519-524.
- [33] Furbo, S., Andersen, E., Thur, A., Shah L. J., Andersen K. D., 2005, Performance Improvement by Discharge from Different levels in solar storage tanks, Solar Energy, 79, pp 431-439

- [34] Ghaddar, N. K., 1994, Stratified Storage tank influence on performance of solar water heating system tested in Beirut, *Renewable Energy*, 4(8), pp 911-925.
- [35] Klein, S. A., 1975, Calculation of Flat-Plate Loss Coefficient, *Solar Energy*, **17**
- [36] Chapra, S. C., 2007, *Applied Numerical Methods with MATLAB for Engineers and scientist*, McGraw-Hill Higher Education, New York.
- [37] Domestic Heating Compliance Guide, 2006, Office of Deputy Prime Minister, UK
- [38] SAP 2005, Government Standard Assessment Procedure for Energy Rating of Dwelling, 2005, Version 9.82, UK
- [39] Soo Too Y.C., Morrison, G. L., M. Behnia M., 2009, Performance of solar water heaters with narrow mantle heat exchangers, *Solar Engineering*, 83, pp 350-362.
- [40] Lou, J. H., Lin, J. Y., Chuah, Y. K., 1989, Parametric study of Immersed –Coil Heat Exchanger, Energy and Mining Research/Service Organization, Industrial Technology Research Institute, Taiwan
- [41] Farrington, R. B., Bingham, C. E., 1987, Testing and Analysis of load –side immersed heat exchanger for solar domestic hot water systems, Technical Report, Solar Energy Research Institute, USA.
- [42] Furbo, S., 1993, Optimum design of small DHW, low flow system, In: *Proceedings of ISES solar world congress*.
- [43] Tsilingiris, P. T., 1996, Solar Water Heating Design – A new Simplified Dynamic Approach, *Solar Energy*, 57, (1), pp 19-28.
- [44] Dorato, P., 1983, Optimal temperature control of Solar Energy System, *Solar Energy*, 30 (2), pp 147-153
- [45] TRNSYS Version 16.01.0003, 2007, Solar Energy Laboratory, University of Wisconsin-Madison, USA
- [46] <http://www.solartwin.com/brochure/download-brochure/> accessed on July 26, 2009
- [47] ASHRAE Handbook 2005, Fundamental, Chapter 21, ASHRAE, Atlanta, USA.
- [48] Roger, G. F. C., Mayhew, Y. R., *Thermodynamic and Transport Properties of Fluids*, Fifth Edition, Blackwell, UK
- [49] Hobbi, A., Siddiqui, K., 2009, Optimal Design of Forced Circulation Solar Water Heating System for Residential Unit in Cold Climate Using TRNSYS, *Solar Engineering*, 83, pp 700-714.
- [50] <http://www.simplifydiy.com/plumbing-and-heating/hot-water-storage> accessed on July 26, 2009

- [51] Hagan, M. T., Demuth, H. B., Beale, M., 1996, Neural Network Design, PWS Publishing Company, ITP, USA
- [52] Kalogirou, S. A., 2001, Artificial Neural Network in Renewable Energy System Application: A review, Renewable and Sustainable Energy Reviews, 5, pp 373-401
- [53] MATLAB<sup>®</sup> 7.5.0.342 (R2007b), Neural Network Toolbox, The MathWorks Inc, USA.
- [54] Dickinson, W. C., Cheremisinoff, P. N., Solar Energy Technology Handbook Part-B Applications, System Design, and Economics, Butterworths, USA
- [55] Kelly, N, 2009, lecture notes on Energy Resource and Policy for MSc Energy System and the Environment and Policy, University of Strathclyde, UK



## Appendix A: Calculation of tilt angle for maximum heat gain in solar collector

Following steps are to be followed in order to calculate the tilt angle for the optimum energy recovered for a given location and orientation <sup>[55]</sup>. (For better understanding of the various angles, please refer figure A1.)

Step-1: Get the data from meteorological file.

Step-2: Divide  $\Pi/2$  in to 20 division (0.08, 0.16, ..... 1.49, 1.57 radian).

Step-3: Calculate of the two parameters declination angle ( $\rho$ ), solar angle ( $h$ ) for day-1 and time-1h. Latitude ( $l$ ) angle is constant.

$$\rho = 23.5 * \sin[360 * (284 - n) / 365] \quad \text{A-1}$$

Where  $n$  is day number in a year.

$$t_{sol} = t_{ref} + [4 * (L_{ref} - L) + E] / 60 \quad \text{A-2}$$

$$h = 15 * [abs(12 - t_{sol})] \quad \text{A-3}$$

Where,

$t_{sol}$  is local solar time, h

$t_{ref}$  is reference solar time, h.

$L_{ref}$  is reference latitude, degree.

$L$  is local latitude, degree.

$E$  is calculated by equation (A-4) and equation (A-5) represents.

$$E = 9.87 * \sin 2B - 7.35 * \cos B - 1.5 * \sin B \quad \text{A-4}$$

$$B = \frac{360 * (n - 81)}{364} \quad \text{A-5}$$

Step-4: Calculate the Solar elevation angle ( $\beta$ ) and solar azimuth angle ( $\gamma_s$ ) for day-1 and h-1.

$$\beta = \sin^{-1}[\cos(l) * \cos(h) * \cos(\delta) + \sin(l) * \sin(\delta)] \quad \text{A-6}$$

$$\gamma_s = \cos^{-1}\left(\frac{\sin(l) * \cos(h) * \cos(\delta) - \cos(l) * \sin(\delta)}{\cos(\beta)}\right) \quad \text{A-7}$$

Step-5: Calculate direct, diffuse, and total solar radiation falling on tilted panel.

$$I_{b\phi} = I_b * [\cos(\beta) * \cos(\gamma_s) * \cos(\phi) + \sin(\beta) * \sin(\phi)] \quad \text{A-9}$$

$$I_{d\phi} = I_{dH} * (1 + \sin(\phi)) / 2 \quad \text{A-10}$$

$$I_{tot} = I_{b\phi} + I_{d\phi} \quad \text{A-11}$$

Where

$I_{b\phi}$  is direct solar radiation in tilt angle direction, which is measured from vertical,  $\text{W/m}^2$

$I_b$  is direct solar radiation,  $\text{W/m}^2$ .

$I_{d\phi}$  &  $I_{dH}$  are diffuse solar radiation in tilt direction and horizontal direction respectively,  $\text{W/m}^2$

Step-6: From Hottel - Whiller equation, calculate the heat recovered (Q, Wh) for day-1 and h-1

$$Q = I_{tot} * A_c * \tau * \alpha - U * A_c * (T_{pm} - T_a) \quad \text{A-12}$$

where,

A is the collector area,  $\text{m}^2$

$\tau$  is the transmission coefficient, (0.87)

$\alpha$  is the absorption coefficient (0.95)

U is total heat transfer coefficient,  $\text{kW/m}^2\text{K}$

$T_a$  is the ambient temperature,  $^{\circ}\text{C}$

$T_p$  is the Operation temperature  $^{\circ}\text{C}$

Step-7: Now go to day-1 and h-2. Repeat step 4 to 6 till day-365 & h-24.

Step-8: Sum the total energy captured and converts it in kWh.

Step-9: Take next value of tilt angle and repeat step-3 to step-8.

Step-10: Plot value between tilt angle and energy recovered in year and carry out curve fitting by third order polynomial.

Step-11: Use MATLAB function *fminsearch* to get the maximum tilt angle.

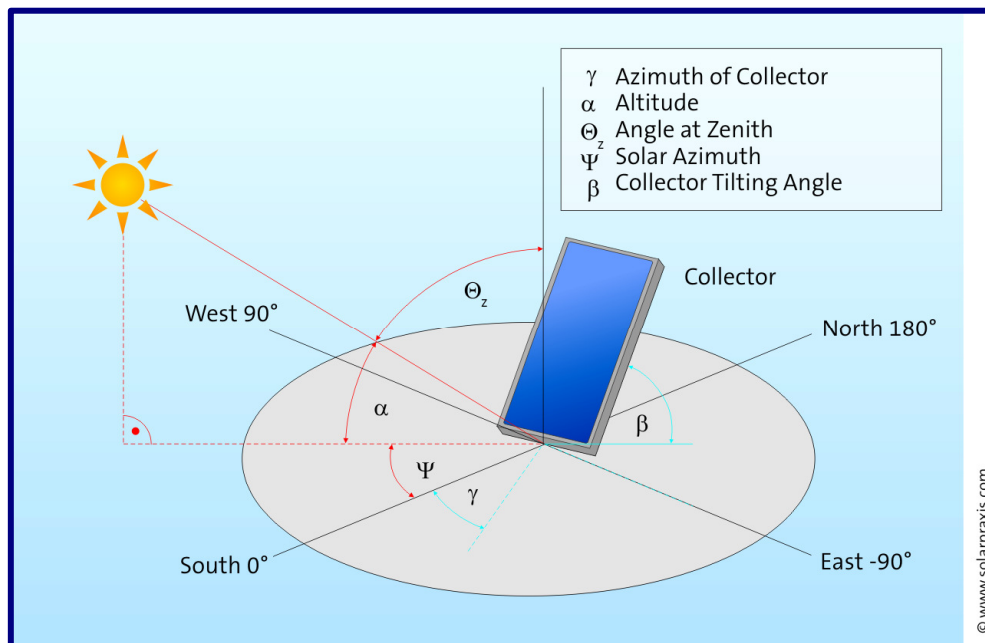


Figure A1: Description of various angle used in appendix A

## Appendix B: MATLAB Code for the solar modelling

```
%% Matlab Program for Maximun tilt angle for given solar configuration
%% Solar data input data for SDHW
%function [Q]= A_max_tilt_radiation_july11( )
clc;clear;
% Opening commands for files. Input_1 contains three columns, viz direct,
% diffuse and ambient temperature.
fid1 = fopen('input_1.txt');
% Reading commands parameters
a = fscanf(fid1,'%g',[5,8760]);
direct_solar = a(1,:);
diffuse_solar = a(2,:);
temp_amb = a(3,:);
L_1 = [(1:1:8760); a(4,:)]; % Normal load Profile in % of total hot water demand
L_2 = [(1:1:8760); a(5,:)]; % RAND load Profile in % of total hot water demand
% Tank parameters
V1=80; Va=0.8*V1; Vb=0.2*V1;
% Tank UA
UA_upper=0.72; UA_lower=0.08; UA_tot=UA_upper + UA_lower;
%initial condition of storage tank C
int_con=10;
%% Basic input for mathematical modelling of solar plate collector
% Latitude and longitude of the location in radian
lat=0.98; longitute=0.1;
% Absorption, transmittance and ground reflectance coefficients
alpha=0.95; tau=0.87; rho=0.6;
% Area of flat plate collector, sq. m
area=2.8;
% Room temperature where panel is kept, C
RTa=10;
```

```

%% Calculation of overall heat transfer coefficient, U, W/(sq. m K)
% Number of glas cover
N=1;
% Plate to Plate spacing, mm
pp = 25;
% Plate & glass emittance
ep = 0.95; eg=0.88;
% Ambient temperature, degree C
amb_T = mean(temp_amb)+273.15;
% Mean Plate temperature, degree C
mean_Tp = 30+273.15;
% Collector tilt, degree
tilt = 45;
% Wind Heat transfer coefficient, W/(sq m C)
h_wind = 15;
% Stefan-Boltzmann constant,
sb_c=5.67e-8;
% Calculation of some other parameters
f = (1+0.089*h_wind-0.1166*h_wind*ep)*(1+0.07866*N);
C=520*(1-0.000051*tilt^2);
e1=0.430*(1-100/(mean_Tp));
% Overall heat transfer coefficient, W/(sq.m C)
U_1 = ((N/((C/mean_Tp)*((mean_Tp-amb_T)/(N+f))^e1)+1/h_wind))^-1;
U_2 = sb_c*(mean_Tp+amb_T)*(mean_Tp^2+amb_T^2);
U_3 = (ep+0.00591*N*h_wind)^-1 + ((2*N+f-1+0.133*ep)/eg)-N;
%u = 1.1*(U_1+U_2/U_3);
u=0.1;
%% Data for Solar Panel and heat exchanger
% Plate efficiency factor
F1=0.85;
% Flow rate of fluid in flate plate collector, kg/s and heat capacity, J/kg-K
mc=50/(area*3600); cp=3800;

```

% Dimensional collector mass flow rate

$m_{cc} = m_c \cdot c_p / (area \cdot u \cdot F_1)$ ;

% Solar plate collector flow factor

$F_2 = m_{cc} \cdot (1 - \exp(-1/m_{cc}))$ ;

% Heat removal factor of solar plate collector

$F_r = F_1 \cdot F_2$ ;

% Flow rate of water in flat plate collector, kg/s and heat capacity, J/kg-K

$\dot{m}_w = 119 \cdot load\_profile\_normal$ ;

$c_{p\_w} = 4184$ ;

%% Basic input for mathematical modelling of heat exchanger inside the storage tank

% Effectiveness of heat exchanger

$effect\_HX = 0.8$ ;

% Heat exchanger penalty in SDHW

$F_{rr} = F_r \cdot ((1 + (1/m_{cc}) \cdot ((1/effect\_HX) - 1))^{-1})$ ;

%% This block calculate the tilt angle for maximum value of total solar radiation falling on collector.

for k=1:1:20;

    %tilt(k)=k\*pi/40;

    tilt(k)=0.785398;

    for j=1:1:365

        days(j)=j;

        for i=1:1:24;

            t(i)=i;

            % Declination angle, radian

$d\_declin(i) = (\pi/180) \cdot (23.5 \cdot (\sin((\pi/180) \cdot ((360 \cdot (284 + days(j))/365))))))$ ;

            % Factor B

$B(i) = (\pi/180) \cdot (360 \cdot (days(j) - 81)/364)$ ;

            % Factor E

$E(i) = 9.87 \cdot \sin(2 \cdot B(i)) - 7.35 \cdot \cos(B(i)) - 1.5 \cdot \sin(B(i))$ ;

            % Local solar time, hour

$lst(i) = t(i) + ((4 \cdot (0 - 5.5)) + E(i))/60$ ;

            % Hour angle, radian

```

h_angle(i)=(pi/180)*(15*abs(12-lst(i)));
% Solar elevation angle, radian
sol_elv(i)=asin((cos(lat))*(cos(h_angle(i)))*(cos(d_declin(i)))+(sin(lat))*sin(d_declin(i)));
% Solar azimuth angle, radian
sol_azim(i)=acos(((sin(lat))*(cos(h_angle(i)))*(cos(d_declin(i)))-
(cos(lat))*(sin(d_declin(i))))/cos(sol_elv(i)));
% Direct component of Solar radiation, kJ/hr-sq. m
I_dir(i)=(direct_solar(i+(j-
1)*24))*((cos(sol_elv(i)))*(cos(sol_azim(i)))*(cos(tilt(k)))+(sin(sol_elv(i))*sin(tilt(k)));
% Diffuse component of solar radiation, kJ/hr-sq. m
I_diff(i)=(diffuse_solar(i+(j-1)*24))*(1+sin(tilt(k)))/2;
% Diffuse component solar radiation from ground, kJ/hr-sq. m
I_ground(i)=rho*((direct_solar(i+(j-1)*24))+(diffuse_solar(i+(j-1)*24)))*(1-sin(tilt(k)))/2;
% Total solar radiation on flat plate collector, kJ/hr-sq. m
I_tot(i)=I_dir(i)+I_diff(i)+I_ground(i);
% As the data for total solar radiation in kJ/hr-sq. m, a factor is multiplied to convert in it
% W/sq.m. So the value of heat is in W.
heat_rate(i) =(1000/3600)*area*Frr*((I_tot(i))*tau*alpha-u*(30-(temp_amb(i+(j-1)*24))));
% This part of code makes the negative value of heat to zero
% and convert the heat rate in to energy, Q in J.
if ( heat_rate(i)<= 0 )
    Q_tot(i)=0;
else
    % Multiplication factor of 1000 will convert the Q_tot(i)
    % in to kWh
    Q_tot(i)=(heat_rate(i))/1000;
end
QQ(i+(j-1)*24)=Q_tot(i);
t_col(i+(j-1)*24)=(3.6e6)*(QQ(i+(j-1)*24))/(mc*3600*cp)+10;

end

Q_tot2(j)=sum(Q_tot);

```

```

end

Q_tot1(k)=sum(Q_tot2);
end
% Variable to be used in simulink
Q=[(1:1:8760); QQ]';
t_co=[(1:1:8760); (t_co1)']';
% Some parameters to understand the estimate energy gain through solar
% panel
Q_jan=sum(Q(265:265+23,2));
Q_april=sum(Q(2425:2425+23,2));
Q_july=sum(Q(4585:4585+23,2));
Q_oct=sum(Q(6817:6817+23,2));
Q_average=sum(Q(1:8760,2))/365;
Q_total=sum(Q(1:8760,2));
t_mean_plate=mean(t_co1);
% Calculation of monthly average for a year
for i=1:1:1
Q_month_(i)=mean(Q(1:744,2));
Q_month_(i+1)=mean(Q(744:1416,2));
Q_month_(i+2)=mean(Q(1416:2160,2));
Q_month_(i+3)=mean(Q(2160:2880,2));
Q_month_(i+4)=mean(Q(2880:3624,2));
Q_month_(i+5)=mean(Q(3624:4344,2));
Q_month_(i+6)=mean(Q(4344:5088,2));
Q_month_(i+7)=mean(Q(5088:5832,2));
Q_month_(i+8)=mean(Q(5832:6552,2));
Q_month_(i+9)=mean(Q(6552:7296,2));
Q_month_(i+10)=mean(Q(7296:8016,2));
Q_month_(i+11)=mean(Q(7296:8760,2));
end
% plot(Q_month_, 'LineWidth',3)
% xlabel('Time, month');ylabel('Q, kWh');

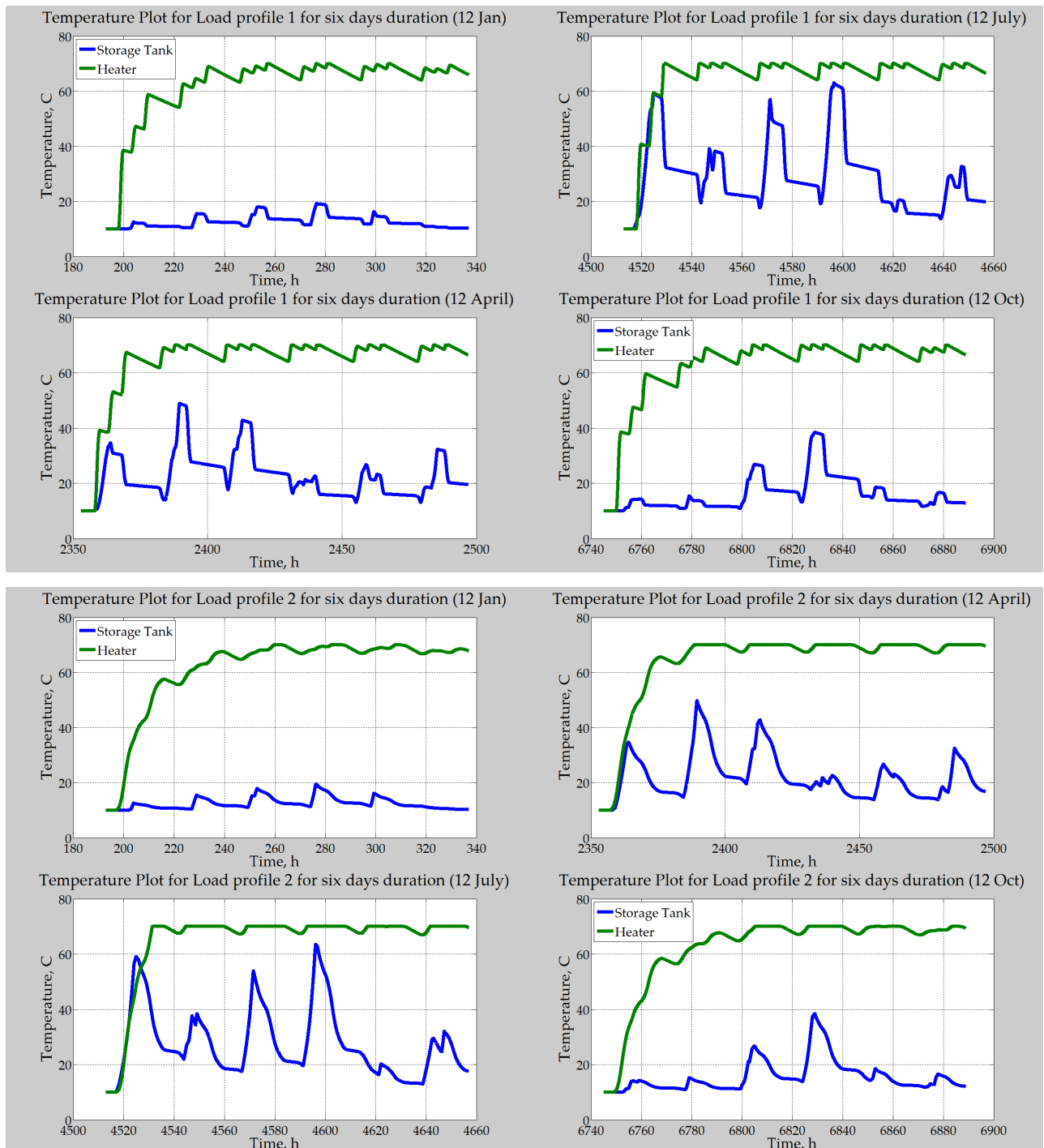
```



```
% title({'Heat Recovered from Solar Panel','based on monthly average'});
% xlim([1 12]);
%% This block calculate the incident radiation on the flat plate collector for optimum tilt angle
% %To fit the tilt angle and the total solar radiation received on flat plate collector, fitting a cubic
polynomial and finally finding out the
% %maximum value of the total solar radiation at particular tilt angle.
% z=polyfit(tilt, Q_tot1,3);
% zz=polyval(z,tilt);
% plot(tilt,zz,'ro',tilt,Q_tot1,'.b')
% h=legend('cal','interpolated','Location','SouthEast');grid on;
% title('Appendix A:Plot of Recovered energy from Solar Panel and interpolated values');
% xlabel('Tilt angle, radian');ylabel('Annual Energy Q, kWh');
% %To minimize the function, the actual function is put as -f(x) to calculate minimum.
% f = @(p)(-z(1)*p^3-z(2)*p^2-z(3)*p-z(4));
% [tilt_max,fval,exitflag,output] = fminsearch(f,-1,1);
% %This block is used to verify the calculated and interpolated between the curves visually.
% fclose('all');
% return;
```

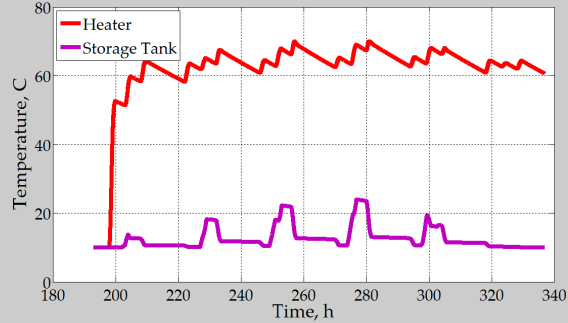
## Appendix C: Temperature profiles for all the Cases Considered in Analysis

### CASE-1: Temperature profiles for the SDHW configuration with Twin Cylinders

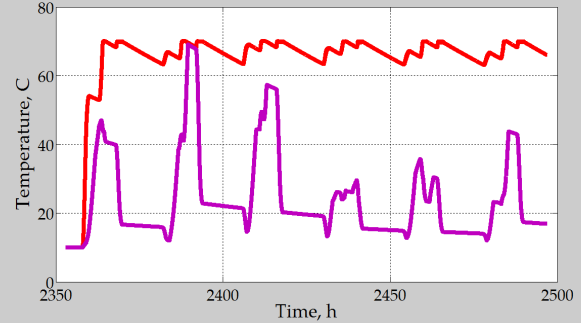


## Case-2: Temperature profiles for SDHW configuration with single cylinder

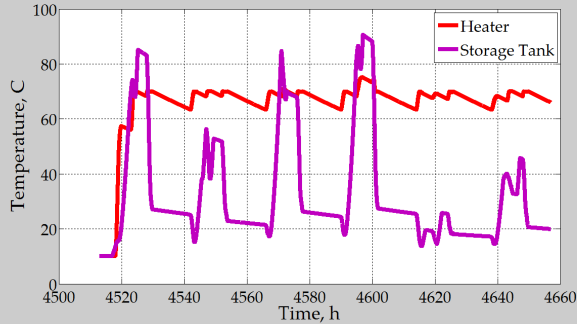
Temperature Plot for Load profile 1 for six days duration (12 Jan)



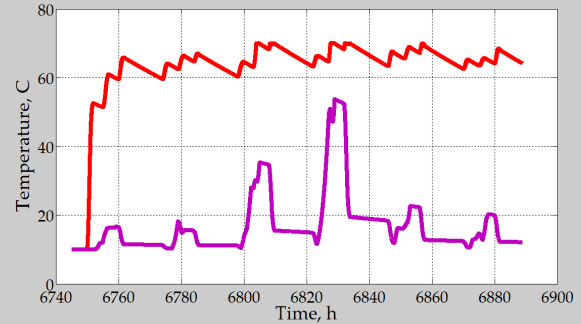
Temperature Plot for Load profile 1 for six days duration (12 April)



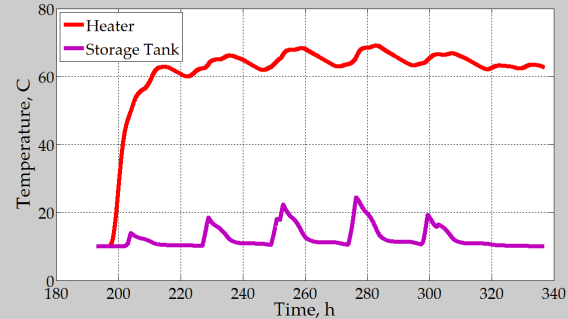
Temperature Plot for Load profile 1 for six days duration (12 July)



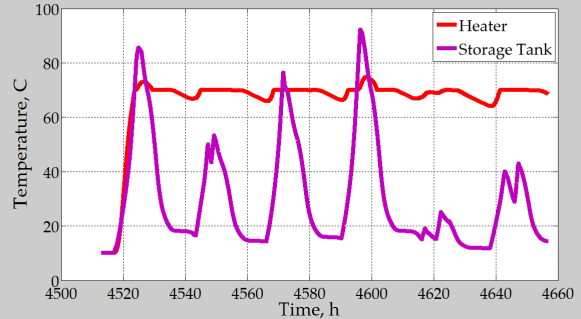
Temperature Plot for Load profile 1 for six days duration (12 Oct)



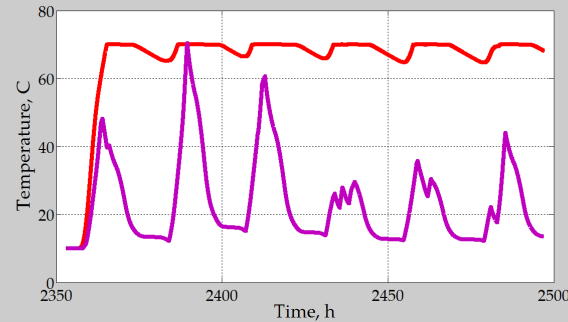
Temperature Plot for Load profile 2 for six days duration (12 Jan)



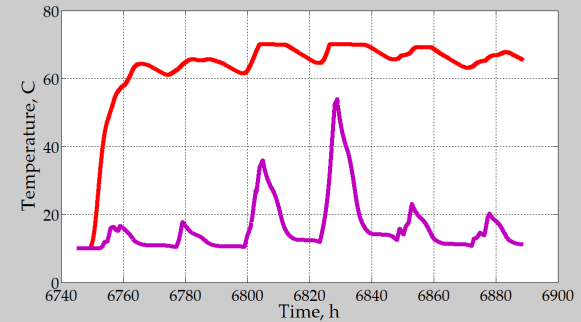
Temperature Plot for Load profile 2 for six days duration (12 July)



Temperature Plot for Load profile 2 for six days duration (12 April)

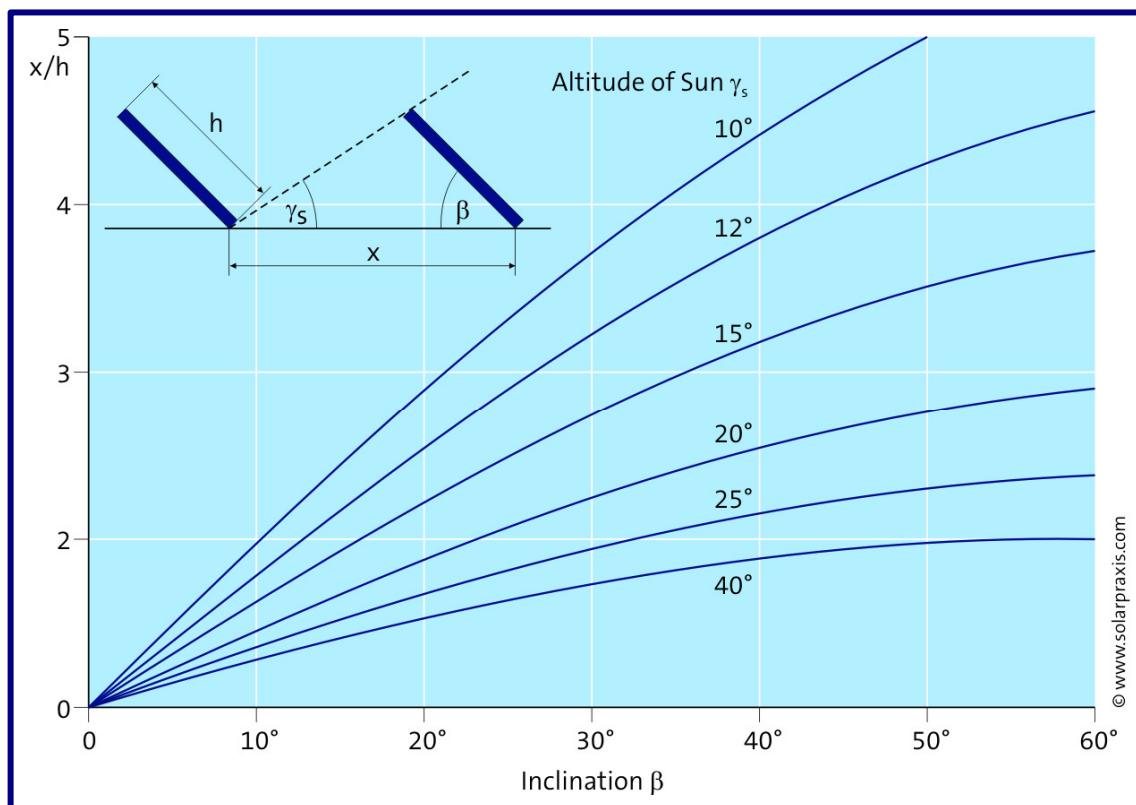


Temperature Plot for Load profile 2 for six days duration (12 Oct)



## Appendix D: Best Possible Arrangement of the Solar Collector Panel in Multiple Rows

The following graph <sup>[11]</sup> suggests the best possible arrangement for more than one panel in row based on angle of altitude for particular location and inclination angle of the panel.



## Appendix E: MATLAB Code for Heat Recovered Prediction by Neural Network

```
function net = fitwithnet(p,t)
%FITWITHNET Creates and trains a neural network to fit input/target data.
%
% [NET,PS,TS] = FITWITHNET(P,T) takes:
%   P - RxQ matrix of Q R-element input samples
%   T - SxQ matrix of Q S-element associated target samples
% arranged as columns, and returns these results:
%   NET - The trained neural network
%   PS - Settings for preprocessing network inputs with MAPMINMAX.
%   TS - Settings for postprocessing network outputs with MAPMINMAX.
%
% For example, to create an network with this function:
%
% load housing
% net = fitwithnet(p,t);
%
% To test the network on the original or new data:
%
% y = sim(net,p); % Apply network
% e = t - y; % Compare targets and outputs
%
% To reproduce the results you obtained in NFTOOL:
%
% net = fitwithnet(vij',output');

% Create Network
numHiddenNeurons = 100; % Adjust as desired
```

```

net = newff(p,t,numHiddenNeurons);

% Division of Samples
% (Delete these lines to use default settings of 0.6, 0.2 and 0.2.)
net.divideParam.trainRatio = 0.80; % Adjust as desired
net.divideParam.valRatio = 0.10; % Adjust as desired
net.divideParam.testRatio = 0.10; % Adjust as desired

% Random Seed for Reproducing NFTool Results
% (Delete these lines to get different results each time this function is called.)
rand('seed',1148498720.000000)
net = init(net);

% Train Network
[net,tr] = train(net,p,t);

% Simulate Network
[trainOutput,Pf,Af,E,trainPerf] = sim(net,p(:,tr.trainInd),[],[],t(:,tr.trainInd));
[valOutput,Pf,Af,E,valPerf] = sim(net,p(:,tr.valInd),[],[],t(:,tr.valInd));
[testOutput,Pf,Af,E,testPerf] = sim(net,p(:,tr.testInd),[],[],t(:,tr.testInd));

% Display Performance
fprintf('Train vector MSE: %f\n',trainPerf);
fprintf('Validation vector MSE: %f\n',valPerf);
fprintf('Test vector MSE: %f\n',testPerf);

% Plot Regression
figure
postreg({trainOutput,valOutput,testOutput}, {t(:,tr.trainInd),t(:,tr.valInd),t(:,tr.testInd)}});

```