Study of Hybrid Photovoltaic Solar Thermal systems during summer months in Bangladesh

BY

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CANDIDATE'S DECLARATION

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

A hybrid photovoltaic (PVT) solar system combines a simultaneous conversion of the absorbed solar radiation into electricity and heat. In this study the design of an experimental PVT/dual system, both air & water circulation with modifications in the air channel is presented. First modification is to place a thin flat metallic sheet (TMS) inside the air channel & second one is to use painted Black ribbed surfaces at the bottom of the air channel. To observe the variations of heat transmittance with change of the shape of the ribs four experimental setups with a Trapezoidal, a Saw tooth forward, a Saw tooth backward ribbed surfaces and a flat plate have been used Natural convection is applied instead of forced convection to increase the system net electrical output & thereby the overall system efficiency. All setups of the same capacity, projected area, and water heat extraction method and average depth.

Performance study is carried out during the months of February to June, 2012 at IUT campus, Gazipur, Bangladesh. Significant performance has been observed with the above stated modifications. In an intense sunny day of March, the maximum temperature of water is found to be 45ºC for Trapezoidal, 44º C for Saw tooth forward, 43ºC for Saw tooth backward and 41ºC for flat plate setup. Maximum temperature of air inside the air channel is found to be 39ºC for Trapezoidal, 38ºC for Saw tooth forward, 37ºC for Saw tooth backward ribbed surfaces and 36ºC for flat plateƞ in an intense sunny day of march 2012 with an ambient temperature of 34ºC.

The average efficiency from all calculated values is found to be 64% for Trapezoidal, 62% for Saw tooth forward, 61% for Saw tooth backward & 58% for flat plate setup.

Keywords: Hybrid Thermal System, Solar Energy, Thin Metallic Sheet (TMS), Painted Black ribbed surface.

NOMENCLATURE

A,	Aperture Area, m^2
C_p,	Specific Heat at Constant Pressure. J/kg.k
G,	Incoming Solar Radiation. w/m^2
K,	Thermal Conductivity, W/m.k
M,	Mass Flow Rate, kg/s
Q_{ab},	Heat Energy Absorbed, w/m^2
TMS,	Thin Metallic Sheet
WHX,	Water Heat Exchanger
T_{pv},	PV Module Temperature, ºC
T_{whx},	Water Heat Exchanger Temperature, ºC
T_i,	Input Fluid Temperature, ºC
T_o,	Output Fluid Temperature, ºC
T_{amb},	Ambient Temperature, ºC
T_{air},	Air Temperature in Channel, ºC
$T_{ri}b$,	Ribbed Surface Temperature, ºC
ΔT_w,	Temperature Difference of Water, (T_o-T_i) ºC
ΔT,	Temperature Difference, (T_i-T_{amb}), ºC
η^{th},	Thermal Efficiency

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Chapter 1

Introduction

The need for alternative energy sources is getting urgent, hence the development of renewable energy is moving fast. Nationally and internationally various individuals and research companies are creating new and exciting energy systems. Some of these apparatus are great works and need improving for massive use. Politician world-wide are drafting policies and are making agreements to make greater use of these energy sources.

Regarding the conventional source of energy the problem is that the fossil fuels are depleting in a rapid rate and are harder to retrieve. The consequence is we can be facing an energy crisis in the future, which we are not careful today. The energy prices will sky rocket and not be available for many individuals or countries. To avoid this doom scenario we need to find alternatives and use them to their full potential.

A wide use of fossil fuels today is very harmful for the environment. In the early seventies and eighties there were people and even scientist who preach otherwise, but today the negative effects are showing. The earth is warming up and climates are changing. There are parts in the world where there will be more rain and sunshine and others parts will become dryer than they already are. Another negative effect is that the ozone layer is getting thinner which also leads to a warming up of the earth. These two effects complement each other and make it even more crucial to make another step in a different direction. This step will lead us to the use of renewable energy.

Problem lies also in the development of small countries. Because the energy prices for crude oil are going through the roof, these countries suffer even more. Many of these countries need crude oil for their electricity and means of transportation. These high oil prices have their effect on almost everything. The monthly electricity costs for households increase among others like transport cost and prices for basic products. Hence, these high oil prices make it harder for these small countries to grow their economies.

The solution for the above problems can be resolved by renewable energy. Our beautiful planet gives us the opportunity to make proper use of sunlight, flowing water, strong winds, hot springs and convert these into energy. These energy sources are abundant and free to use. But, we must be sure that we convert the energy in the right way, without causing other problems that can again hurt our environment. Luckily many efforts by individuals and companies show that this can be done.

1.1 Renewable Energy

Renewable energy is derived from an energy source that is rapidly replaced, or renewed by a natural process. It is the energy which comes from natural resources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable in nature. Renewable Energy are basically classified as

Solar energy, Wind and Wave energy, Hydropower, Bio-mass and Geothermal energy

All the above mentioned energy sources originated due to presence of sun, which can collectively referred to as solar energy.

1.1.1 Solar Energy

Solar energy is an important clean, cheap and abundantly available renewable energy. The earth receives an incredible supply of solar energy. The sun, an average star, is a fusion reactor that has been burning over 4 billion years. It provides enough energy in one minute to supply the world's energy needs for one year. In one day, it provides more energy than our current population would consume in 27 years. In fact, "The amount of solar radiation striking the earth over a three-day period is equivalent to the energy stored in all fossil energy sources."

The earth receives around ($1.74 * 10^{17}$ W) of solar energy and the solar constant is (1353 W/m^2) which resulted by several experimental programs (Thekaekara and Drummond 1971) assuming eight hours of sunshine a day and was accepted by NASA (NASA 1971).

The heat and light received from the sun also supports the environment on the earth’s various natural effects such as temperature balance on the earth, photosynthesis by biological plants, wind due to unequal heating of water and land surfaces, water cycle, heating ocean water, waves in ocean, tides in ocean etc. Solar radiation, along with secondary solar-powered resources such as wind and wave power, hydroelectricity and biomass, account for over 99.9 percent of the available renewable energy on earth. Only a minuscule fraction of the available solar energy is used.

Solar energy also describes technologies that utilize sunshine to produce other forms of energy. These technologies date from the time of the early Greeks, Native Americans and Chinese, who warmed their buildings simply by orienting them toward the sun. Modern solar technologies continue to harness the sun, but in more innovative ways, to provide heating, lighting, electricity and even flight.

From technical point of view there are many problems associated with the use of solar energy. The main problem is that it is a dilute source of energy where its radiation flux is low. Consequently, large collecting area is required in many applications and these results in excessive costs. Another problem associated with the use of solar energy is that its availability varies widely with time. The variation in availability occurs daily because of the day-night cycle and also seasonally because of the earth’s orbit around the sun.

However, there is a good prospect of harnessing solar power in Bangladesh. In a recent study conducted by Renewable Energy Research Centre, it is found that average solar radiation varies between 4 to 6.5 $kWhm^{-2}$ day^{-1}. Maximum amounts of radiation are available in the month of March-April and minimum in December-January.

1.1.2 Solar Energy Collections

Mainly there are two ways to collect solar energy: Natural collection and Technological collection.

Natural Collection of Solar Energy

Waves, winds, biological conversions are some examples of natural collection of solar energy. About 71 percent of the world’s surface is covered with oceans provides tremendous store of solar energy. Movement of the wind which causes waves at sea, and the evaporation of water to form rainfall, which accumulates in rivers and lakes, is also powered by the Sun. Therefore, hydroelectric power and wind and wave power are forms of indirect solar energy. Coal, oil, and natural gas derive from ancient biological material that took its energy from the Sun (via photosynthesis) millions of years ago. All the energy in wood and foodstuffs also comes from the Sun. These energies are collected naturally for various environmental systems.

Technological Collection of Solar Energy

There are two methods for technological collection of solar energy.

- Photovoltaic Conversion Method
- Thermal Conversion Method

Photovoltaic Conversion Method

In the photovoltaic conversion method, solar energy converted directly to electricity by means of semiconductor photo cells that exhibit the photovoltaic effect. In photovoltaic effect the electrons are ejected from a material's surface upon exposure to radiation of sufficient energy. The generated electrons are transferred from different bands (i.e. from the valence to conduction bands) within the material, resulting in the buildup of a voltage between two electrodes. In most photovoltaic applications the radiation is sunlight and for this reason the devices are known as solar cells. Solar cells are usually made from silicon. The silicon is treated or "doped" so that when light strikes it electrons are released, so generating an electric circuit.

1.1.3 Thermal Conversion Method

In this method, the solar radiation is collected as heat energy employing different techniques of collector technology. Such as, solar water heater, solar cooker, solar band, stills etc. Thermal conversion technology is discussed below in details under the heading of different types of solar collectors.

1.2 Hybrid Photovoltaic/Thermal (PV/T or PVT) Solar Energy Systems

Different Photovoltaic cell converts only 5-15% of the incoming solar radiation into electricity, with the greater percentage converted into heat. The solar radiation converted into heat increases the temperature of the PV modules, resulting in the drop of their electrical efficiency. This undesirable effect can be partially avoided by applying a suitable heat extraction mode with a fluid circulation, keeping the electrical efficiency at a satisfactory level. Furthermore, this extracted heat can be utilized for heating air and/or water. For this purpose the concept of Hybrid photovoltaic/thermal (PV/T or PVT) solar systems developed.

The PV modules that are combined with thermal units, where circulating air or water of lower temperature than that of PV modules is heated constitute the Hybrid PVT solar systems. It provides electrical and thermal energy, increasing therefore the total energy output from PV modules using the same projected area.

The Hybrid PVT solar system consists of PV modules coupled to water and/or air heat extraction devices which convert the absorbed solar radiation into electricity and heat. This system is simple and suitable for building integration for providing hot water/air depending on the season and the thermal needs of the buildings.

The improved PVT systems have aesthetic and energy advantages and could be used instead of separate installation of plain PV modules and thermal collectors. For building integration, it uses the same floor/wall area as plain PV installations.

There are three basic types of hybrid PVT system:

- PVT/air system, where air is used for heat extraction from PV panel rear surface. Thus electricity and hot air is output.
- PVT/water system, where water is used for heat extraction from PV panel rear surface. Thus electricity and hot water is output.
- PVT/dual (air and water) system, where both air and water is used for heat extraction. Thus the output is both hot air and water with electricity.

In PVT system applications, the main priority is to produce electricity so the operating temperature should be within certain range to keep the electrical efficiency at sufficient level. This requirement limits the effective operation range of the PVT unit for low temperatures thus the extracted heat can be used mainly for low temperature applications. The PVT solar system can be effectively used in the domestic and the industrial sectors.

- Considering water as heat removal fluid, it can be used in residential buildings, hotels, hospitals etc.
- Considering air for heat extraction, it is used for space heating, natural ventilation etc.

The system can be suitable for building integration for providing hot water/air depending on the season and the thermal needs of the buildings.

By using these systems the electrical output of the PV is increased, while avoiding building overheating during summer and covering part of the building space heating needs during winter. For residential use, in most cases the temperature of water needed is around 20^0C above ambient temperature. This water is mainly for kitchen use, bathroom use etc. For commercial sectors in swimming pools of hotels, hospitals etc

Many commercial units of hybrid PVT system are available now-a-days in the marker for both residential and industrial use.

1.3Objectives with specific aims:

The objectives of this study are to carry out an experimental investigation to compare the performances of four PVT collectors having three different ribbed surfaces (Trapezoidal, Saw tooth forward, Saw tooth backward rib) and a flat plate opposite to each absorber plate. All collectors will be of same capacity, same projected area, and same average depth. Tests will be carried out in IUT campus from February 2012 to June 2012.

1.4 Possible Outcomes:

Performance study of each Hybrid PVT collector will be carried out. It is expected that from this study the following outcomes may be found out:

1. Water and Air temperature may increase with increasing of PV panel temperature.
2. Thermal and Electrical efficiency may increase.

Results obtained here will be compared with available information in the literature.

Chapter 2

LITERATURE REVIEW

2.1 Literature on PVT systems

Many theoretical and experimental works have been carried out for the improvement of hybrid PVT solar systems since its appearance in 1980’s.

Among the first, Kern and Russell, (1978), give the main concepts of these systems with results, by the use of water or air as heat removal fluid. Hendrie, (1979), presents a theoretical model on PVT systems using conventional thermal collector techniques, Bhargava et al. 1991 and Prakash 1994, present results regarding the effect of air mass flow rate, air channel depth, length and fraction of absorber plate area covered by solar cells (packing factor, PF) on single pass, Sopian et al. on double pass, 1995 and on single pass and double pass hybrid PVT system performance, 1996.Garg and Adhikari (1997) present a variety of results regarding the effect of design and operation parameters on the performance of air type PVT systems.

In the above works the calculated thermal efficiencies of liquid type PVT systems are in the range of 45% to 65%, the higher values derived for systems that include thermal losses suppression by using air gap with glazing. Regarding air type PVT systems, the thermal efficiency depends strongly on air flow rate, air duct depth and collector length. For higher values of air flow rate, small air duct depth and long PVT systems, thermal efficiencies up to about 55% are given by the theoretical models. The packing factor is an important parameter in most of the above papers.

Because of their easier construction and operation, hybrid PVT systems with air heat extraction are more extensively studied, mainly as an alternative and cost effective solution to building integrated PV systems (BIPV). Following the above referred studies, test results from PVT systems with improved air heat extraction are given by Ricaud and Roubeau (1994) and from roof integrated air-cooled PV modules by Yang et al. (1994).

Brinkworth et al. (1997), Moshfegh and Sandberg (1998), Schroer et al. (1998), Brinkworth (2000), and also Brinkworth et al. (2000) present design and performance studies regarding air type building integrated hybrid PVT systems.

The building integrated photovoltaics is going to be a sector of a wider PV module application and the works of Hegazy (2000), Lee et al. (2001), Chow et al. (2003) and Ito and Miura (2003) give interesting modeling results on air cooled PV modules.The works on building integrated air-cooled photovoltaics include the studies on the multi-operational ventilated PVs with solar air collectors (Cartmell et al., 2004), the ventilated building PV facades (Infield et al., 2004; Guiavarch and Peuportier, 2006; Charron and Athienitis, 2006) and the design procedure for cooling air ducts to minimize efficiency loss (Brinkworth and Sandberg, 2006).

Despite these improvements, commercial application of PVT/air collectors is still marginal, but it is expected to be wider in the future where many building facades and inclined roofs will be covered with photovoltaic.

PVT/water systems are more expensive than PVT/air systems due to additional cost of the thermal unit with the pipes for the water circulation. On the other hand water from mains does not often exceeds 25^0C and ambient air is usually higher during summer in low latitude countries and water heat extraction is of more practical value at these locations as it can be used during all seasons.

The liquid type hybrid PVT systems are less studied than air type systems and the works that follow the first period of PVT system development are the study of Bergene and Lovvik (1995) for a detailed analysis on liquid type PVT systems, of Elazari (1998) for the design, performance and economic aspects of a commercial type PVT water heater, of Hausler and Rogash (2000) for a latent heat storage PVT system and of Kalogirou (2001) with TRNSYS results for water type PVT systems. Later, Huang et al. (2001) present a PVT system with hot water storage and Sandness and Rekstad (2002) give results for PVT collectors with polymer absorber.

Regarding recent works, modeling results (Chow, 2003; Jie et al., 2003), the study on domestic PVT systems (Coventry and Lovegrove, 2003), the performance and cost results of a roof sized PVT system (Bakker et al., 2005) and the theoretical approach for domestic heating and cooling with PVT collectors (Vokas et al., 2006) and the performance evaluation results (Tiwari and Sodha, 2006), can be referred. PVT/ water collectors can replace thermal collectors for water heating in the domestic and industrial sectors, but they are not yet cost effective and this is the main reason for their niche market penetration.

An experimental study of facade-integrated photovoltaic/water-heating system is done by Chow T.T. (2006). This work describes an experimental study of a centralized photovoltaic and hot water collector wall system that can serve as a water pre-heating system. Collectors are mounted at vertical facades. Different operating modes were performed with measurements in different seasons. Natural water circulation was found more preferable than forced circulation in this hybrid solar collector system. The thermal efficiency was found 38.9% at zero reduced temperature, and the corresponding electricity conversion efficiency was 8.56%, during the late summer of Hong Kong.

In China, the energy performance of PV/water-heating collector systems with natural circulation of water has been examined by the authors T.T. Chow, J. Ji, W. He (2005 and 2006) based on the weather conditions of Hong Kong and Hefei. These studies showed that the use of a flat-box type thermal absorber is very effective. In Hong Kong for a stand-alone PVT collector system with mono-crystalline solar cells, the daily thermal efficiency was found 48.3% in winter and 45.4% in summer at zero reduced temperature (i.e. when the initial water temperature in the storage tank is as cold as the mean ambient temperature on the day of measurement). This was for water storage to collector-area ratio (M/Ac) of 96.6 kg/m2 and at a desirable tilt angle.

Design and performance improvements of hybrid PVT systems with water or air as heat removal fluid have been carried out at the University of Patras, Greece including modifications that contribute to the decrease of PV module temperature and to improve the total energy output (electrical and thermal) of the PVT systems (Souliotis,2008). Two systems (PVT/UNGLAZED and PVT/GLAZED) were tested outdoors, consisted of pc-Si PV modules and heat exchanger of copper sheet with copper pipes.

Also, PVT solar water heaters of ICS (Tripanagnostopoulos et al., 1998) and of thermosiphonic (Tselepis and Tripanagnostopoulos, 2002) type have been studied. The diffuse reflector is suggested to increase both electrical and thermal output of PVT systems (Tripanagnostopoulos et al., 2002a) and LCA results for PVT/water (Tripanagnostopoulos et al., 2005) and PVT/air (Tripanagnostopoulos et al., 2006) systems, compared with standard PV modules, give an idea about the positive environmental impact of the suggested systems.

Design concepts, prototypes and test results for water and air-cooled PVT systems with and without additional glass cover are extensively presented in Tripanagnostopoulos et al. 2002. The test results of thermosyphon-type PVT systems indicated that, compared to the unglazed systems, the glazed PVT systems for water-heating improved the thermal efficiency up to about 30%, but reduced the electrical efficiency by about 16%.

A detailed description of hybrid PVT solar systems is included in a recently published Roadmap (Zontag et al., 2005; Affolter et al., 2006), where many aspects regarding technology, present status and future perspectives of these solar energy conversion systems are presented.

In IUT, Akhanda M.A.R et al. (2001) carried out an experimental investigation to compare the performance between two collector-cum-storage type solar water heaters having flat absorber plate and vee corrugated absorber plate. The average efficiency of vee corrugated absorber was found to be more than that of flat absorber plate by 17 percent in November.

Tripanagnostopoulos et al. 2007, at the University of Patras, Greece has done an extended research on PVT systems aiming at the study of several modifications for system performance improvement. A new type of PVT collector with dual heat extraction operation, either with water or with air circulation is presented. Experiments with dual type PVT models of alternative arrangement of the water and the air heat exchanging elements were performed. The most effective design was further studied, applying to it low cost modifications for the air heat extraction improvement. The modified dual PVT collectors were combined with booster diffuse reflectors, achieving a significant increase in system thermal and electrical energy output..

Rezwan and Akhanda (2011) studied a hybrid photovoltaic/Thermal (PVT) solar system can simultaneously provide electricity and heat, achieving a higher conversion rate of the absorbed solar radiation than that of a standard PV module. This system consists of a PV module coupled with water or air heat extraction devices. In this paper, an experimental study of a PVT dual system, both simultaneous air and water circulations with modifications in the air channel are presented. First modification is to place a thin flat metallic sheet (TMS) inside the air channel & second one is to mount painted Black ribbed surfaces at the bottom of the air channel. Natural convection is allowed to take place instead of forced convection to increase the system net electrical output & thereby the overall system efficiency. To observe variations of heat transmittance with change of the shape of ribs (Triangular, Semicircular, Rectangular and Flat Surfaces), four experimental systems have been fabricated. Results obtained here have been compared with previous work in this area of research.

2.2 Scope of the Present Work

A brief overview of the literature survey and the aspects for studies, technologies and improvements of hybrid PVT solar collector shows the perspective and limitations of these new solar energy devices. The PVT/water collectors can effectively operate in all seasons, mainly for application at location in low latitudes without freezing problems, but for low latitude applications in the summer period with the ambient temperatures PV cooling by the circulating air is less effective.

A combination of both heat extraction modes in one device could possibly overcome the limitations of two PVT type collectors. Based on this principle, a new type of PVT collector with dual heat extraction operation (PVT/dual) either to heat water or to heat air depending on the weather conditions and building needs, was investigated by (Tripanagnostopoulos et al., 2001b)

The present work will study for performance of Hybrid Photovoltaic Thermal (PVT) dual solar collector using different ribbed surfaces placed opposite to the air channel wall. Tests will be carried out in the months of February to June, 2012 at IUT campus, Gazipur, Bangladesh.

Four PVT collectors having three different ribbed surfaces of Trapezoidal, Saw tooth forward, saw tooth backward and a Flat surface opposite to the air channel wall will be studied.

CHAPTER 3

Experimental Setup & Test Procedure

3.1 Experimental Setup

Four experimental setups were fabricated with similar design and dimensions except the shape of the ribs. All works were done in the mechanical workshop of IUT. The whole setup is constructed in a wooden box. PV panels are set at the top of the box. Thin Metallic Sheet (TMS) is placed at the middle part of the box on top of which pipes are set for water circulation. Air channel of 0.1m height is kept under the water heat exchanger. Different ribbed surfaces (*Trapezoidal, Saw tooth forward, Saw tooth backward) and a Flat plate* of same height and dimension are placed on opposite wall of the air channel. The whole inner portion of the box is insulated. TMS and Ribbed plates are painted black for better heat absorption. Fig 3.1 shows the schematic diagram of each experimental setup with different ribbed surfaces. Photograph of the installed setup at IUT campus, shows in fig. 3.5.

The main components of each setup consists of a PV panel, wooden box, water heat exchanger (WHX) & the absorber (TMS), ribbed plates at the opposite of air channel, water storage tank, insulation, steel frame and stand. Detailed descriptions of the components are given below.

(a)Solar Photovoltaic Panel

For this project Polycrystalline-Silicon (pc-Si) PV panels are used with a rating of 50 watts and 0.45m^2 aperture area having approximate dimensions of (839 × 537 × 50) mm.

The selection of the pc-Si PV panel is based on the justification discussed in the design portion.

(b)Wooden Box

The whole setup is fabricated in a wooden box with a dimension suitable to the dimension of the PV panel. Chemically treated Kerosene wood is used for better longevity of the setup.

(c)Water Heat Exchanger (WHX)

For circulating water copper tubes were used in the project, as copper has got higher thermal conductivity which is a necessary requirement of the project. The optimum diameter 1.25 cm (½″) is selected to facilitate the high rate of heat transfer and sufficient rate of flow.

For the header portion, copper pipe of diameter 3.8 cm (1.5”) is used. The diameter of the header is found by calculating the cross-sectional area of the copper tubes corresponding to header cross-sectional area to maintain a uniform flow rate through all the tubes. For water flow to and from the storage tank nylon pipe of diameter 2.5 cm is used. Nylon pipes are flexible and don’t bend to interrupt the flow.

(d)TMS and Ribbed Plate

For the TMS and RIB, GI Sheet of 22 gauges is used. The GI sheets are painted black to increase the heat absorbency, which will improve the heat transfer with air and water.

Trapezoidal, Saw tooth forward, Saw tooth and a Flat plate are made for the four experimental setup

(e)Insulation

Glass wool is used as insulation for its low conductivity (K) of 0.04 W/mK, and of moderate cost. Insulation of 2.5 cm is applied at the inner surface of the wooden box to avoid any kind of heat transfer to and from the setup which may decrease the efficiency of the PVT system.

(f)Water Storage Tank

Capacity of the water storage tank is 30 liters. Plastic drums are used with heavy insulation so hot water can be used.

(g)Steel frame and stand

A supporting steel structure is made for the collectors and storage tanks. The collectors are set on inclination angle (β) 23.5^0 and directed towards south.

3.2: Details of Hybrid Collector

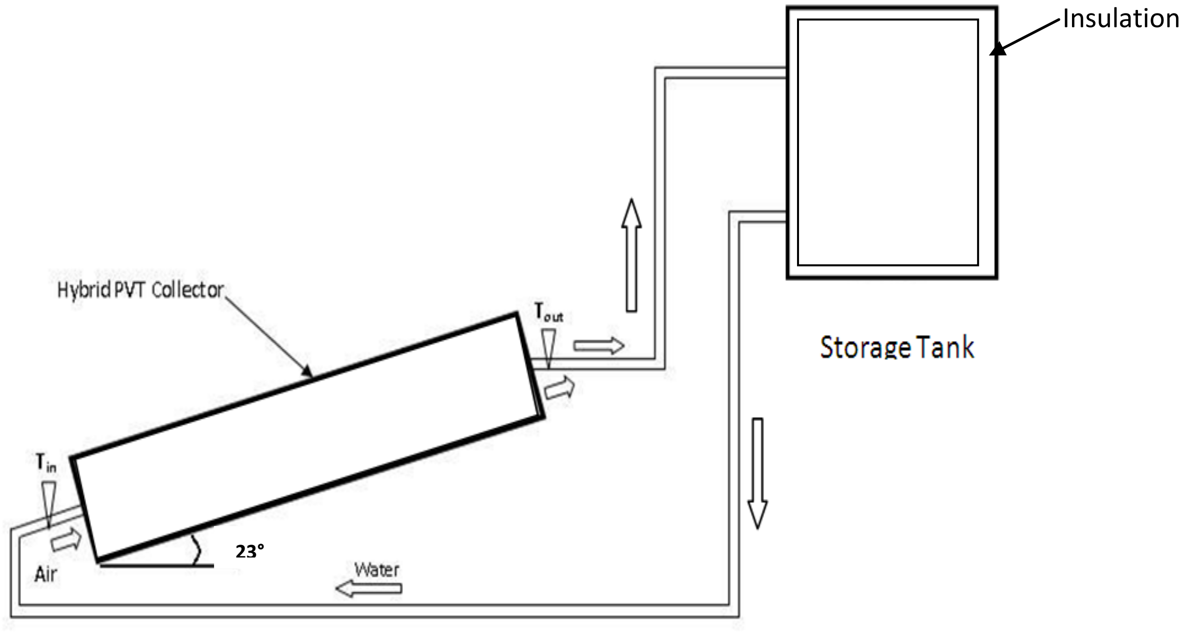


Figure 3.1: Schematic diagram of each experimental setup.

Details of hybrid collector and test specimens used in this study are shown in fig. 3.2 and in fig. 3.3. Photograph of the Interior view showing the TMS with water heat exchanger shows in fig. 3.4.

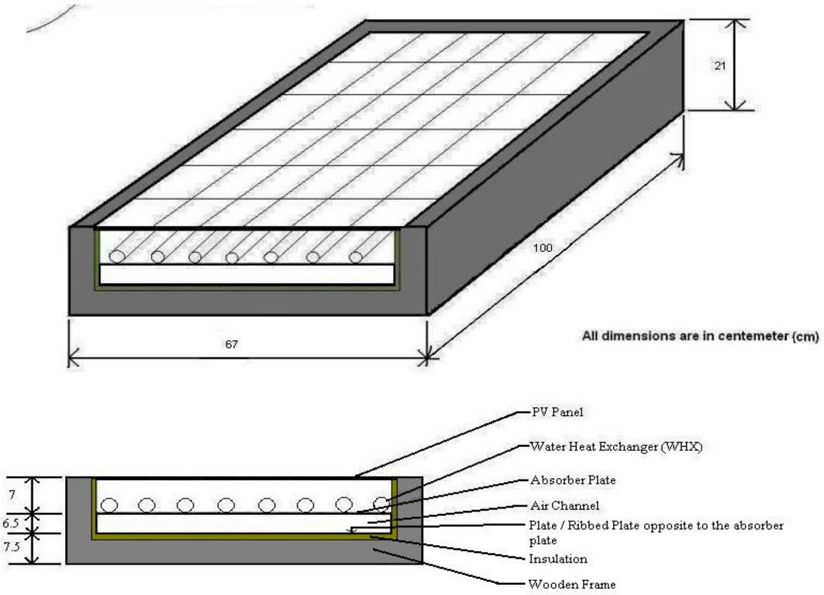
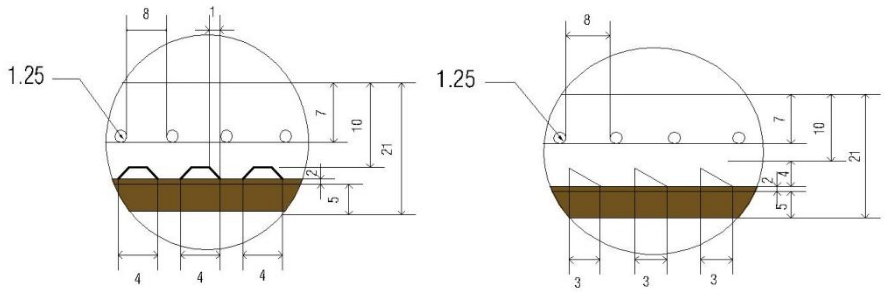
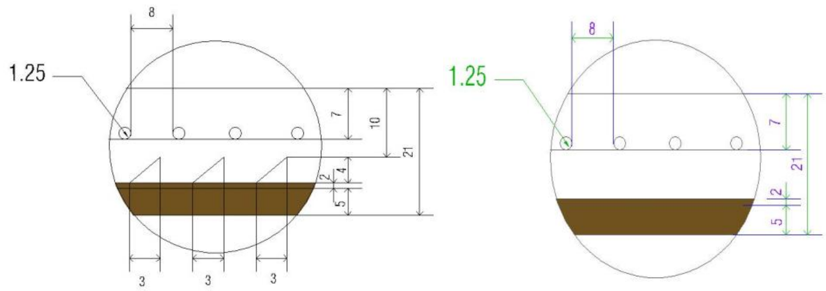


Figure3.2: Details of Hybrid Collector. (All dimensions are in cm)



(a) Trapezoidal rib

(b) Saw tooth forward rib



(c) Saw tooth backward rib

(d) Flat plate

Figure 3.3: Test specimens. (All dimensions are in mm)

Fig 3.4 Photograph of the Interior view showing the TMS with water heat exchanger.

Fig 3.5 Photograph of the installed setup at IUT campus.

3.2 Test Procedures:

All the collector's are installed in front of the IUT workshop where there is no obstacle to sunshine and faced towards south with an inclination angle of 23.5^0 which is the best angle to collect as much as available radiation. Photograph of which are shown fig. 3.1.

All storage tanks are filled early in the morning with fresh water. Temperatures are measured for PV panel (T_{PV}), Water heat exchanger (T_{WHX}), Inlet and Outlet of water (T_i and T_O), Air in the channel (T_{air}) and the rib temperature (T_{rib}) in air channel by using seven 36 S.W.G. Chromel-Alumel thermocouples. Selector switches are used to switch between the thermocouples.

Ambient temperatures (Tamb), solar radiation (G) are recorded hourly each day from at 8 AM up to 6 PM. All readings are recorded in data sheets.

3.3 Equations Used

To calculate the thermal efficiency (η_{th}) of the collector the following equations are used:

Heat energy absorbed at any time for the projected area, $Q_{ab} = m \times C_p \times \Delta T_w / A_a$ (Wm^{-2})

Here, ΔT_w is the temperature difference between inlet and outlet of water.

Solar radiation received in that time for the projected area, G (Wm^{-2})

So thermal efficiency can be found from, $\eta_{th} = Q_{ab} / G$

Chapter 4

Results and Discussions

Performance study of four hybrid PVT systems was carried out in IUT Campus, Gazipur, Bangladesh during the months of February to June 2012.

PV panel temperature, water heat exchanger surface temperature, Outlet temperature of water, Air temperature in the air channel and the rib temperature in the air channel are recorded and plotted against time. These are presented from Fig.4.1 to Fig.4.54.

Thermal efficiency is calculated for all the setups and average plotted of presented in fig. 4.55.

Thermal output is emphasized more than the electrical output in this study. As no electrical load is used as a part of the setup, output from PV panel is not hampered.

4.1 PV panel temperature

Temperature distributions of PV panels of different setups with time are shown in Fig.4.01 to Fig.4.10. As the PV panel receives the solar energy directly on top of the setup, panel temperature rises very quickly with time. The figures shows similar patterns of temperature survey with slight difference among four setups. PV panel temperature rises from 8:00 am to 12:00 noon and then decreases after 2:00 pm rapidly. In a sunny day of 15February 2012, the maximum temperature of PV panel is found 61ºC for Flat plate, 57ºC for Trapezoidal, 57ºC for Saw tooth forward and 59ºC for Saw tooth backward plate. In a sunny day of 30 February 2012 the maximum temperature of PV panel is found 60ºC for Flat plate, 56ºC for Trapezoidal, 57ºC for Saw tooth forward and 58ºC for Saw tooth backward plate. In an intense sunny day of 15March2012, the maximum temperature of PV panel is found 62ºC for Flat plate, 56ºC for Trapezoidal, 57ºC for Saw tooth forward and 59ºC for Saw tooth backward plate. In a sunny day of 30March2012, the maximum temperature of PV panel is found 62ºC for Flat plate, 56ºC for Trapezoidal, 57ºC for Saw tooth forward and 60ºC for Saw tooth backward plate. In a sunny day of 15April2012, the maximum temperature of PV panel is found 62ºC for Flat plate, 55ºC for Trapezoidal, 556ºC for Saw tooth forward and 59ºC for Saw tooth backward plate. In a sunny day of 30April2012, the maximum temperature of PV panel is found 61ºC for Flat plate, 54ºC for Trapezoidal, 56ºC for Saw tooth forward and 59ºC for Saw tooth backward plate. In a partly cloudy day of 15 May 2012, the maximum temperature of PV panel is found 40ºC for Flat plate, 44ºC for Trapezoidal, 43ºC for Saw tooth forward and 42ºC for Saw tooth backward plate at the time was 02:00 PM. In a Rainy day of 30May2012, the maximum temperature of PV panel is found 40ºC for Flat plate, 41ºC for Trapezoidal, 40ºC for Saw tooth forward and 39ºC for Saw tooth backward plate. In an intense sunny day of 15 June 2012, the maximum temperature of PV panel is found 64ºC for Flat plate, 63ºC for Trapezoidal, 62ºC for Saw tooth forward and 60ºC for Saw tooth backward plate. In a sunny day of 30June 2012, the maximum temperature of PV panel is found 62ºC for Flat plate, 61ºC for Trapezoidal, 60ºC for Saw tooth forward and 59ºC for Saw tooth backward plate.

Setup with Saw tooth forward and Saw tooth backward ribs setup give lower temperature of the panel which shows better cooling of PV. Trapezoidal ribbed plate gives moderate cooling better than that of flat plate setup. In flat plate setup PV temperature is found always high, which shows inadequate heat transfer for PV cooling.

4.2 Water Heat Exchanger (WHX) Surface temperature

Water heat exchanger surface temperature distributions of different setups with time are shown in Fig. 4.11 to Fig.4.20. Water heat exchanger with TMS is placed below the PV panel at the middle section of the setup. Heat energy is absorbed here from the PV rear surface and water is heated flowing through it. It is evident from these figures that the temperature of this heat exchanger also rises with time from 8:00 am to 12:00 noon and then decreases after 2:00 pm rapidly. In a sunny day of 15February 2012, the maximum temperature of WHX is found 50ºC for Flat plate, 48ºC for Trapezoidal, 49ºC for Saw tooth forward and 51ºC for Saw tooth backward plate. In a sunny day of 30 February 2012 the maximum temperature of WHX is found 49ºC for Flat plate, 46ºC for Trapezoidal, 50ºC for Saw tooth forward and 48ºC for Saw tooth backward plate. In an intense sunny day of 15March2012, the maximum temperature of WHX is found 48ºC for Flat plate, 46ºC for Trapezoidal, 49ºC for Saw tooth forward and 47ºC for Saw tooth backward plate. In a sunny day of 30March2012, the maximum temperature of WHX is found 48ºC for Flat plate, 46ºC for Trapezoidal, 49ºC for Saw tooth forward and 48ºC for Saw tooth backward plate. In a sunny day of 15April2012, the maximum temperature of WHX is found 49ºC for Flat plate, 52ºC for Trapezoidal, 52ºC for Saw tooth forward and 49ºC for Saw tooth backward plate. In a sunny day of 30April2012, the maximum temperature of WHX is found 49ºC for Flat plate, 47ºC for Trapezoidal, 51ºC for Saw tooth forward and 49ºC for Saw tooth backward plate. In a partly cloudy day of 15 May 2012, the maximum temperature of WHX is found 36ºC for Flat plate, 38ºC for Trapezoidal, 37ºC for Saw tooth forward and 36ºC for Saw tooth backward plate at the time was 02:00 PM. In a Rainy day of 30May2012, the maximum temperature of WHX is found 34ºC for Flat plate, 37ºC for Trapezoidal, 36ºC for Saw tooth forward and 35ºC for Saw tooth backward plate. In an intense sunny day of 15 June 2012, the maximum temperature of WHX is found 45ºC for Flat plate, 48ºC for Trapezoidal, 47ºC for Saw tooth forward and 46ºC for Saw tooth backward plate. In a sunny day of 30June 2012, the maximum temperature of WHX is found 45ºC for Flat plate, 47ºC for Trapezoidal, 48ºC for Saw tooth forward and 46ºC for Saw tooth backward plate.

Average good temperature is found in case of setup with Saw tooth forward rib. Average temperature difference between PV panel and WHX is around 10-12ºC.

4.3 Water outlet temperature

Distributions of Water outlet temperature of different setups with time are shown in Fig. 4.21-4.30. Water is one of the heat removal fluids of these hybrid PVT systems and is also important for meeting thermal needs. Water temperature is raised by taking absorbed heat from heat exchanger. In a sunny day of 15February 2012, the maximum temperature of water is found 41ºC for Flat plate, 43ºC for Trapezoidal, 42ºC for Saw tooth forward and 42ºC for Saw tooth backward plate. In a sunny day of 30 February 2012 the maximum temperature of water is found 40ºC for Flat plate, 42ºC for Trapezoidal, 41ºC for Saw tooth forward and 41ºC for Saw tooth backward plate. In an intense sunny day of 15March2012, the maximum temperature of water is found 39ºC for Flat plate, 41ºC for Trapezoidal, 40ºC for Saw tooth forward and 59ºC for Saw tooth backward plate. In a sunny day of 30March2012, the maximum temperature of water is found 40ºC for Flat plate, 42ºC for Trapezoidal, 41ºC for Saw tooth forward and 41ºC for Saw tooth backward plate. In a sunny day of 15April2012, the maximum temperature of water is found 40ºC for Flat plate, 43ºC for Trapezoidal, 42ºC for Saw tooth forward and 41ºC for Saw tooth backward plate. In a sunny day of 30April2012, the maximum temperature of water is found 38ºC for Flat plate, 40ºC for Trapezoidal, 39ºC for Saw tooth forward and 39ºC for Saw tooth backward plate. In a partly cloudy day of 15 May 2012, the maximum temperature of water is found 35ºC for Flat plate, 38ºC for Trapezoidal, 37ºC for Saw tooth forward and 36ºC for Saw tooth backward plate at the time was 02:00 PM. In a Rainy day of 30May2012, the maximum temperature of water outlet is found 35ºC for Flat plate, 37ºC for Trapezoidal, 36ºC for Saw tooth forward and 35ºC for Saw tooth backward plate. In an intense sunny day of 15 June 2012, the maximum temperature of Water outlet is found 43ºC for Flat plate, 46ºC for Trapezoidal, 45ºC for Saw tooth forward and 44ºC for Saw tooth backward plate. In a sunny day of 30June 2012, the maximum temperature of Water is found 43ºC for Flat plate, 45ºC for Trapezoidal, 44ºC for Saw tooth forward and 44ºC for Saw tooth backward plate.

Temperature of the water in supply lines varies between 23-26ºC. The maximum temperature rise found to be 43ºC using hybrid PVT systems. Average temperature of water is found to be around 40ºC. Water at this temperature is very much suitable for household activities, in kitchens, in bathrooms for washing purpose and taking bath etc. Also this water can be used as pre-heated water in many chemical industries.

4.4 Air temperature in the air channel

Distributions of air temperature in the air channel of different setups with time are shown in Fig.4.31-4.40. Air is one of the heat removal fluids of these hybrid PVT systems. As natural circulation of air is preferred, air flow inside the channel is found to be insufficient for heat extraction. As a result, the air temperature inside the channel is found to be only a few degrees above the ambient temperature and sometimes remains same. In a sunny day of 15February 2012, the maximum temperature of air is found 34ºC for Flat plate, 36ºC for Trapezoidal, 35ºC for Saw tooth forward and 35ºC for Saw tooth backward plate. In a sunny day of 30 February 2012 the maximum temperature of air is found 32ºC for Flat plate, 37ºC for Trapezoidal, 36ºC for Saw tooth forward and 35ºC for Saw tooth backward plate. In an intense sunny day of 15March2012, the maximum temperature of air is found 33ºC for Flat plate, 37ºC for Trapezoidal, 36ºC for Saw tooth forward and 35ºC for Saw tooth backward plate. In a sunny day of 30March2012, the maximum temperature of air is found 32ºC for Flat plate, 37ºC for Trapezoidal, 36ºC for Saw tooth forward and 35ºC for Saw tooth backward plate. In a sunny day of 15April2012, the maximum temperature of air is found 33ºC for Flat plate, 36ºC for Trapezoidal, 35ºC for Saw tooth forward and 34ºC for Saw tooth backward plate. In a sunny day of 30April2012, the maximum temperature of air is found 33ºC for Flat plate, 36ºC for Trapezoidal, 35ºC for Saw tooth forward and 35ºC for Saw tooth backward plate. In a partly cloudy day of 15 May 2012, the maximum temperature of Air is found 33ºC for Flat plate, 35ºC for Trapezoidal, 34ºC for Saw tooth forward and 34ºC for Saw tooth backward plate at the time was 02:00 PM. In a Rainy day of 30May2012, the maximum temperature of Air channel is found 33ºC for Flat plate, 35ºC for Trapezoidal, 34ºC for Saw tooth forward and 34ºC for Saw tooth backward plate. In an intense sunny day of 15 June 2012, the maximum temperature of Air channel is found 35ºC for Flat plate, 38ºC for Trapezoidal, 37ºC for Saw tooth forward and 36ºC for Saw tooth backward plate. In a sunny day of 30June 2012, the maximum temperature of Air Channel is found 35ºC for Flat plate, 38ºC for Trapezoidal, 37ºC for Saw tooth forward and 37ºC for Saw tooth backward plate.

Maximum air temperature in the air channel is found to be maximum 4-5ºC higher than the ambient temperature. Although this temperature rise is much lower than water, air as a heat removal fluid of hybrid PVT system can be used for natural ventilation of buildings. In winter when the inside/room temperature.

4.5 Ribbed surface temperature

Variations of ribbed surface temperature with time for different setups with time are shown in Fig.4.41-4.50. Ribbed surface is placed at the bottom of the setup in the air channel. It receives heat from the whx. Temperature on the ribbed surface gives idea about heat transfer to air in the channel. In a sunny day of 15February 2012, the maximum temperature of rib surface is found 33ºC for Flat plate, 36ºC for Trapezoidal, 35ºC for Saw tooth forward and 34ºC for Saw tooth backward plate. In a sunny day of 30 February 2012 the maximum temperature of rib surface is found 32ºC for Flat plate, 35ºC for Trapezoidal, 34ºC for Saw tooth forward and 33ºC for Saw tooth backward plate. In an intense sunny day of 15March2012, the maximum temperature of rib surface is found 33ºC for Flat plate, 36ºC for Trapezoidal, 35ºC for Saw tooth forward and 34ºC for Saw tooth backward plate. In a sunny day of 30March2012, the maximum temperature of rib surface is found 34ºC for Flat plate, 37ºC for Trapezoidal, 36ºC for Saw tooth forward and 35ºC for Saw tooth backward plate. In a sunny day of 15April2012, the maximum temperature of rib surface is found 35ºC for Flat plate, 38ºC for Trapezoidal, 37ºC for Saw tooth forward and 36ºC for Saw tooth backward plate. In a sunny day of 30April2012, the maximum temperature of rib surface is found 36ºC for Flat plate, 39ºC for Trapezoidal, 38ºC for Saw tooth forward and 37ºC for Saw tooth backward plate. In a partly cloudy day of 15 May 2012, the maximum temperature of rib surface is found 33ºC for Flat plate, 36ºC for Trapezoidal, 34ºC for Saw tooth forward and 34ºC for Saw tooth backward plate at the time was 02:00 PM. In a Rainy day of 30May2012, the maximum temperature of rib surface is found 33ºC for Flat plate, 36ºC for Trapezoidal, 35ºC for Saw tooth forward and 34ºC for Saw tooth backward plate. In an intense sunny day of 15 June 2012, the maximum temperature of rib surface is found 34ºC for Flat plate, 37ºC for Trapezoidal, 36ºC for Saw tooth forward and 35ºC for Saw tooth backward plate. In a sunny day of 30June 2012, the maximum temperature of rib surface is found 35ºC for Flat plate, 38ºC for Trapezoidal, 37ºC for Saw tooth forward and 36ºC for Saw tooth backward plate.

Maximum air temperature in the rib surface is found to be maximum 3-4ºC higher than the ambient temperature.

4.6 Temperature distribution

A hybrid PVT/dual system has several heat exchanging surfaces. PV panel, WHX, water, air and rib temperature varies accordingly. Fig. 4.51 to 4.54 shows the temperature distribution in four hybrid PVT systems with ambient temperature. It is found from these figures that temperature of the PV panel is highest as it receive heat from PV rear surface and temperature is found to be 36 ºC -48 ºC in this region. Water acts as a heat carrier fluid here and the temperature of water is rises with rising of WHX temperature. Water temperature is found to be within 34 ºC to 50 ºC. After WHX, air in the channel is receiving heat from TMS and WHX. Air temperature varies in between 35 ºC to 45 ºC. The last portionis the ribbed surfaces placed at the bottom of air channel of the setup. Temperature of ribbed surface varies in between 32 ºC to 39 ºC.

4.7 Thermal efficiency comparison

Thermal efficiency regarding water is compared as a function of ΔT/G ($Kw^{-1}m^2$).ΔT is the temperature difference between input fluid and the ambient temperature. Efficiency of all four setups is compared along with the work of Tripangnostopoulos (2007) and Rezwan (2011) in Fig. 4.55 for comparison.

Tripangnostopoulos studied a hybrid PVT/dual system having corrugated rib on opposite air channel with WHX placed just under the PV panel in 2007 at the University of Patras, Greece.

M.R.Karim and Akhanda studied hybrid photovoltaic thermal solar system using three different rib surfaces (Triangular, Semicircular, and Square) and flat plate in 2011 at IUT.

In the present study hybrid photovoltaic thermal solar system using three different ribbed surface (Trapezoidal, Saw tooth forward, Saw tooth backward) and a flat plate in 2012 at IUT, Bangladesh.

The efficiency of Trapezoidal is 36% to 73%, Saw tooth forward is 37% to 70%, Saw tooth backward is 36% to 67% and Flat plate is 33% to 59%. Tripangnostopoulos (2007) PVT system is found to vary from 45% to 62% and Rezwan (2011) is found to vary from 35% to 70%. The average efficiency from all calculated values is found to be 67% for Trapezoidal, 62% for Saw tooth forward, 61% for Saw tooth backward and 54% foe flat plate setup.

The range of efficiency varies with the operating temperature of the system. The thermal efficiency of PVT/dual system for water heat extraction is extended in negative $\Delta T/G$ axis, as some experiments were performed for ambient temperature being higher than the water temperature at system input. Data taken for comparisons of setups are similar with $\Delta T/G$ values, to make the comparison more correct.

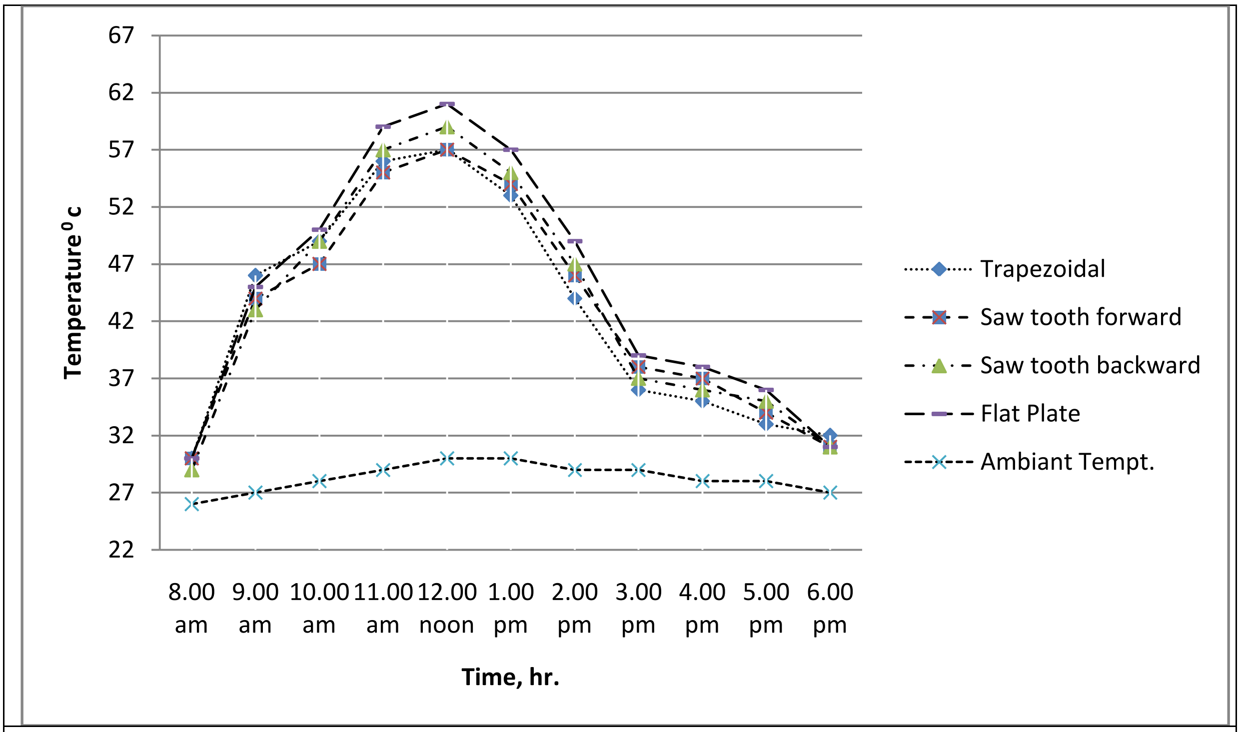


Fig.: 4.01 Temperature distribution of PV panel temperature on 15/02/2012

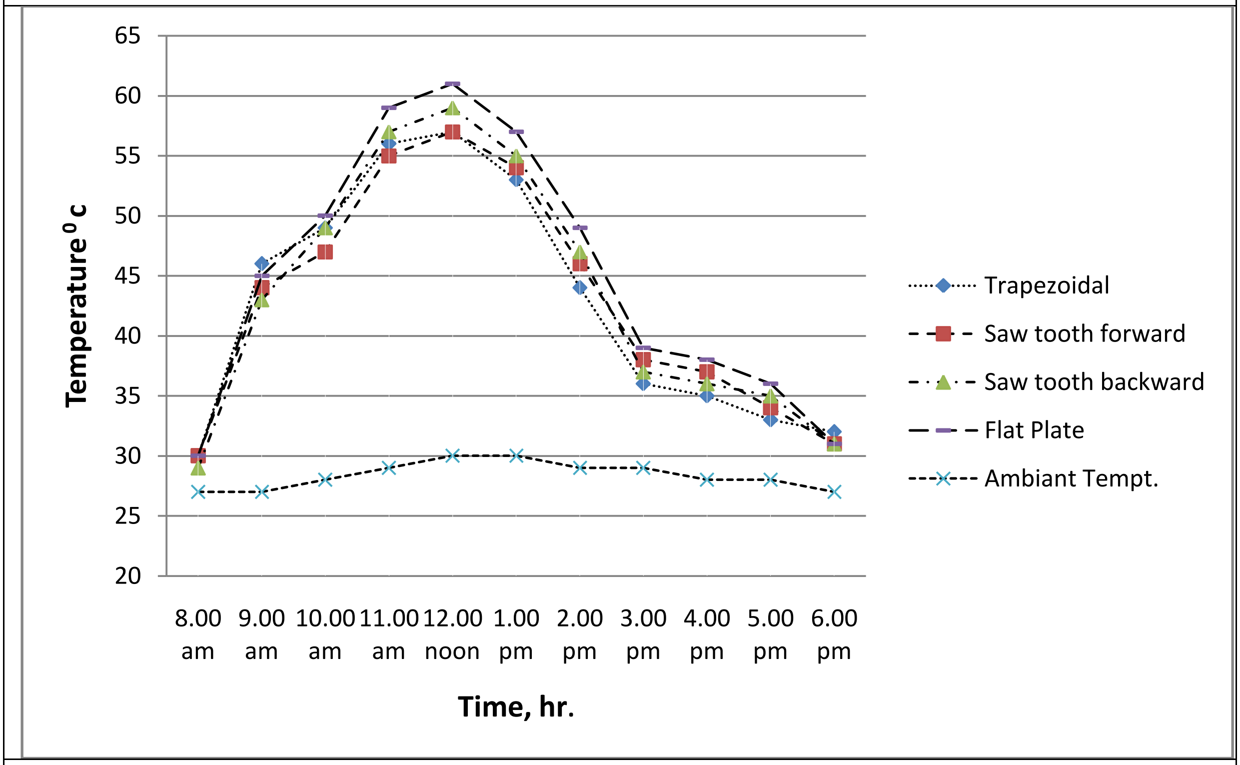


Fig.: 4.02 Temperature distribution of PV panel temperature on 30/02/2012

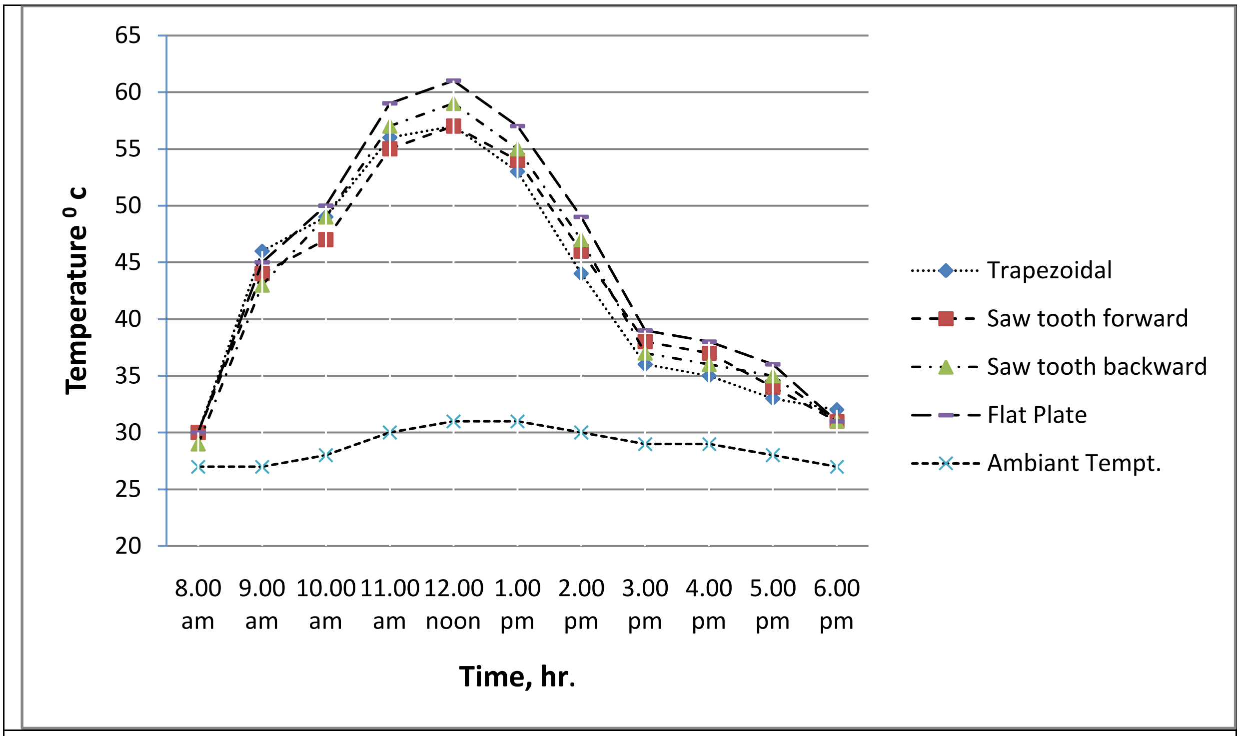


Fig.: 4.03 Temperature distribution of PV panel temperature on 15/03/2012

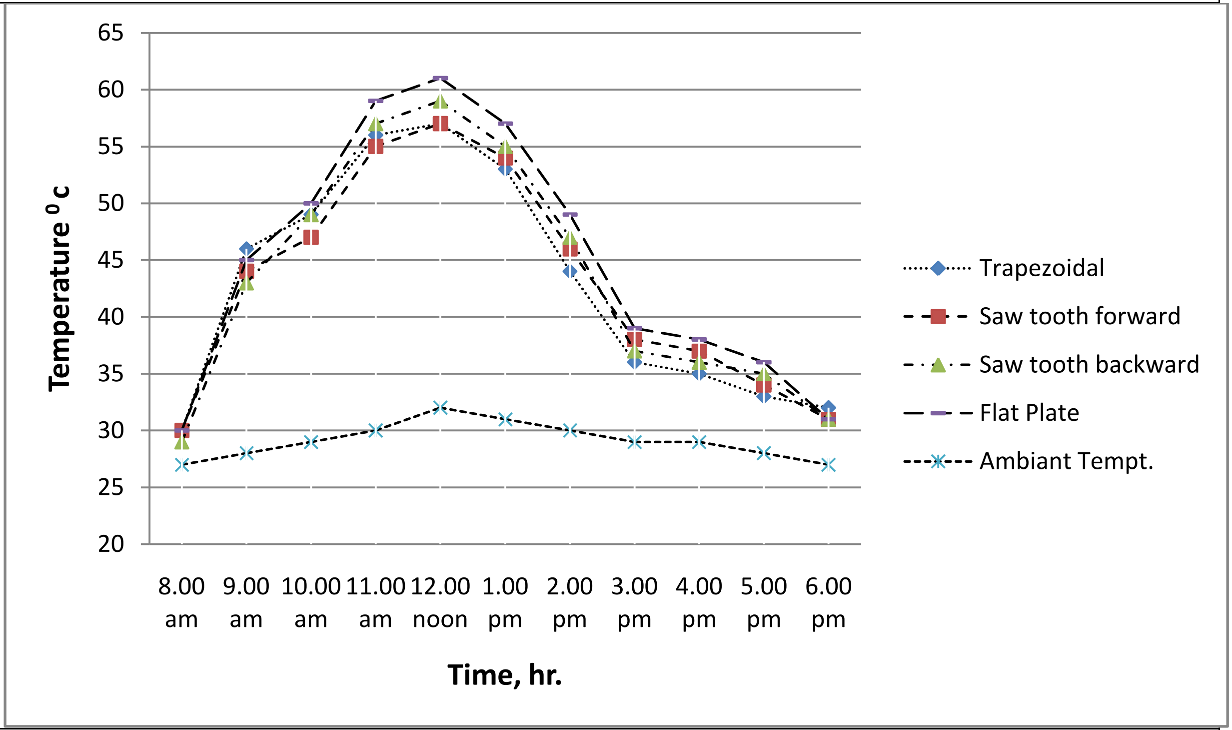


Fig.: 4.04 Temperature distribution of PV panel temperature on 30/03/2012

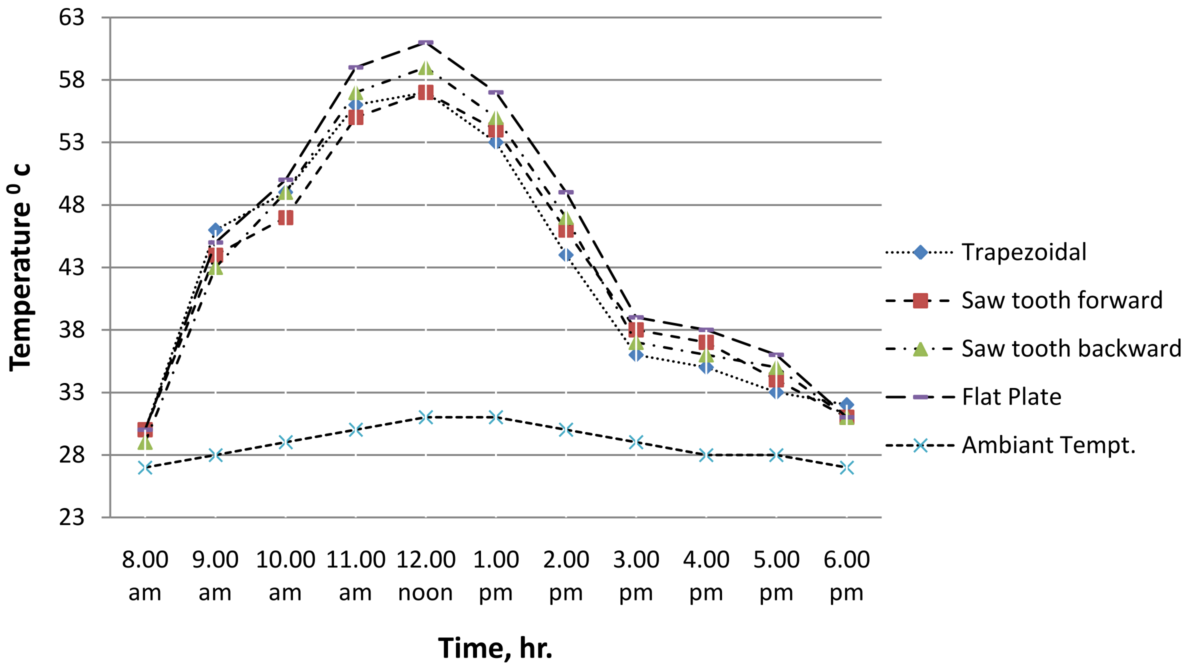


Fig.: 4.05 Temperature distribution of PV panel temperature on 15/04/2012

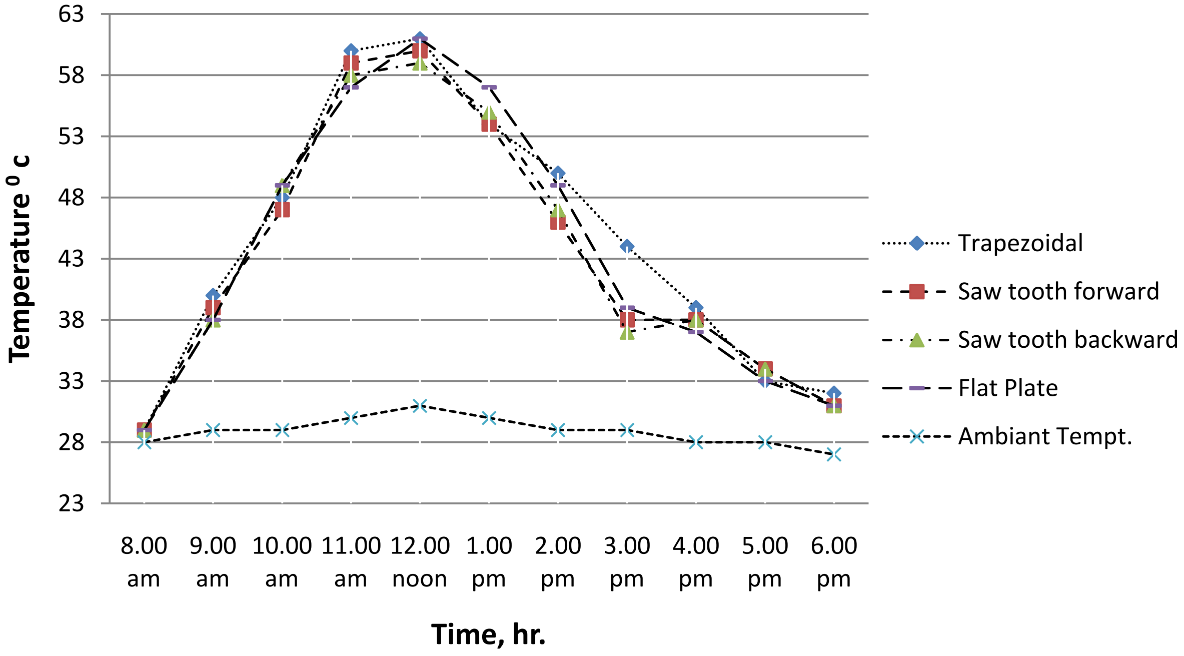


Fig.: 4.06 Temperature distribution of PV panel temperature on 30/04/2012

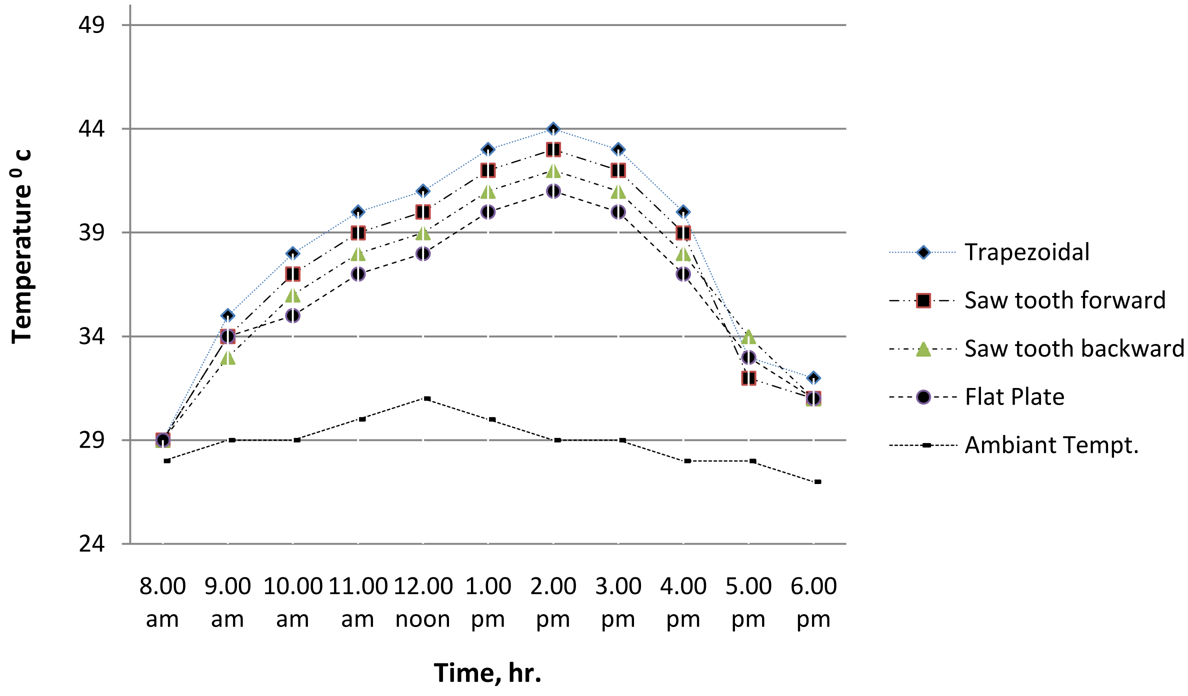


Fig.: 4.07 Temperature distribution of PV panel temperature on 15/05/2012

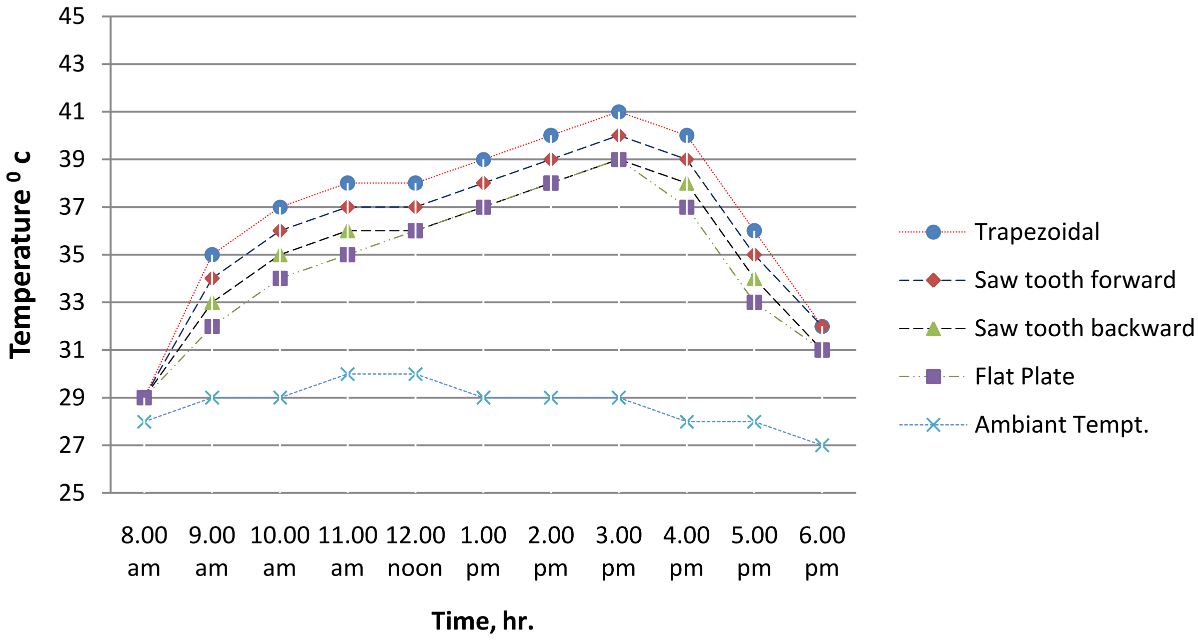


Fig.: 4.08 Temperature distribution of PV panel temperature on 30/05/2012

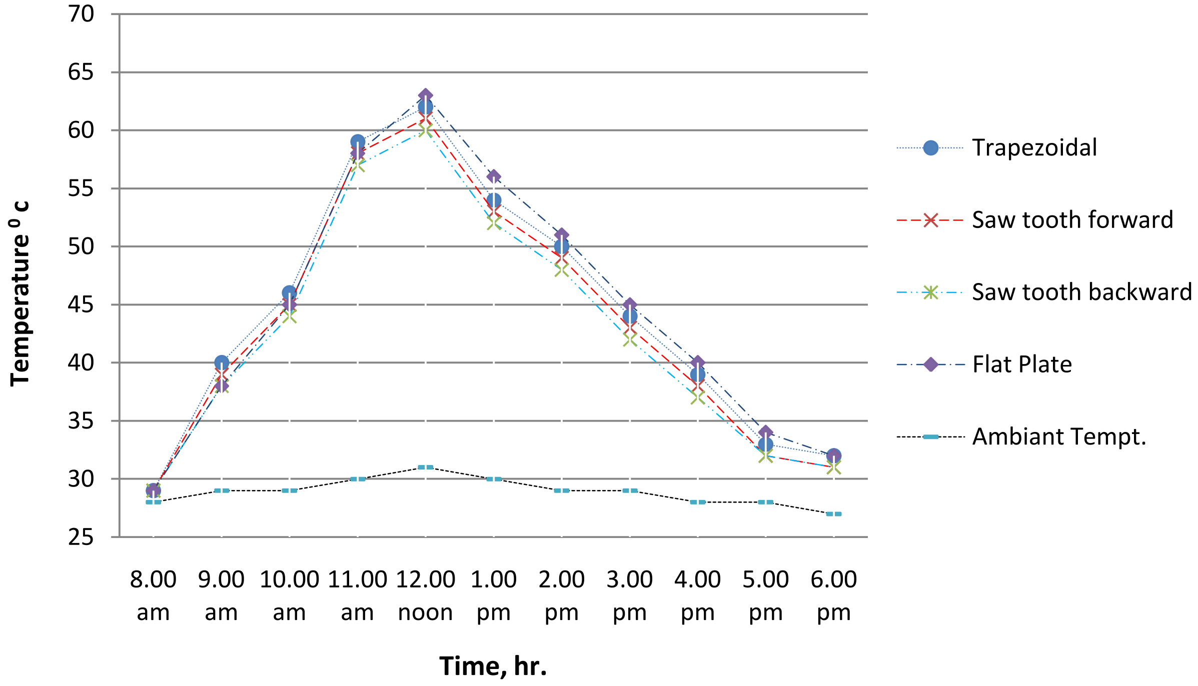


Fig.: 4.09 Temperature distribution of PV panel temperature on 15/06/2012

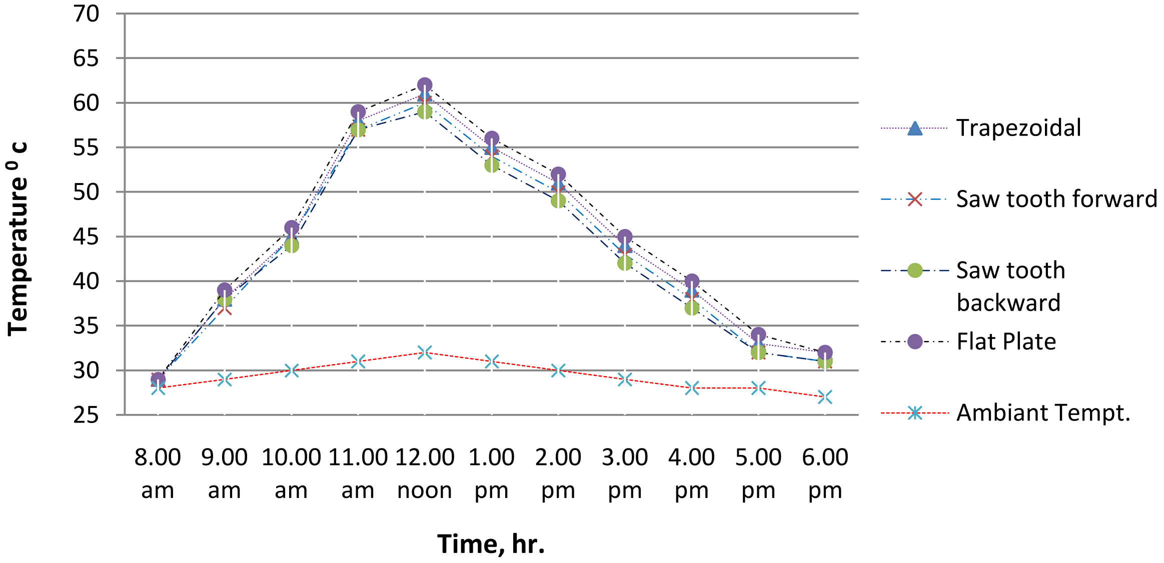


Fig.: 4.10 Temperature distribution of PV panel temperature on 30/06/2012

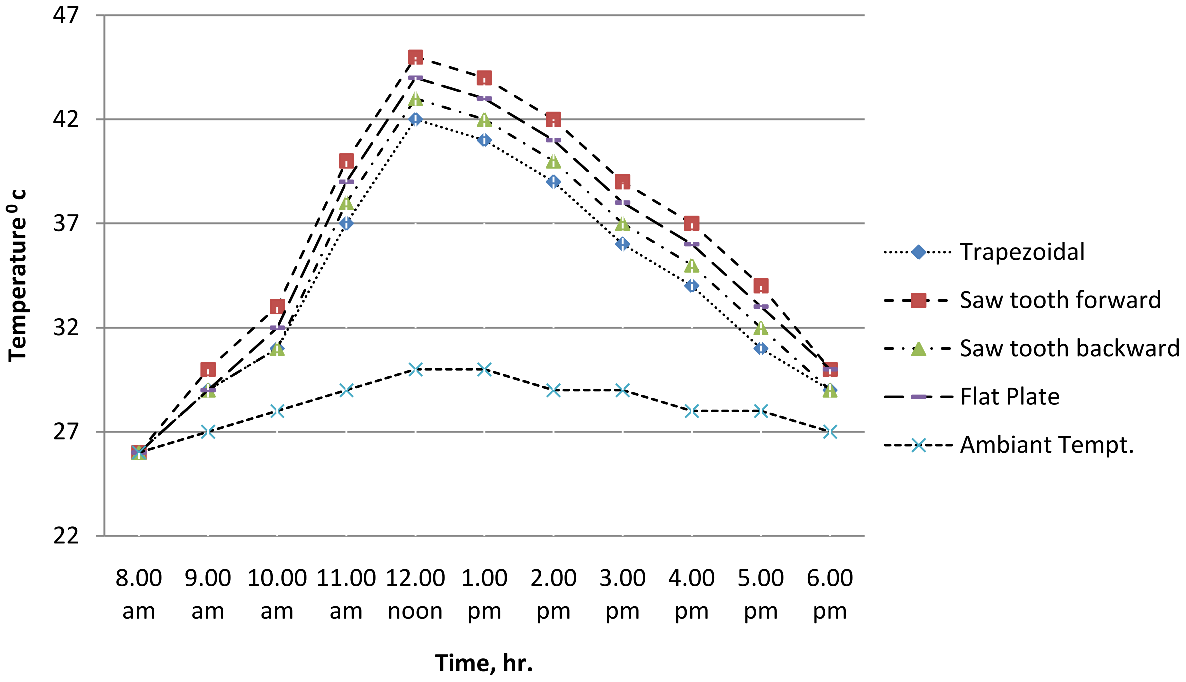


Fig.: 4.11 Temperature distribution of water heat exchanger temperature on 15/02/2012

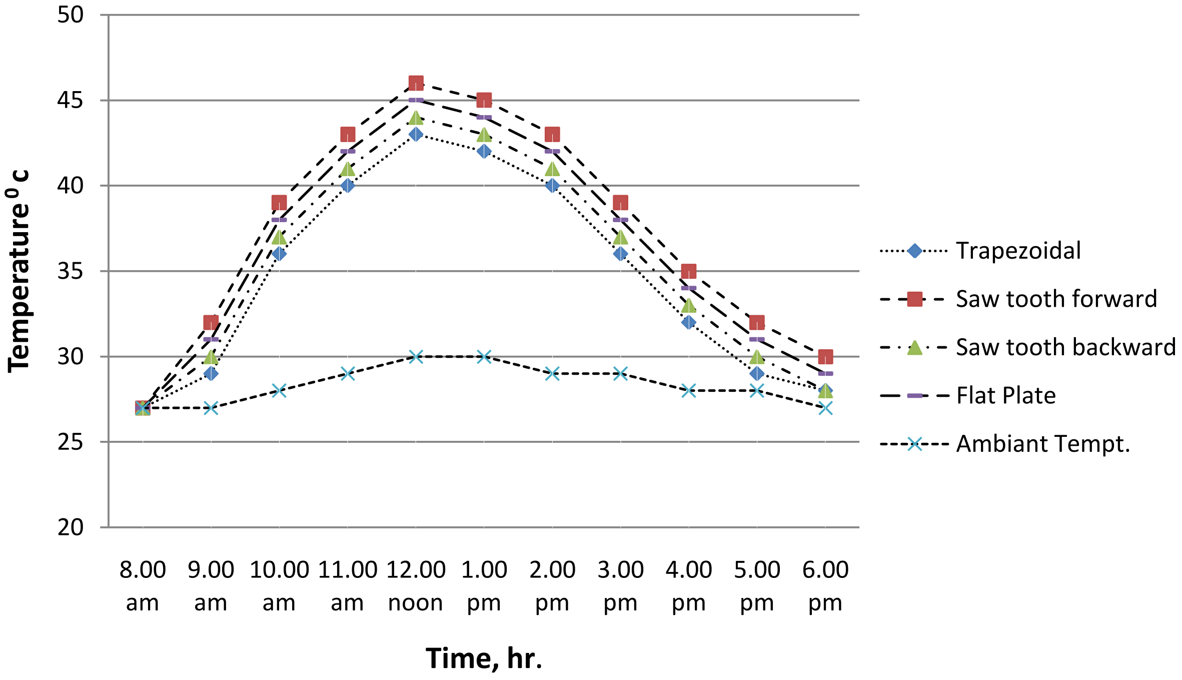


Fig.: 4.12 Temperature distribution of water heat exchanger temperature on 30/02/2012

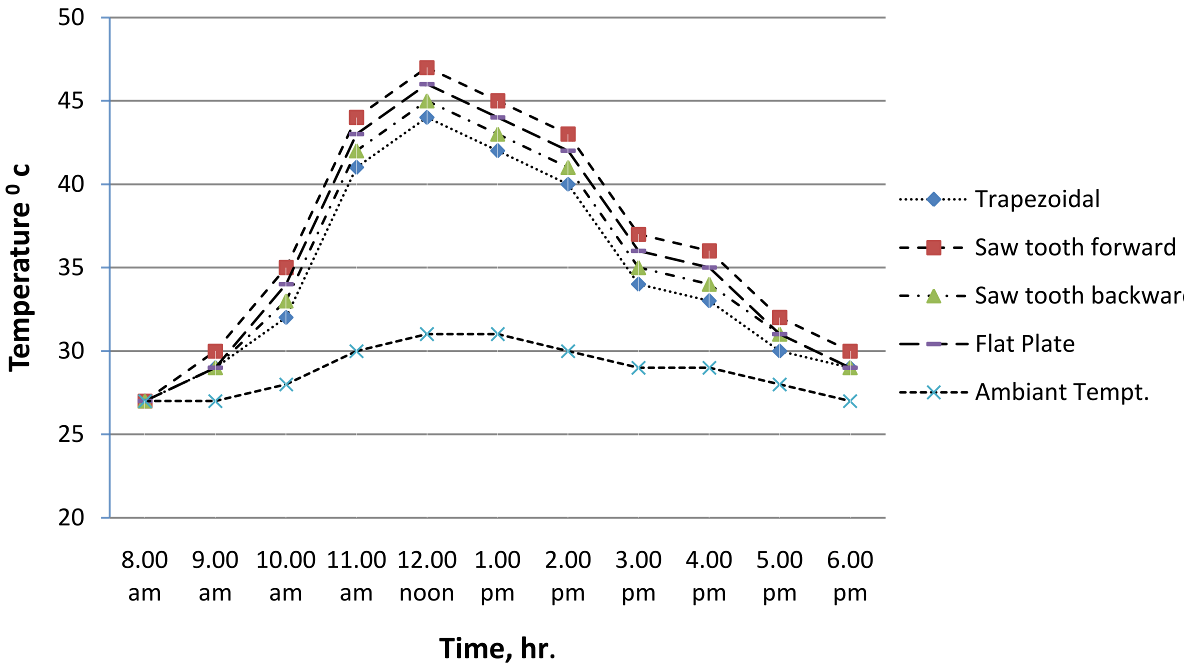


Fig.: 4.13 Temperature distribution of water heat exchanger temperature on 15/03/2012

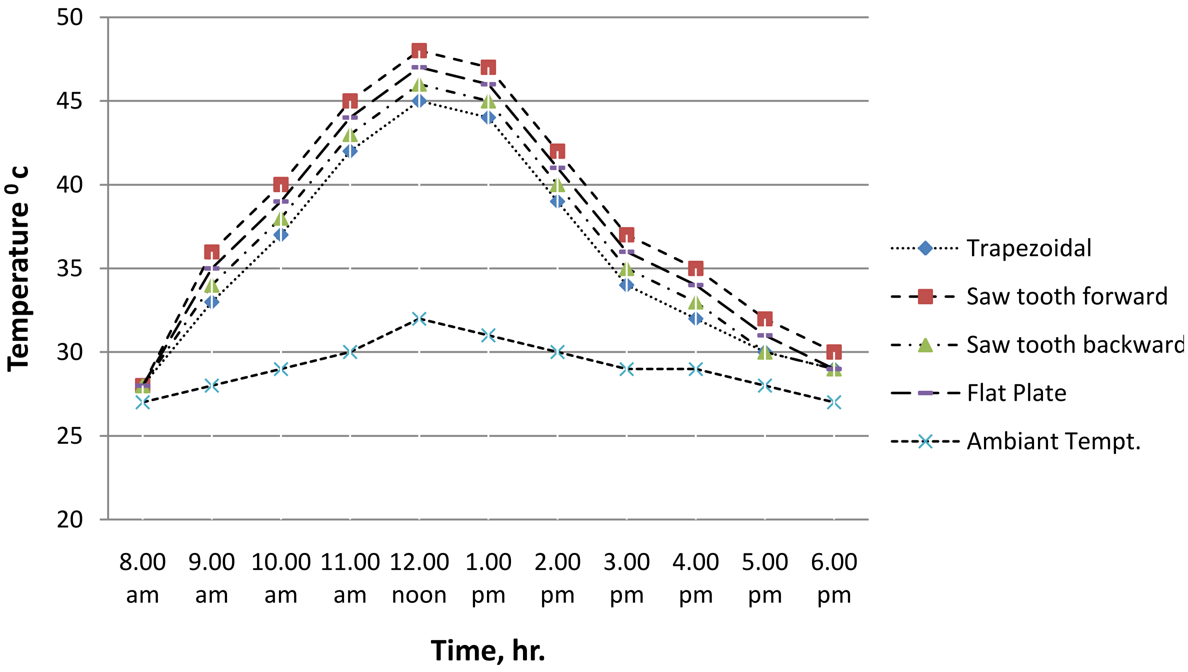


Fig.: 4.14 Temperature distribution of water heat exchanger temperature on 30/03/2012

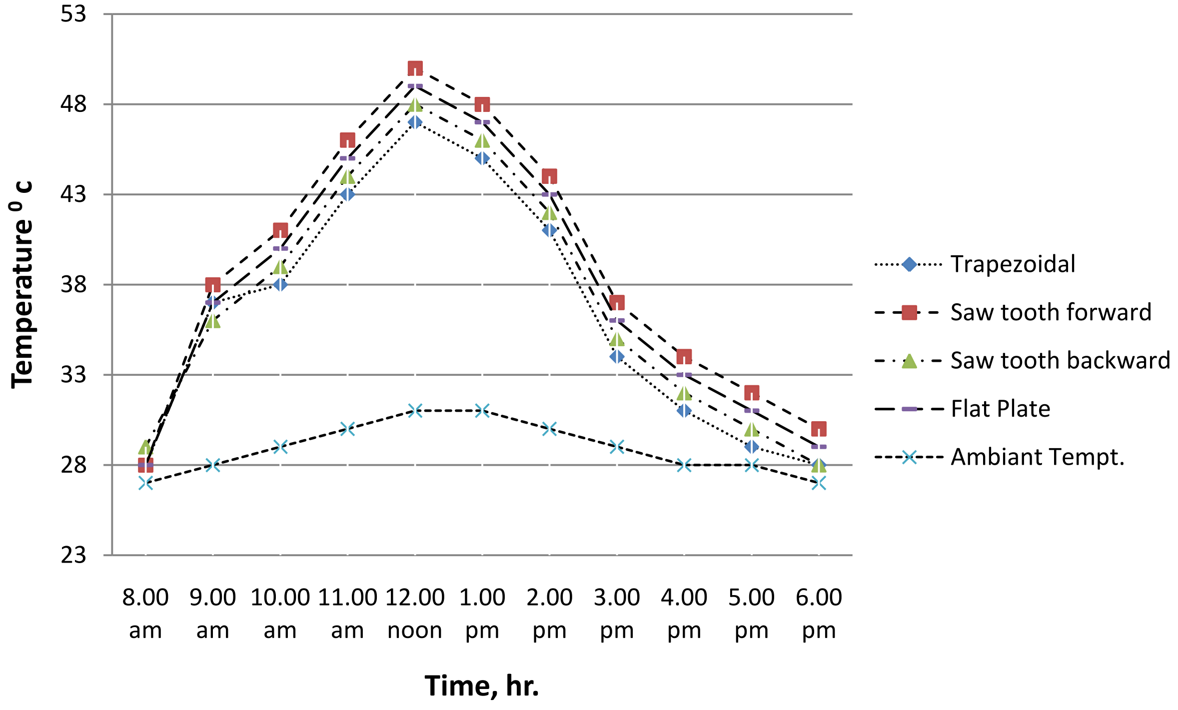


Fig.: 4.15 Temperature distribution of water heat exchanger temperature on 15/04/2012

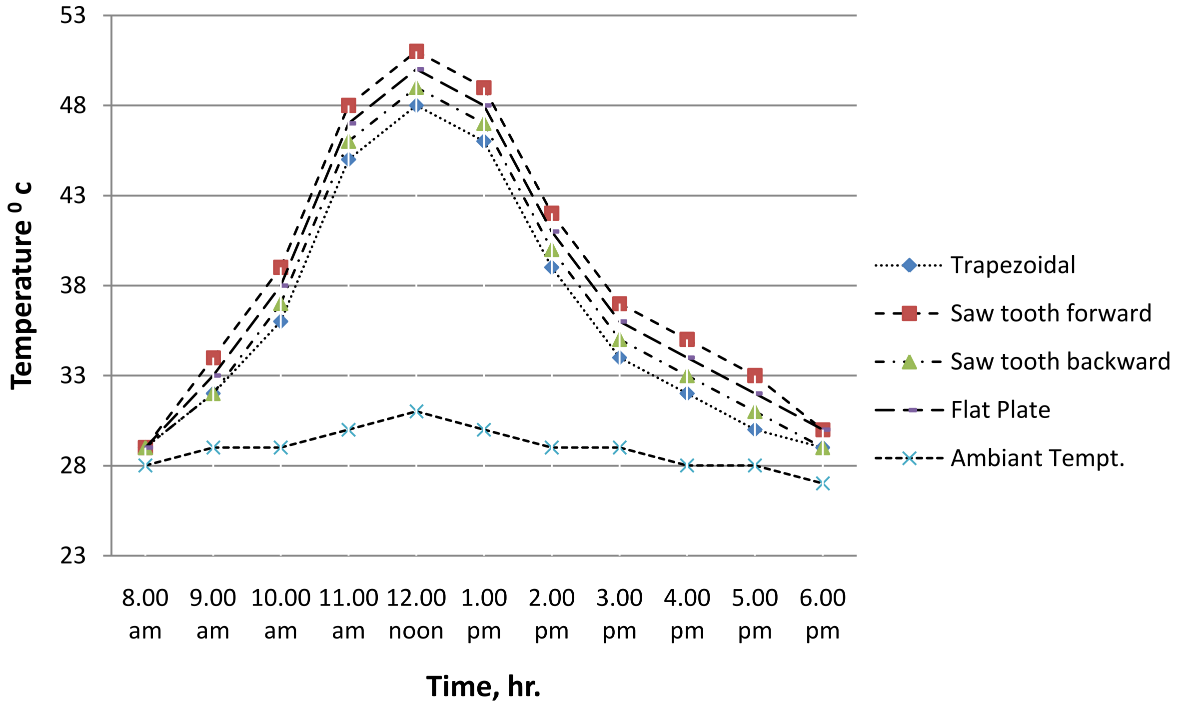


Fig.: 4.16 Temperature distribution of water heat exchanger temperature on 30/04/2012

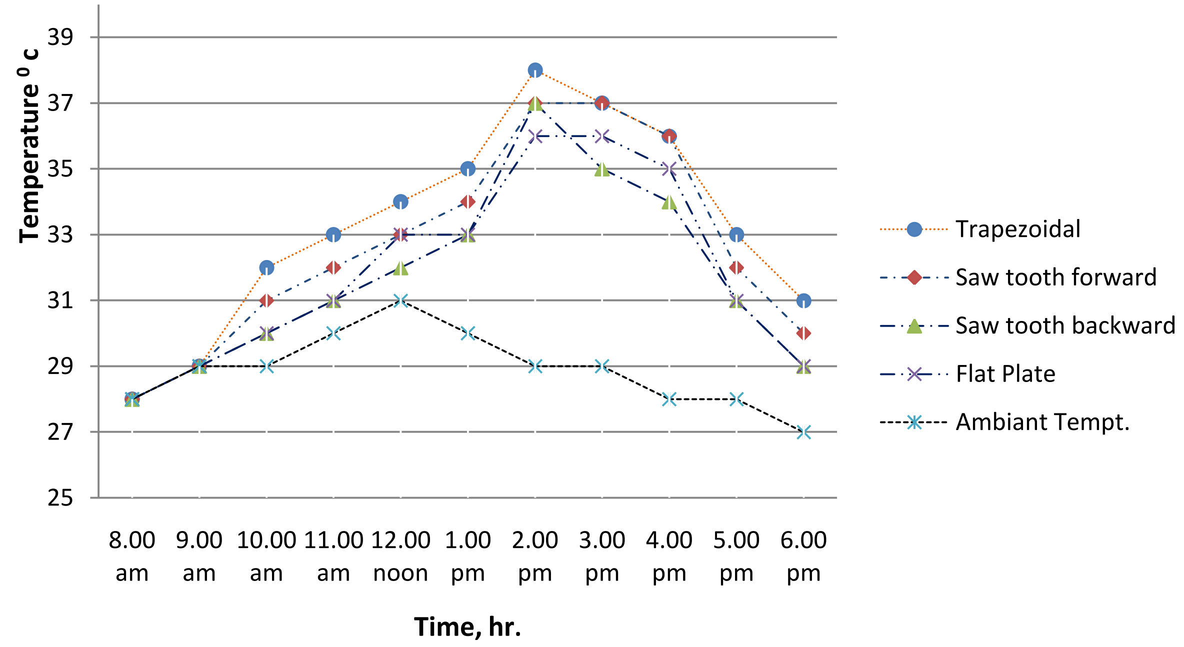


Fig.: 4.17 Temperature distribution of water heat exchanger temperature on 15/05/2012

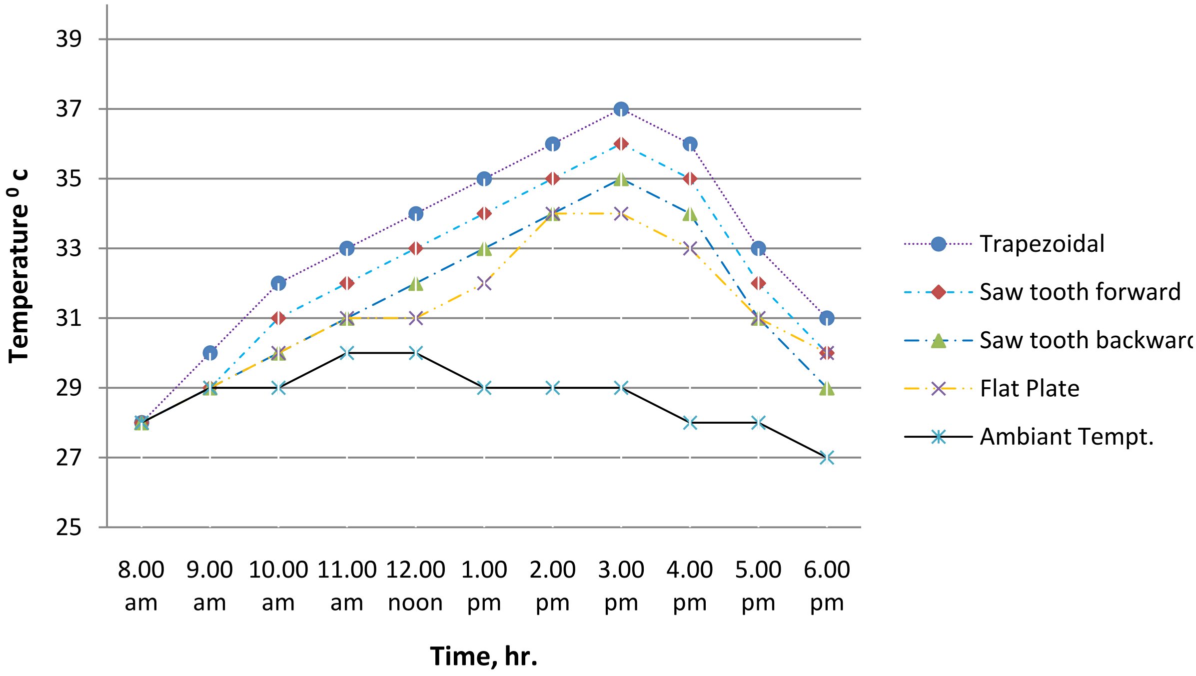


Fig.: 4.18 Temperature distribution of water heat exchanger temperature on 30/05/2012

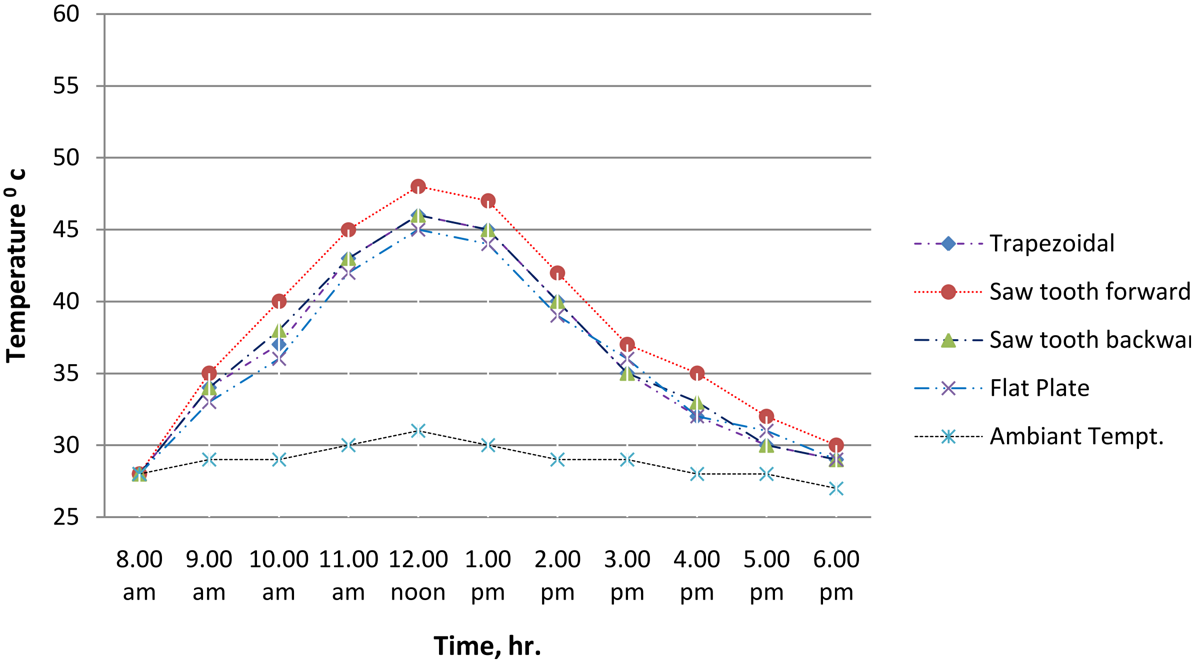


Fig.: 4.19 Temperature distribution of water heat exchanger temperature on 15/06/2012

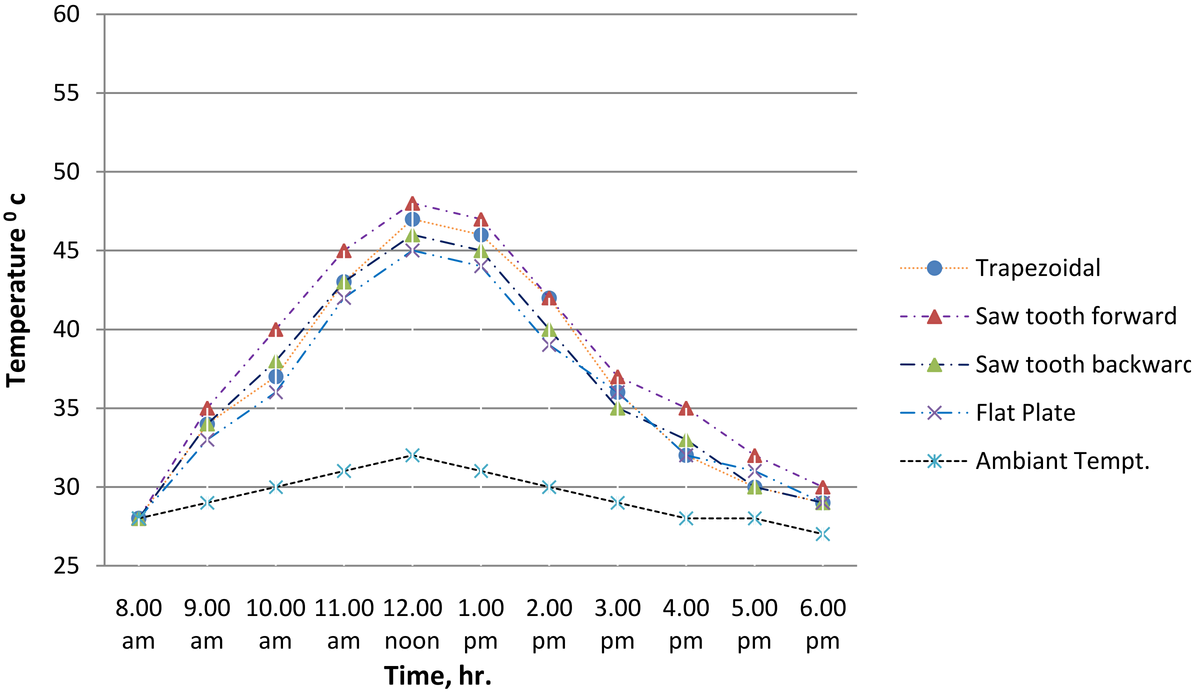


Fig.: 4.20 Temperature distribution of water heat exchanger temperature on 30/06/2012

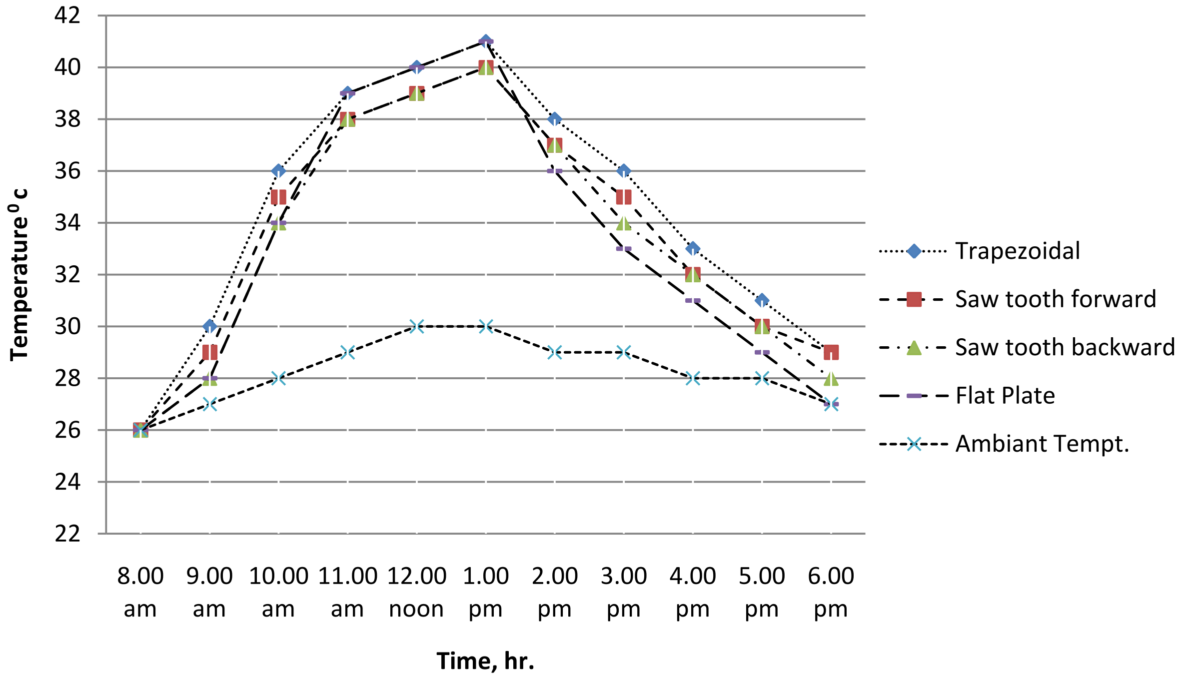


Fig.: 4.21 Temperature distribution of water outlet temperature on 15/02/2012

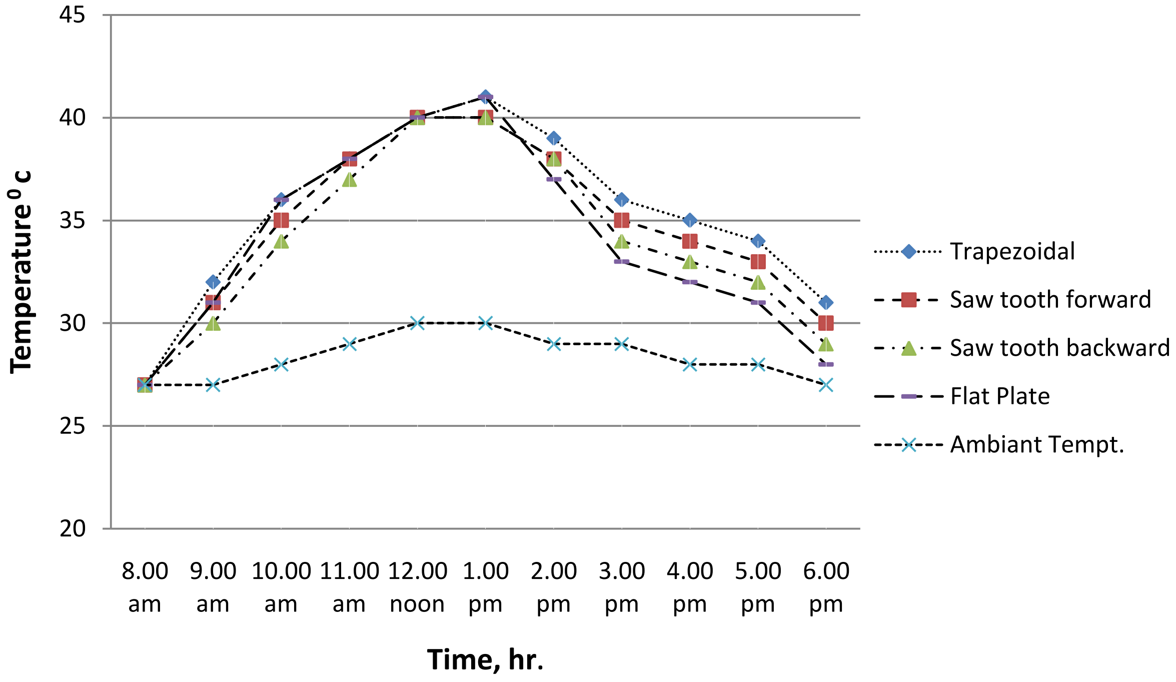


Fig.: 4.22 Temperature distribution of water outlet temperature on 30/02/2012

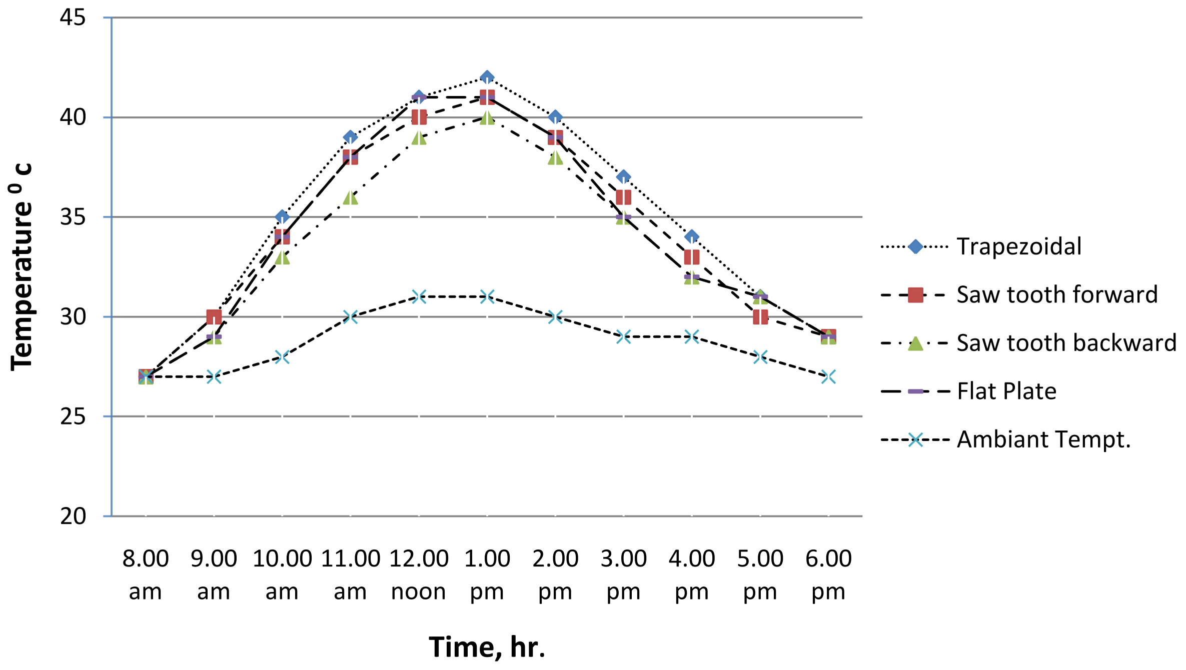


Fig.: 4.23 Temperature distribution of water outlet temperature on 15/03/2012

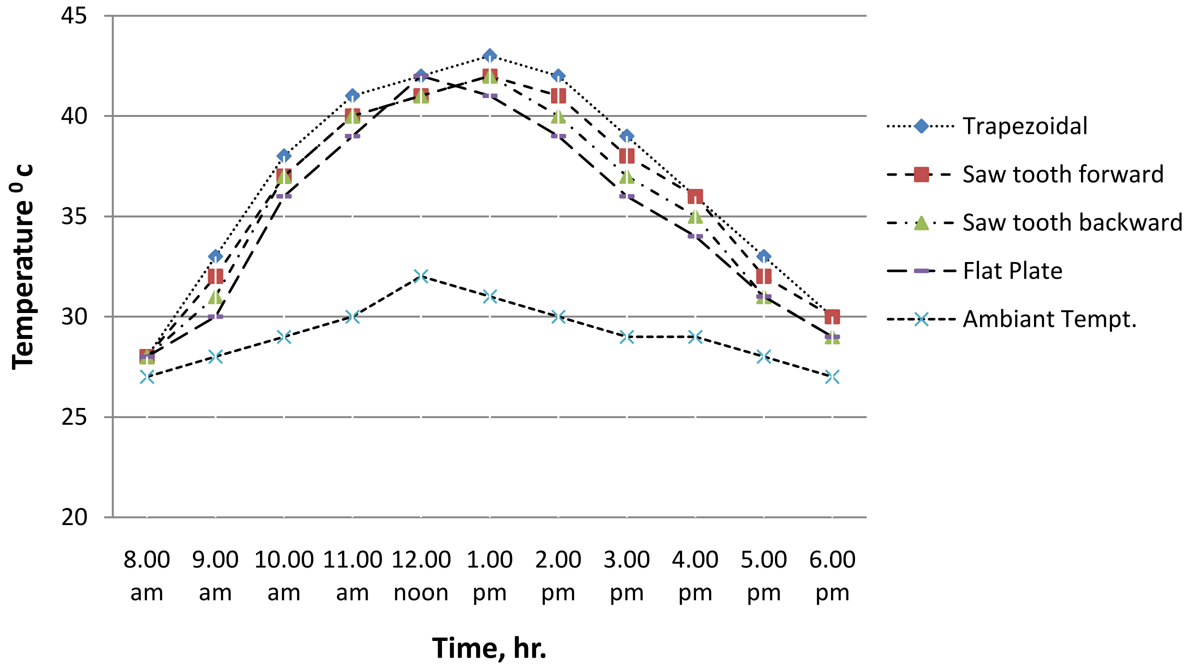


Fig.: 4.24 Temperature distribution of water outlet temperature on 30/03/2012

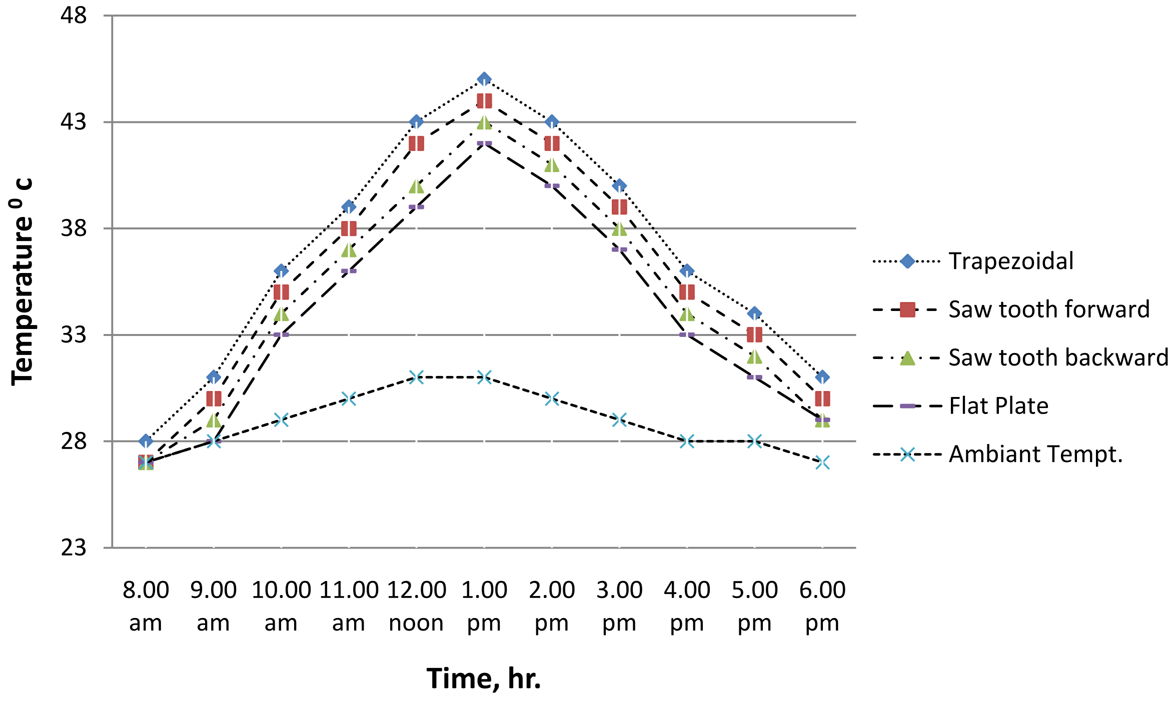


Fig.: 4.25 Temperature distribution of water outlet temperature on 15/04/2012

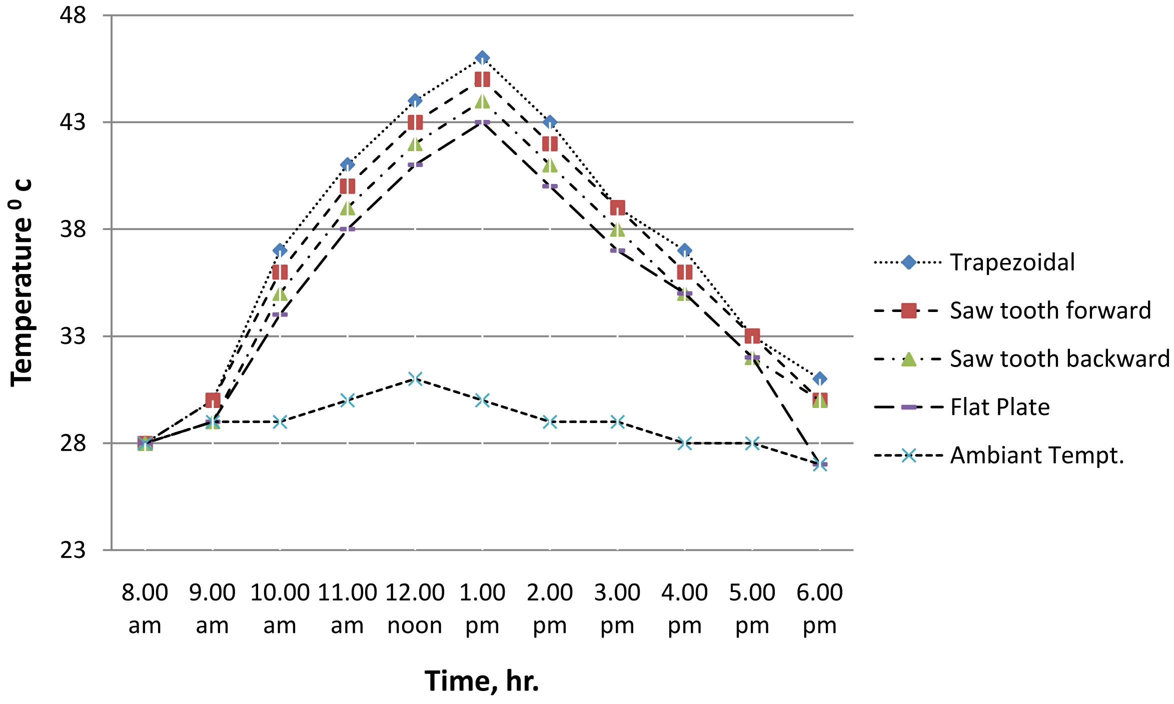


Fig.: 4.26 Temperature distribution of water outlet temperature on 30/04/2012

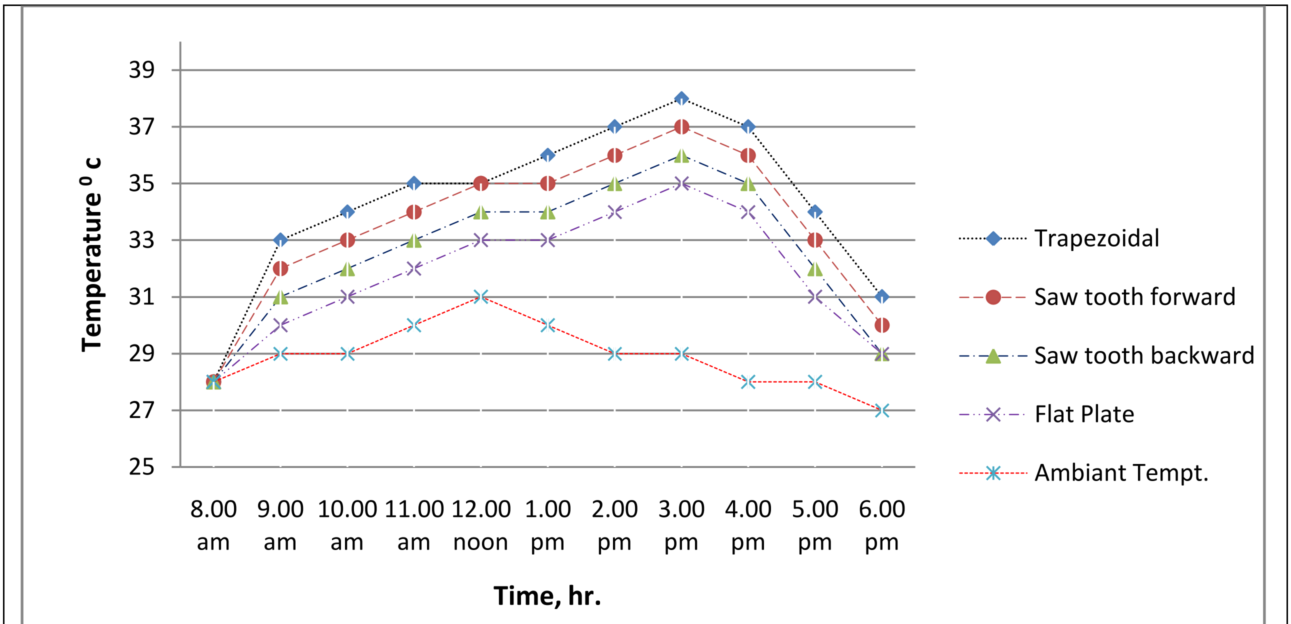


Fig.: 4.27 Temperature distribution of water outlet temperature on 15/05/2012

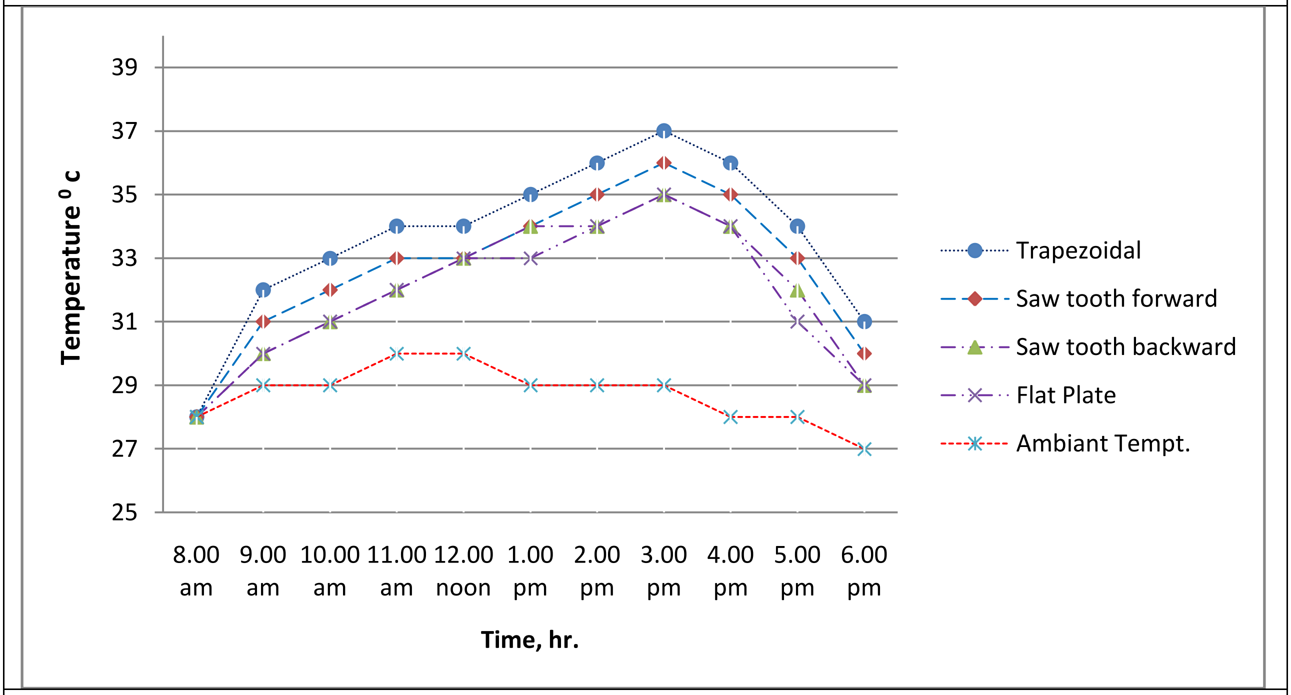


Fig.: 4.28 Temperature distribution of water outlet temperature on 30/05/2012

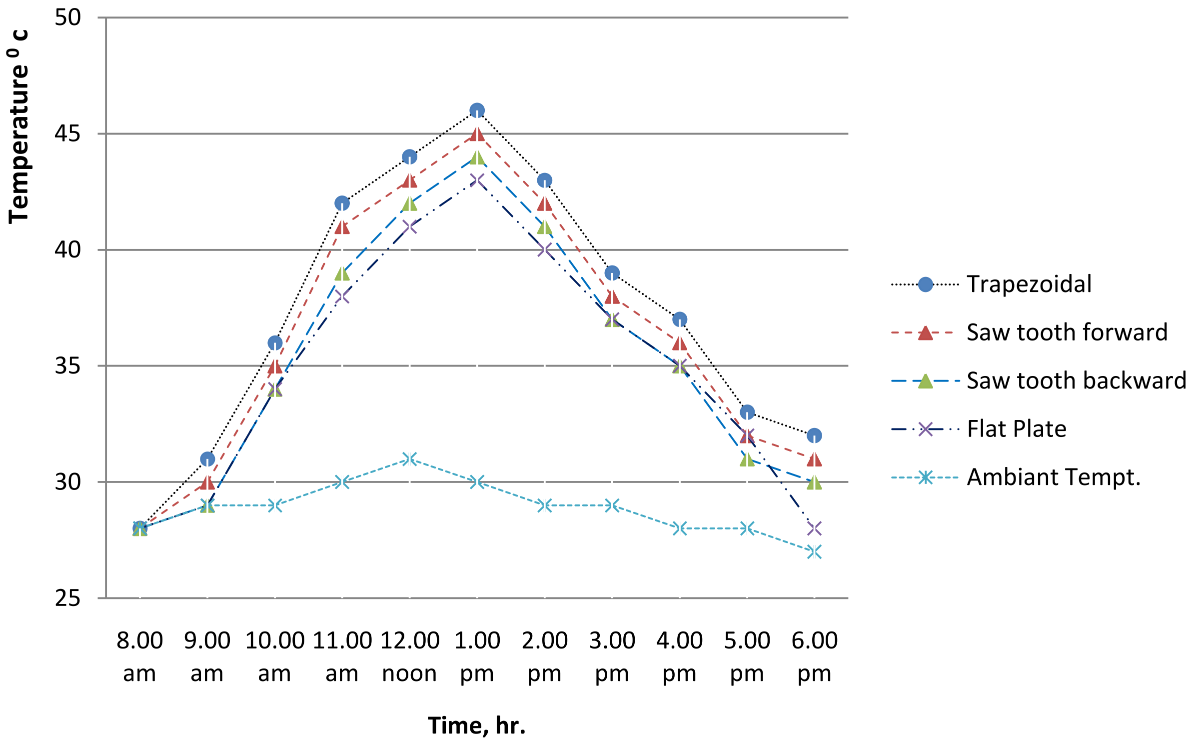


Fig.: 4.29 Temperature distribution of water outlet temperature on 15/06/2012

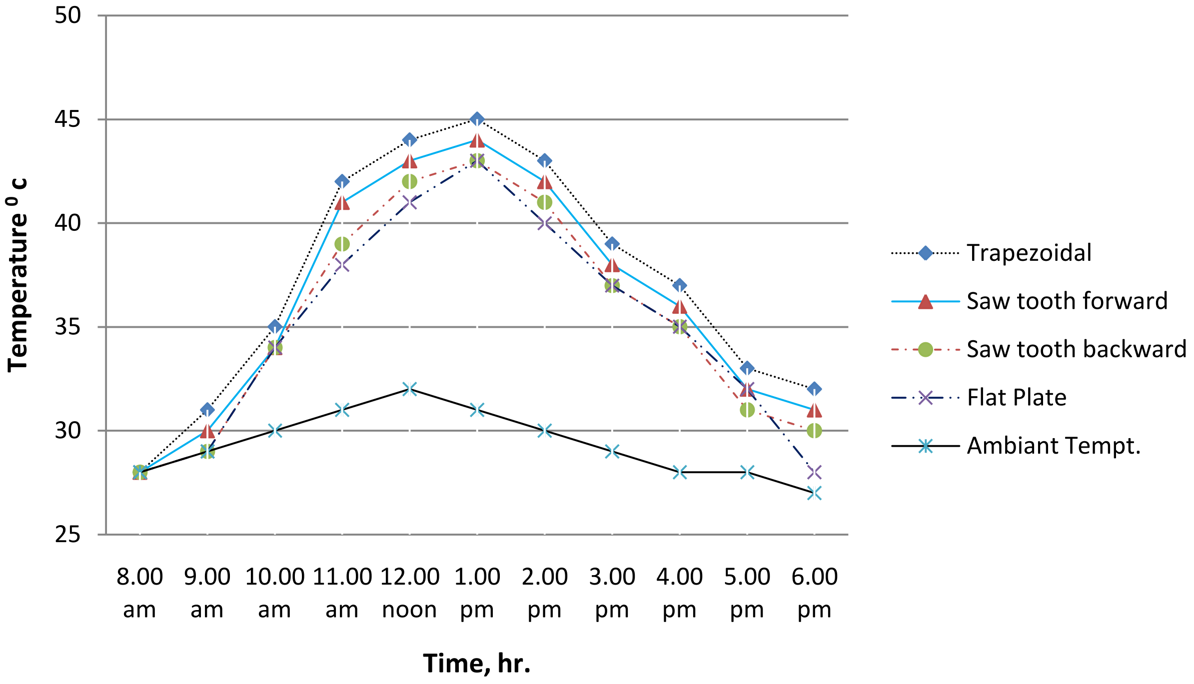


Fig.: 4.30 Temperature distribution of water outlet temperature on 30/06/2012

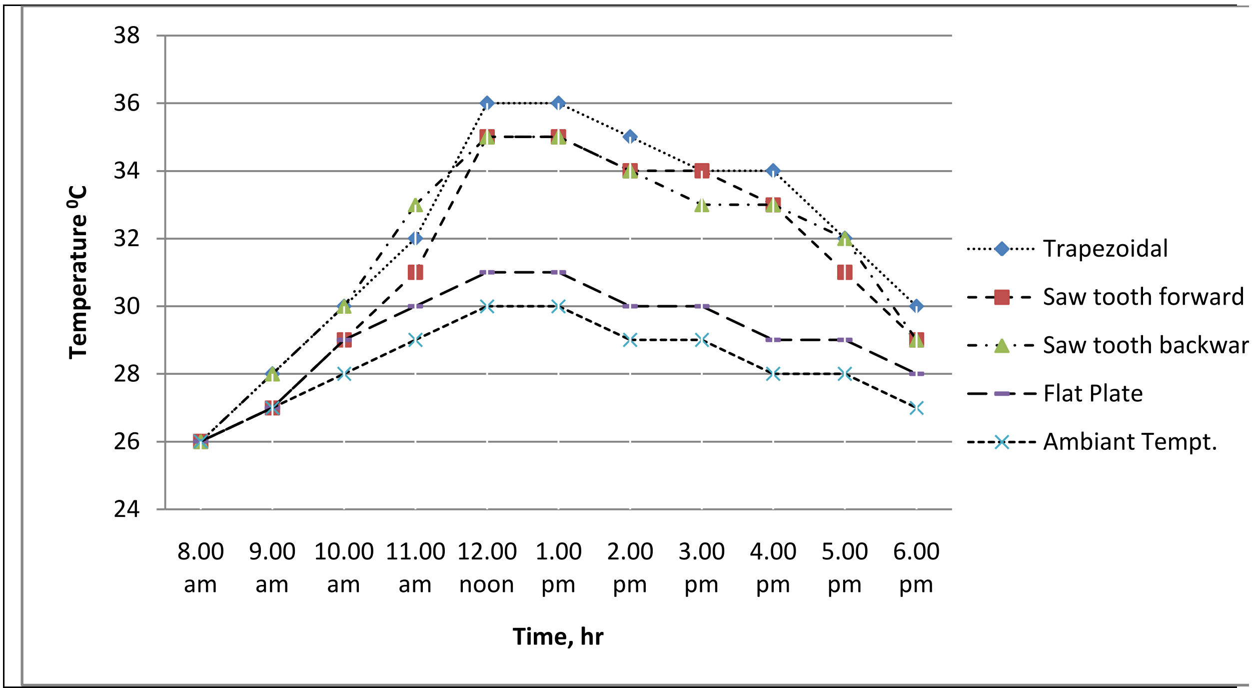


Fig.: 4.31 Temperature distribution of Air Channel temperature on 15/02/2012

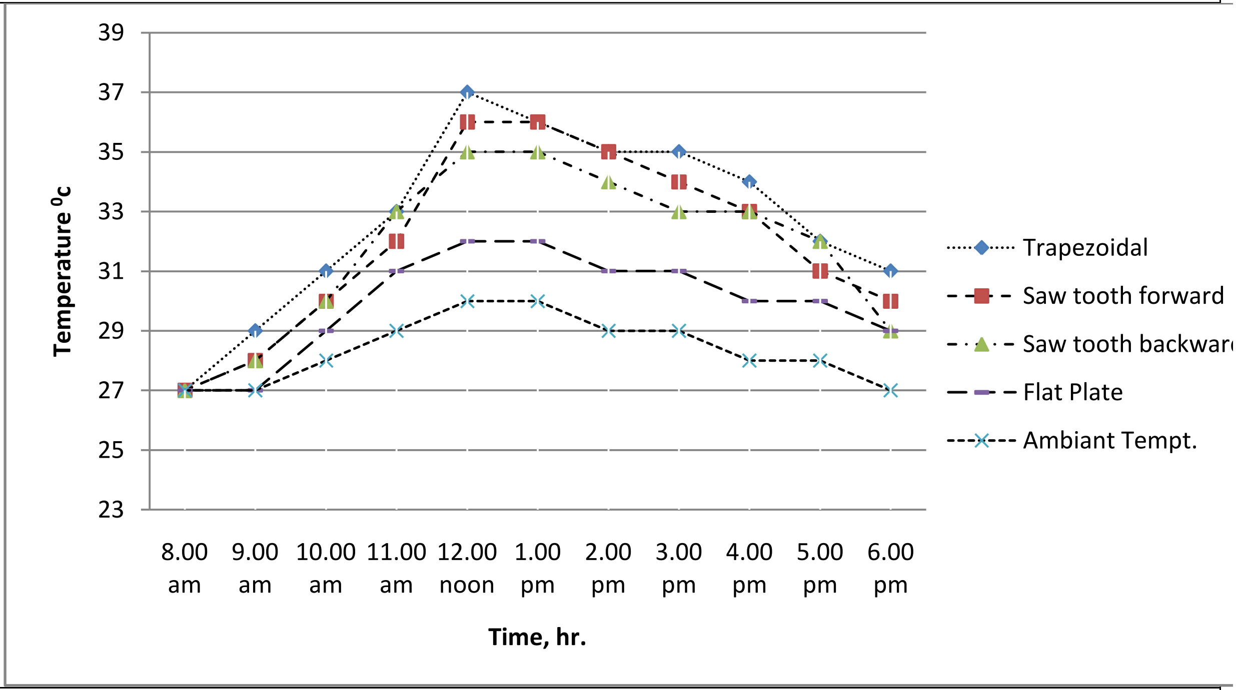


Fig.: 4.32 Temperature distribution of Air Channel temperature on 30/02/2012

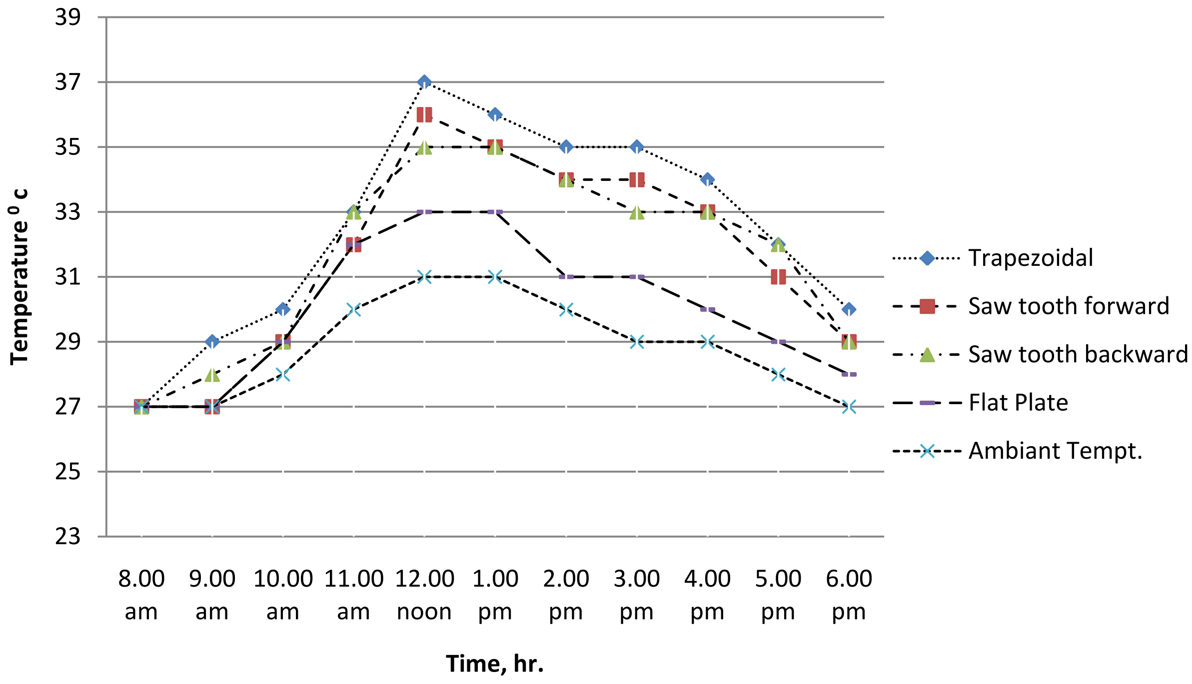


Fig.: 4.33 Temperature distribution of Air Channel temperature on 15/03/2012

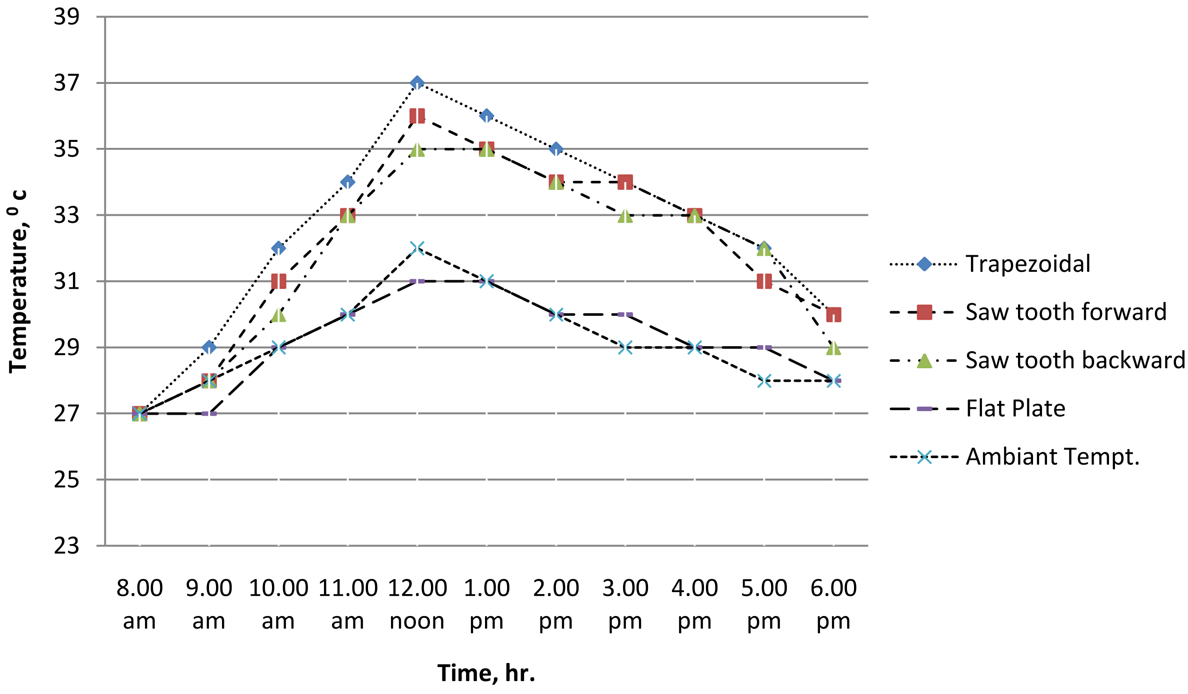


Fig.: 4.34 Temperature distribution of Air Channel temperature on 30/03/2012

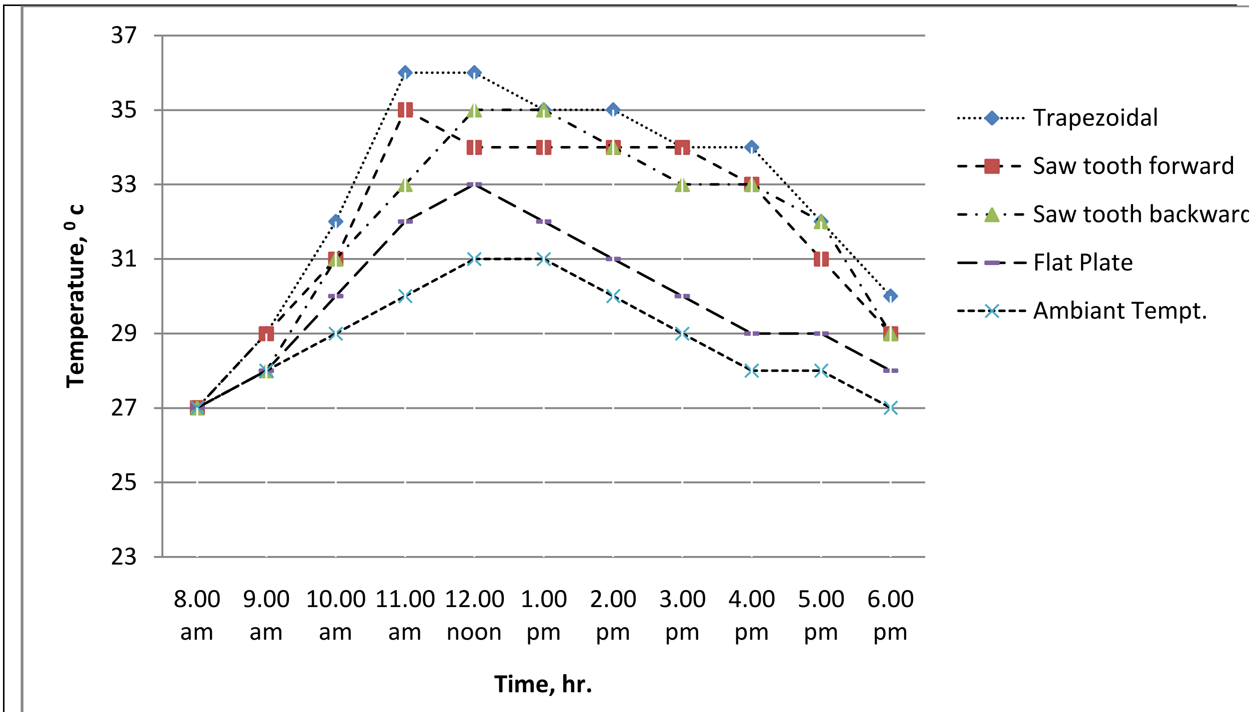


Fig.: 4.35 Temperature distribution of Air Channel temperature on 15/04/2012

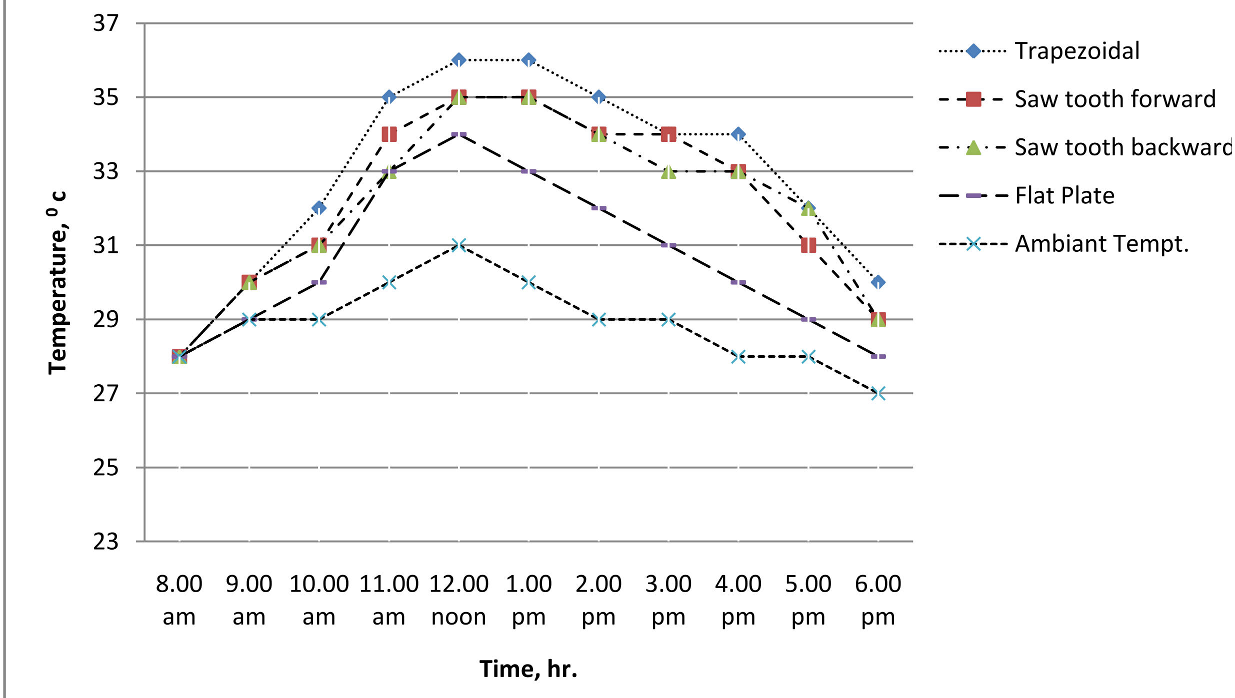


Fig.: 4.36 Temperature distribution of Air Channel temperature on 30/04/2012

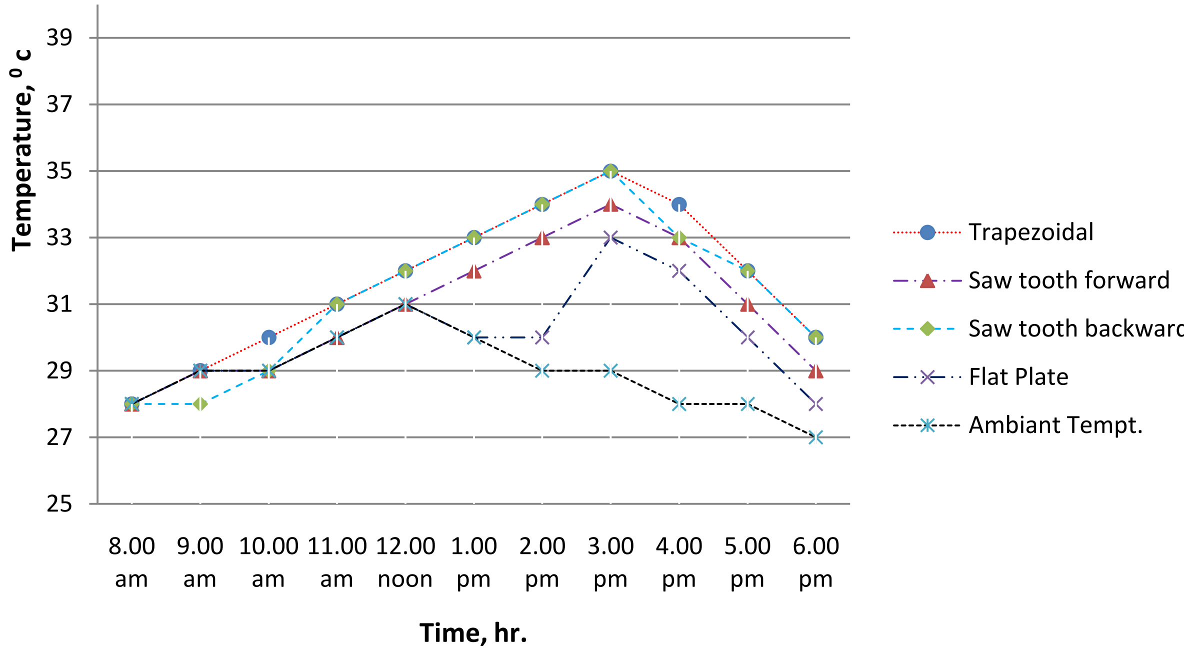


Fig.: 4.37 Temperature distribution of Air Channel temperature on 15/05/2012

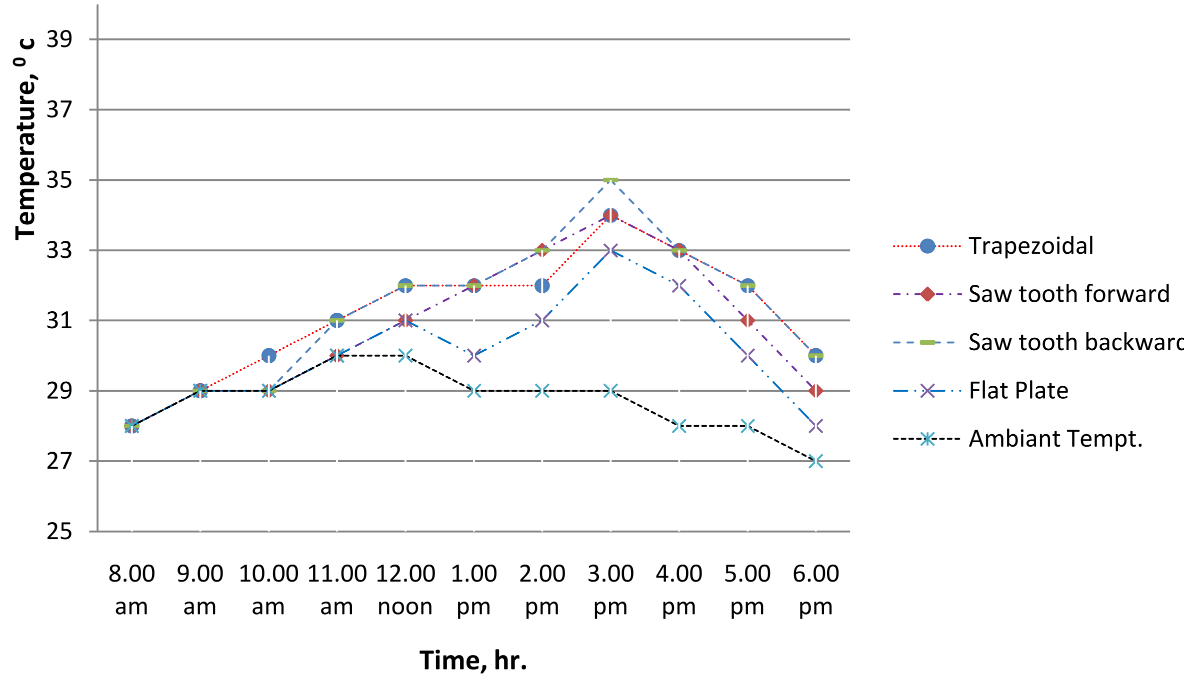


Fig.: 4.38 Temperature distribution of Air Channel temperature on 30/05/2012

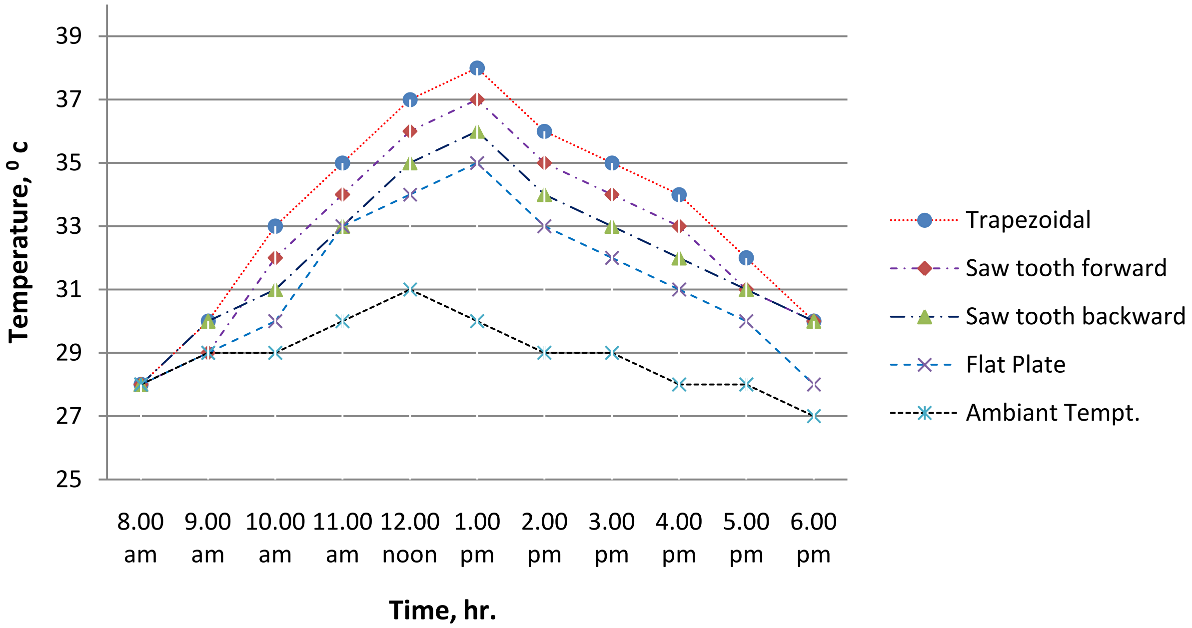


Fig.: 4.39 Temperature distribution of Air Channel temperature on 15/06/2012

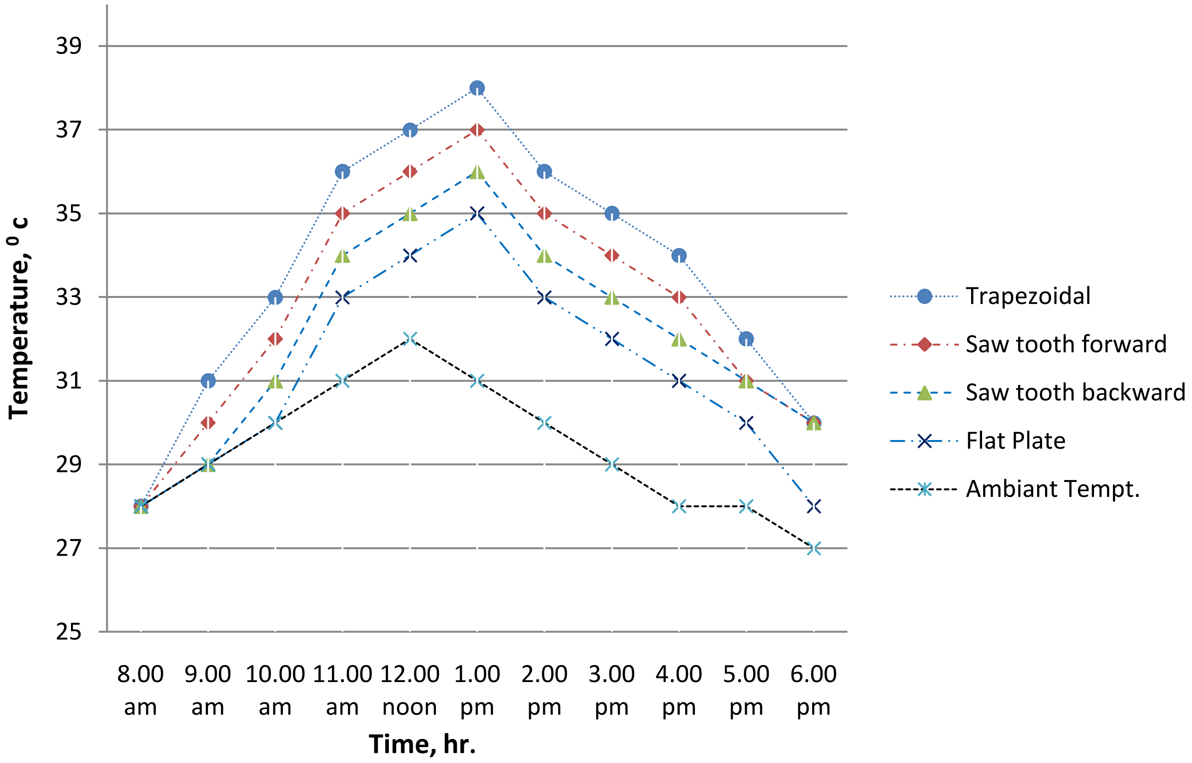


Fig.: 4.40 Temperature distribution of Air Channel temperature on 30/06/2012

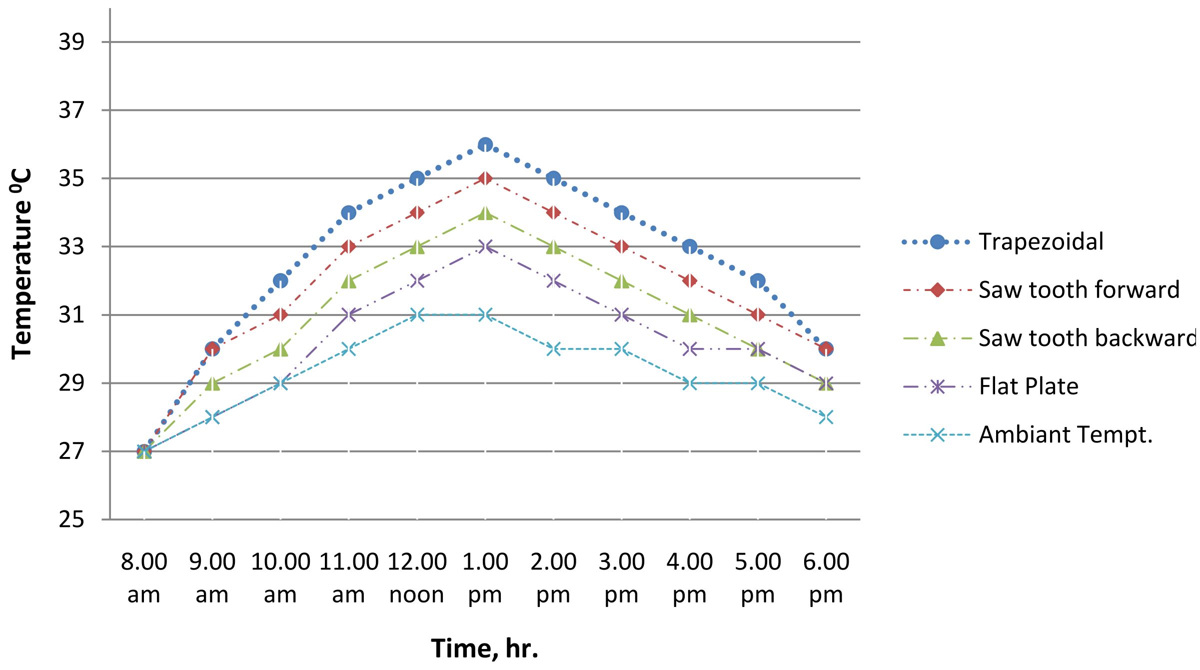


Fig.: 4.41 Temperature distribution of Ribbed surface temperature on 15/02/2012

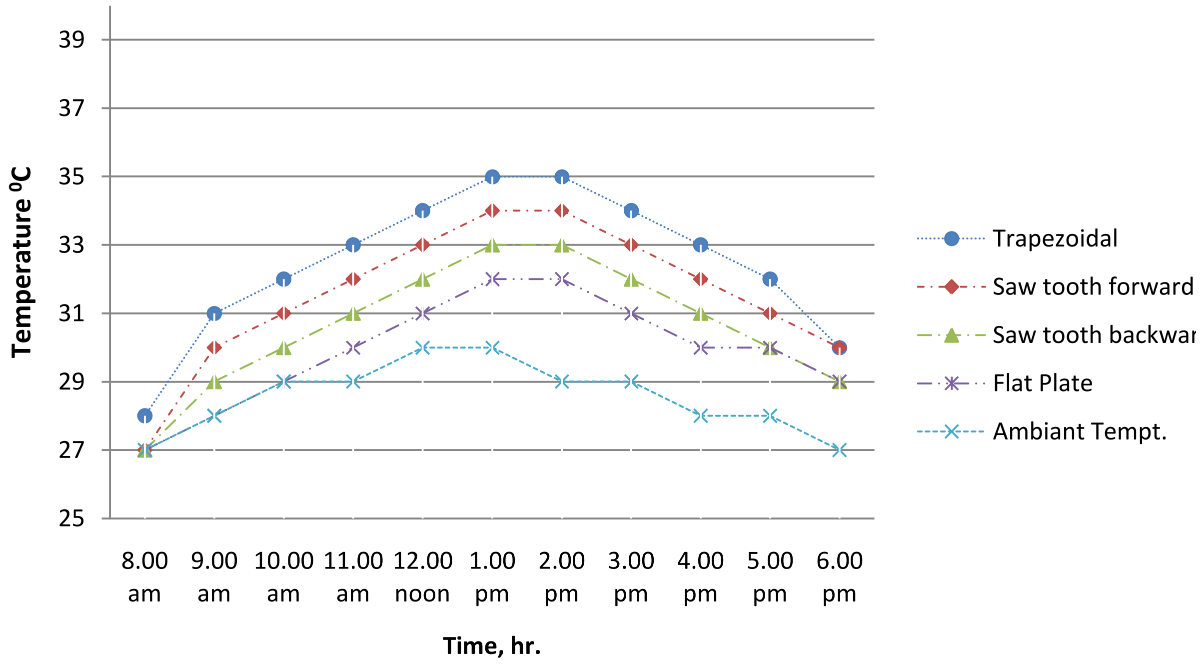


Fig.: 4.42 Temperature distribution of Ribbed surface temperature on 30/02/2012

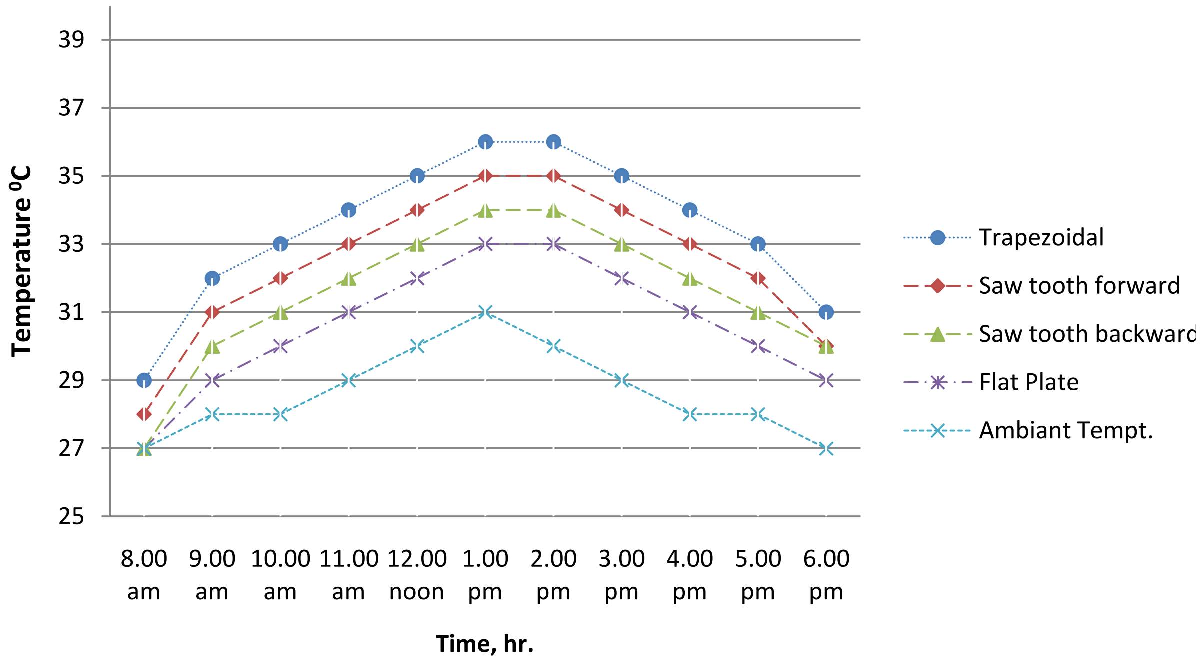


Fig.: 4.43 Temperature distribution of Ribbed surface temperature on 15/03/2012

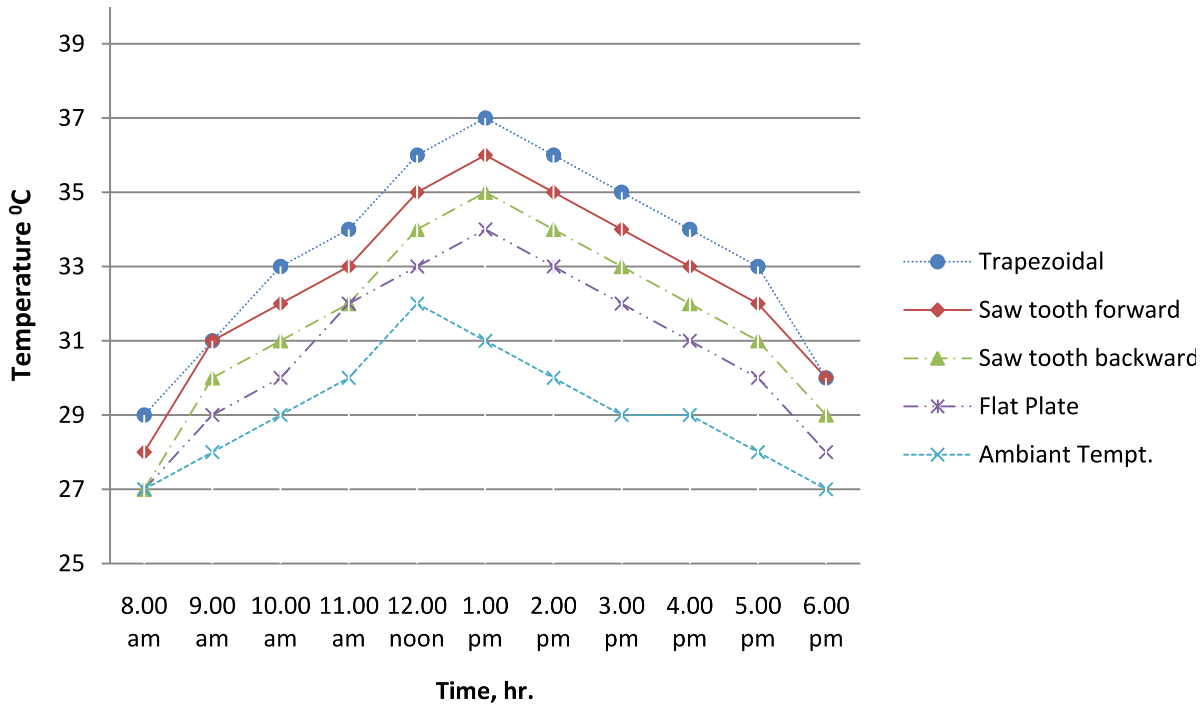


Fig.: 4.44 Temperature distribution of Ribbed surface temperature on 30/03/2012

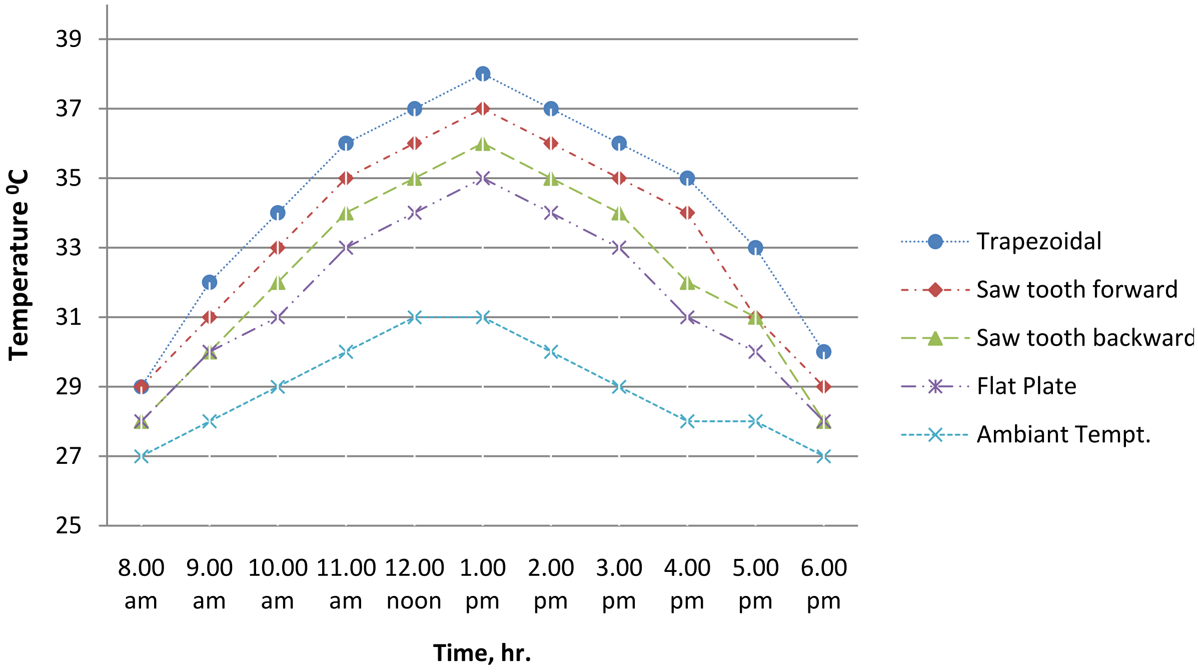


Fig.: 4.45 Temperature distribution of Ribbed surface temperature on 15/04/2012

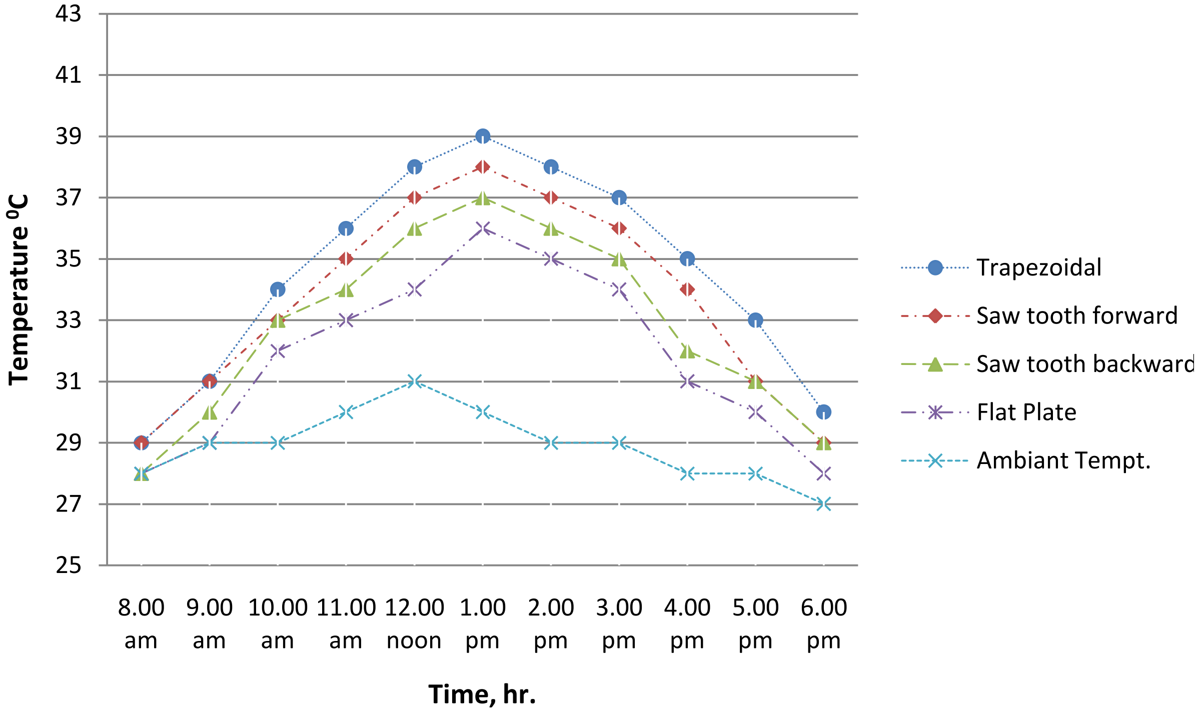


Fig.: 4.46 Temperature distribution of Ribbed surface temperature on 30/04/2012

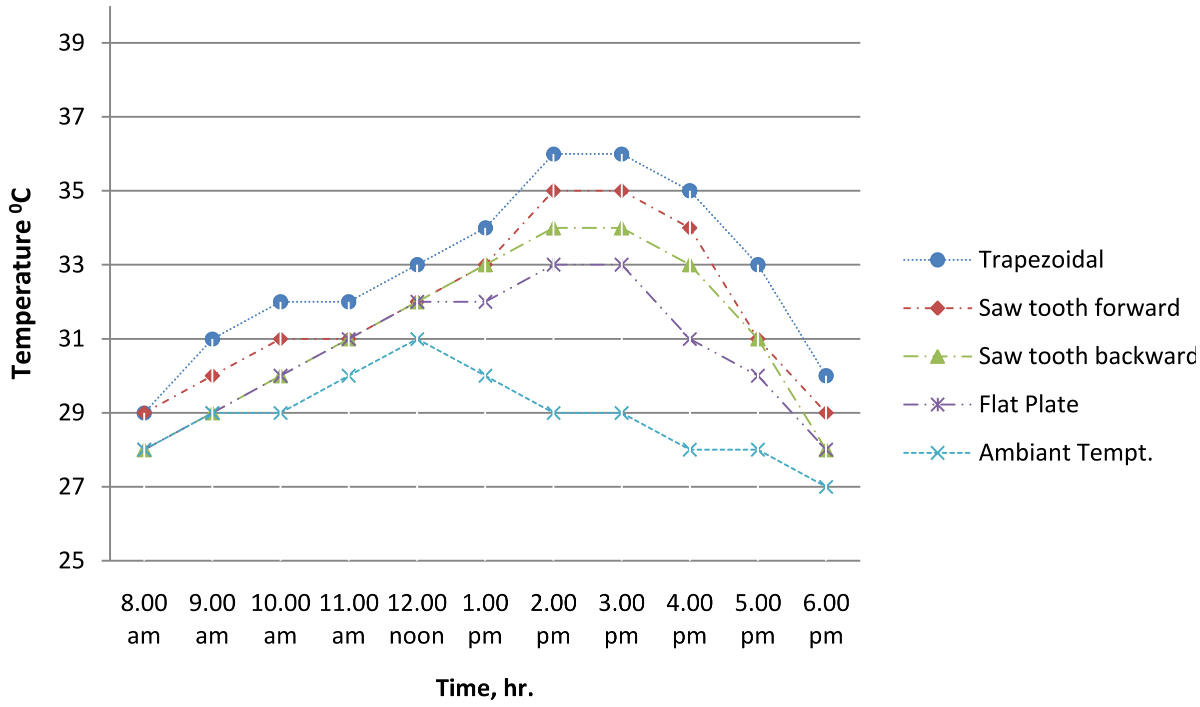


Fig.: 4.47 Temperature distribution of Ribbed surface temperature on 15/05/2012

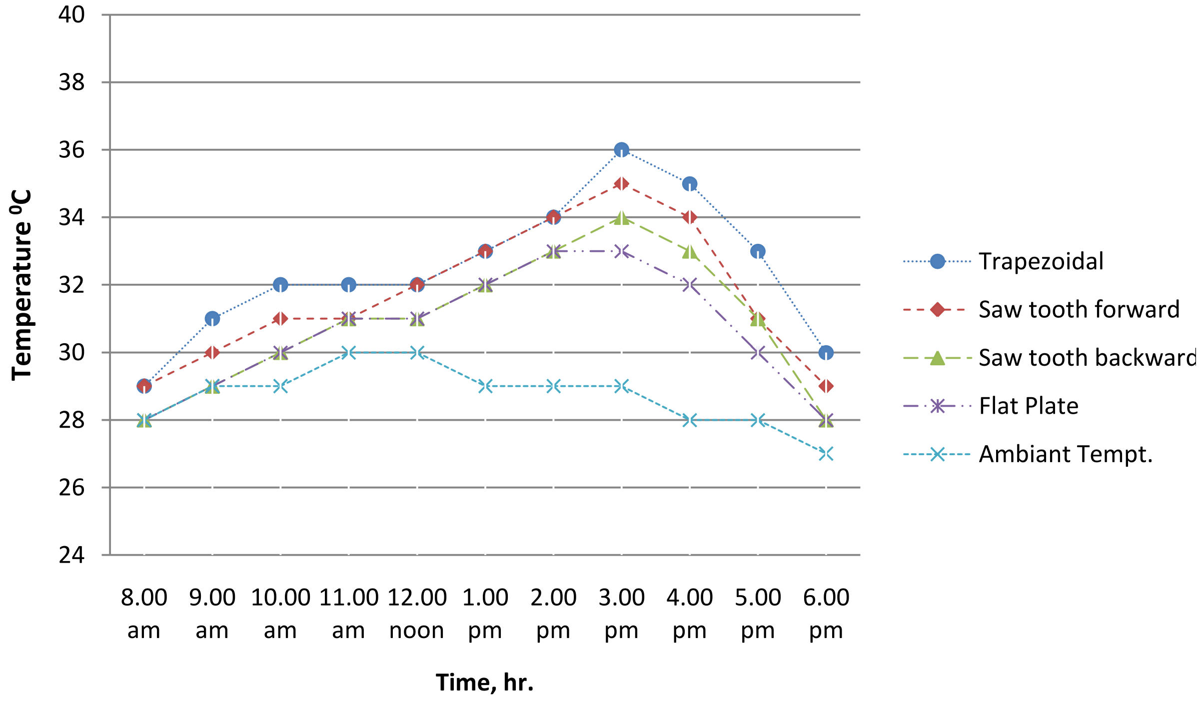


Fig.: 4.48 Temperature distribution of Ribbed surface temperature on 30/05/2012

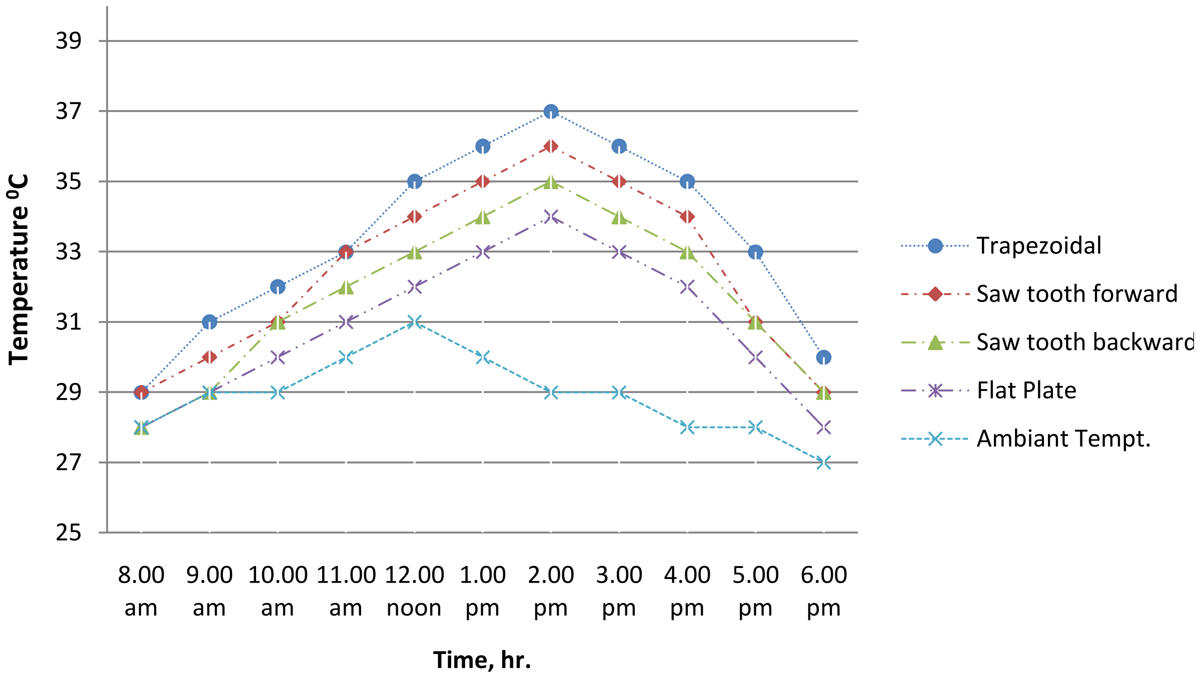


Fig.: 4.49 Temperature distribution of Ribbed surface temperature on 15/06/2012

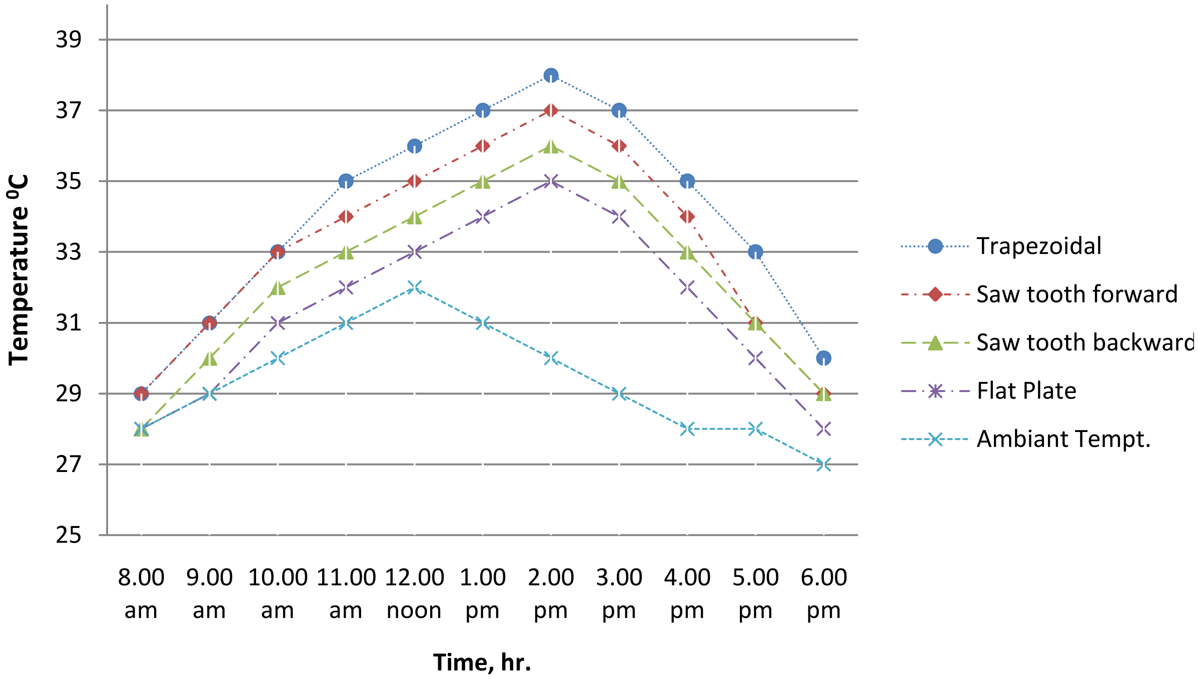


Fig.: 4.50 Temperature distribution of Ribbed surface temperature on 30/06/2012

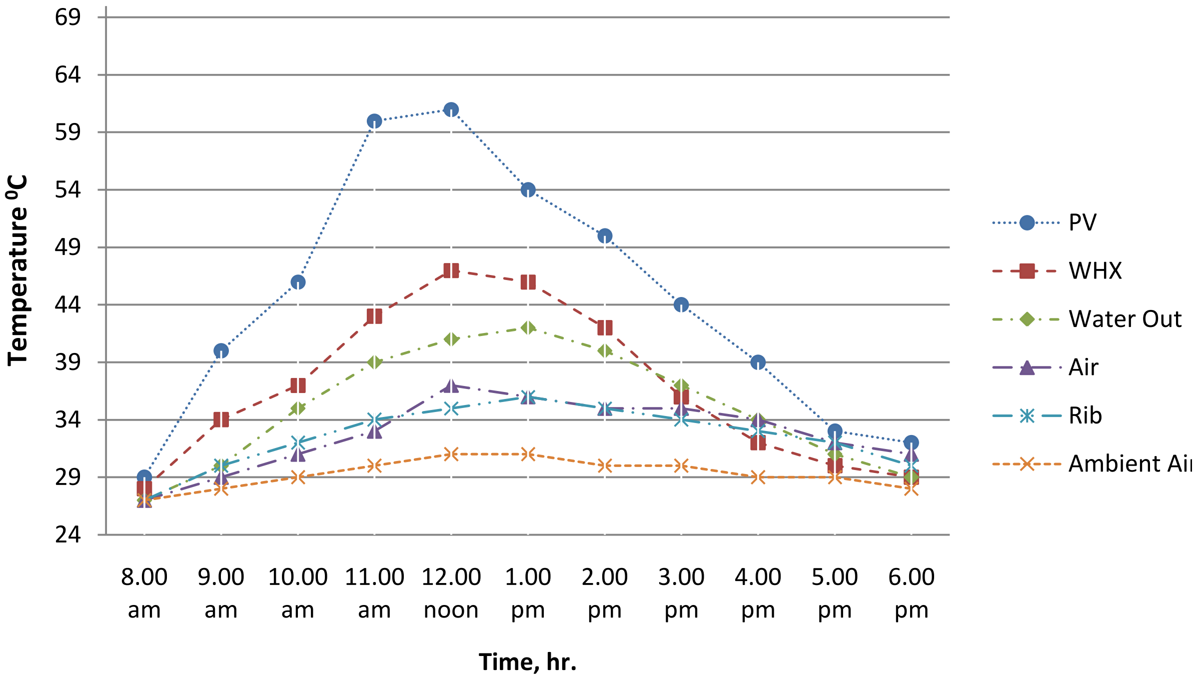


Fig.: 4.51 Temperature distribution in Trapezoidal ribbed setup on 15/02/2012

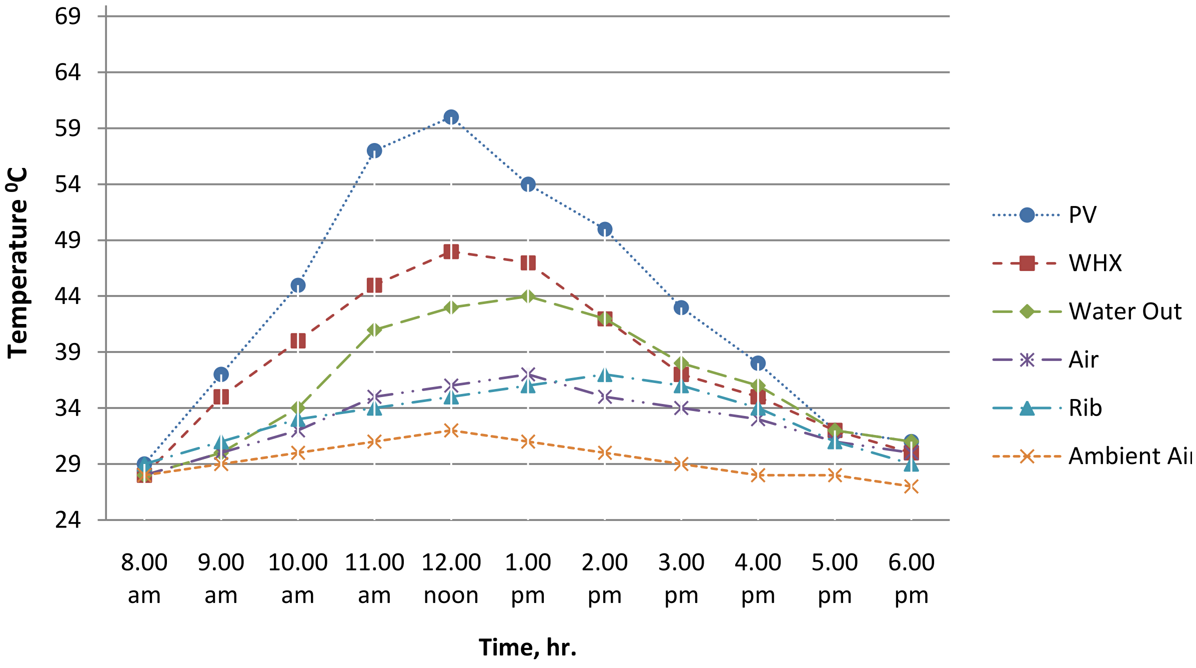


Fig.: 4.52 Temperature distribution in Saw tooth forward ribbed setup on 15/06/2012

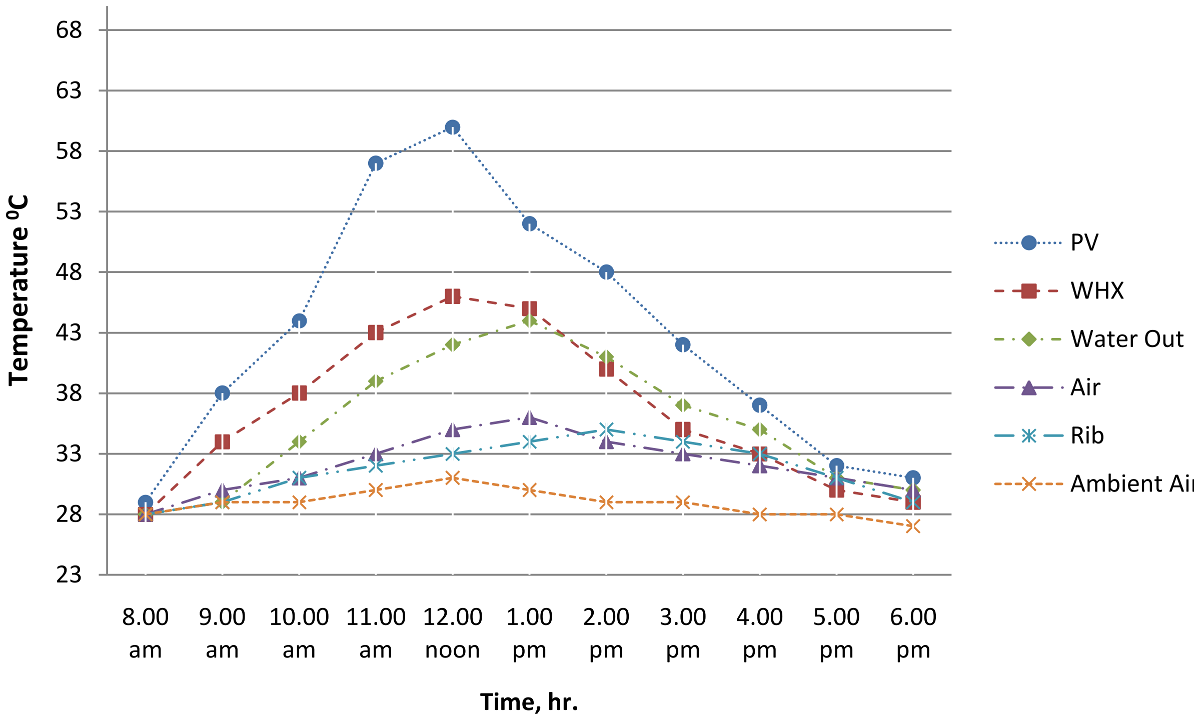


Fig.: 4.53 Temperature distribution in Saw tooth backward ribbed setup on 30/06/2012

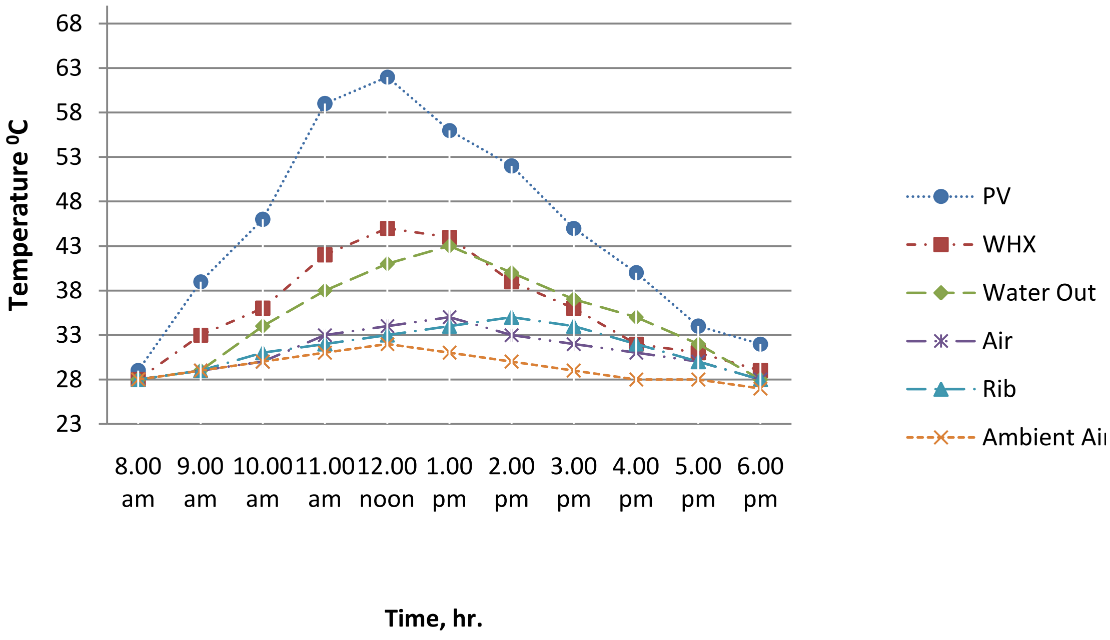


Fig.: 4.54 Temperature distribution in Flat plate setup on 30/06/2012

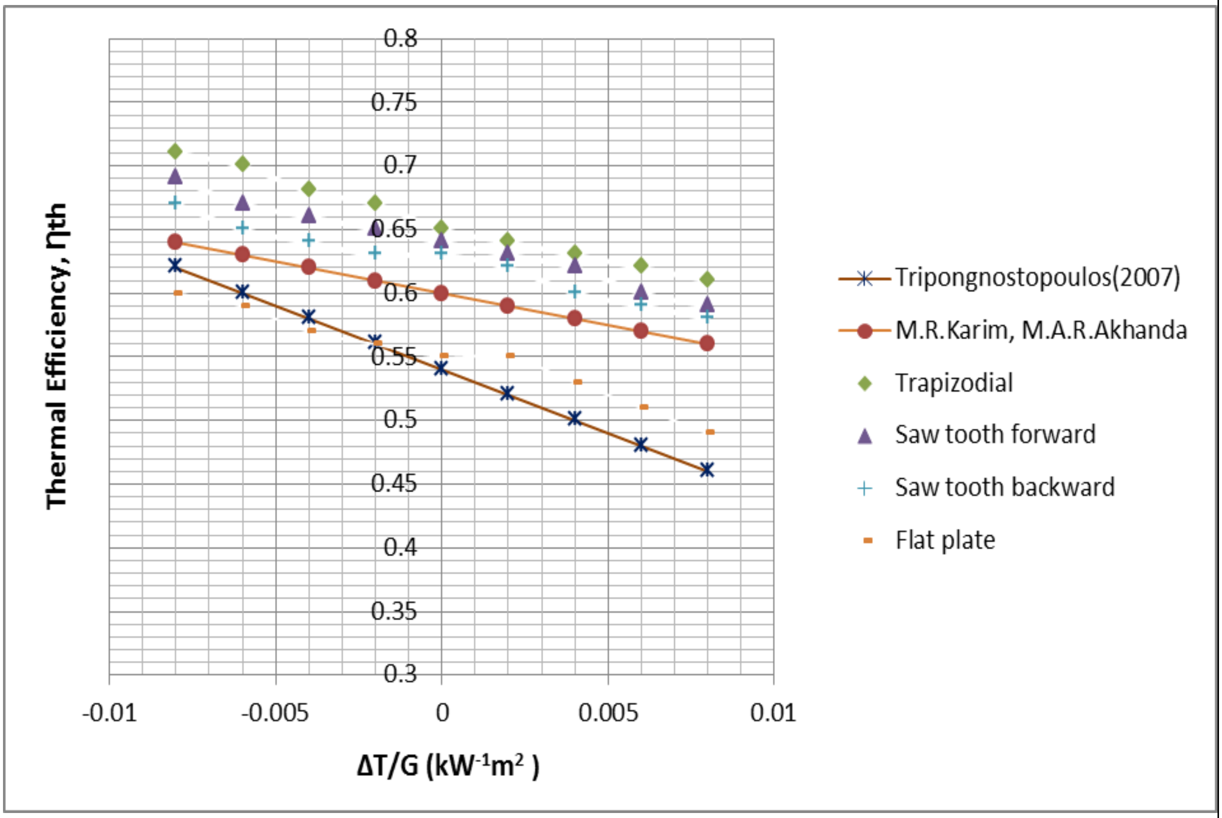


Figure 4.55 Comparison of Thermal efficiencies of all four systems.

CHAPTER 5

CONCLUSIONS AND RECOMMANDATIONS

5.1 Conclusions

From this experimental study the following conclusions may be drawn;

1. With the increase of PV panel temperature the water and air temperature also increase and reach a maximum value at a maximum PV temperature around noon. Water and air temperature then decrease slowly with the ambient temperature also.

2. The energy absorbed in the system from 8AM to 12 Noon is faster than that absorbed in the afternoon for all systems, tested in this study.

3. Average water and air temperature rise is found to be better in Trapezoidal and Saw tooth forward ribbed surface then those of surfaces with Saw tooth backward and Flat plate. Setup with Saw tooth forward ribbed surface shows better performance than that of Flat plate but its average performance is lower than that of setup with Trapezoidal and Saw tooth forward ribs.

4. Thermal efficiency is found to be best in the setup with Trapezoidal ribs among all setups, applying similar experimental conditions (T/G). Efficiency of Saw tooth forward, saw tooth backward and flat plate is also found satisfactory within the range of experimental conditions.

5. PVT/dual system can be used either to heat water or to heat air depending on the weather conditions and building needs. The water heat extraction part could operate mainly during periods of higher ambient temperature and the air heat extraction part to operate mainly when the ambient temperature low. In mild weather conditions (like Bangladesh) it is possible to operate both heat extraction modes, if it is considered useful for the application.

5.2 Recommendations

Further study of hybrid PVT/dual system is needed to find out more details about its performance. For this, following recommendations are may be suggested;

1. The year round performance of PVT/dual system is required for its applications. In Bangladesh as the weather condition is favorable it is possible to use both the heat extraction mode together.
2. PVT/dual collectors can be combined with booster reflectors to increase both the electrical and thermal energy output. This method can be considered as a cost effective and suitable for horizontal roof or ground collector installation for collecting thermal energy mainly from November to April.
3. Electrical efficiency for PVT/dual systems with these modifications can be studied thoroughly. To find out the electrical output effective load must be applied according to the system capacity. Electrical data must be gathered more frequently, preferably using data loggers. Because the electrical output in a PV system varies rapidly with the change of incoming the solar radiation.
4. PVT/dual system can be installed in a building roof or facades. Building integration of PVT system ensures natural convection of air, as air flow is naturally higher in elevated regions like roofs, south facing walls etc.

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APPENDICES A

Calibration of Thermocouple

Serial No.	Temperature recorded by Glass Tube Thermometer, ^{0}C	Temperature recorded by Thermocouple, ^{0}C
1	0	0
2	15	14.5
3	25	24
4	35	33.5
5	45	43.5
6	55	53
7	65	63.5
8	75	73

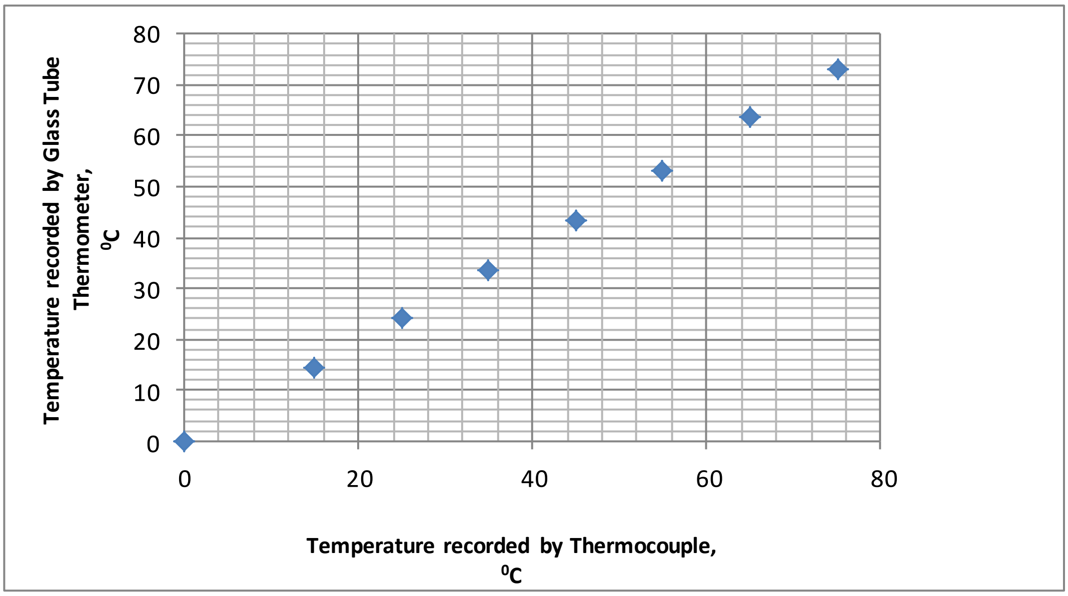

Fig. Calibration of thermocouples

APPENDICES B

Heat energy absorbed in 1 hour for the projected area can be calculated by the equation

$Q_{ab} = m \times C_p \times \Delta T_w / A_a$

Where, m= Mass of water in the tank, kg

C_p =Specific heat at constant pressure, j/kg.k

ΔT_w = Temperature difference of water in 1 hour, (To-Ti) ◦C

Solar radiation received in 1 hour for the projected area can be calculated by the equation of

$I = G \times A_a \times 3600$ (joule)

Where, g = Incoming Solar radiation, W/m^2

A_a = Aperture area, m^2

Thermal efficiency can be obtained

$\eta_{th} = Q_{ab} / I$