

**MODELING, ANALYSIS, EVALUATION, SELECTION
AND EXPERIMENTAL INVESTIGATION OF PARABOLIC
TROUGH SOLAR COLLECTOR SYSTEM**

**A
THESIS**

**Submitted in the partial fulfillment of the requirement for the award of degree of
Master of Engineering**

**In
Thermal Engineering**

Submitted by

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UNDER THE GUIDANCE OF

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JULY 2012

DECLARATION

I hereby declare that the thesis entitled “**MODELING, ANALYSIS, EVALUATION, SELECTION AND EXPERIMENTAL INVESTIGATION OF PARABOLIC TROUGH SOLAR COLLECTOR SYSTEM**” is an authentic record of my study carried out as requirement for the award of degree of **Master of Engineering (Thermal Engineering)** at **Thapar University, Patiala** under the guidance of **Dr. V.P. AGRAWAL**, visiting Professor, Department of Mechanical Engineering, Thapar University, Patiala during **July 2011 to June 2012**. The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any other degree.



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This is to certify that above declaration made by the student concerned is correct to the best of my knowledge and belief.

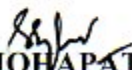


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Abstract

The PTSC (Parabolic Trough Solar Collector) technology is very useful as it is used for approximately all solar energy applications such as steam and power generation, water heating, air heating etc. In this thesis work the evaluation, comparison, ranking and optimum selection of a PTSC system from the different alternative designs available in the global market is done with the use of systems approach (MADM-TOPSIS, Graph theory). In MADM approach the maximum number of attributes of the PTSC system are identified in an exhaustive way and classified under different categories. The attributes are identified taking into account all the factors i.e. performance, design, materials, cost, quality etc. that affect the PTSC system and are listed in a tabular form. The attributes are assigned codes (numeric, alphabetic) in the coding scheme with an illustration. The ranking and optimum selection of PTSC is done by the use of a mathematical technique called as TOPSIS, and also by line graph and spider graph representation. In Graph Theoretical approach the structural constituents of the PTSC system are identified along with interactions and bonding between them. Five Different subsystems and their sub subsystems along with the interactions between them are identified and represented by a tree diagram and a digraph respectively. The various matrix models and permanent function models are developed for the complete analysis of the PTSC system. A permanent function forms a numerical index and is a unique representation of a PTSC system. The use of systems approaches for the evaluation, ranking and optimum selection of a PTSC is explained and presented in the proposed work with the help of an illustrated example. Also in the proposed work a PTSC system is fabricated for hot water production. Water is used as a working fluid and is recirculated from the storage tank to the absorber tube with the help of a pump. The main aim in the proposed work is to increase the temperature of water in the storage tank to a maximum value. An experimental analysis is done with the main work concentrates on the absorber tube. The values of useful heat gain, overall thermal efficiency, instantaneous efficiency and hourly thermal efficiency are calculated and their variation with time and solar intensity are represented graphically. Firstly a bare Copper and Aluminium tube with 32.5 mm outside diameter and 31.5 inside diameter are used and compared. Then the performance analysis of copper tube with four glass cover tubes of different outside diameters i.e. 45 mm, 55 mm, 65 mm, and 75 mm as an absorber tube is done in terms of temperature of water in the storage tank, useful heat gain, hourly thermal efficiency and instantaneous efficiency to find the optimum design.

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Abbreviations

- 1) PTSC - Parabolic Trough Solar Collector
- 2) MADM - Multi Attribute Decision Making
- 3) TOPSIS - Technique for Order Preference By Similarity To Ideal Solution
- 4) HTF - Heat Transfer Fluid
- 5) HWST - Hot Water Storage Tank
- 6) PTC - Parabolic Trough Concentrator

Chapter - 1

Introduction

The global need for energy is constantly increasing and makes it inevitable to reinforce the use of alternative resources. The sun is one of the richest energy sources in this context and is almost inexhaustible. Energy efficiency and solar technology are important elements to any building or community design. Also, they are important to the nation and to the Earth. The Sun is a massive reservoir of clean energy and the power from the sun's rays that reach the earth is called as solar energy. Solar energy is the most readily available source of energy. Solar energy received in the form of radiation can be converted directly or indirectly into other forms of energy such as heat and electricity which can be utilized by the man. Since the sun is expected to radiate essentially at a constant rate for a billion years it may be regarded as an in-exhaustible source of useful energy. Solar energy has been used since prehistoric times, but in a most primitive manner. Before 1970, some research and development was carried out in a few countries to exploit solar energy more efficiently, but most of this work remained mainly academic. After the dramatic rise in oil prices in the 1970s, several countries began to formulate extensive research and development programmes to exploit solar energy.

1.1) The Sun and the Earth:

The Sun is the largest member of the solar system with other members revolving around it. It is a sphere of intensely hot gaseous matter with a diameter of 1.39×10^9 m and on an average, at a distance of 1.5×10^{11} m from earth. As observed from earth the Sun rotates on its axis about once every four weeks. The Sun has an effective black body temperature of 5777K with several fusion reactions taking place on it and hence acts as a continuous reactor. The energy produced from the sun is radiated into space by Stefan-Boltzmann law which is

$$E = \epsilon \sigma T^4 \quad [47] \quad (1)$$

Where,

ϵ = Emissivity of the surface, σ = Stefan-Boltzmann constant

The earth is almost round in shape having a diameter of about 12.75×10^6 metres. It revolves around the sun once in about a year. Nearly 70 per cent of the earth is covered by water and remaining 30 per cent is land. Earth reflects one third of the sunlight that falls on it. The earth is spinning about its axis constantly. Its axis is inclined at an angle of 23.5° .

1.2) Solar Spectrum and Solar Radiation:

Solar radiation is a general term for the electromagnetic radiation emitted by the sun. The solar radiations falling on the earth's surface is categorized into ultra violet radiations, visible light and infrared radiations according to the solar spectrum.

1.2.1) Solar Spectrum: When the sun's energy reaches the earth's orbit, the emitted solar radiation is the composite result of the several layers that emit and absorb radiation of various wavelengths. In passing through the earth's atmosphere, harmful rays (X-rays, Gamma rays) are largely filtered out along with some wavelengths of visible light. The maximum spectral intensity occurs at about $0.48\mu\text{m}$ wavelength (λ) in the visible spectrum. About 6.4 percent of the total energy is contained the ultraviolet region ($\lambda < 0.38\mu\text{m}$); another 48 percent is contained in the visible region ($0.38 \mu\text{m} < \lambda < 0.78 \mu\text{m}$) and the remaining 45.6 percent is contained in the infrared region ($\lambda > 0.78 \mu\text{m}$) [47].

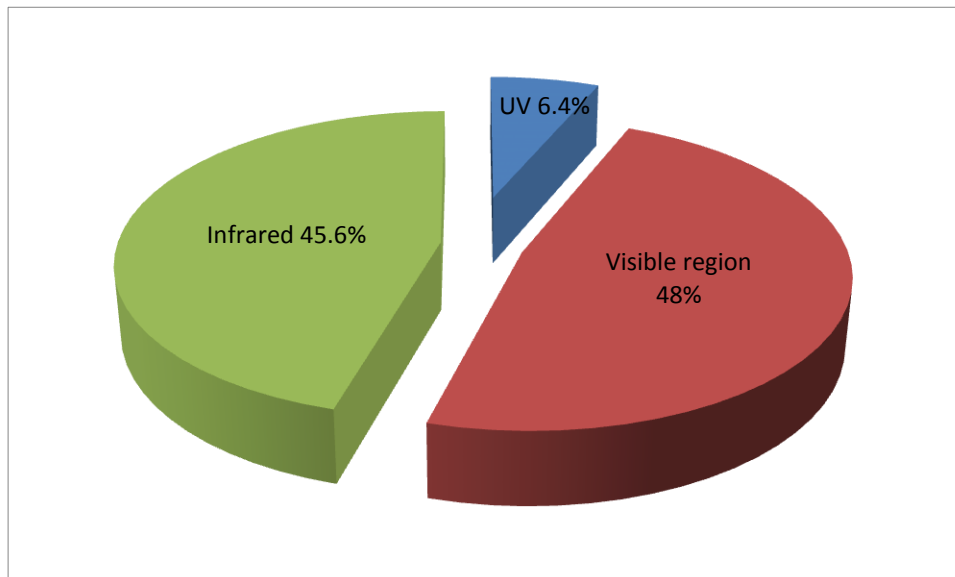


Figure.1 [47] Spectral Solar radiation distribution

1.2.2) Diffuse and Direct Solar Radiation: The UV radiations are absorbed by the Ozone layer and infrared radiations are absorbed by the water vapours, and carbon dioxide. So the intensity of radiation reaches the earth decreases. Radiations reaches on the earth are of two types:

- a) **Diffuse solar radiation:** As sunlight passes through the atmosphere some of it is absorbed, scattered, and reflected by the air molecules, water vapours, clouds, dust, pollutants, forest fires, volcanoes etc. This is called as diffuse solar radiation.
- b) **Direct (beam) solar radiation:** The solar radiation that reaches the earth's surface without being diffused is called as direct solar radiation. It is also referred to as the

solar radiation propagating along the line joining the receiving surface and the sun. Atmospheric conditions can reduce direct beam radiation by 10% on clear, dry days and by 100% during thick, cloudy days. The radiant energy flux received per second by a surface of unit area held normal to the direction of sun's rays at the mean earth-sun distance outside the atmosphere is called as **solar constant I_{sc}** . It is practically constant throughout the year and its adopted value is 1367 W/m^2 .

1.3) Sun and Earth angles:

The following are the important sun-earth angles:

- Zenith angle (θ):** It is the angle between sun's ray and perpendicular line to the horizontal plane. It is shown in figure 2.
- Altitude angle (α):** It is defined as the angle between sun rays and a horizontal plane. It is shown in figure 2.
- Surface Azimuth angle (γ):** It is the angle in a horizontal plane, between the line due south and the projection of normal to the surface on the horizontal plane. It is also shown in figure 2.

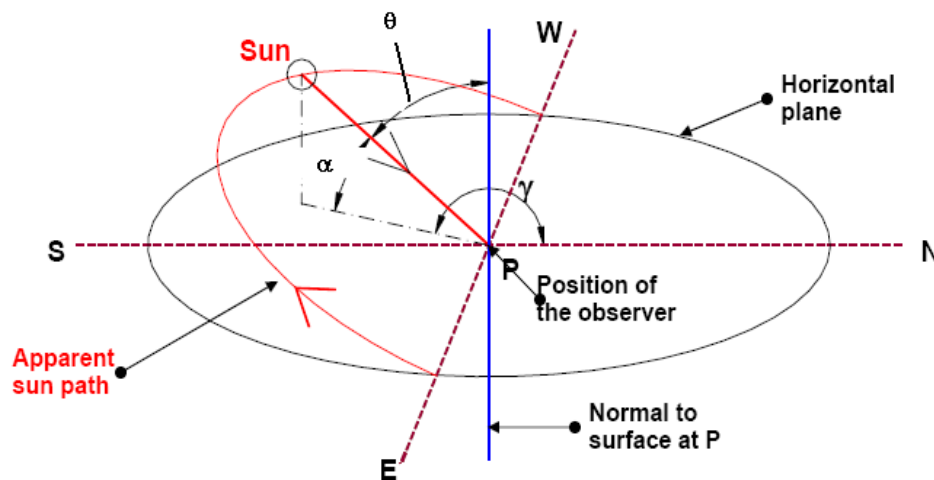


Figure.2 [53] Sun and Earth angles

- Latitude (ϕ):** The latitude of a location is the angle made by the radial line joining the given location to the centre of the earth with its projection on the equatorial plane.
- Declination (δ):** The angle between the line joining the centres of the sun and earth and its projection on the equatorial plane is called as declination angle.

Declination is due to the rotation of earth about an axis which makes an angle $66\frac{1}{2}^\circ$ with the plane of its rotation around the sun.

f) **Hour angle (ω):** The angle through which the earth must be rotated to bring the meridian of the plane directly under the sun is called as hour angle.

g) **Angle of incidence (θ_i):** It is the angle between beam radiation on a surface and the normal to that surface. The angle of incidence is calculated by the following formulae:

$$\cos \theta_i = \sin \varphi (\sin \delta \cos \beta + \cos \delta \cos \gamma \cos \omega \sin \beta) + \cos \varphi (\cos \delta \cos \omega \cos \beta - \sin \delta \cos \gamma \sin \beta) + \cos \delta \sin \gamma \sin \omega \sin \beta \quad [47] \quad (2)$$

φ – Latitude, δ – Declination angle, β – Slope, γ – Surface Azimuth angle,
 ω – Hour angle,

If θ be the angle of incidence of a beam of flux I , incident on a plane surface then the flux incident on the plane surface is, $I = I_n \cos \theta$

where,

I_n – intensity at the horizontal surface

I – intensity at the given inclined surface

1.4) Solar energy in India:

India is one of the few countries with long days and plenty of sunshine, especially in the Thar Desert region. On average, the country has 300 sunny days per year and receives an average hourly radiation of 200 MW/km². The India Energy Portal estimates that around 12.5% of India's land mass, or 413,000 km², could be used for harnessing solar energy [47]. This zone, having abundant solar energy available, is suitable for harnessing solar energy for a number of applications. In areas with similar intensity of solar radiation, solar energy could be easily harnessed. Solar thermal energy is being used in India for heating water for both industrial and domestic purposes. A 140 MW integrated solar power plant is to be set up in Jodhpur but the initial expense incurred is still very high. India receives solar energy equivalent to over 5000 trillion kWh/year [50], which is far more than the total energy consumption of the country. In India the energy problem is very serious. In spite of discoveries of oil and gas off the west coast, the import of crude oil continues to increase and the price paid for it now dominates all other expenditure. As far as India is concerned there are 33 solar photovoltaic (PV) power plants with total 425.9 (MW) DC peak power and the total of 979.4 MW power

production throughout the country. The maximum power production from the solar energy is from the state of Gujarat with 654.8 MW i.e. 66.4% contribution [50]. The second best power producing state is Rajasthan with 197.5 MW with 20.5% contribution [50].

1.5) Applications of Solar Energy:

The application areas of solar energy can be categorized as follows:

- Architecture and urban planning
- Agriculture and horticulture
- Solar thermal energy can be used for:
 - Cooking/heating
 - Drying/Timber seasoning
 - Distillation,
 - Electricity/Power Generation
 - Cooling and Refrigeration
 - Process heating
- Solar energy can also be used to meet our electricity requirements. Through Solar Photovoltaic (SPV) cells, solar radiation gets converted into DC electricity directly. This electricity can either be used as it is or can be stored in the battery. This stored electrical energy then can be used at night. SPV can be used for a number of applications such as:
 - Domestic lighting
 - Street lighting
 - Village Electrification
 - Water pumping
 - Desalination of salty water
 - Powering of remote telecommunication repeater stations and
 - Railway signals.

If the means to make efficient use of solar energy could be found, it would reduce our dependence on non-renewable sources of energy and make our environment cleaner.

1.6) Solar Energy collectors:

A solar collector is a device used for collecting solar radiation and transfers the energy to a fluid passing in contact with it. Utilization of solar energy requires solar collectors. These are general of two types:

- Non-concentrating type

- Concentrating type

The solar energy collector with its associated absorber is the essential component of any system for the conversion of solar radiation energy into more usable form e.g heat or electricity. In the non-concentrating type the collector area is same as the absorber area. On the other hand in concentrating collectors the area intercepting the solar radiations is greater, sometimes hundred times greater than the absorber area.

1.6.1) Non-concentrating:

1.6.1.1) Flat plate type solar collector:

The main components of a flat plate solar collector (Fig.1) are:

- **Absorber plate** made of any material, which will rapidly absorb heat from sun's rays and quickly transfer that heat to the tubes or fins attached in some manner, which produces a good thermal bond.
- **Tubes or fins** for conducting or directing the heat transfer fluid from the inlet header or duct to the outlet.
- **Glazing**, this may be one or more sheets of glass or a diathermanous (radiation transmitting) plastic film or sheet.
- **Thermal insulation**, which minimizes downward heat loss from the plate.
- **Cover strip**, to hold the other components in position and make it all Watertight.
- **Container or Casing**, which surrounds the foregoing components and keeps them free from dust, moisture, etc.

Flat plate solar collectors are classified into two types:

- **Water-type** collectors, using water as the heat-transfer fluid, and
- **Air-type** collectors, using air as the heat-transfer fluid.

Advantages:

1. It is the easiest and least expensive to fabricate, install, and maintain.
2. It is capable of using both the diffuse and the direct beam solar radiation.
3. They do not require orientation towards the sun.
4. They are mechanically simpler than concentrating collectors.
5. Flat plate collectors easily attain temperatures of 40 to 70°C to heat swimming pools, domestic hot water, and buildings.

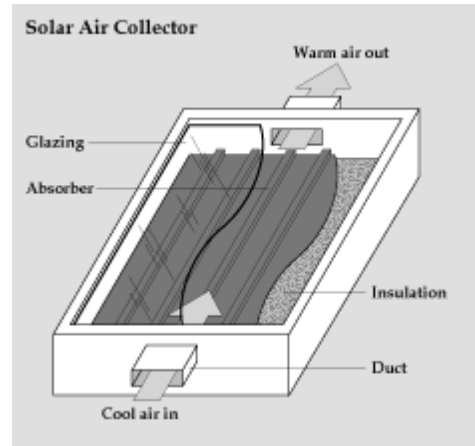
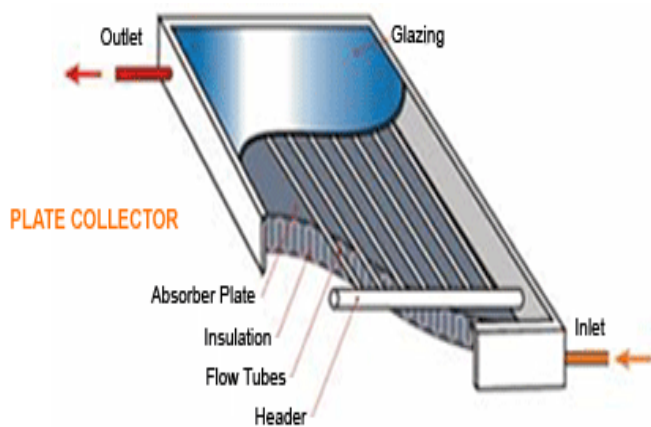


Fig.3 [55] Flat plate collector for water heating Fig.4 [56] Flat plate collector for air heating

1.6.1.2) Evacuated-tube collectors:

These collectors are usually made of parallel rows of transparent glass tubes. Each tube contains a glass outer tube and metal absorber tube attached to a fin. The fin is covered with a coating that absorbs solar energy well, but which inhibits radiative heat loss. Air is removed, or evacuated, from the space between the two glass tubes to form a vacuum, which eliminates conductive and convective heat loss.

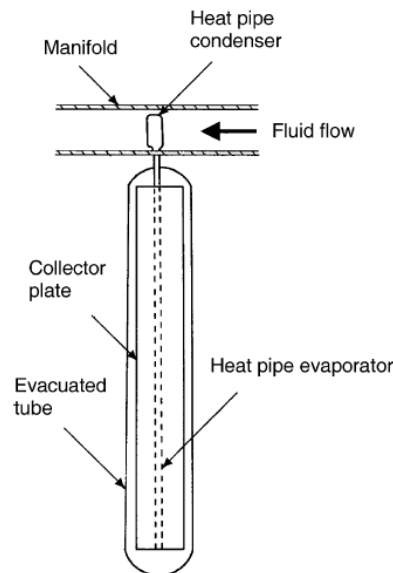


Fig.5 [13] Evacuated tube collector

A new evacuated-tube design with a cavity to transfer the heat to the storage tank and also there are no glass-to-metal seals. This type of evacuated tube has the potential to become cost-competitive with flat plate collectors.

Advantages:

- 1) Higher operating temperatures than flat plate collector.
- 2) Less number of heat losses in comparison to flat plate collectors.
- 3) Compact design

1.6.2) Concentrating Type Solar Collector:

There are four basic types of concentrating collectors:

- 1) Parabolic trough solar collector system
- 2) Linear fresnel reflector
- 3) Parabolic dish
- 4) Power tower

1.6.2.1) Parabolic Trough Solar Collector:

A parabolic trough solar collector uses a reflector in the shape of a parabola which is mostly a mirror, or an anodized Aluminium sheet depending on the required applications to reflect and concentrate the solar radiations towards a receiver tube located at the focus line of the parabola. The absorber tube may be made of mild steel or copper and is coated with a heat resistant black paint for the better performance. The receiver absorbs the incoming radiations and transforms them into thermal energy, which is being transported and collected by a fluid medium circulating within the receiver tube. The heat transfer fluid flows through the absorber tube, gets heated and thus carries heat. The temperature of the fluid reaches up to 400°C. Depending on the heat transfer requirement different heat transfer fluids may be used.

a) Working Principle:

The Solar radiations coming parallel to the focal line of the parabola (reflector) collect at the surface of reflector and concentrate it to the focal point F as shown in figure.7. If the reflector is in the form of trough with parabolic cross section, the solar radiation focuses along a line. In concentrating collectors the term concentration ratio (C) is a very important parameter. It is defined as the ratio of the collector area at which radiation collects to the area (absorber) at which these radiations are concentrated. Concentration ratio is defined as the ratio of the collector area to the absorber area. So with the decrease in the absorber area the concentration ratio increases and hence more quickly the high temperatures are reached. So higher concentration ratio means higher temperature can be achieved. The schematic diagram of the parabolic trough solar collector with absorber tube, tracking mechanism and support structure is shown in figure.6.

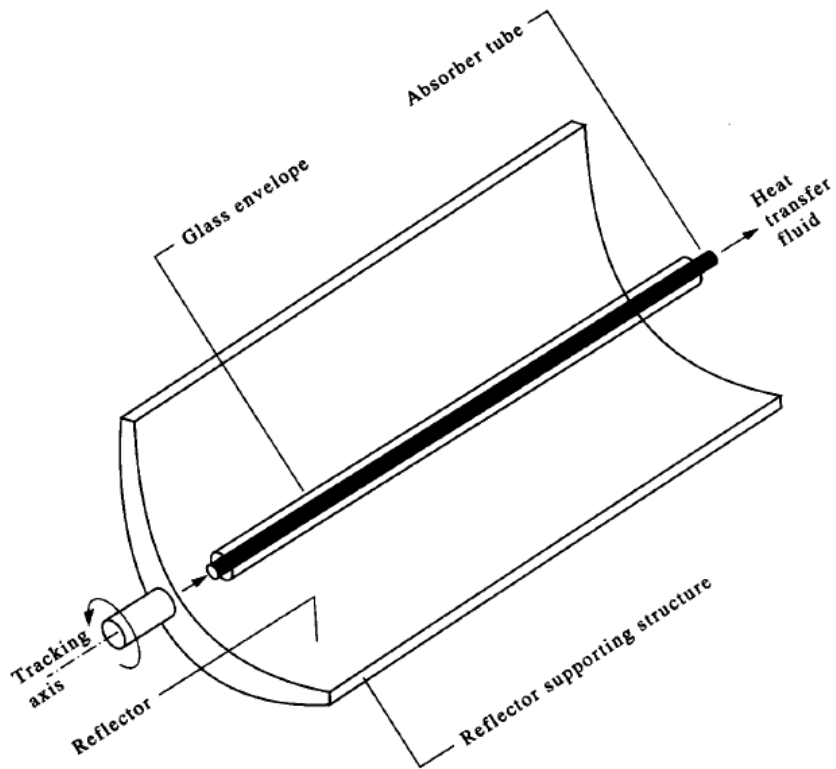


Fig.6 [3] Parabolic Trough Solar Collector System

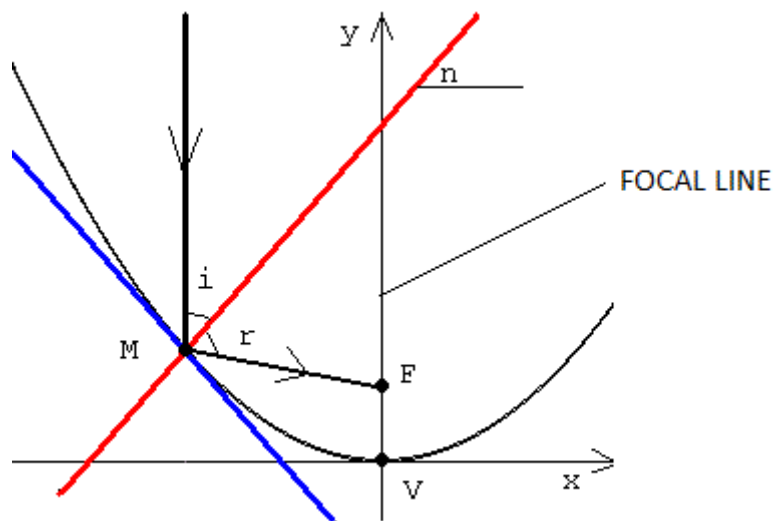


Fig.7 [52] Design specifications of a reflector

F – focus point, i – angle of incidence, r – angle of reflection, V – vortex,
 n – angle made by the normal of the parabola at point M with horizontal axis

b) Parabolic Trough Solar Collector System Components:

The main components of parabolic trough solar collector system are:

- 1) **Reflector:** A parabolic reflector reflects and concentrates all the sun's rays to the receiver tube which is at the focal point of the parabola. The reflectors are parabolic shaped mirrors with a reflectivity of 96%. The mirror is a second surface silvered glass mirrors with reflective silver layer coating on the back side of the glass. A special multilayer paint coating protects the silver on the back side of the mirror for the better performance of the reflector. The specifications and terms used in the reflector are shown in figure.
- 2) **Absorber tube:** An absorber tube is a linear receiver located at the focus line of parabolic reflective surface at the focus line of parabolic reflective surface, with means of transferring the absorbed solar energy to a heat transfer fluid. It has glass to metal seals and metal bellows to accommodate for differing thermal expansions between steel tubing and glass envelop. It has a vacuum type enclosure to reduce the heat losses. The selective coating on the steel tube has a good solar absorbance.

The getters are metallic compounds which are used to absorb gas molecules are installed in the vacuum space to absorb hydrogen and other gases that permeate through annulus over time.

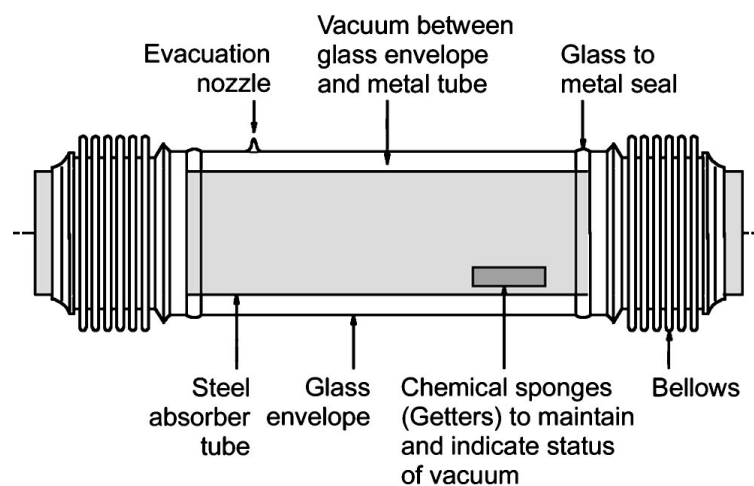


Fig.8. [8] Receiver tube

- 3) **Glass cover tube:** A concentric tubular glass cover surrounding the absorber with a gap of 1-2 cm with glass to metal seal to create vacuum so as to minimize the conduction, convection, and radiation losses. Glass tube nearly transparent to the radiations of short wavelength (coming from sun) and opaque to the radiations of long wavelength (emitted by the absorber). Transmittance of the glass tube can be increased by decreasing the iron content from the glass material. Evacuated glass tube

also used which reduce heat losses more efficiently than the simple glass tube. Also the spacing distance between the glass tube and absorber tube affects the heat losses.

- 4) **Support structure:** Steel supported structure is there in the back of the reflector mirror so as to provide strength to the collector so as to provide mechanical strength to the collector to withstand the wind loads. The main emphasis is to reduce the weight of the support structure and also to reduce the structure deformations so that trough focuses the sun more effectively.
- 5) **Tracking mechanism:** In a Tracking mechanism the trough is usually aligned on a north-south axis, and rotated to track the sun as it moves across the sky each day. Alternatively the trough can be aligned on an east-west axis; this reduces the overall efficiency of the collector, due to cosine loss, but only requires the trough to be aligned with the change in seasons, avoiding the need for tracking motors.

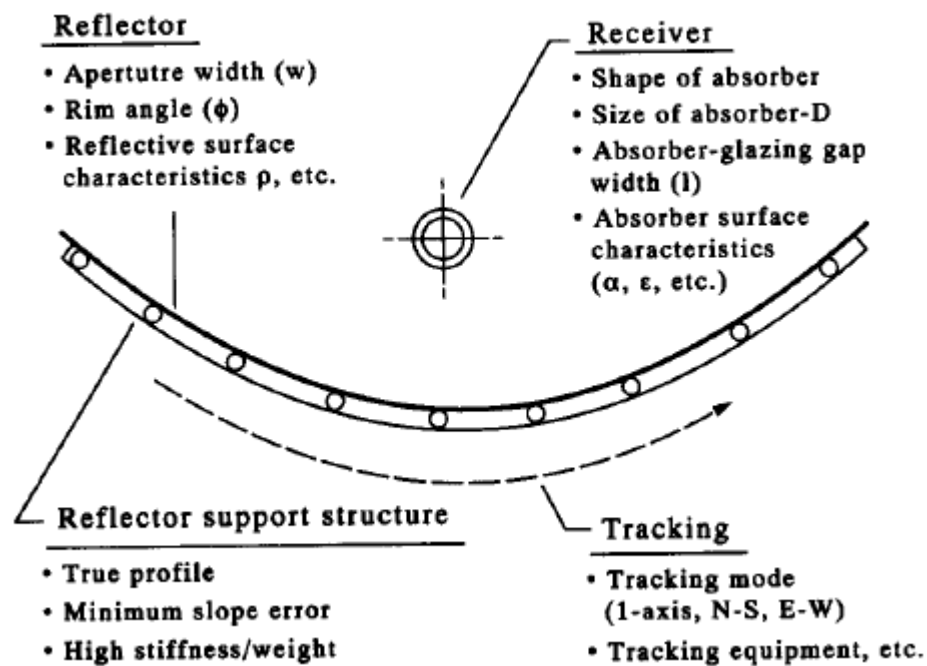


Fig.9.[3] Subsystems of Parabolic Trough Collector system

The subsystems of parabolic trough solar collector system with the different factors affecting the performance of the system are shown in the above figure.9.

Advantages:

- 1) Higher operating temperatures 150-300°C can be obtained.
- 2) High efficiency and low cost.
- 3) It can be used either for thermal energy collection, or for generating electricity.
- 4) There are unlimited number of location options
- 5) Flexible implementation
- 6) Possibility of thermal energy storage.

The parabolic trough solar collector system uses water or thermal oil as heat transfer fluid in industry for the power generation applications. A heat transfer fluid is heated up as high as 393°C as it circulates through the receiver and returns to a series of heat exchangers in the power block in case of thermal oil, where the fluid is used to generate high-pressure superheated steam at 100 bar, 371°C. The superheated steam is then fed to a conventional reheat steam turbine/generator to produce electricity. The spent steam from the turbine is condensed in a standard condenser and returned to the heat exchangers via condensate and feed-water pumps to be transformed back into steam. In the direct steam generation applications water is used as a heat transfer fluid. Parabolic troughs are one of the lowest cost solar electric power options available today and have significant potential for further cost reduction and hence is the best suited for the steam generation.

Performance Parameters of the Parabolic Trough Solar Collector are as follows:

- i. Concentration ratio which gives indication of the maximum temperature produced by the collector.
- ii. Optical efficiency gives information of the fraction of total solar energy incident on collector area absorbed by the absorber.
- iii. Thermal efficiency gives information of the fraction of total energy incident on the collector area that we get in the form of heat from the collector.

The thermal efficiency of the parabolic trough solar collector system depends on the optical efficiency of the system. More is the optical efficiency of the reflector better will be the thermal efficiency and hence the overall performance of the system. Figure.10 shows the different parameters that affect the optical efficiency of the reflector with the help of a cause and effect diagram.

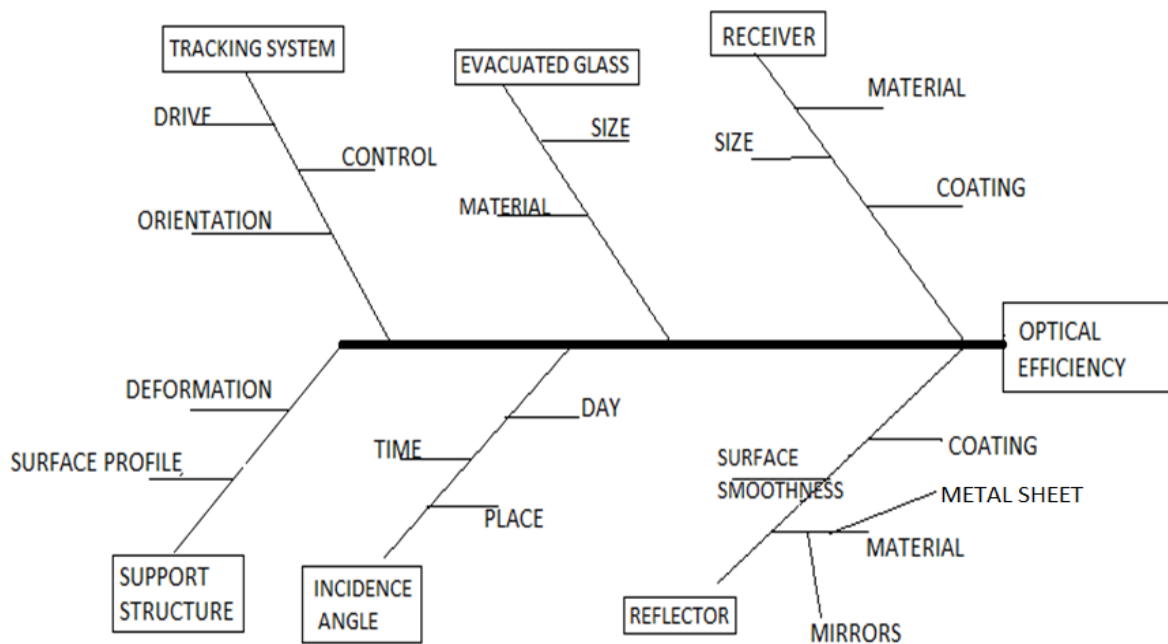


Fig.10 Parameters Affecting Optical efficiency

Similarly the direct overall cost of a parabolic trough solar collector is represented with the help of a cause and effect diagram which is as follows:

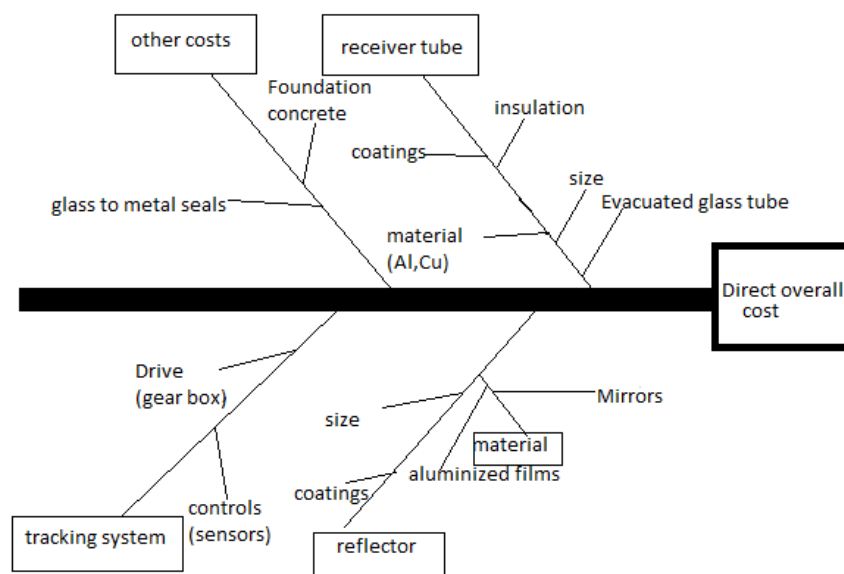


Fig.11 Cause and effect diagram for direct overall cost

The above figure represents all the causes and the effects of different subsystems of parabolic trough solar collector system on the direct overall cost of the system.

1.6.2.2) Linear fresnel reflector:

It is an array of linear mirror strips which concentrate light on to a fixed receiver mounted on a linear tower. The LFR field can be imagined as a broken-up parabolic trough reflector, but unlike parabolic troughs, it does not have to be of parabolic shape, large absorbers can be constructed and the absorber does not have to move.

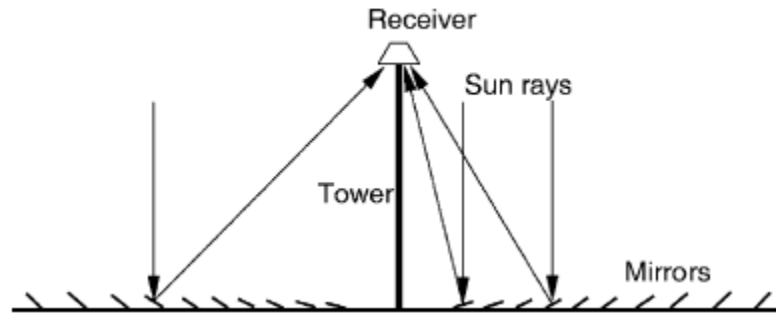


Fig.12[13] Linear fresnel reflector

Advantages:

1. It uses flat reflectors which are cheap.
2. They are mounted close to the ground thus minimizing structural requirements.

Disadvantages:

- 1) Avoidance of shading and blocking between adjacent reflectors leads to increased spacing between reflectors.
- 2) It has lower efficiency than parabolic trough.

1.6.2.3) Parabolic dish:

A parabolic dish reflector is a point-focus collector that tracks the sun in two axes, concentrating solar energy onto a receiver located at the focal point of the dish. The dish structure must track fully the sun to reflect the beam into the thermal receiver. The receiver absorbs the radiant solar energy, converting it into thermal energy in a circulating fluid. The thermal energy can then either be converted into electricity or it can be transported to the pipes to central power conversion system. Parabolic dish can attain a temperature of about 1500°C.

Advantages:

1. Because they are always pointing the sun, they are the most efficient of all collector systems
2. They typically have concentration ratio in the range of 600–2000, and thus are highly efficient at thermal-energy absorption and power conversion systems

3. They have modular collector and receiver units that can either function independently or as part of a larger system of dishes.

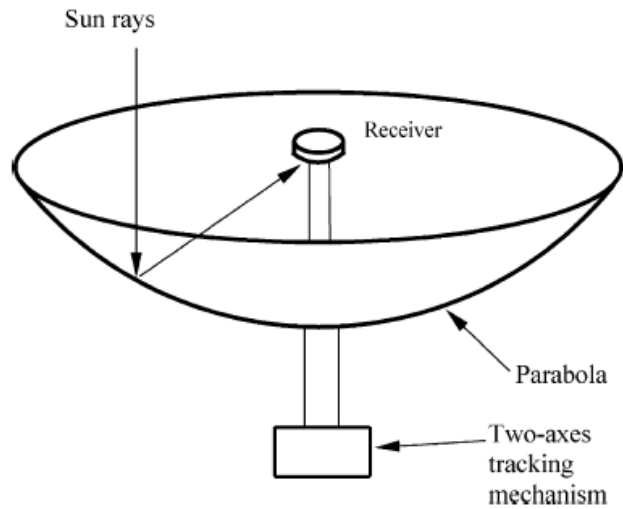


Fig.13 [13] Parabolic dish collector

Disadvantages:

- 1) Need of sun tracking to maintain Sunlight focus at the collector.
- 2) It is a point focussing collector mainly used in stirling engines, only for small electricity production

1.6.2.4) Power tower:

A power tower is a large tower surrounded by tracking mirrors called heliostats. These mirrors align themselves and focus sunlight on the receiver at the top of tower, collected heat is transferred to a power station. The average solar flux impinging on the receiver has values between 200 and 1000 kW/m². This high flux allows working at relatively high temperatures of more than 1500°C.

Advantages:

1. Very high concentration ratio of 300-1500 can be achieved.
2. They can conveniently store thermal energy.
3. They are quite large and thus benefits from economies of scale.

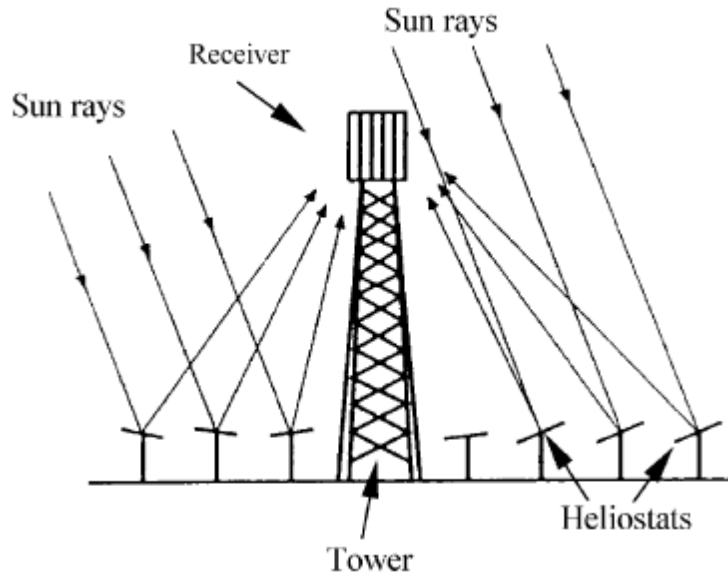


Fig.14 [13] Power Tower

Disadvantages:

- 1) Relatively expensive in comparison to the parabolic trough.
- 2) Complex structure as the receiver is located on the tower.

1.7) Comparison of different collectors:

The below table shows the comparison of different solar collectors with their operating temperature range and application areas.

Table.1 Comparison of different solar collectors

Sr.no	Name of collector	Type	Operating temperature(°C)	Concentration ratio	Heat transfer medium	Application areas
1	Flat plate	Non-concentrating	30-80	1	Water or air	Air-heating and water-heating
2	Evacuated tube	Non-concentrating	50-200	1	Water or air	Water, oil, air heating
3	Parabolic trough	Line-focussing	60-300	15-45	Water, air, thermal	Power generation, water and

					oil	air heating
4	Linear Fresnel reflector	Line-Focussing	60-250	10-40	Water, air, thermal oil	Water and air heating
5	Dish type	Point-focussing	100-500	100-1000	Water, Thermal oil	Steam generation, Parabolic dish engines
6	Power tower	Point-focussing	150-2000	100-1500	Thermal oil	Power generation

- The evacuated tube collector receives diffuse light that the concentrating collector cannot do. However, the evacuated tube collector has a much greater thermal loss ratio, so the extra heat collection is more or less lost.
- The amount of diffuse energy collected by flat-plate collectors in most regions is not sufficient to compensate for the tracking capability of the troughs.
- Also that the typically higher optical efficiency of the flat-plate collector compensates only partially for the higher thermal efficiency of the concentrators.
- Flat plate collectors have a lower thermal efficiency in comparison to the parabolic trough collectors.
- The parabolic trough collector has a much less internal heat capacity for the fluid circulating in it and hence very small heat loss when the system turns on at every morning.

1.8) Objectives of the Proposed study:

The proposed work has the following objectives and contributions in the field of parabolic trough solar collector system:

1. To develop a flexible mathematical model by using systems approach and integration of all the parameters that defines the whole system, and also analysing the interactions and relationships between different parameters affecting the PTSC system.
2. To propose a methodology by which the design and selection of parabolic trough solar collector system can be made comprehensive and easy.
3. The above model is to be used in modelling and analysis for in depth study of the whole system.
4. Optimization of PTSC system with respect to the performance i.e. thermal efficiency, collector efficiency, quality, reliability, durability and most importantly the cost of different materials constituting the PTSC system.
5. Complete analysis, evaluation, and comparison of the different PTSC systems available in the global market, and also the ranking and optimum selection of the PTSC system.
6. To design and fabricate the Prototype Parabolic Trough Solar Collector system for hot water generation and its feasibility in other applications.
7. To fabricate a cost efficient parabolic trough solar collector system with the use of different alternative materials.
8. To calculate the performance of the PTSC system for the hot water production in terms of useful heat gain, temperature of water in the storage tank, instantaneous efficiency, hourly and overall thermal efficiency.
9. Experimental analysis, performance evaluation and comparison of glass cover tubes of different diameters in terms of efficiency and selecting the best result for improved efficiency of the fabricated PTSC system.
10. To calculate the values of performance parameters of the optimum design thus obtained from the experimental analysis.

1.9) Methodology:

For the fulfilment of the objectives shown above the following methodology are used:

- System approach(MADM Approach, Graph Theoretical Approach)

2.6.1) MADM approach: The step wise procedure in MADM methodology is as follows:

- i. Identification and categorisation of attributes under different parameters affecting the PTSC system.
- ii. Development of cause and effect diagram for the identification of appropriate attributes for the selection and evaluation of the system.
- iii. Collect the comprehensive and exhaustive information about the each attribute for the precise coding of the attribute alternatives.
- iv. Attributes are assigned codes using n-digit coding scheme.
- v. Elimination search to find out the limited number of attributes which are affecting the selection more as per the requirements. Threshold values of these attributes are calculated or given by the team of experts for a particular application.
- vi. Develop decision matrix in terms of attributes for accepted systems. A Relative importance matrix for any particular application is developed by the team of experts.
- vii. Weight vectors are calculated and hence a weighted normalized matrix is developed for the accepted systems.
- viii. TOPSIS technique, Line graph and spider graph representations are used for the ranking and selection of the system.

2.6.2) Graph Theory: The step wise procedure in Graph Theory is as follows:

- i. The system is divided into different subsystems.
- ii. Different parameters or structural constituents under each subsystem are identified.
- iii. A digraph is made for the subsystems which show the interaction between them.
- iv. A permanent matrix is formed from the above digraph.
- v. From the above matrix permanent function is derived.
- vi. Digraph of the parameters of each subsystem and their permanent matrices are also made as above which is used in the derivation of permanent function.
- vii. This permanent function is used for evaluation of the system.

Chapter - 2

Literature Review

2.1) Introduction:

In this literature review the thorough study of research papers on the parabolic trough solar collector is done. The 22 research papers starting from the year 1976 to 2011 are studied. After analysing the papers it is observed that a lot of work has been done on the performance characteristics of the PTSC system i.e. thermal efficiency, optical efficiency, and power output. Some research work has been done on different components of the PTSC system i.e. absorber tube, reflector, tracking mechanism, and the support structure. The main area of application of parabolic trough is in power generation so maximum amount of work is done in this field. Also research work on the use of parabolic trough for some other applications is also studied. A lot of research work has been done on the cost reduction of the parabolic trough solar collector system as the cost of electricity obtained from this system is very high. The proposed work that has been done mainly on the basis of the literature review is explained below.

2.2) Categorization of Literature Review: The literature review has been categorized on the basis of:

- Performance
- Design, Materials and economics
- Application
- Systems approach(MADM-TOPSIS, Graph theoretical approach)

2.2.1) Performance:

Ari Rabl (1976) compared a variety of different solar concentrators in terms of their most important general characteristics namely concentration, acceptance angle, sensitivity to mirror errors, size of reflector area and average number of reflections. The connection between concentration, acceptance angle and operating temperature of a solar collector is analyzed in simple intuitive terms for designing for designing collectors with maximum concentration. Some new concentrators are also proposed including the use of compound parabolic concentrators as second stage concentrators for conventional parabolic or Fresnel mirrors. Such a combination approaches the performance of an ideal concentrator without demanding a large reflector.

Soteris Kalogirou et al. (1997) presented a parabolic trough solar collector system used for steam generation. A modelling program called as PTCDES which is written in BASIC

language is developed for determining the quantity of steam produced by the steam generation system. The flash vessel size, capacity and inventory determine how much energy is used at the beginning of the day for raising the temperature of the circulating water to saturation temperature before effective steam production begins. System performance tests indicate that the modelling program is accurate to within 1.2% which is considered very accurate. The theoretical system energy analysis is presented in the form of Sankey diagram. The analysis shows that only 48.9% of the available solar radiation is used for steam generation.

M J Brookes et al. (2006) tested a parabolic trough solar collector for development in a solar energy research programme. It was a low-temperature testing using water as a working fluid. Both an evacuated glass shielded and unshielded receivers were tested with which the peak thermal efficiencies of 53.8% and 55.2% were obtained respectively. The glass shielded element offered superior performance at the maximum test temperature. The high heat loss sensitivity of the unshielded receiver to the variation in wind speed with corresponding insensitivity of the glass-shielded receiver is determined.

George C. Bakos (2006) performed an experimental study to investigate the effect of using a continuous operation two-axes tracking on the solar energy collected. The collected energy was measured and compared with that on a fixed surface tilted at 40° towards the South. The results indicate that the measured collected solar energy on the moving surface was significantly larger (up to 46.46%) compared with the fixed surface. The proposed two-axis Sun tracking system was characterized by a fairly simple and low-cost electromechanical set-up with low maintenance requirements and ease on installation and operation. It is concluded that when the solar intensity is low and the tracking system operates only on sensor mode, the solar reflector cannot follow the Sun orbit, and the efficiency is decrease significantly, reaching the efficiency of the fixed inclination surface.

Ming Qu et al. (2006) programmed a performance model for solar thermal collector based on a linear, tracking parabolic trough reflector focussed on a surface treated metallic pipe receiver enclosed in an evacuated transparent tube. The effects of solar intensity and incident angle, collector dimensions, material properties, fluid properties, ambient conditions, and operating conditions are considered on performance of the collector. The results from the model are as follows:

1. If the glass envelope is removed, conduction, convection losses enhances.
2. When a vacuum is present in the annulus between the receiver surface and the glass envelope then the losses are effectively eliminated.

3. With the increase in operating temperature the pressure drop decreases because the viscosity of the fluid reduces.
4. The flow rate does not have an impact on PTSC.
5. The efficiency of the collector decreases with the increase in wind speed.
6. Collector efficiency is maximum when the incident angle is zero.

Amirtham Valan Arasu et al. (2006) investigated the performance of a new parabolic trough collector hot water generation system with a well-mixed hot water storage tank. The storage tank water temperature is increased from 35°C at 9.30 h to 73.84°C at 16.00 h when no energy is withdrawn from the storage tank. The average beam radiation during the collection period is 699 W/m². The useful heat gain, collector instantaneous efficiency, energy gained by the storage tank water and the efficiency of the system as a whole are found to follow the variation of incident beam radiation as these parameters are strongly influenced by the incident beam radiation. The values of each of those parameters are observed to be maximum around noon, when the incident beam radiation is maximum.

N. Naeeni et al. (2007) studied that heat transfer from a receiver tube of the parabolic trough collector of the 250kW solar power plants in Shiraz, Iran, is studied taking into account the effects of variation of collector angel of attack, wind velocity and its distribution with respect to height from the ground. The governing equations for the two-dimensional steady state wind flow include continuity, momentum and energy equations and RNG-based k–e model for turbulence scheme. Analysis of wind flow and thermal field around the receiver tube of a large scale of parabolic collectors of a solar thermal power plant shows that the wind flow structure around a receiver tube is completely different than cross flow around a horizontal cylinder Flow field does not strongly depend on wind speed.

S.K. Tyagi et al. (2007) evaluated the exergetic performance of concentrating type solar collector and the parametric study is made using hourly solar radiation from the exergy output is optimized with respect to the inlet fluid temperature and the corresponding efficiencies are computed. The paper concluded the following points:

- i. The parametric study has been made for different mass flow rates and concentration ratio using hourly solar radiation.
- ii. Most of the performance parameters, such as, the exergy output, exergetic and thermal efficiencies, stagnation temperature, inlet temperature, ambient temperature etc. increases as the solar intensity increases.
- iii. Also the exergy output, exergetic and thermal efficiencies are found to be the increasing function of the mass flow rate for a given value of the solar intensity.

K. Ravi Kumar et al. (2009) presented a thermal analysis of an energy efficient receiver for solar parabolic trough concentrator. Various porous receiver geometries are considered for the performance evaluation of a solar parabolic trough concentrator numerical models are proposed for the above receiver for internal heat gain characteristics and heat loss due to natural convection. The analysis is carried out on the basis of RNG-turbulent model and solved using FLUENT. The results showed the improvement in the heat transfer characteristics of the receiver with the introduction of porous inclusions but with a pressure drop as a penalty. The shorter fins were more favourable for improved heat transfer and pressure drop.

P. Rhushi Prasad et al. (2010) compared the performance of fixed flat plate water heater with that of heater with tracking by conducting experiments. A flat plate water heater, which is commercially available with a capacity of 100 litres/day is instrumented and developed into a test-rig to conduct the experimental work. Experiments were conducted for a week during which the atmospheric conditions were almost uniform and data was collected both for fixed and tracked conditions of the flat plate collector. The results show that there is an average increase of 4°C in the outlet temperature. The efficiency of both the conditions was calculated and the comparison shows that there is an increase of about 21% in the percentage of efficiency.

Najla El Gharbi et al. (2011) compared two optical technologies which showed promising results, the first one is the Linear Fresnel mirror and the second one is the parabolic trough. These two technologies are based on linear solar concentration. The main objective of this paper was to report the performance of these technologies by means of numerical analysis. A methodological analysis to design and evaluate the technical feasibility for the use of Fresnel mirror or parabolic trough in a Concentrating Solar Power (CSP) system has been carried out. The influence of ambient conditions and the percentage of different types of energy loss, etc., are analysed. The result of annual collector efficiency for parabolic trough is more than linear Fresnel plant due to the incidence angle and the cosine factor.

M.J. Montes et al. (2011) analysed the contribution of solar thermal power to improve the performance of gas-fired combined cycles in very hot and dry environmental conditions is analysed in this work, in order to assess the potential of this technique, and to feature Direct Steam Generation (DSG) as a well suited candidate for achieving very good results. The particular Integrated Solar Combined Cycle (ISCC) power plant proposed consists of a DSG parabolic trough field coupled to the bottoming steam cycle of a Combined Cycle Gas Turbine (CCGT) power plant. The complementary effect were seen in these cases, because of

the thermal power provided by the solar field compensates the gas turbine part load performance due to the high temperatures. The economic analysis points out that this hybrid scheme is a cheaper way to exploit concentrated solar energy, although it is limited to a small fraction of the combined cycle power. The analysis also shows that the marginal cost of solar electricity is strongly influenced by the goodness of coupling.

Ricardo Vasquez Padilla et al. (2011) performed a one dimensional numerical heat transfer analysis of a PTSC. The receiver and envelope were divided into several segments and mass and energy balance were applied in each segment. Improvements either in the heat transfer correlations or radiative heat transfer analysis are presented as well. The partial differential equations were discretized and the nonlinear algebraic equations were solved simultaneously. Finally, to validate the numerical results, the model was compared with experimental data obtained from Sandia National Laboratory (SNL) and other one dimensional heat transfer models. The results showed a better agreement with experimental data compared to other models.

2.2.2) Design, materials and economics:

Soteris Kalogirou et al. (1994) described a low cost method for mass-production of parabolic surfaces with fibreglass, cavities produced with plastic conduits, covered with fibreglass at the back of the collector surface which provides reinforcement in the longitudinal and transverse directions to increase rigidity. This produces a low-cost high rigidity structure that is an accurate copy of the mould. A synthetic wood with medium density fibres (MDF) of 18mm thickness is used as a mould. The total thickness of the fibreglass is 4mm. The standard deviation of the distribution of the parabolic surface errors is found equal to 4.7 mrad which indicates a very accurate surface. The deflection of the surface to a force corresponding to a wind velocity of 90 MPH is well within reasonable limits.

George C. Bakos et al. (2001) presented the results produced from a simulation program, showing the variation of collector's efficiency as a function of heat transfer fluid flux, pipe diameter, solar radiation intensity and active area of the parabolic trough concentrators. The following results are obtained:

- i. With the increase in flux of the heat transfer fluid the efficiency increases.
- ii. The efficiency drops as the pipe length is increased
- iii. The efficiency increases as the pipe diameter is reduced
- iv. The efficiency increases with the increase in the mirror's active diameter and the intensity of solar radiation.

Hank Price et al. (2002) reviewed the current state of the art of parabolic trough solar power technology and described the R&D efforts that are in progress to enhance this technology. The paper also shows how the economics of future parabolic trough solar power plants are expected to improve. The operating performance of the existing parabolic trough power plants has demonstrated this technology to be robust and an excellent performer in the commercial power industry and since the last commercial parabolic trough plant was built, substantial technological progress has been realized. The various alternative technologies are given for the tracking mechanisms, reflector materials, heat collection elements thermal characteristics, heat transfer fluids and power cycle to reduce the cost of the plant. Parabolic trough solar power technology appears to be capable of competing directly with conventional fossil-fuel power plants in mainstream markets in the relatively near term. Given that parabolic trough technology utilizes standard industrial manufacturing processes, materials, and power cycle equipment, the technology is poised for rapid deployment should the need emerge for a low-cost solar power option

Michael Geyer et al. (2002) worked on the high-performance EuroTrough parabolic trough collector models ET100 and ET150 have been developed for the utility scale generation of solar steam for process heat applications and solar power generation with corresponding receiver tubes which can be used in combination with various heat transfer fluids in large solar fields. Through this absorber tube circulates a heat transfer fluid (HTF), usually synthetic oil, which is heated to a temperature of nearly 400°C. With an optical concentration of 82:1 operating temperatures over 500°C may be reached. There is a cost reduction by simplification of the design, by improvement of the optical performance of the collector, by extension of collector length per drive unit. 14% solar field cost reduction is observed due to weight reduction and collector extension to 150 meters. A 50 MW solar power plant with 549 000 m² of Euro Trough collectors is projected for South Spain.

Daniel M. Blake et al. (2002) worked on the searching for heat transfer and storage fluids and identified the key issues that must be addressed in the development of a new fluid. The properties of a fluid that can be used for both heat collection and storage require a very low vapour pressure at the hot side operating temperature. This requirement can be met by an ionic fluid. Inorganic nitrate salts are the only fluids that have been identified to date that can meet or exceed the 400°C limit and because they are ionic in nature they have negligible vapour pressures. A low freezing point is shown to be particularly important and avoidance of freeze protection measures is demonstrated to allow a fluid cost that is significantly higher than conventional mineral oils or nitrate salts. Freezing points near 0°C seem to dictate

searching for new fluids in the realm of organic salts. The imidazolium salts show promise but they are in an early stage of development.

Maria Brogren et al. (2004) developed a newly aluminium-polymer-laminated steel reflector for use in solar concentrators was evaluated with respect to its optical properties, durability, and reflector performance in solar thermal and photovoltaic systems. The optical properties of the reflector material were investigated using spectrophotometer and scatterometry. The durability of the reflector was tested in a climatic test chamber as well as outdoors. Aluminium-laminated steel reflector has good durability in an outdoor environment, because of the plastic coating that protects the evaporated aluminium foil from moisture and air pollutants. However, the total reflectance decreased significantly and the light scattering became anisotropic when the material was exposed to damp heat and ultraviolet radiation in a climatic test chamber. It was found that the PET coating did not withstand the accelerated testing and that cracks in the PET layer caused the scattering. Therefore, the material may not be suitable as an internal reflector or in other applications where it may be exposed to high temperatures. However, the optical properties of the Al-on-steel reflector remained unchanged during one year of outdoor exposure in Sweden and the material showed potential as a cost-effective reflector in low-concentrating solar thermal and photovoltaic applications.

Nasir. A. (2004) worked on the design, construction and performance of parabolic cylindrical trough air heater and presented an experimental study of the performance of the same. The solar air heater is a double-flat-plate collector type, constructed with galvanized square pipes and assembled into a parabolic cylindrical trough solar collector capable of generating heat after being reflected and concentrated on the absorber. A centrifugal fan was used to provide air circulation. The results showed that the maximum temperature attained was 97°C with an overall thermal efficiency of 65%.

F Mammadov et al. (2008) tried to solve the economic, ecological and energy efficiency problems in dealing with the oil industry through a solar thermal application. They mentioned that a solar energy application has a great advantage for the oil industry to be economical with fossil fuels partly, to improve safety measures and ecology, and to also reduce additional financial expenses. New technical and technological opportunities of a solar energy application in crude oil treatment in oil fields has been established by decreasing the additional expenses and reduction of the production cost of commercial oil the economic advantage of a solar thermal application in crude oil is treated.

Michael Di Grazia et al. (2009) discussed the field and lab test results and properties of Reflectech mirror film. The properties that are tested and the results are as follows:

- i. Stability under ultra violet light through accelerated testing and outdoor real time testing.
- ii. Mechanical stability and resistance to moisture through water immersion tests.
- iii. Mechanical resistance to high wind loads.
- iv. Lighter weight and resistance to breakage that reduces transportation and installation costs.
- v. Lower initial cost compared with the curved glass mirrors.

Rafael Almanza et al. (2009) presented the first aluminum-surface solar mirrors, which, after 12 years of exposure to the aggressive weather conditions of Mexico City, have a reflectance decrease of only 3% (from 0.85 to 0.82), with only small scratches on the SiO₂ layer. Also two alternatives are presented for solar aluminium mirrors which are:

- i. Mirrors with integrated first and second surfaces and
- ii. First-surface compound mirrors.

Each mirror and its fabrication are described, along with their weather tests. The aluminum first-surface solar mirror lasts for at least 12 years, and is a good alternative material for parabolic troughs, heliostats, CPC, Fresnel technology and dish concentrators.

David Barlev et al. (2011) focussed their work on the innovation in CSP technologies over the last decade. A multitude of advancements has been developed during this period, as the topic of concentrated solar power is becoming more mainstream. Improvements have been made in reflector and collector design and materials, heat absorption and transport, power production and thermal storage. Many applications that can be integrated with CSP regimes to conserve and sometimes to produce electricity have been suggested and implemented, keeping in mind the environmental benefits granted by limited fossil fuel usage.

Silverio García-Cortés et al. (2011) shows the work carried out to determine the real shape and the intercept factor of a new prototype of parabolic solar collector. Convergent photogrammetry with off-the-shelf equipment was used to obtain a 3D point cloud that is simultaneously oriented in space and adjusted to a parabolic cylinder in order to calculate the deviations from the ideal shape. When a new design for a solar collector is developed it is necessary to guarantee that its intercept factor is good enough to produce the expected

thermal jump. Deviations of the collector mirrors from its theoretical position are detected. Greatest deviations correspond to the borders of the collector and they are higher for the collector in a horizontal position rather than in a vertical position. The results agree with the expected situation, since the main factor causing the deformation is the weight of the collector. By calculating the normal vectors to the adjusted surface the interception coefficient of the collector is calculated. The results obtained show that nearly 10% of the incidents rays does not reach the absorber. This percentage is slightly below the recommended value for the type of collector analysed.

2.2.3) Applications:

Soteris A. Kalogirou (2004) presented a survey of the various types of solar thermal collectors and applications are presented. Initially, an analysis of the environmental problems related to the use of conventional sources of energy is presented and the benefits offered by renewable energy systems are outlined. A historical introduction into the uses of solar energy is attempted followed by a description of the various types of collectors including flat-plate, compound parabolic, evacuated tube, parabolic trough, Fresnel lens, parabolic dish and heliostat field collectors in order to show the extent of their applicability. These include solar water heating, which comprise thermo syphon, integrated collector storage, direct and indirect systems and air systems, space heating and cooling, which comprise, space heating and service hot water, air and water systems and heat pumps, refrigeration, industrial process heat, which comprise air and water systems and steam generation systems, desalination, thermal power systems, which comprise the parabolic trough, power tower and dish systems, solar furnaces, and chemistry applications. The application areas described in this paper show that solar energy collectors can be used in a wide variety of systems, could provide significant environmental and financial benefits, and should be used whenever possible.

Scrivani et al. (2007) examined the concept of utilizing trough type solar concentration plants for water production, remediation and waste water treatment. This presented study is intended to find applications of the solar trough concentration technology beyond heat and refrigeration. A number of possibilities have been identified are related to clean water production by processes such as solar distillation, atmospheric condensation and waste processing. The fresh water thus obtained can be used for human consumption, but the free heat produced by trough plants makes for an easy way to obtain irrigation water from waste, refuse and landfills. The possibility of obtaining refrigeration without the use of electrical power opens up further possibilities for obtaining water, even from thin air. The possibility of

utilizing this water for irrigation is a concrete step in the favour of agriculture in Mediterranean countries. The system is a low cost, no pollution, and alternative to incineration.

Hazim Mohameed Qiblawey et al. (2008) described several desalination technologies in commercial and pilot stages of development. The primary focus is on those technologies suitable for use in remote areas, especially those which could be integrated into solar thermal energy systems. The Solar energy coupled to desalination offers a promising prospect for covering the fundamental needs of power and water in remote regions, where connection to the public electric grid is either not cost effective or not feasible, and where the water scarcity is severe. As described in the paper the solar desalination processes can be devised in two main types: direct and indirect collection systems. The “direct method” use solar energy to produce distillate directly in the solar collector, whereas in indirect collection systems two sub-systems are employed. Solar thermal desalination plants utilizing indirect collection of solar energy can be classified into the following categories: atmospheric humidification/dehumidification, multi-stage flash (MSF), multi-effect distillation (MED), vapour compression (VC) and membrane distillation (MD).

M. M. Alkilani et al. (2009) presents a theoretical investigation of output air temperature due to thermal energy discharge process from a phase change material (PCM) unit consists of inline single row of cylinders contain a compound of paraffin wax with aluminium powder. This system consists of a single-glazed solar air collector integrated with a PCM unit which is divided into cylinders as an absorber-container installed in the collector in a cross flow of pumped air. The assumptions taken are:

- 1: Air behaves as an incompressible fluid.
- 2: the Stefan number is very low.
- 3: the heat loss assumed very low, and neglected.
- 4: the heat transfer process in every cylinder is radially symmetric;

The heat transfer in PCM is by conduction. To overcome the low thermal conductivity of paraffin wax they added a powder of material which has a good conductivity property such as copper or aluminium powder and paraffin wax with aluminium powder is used to decrease the system cost. A Matlab computer program has been developed to compute the air temperature; cylinder by cylinder along the duct, freezing time for each cylinder, and the time required to discharge all the thermal energy. Output air temperatures due to a discharge process in a solar air heater integrated with a phase change material have been predicted for eight different values of mass flow rate, and reached the maximum temperature (42°C), with

mass flow rate (0.05kg/s). The phase change material consists of paraffin wax with mass fraction 0.5% aluminium powder to enhance the heat transfer, the freezing time for the phase change material unit has been predicted for each mass flow rate, The freezing time of the phase change material cylinders related inversely to the mass flow rate, and take longer time approximately (8 hours) with flow rate of 0.05 kg/s.

A. El Fadar et al. (2009) presented a study of solar adsorption cooling machine, where the reactor is heated by a parabolic trough collector (PTC) and is coupled with a heat pipe (HP). This reactor contains a porous medium constituted of activated carbon, reacting by adsorption with ammonia. A model, based on the equilibrium equations of the refrigerant, adsorption isotherms, heat and mass transfer within the adsorbent bed and energy balance in the hybrid system components has been developed. From real climatic data, the model computes the performances of the machine. In comparison with other systems powered by flat plate or evacuated tube collectors. The numerical results show a great sensitivity of the performance coefficient of the machine to the radius of the absorber and the aperture width of collector. Also:

1. For a given collector configuration, there exists an optimal dimension of the reactor.
2. In the ranges investigated, the optimum performance of the system is COPs = 0.18, when the external radius of the absorber and aperture width of the collector are 14.5 and 70 cm, respectively.
3. The PTC is a useful component for improvement of the solar adsorption refrigeration systems. This system is more efficient and lighter when coupled with heat pipe.

2.2.4) Systems approach (MADM-TOPSIS, Graph theoretical approach)

Ashish Bhateja et al. (1996) presented a methodology for total design and evaluation of optimum spring based on multiple attribute decision making (MADM) approach, taking into account various design attributes at the conceptual stage of the design itself. Springs were first coded using a comprehensive attribute based three tier coded structure presented in the form of an algorithm. 'Elimination search' algorithm is presented for the rapid convergence of very large number to a manageable short-list of potentially suitable springs based on a few pertinent attributes. The short-listed alternatives are ranked on the basis of suggested merit index, by using a MADM method termed TOPSIS. At the last, it is concluded that the method is efficient and may easily be developed into an expert system for total design of springs, providing to be of immense use to the user and manufacturer alike.

P.P. Bhangale et al. (2004) have solved the robot selection problem which arises due to increasing complexity, available features, and facilities offered by different robotic products. The objective of their research is to generate and maintain a reliable and exhaustive database of robot manipulators based on their different pertinent attributes. That database can be used to standardize the robot selection procedure when the manufacturing firm has decided to use the robot for a particular operation. The methodology presented in this paper can help the robot user to save time by providing him a tool for selecting the robot system most suited for his operational needs. This paper presented a robot selection procedure based on the Multiple Attribute Decision Making (MADM) approach. Here by identifying 83 attributes of the robots, the attempt has been made to codify most of the robot characteristics, which will define the robot precisely and accurately. The coding scheme is illustrated with an example of selecting a robot for some pick-n-place operation. It has presented the result of the information processing in terms of a merit value, which is used to rank the robots in the order of their suitability for the given application.

R. T. Durai Prabhakaran et al. (2006) described a methodology for evaluation, coding, ranking, and optimum selection of subsystems for a composite product used directly by its manufacturers. The 77-attribute electronic coding scheme and the evaluation techniques are presented in this paper and are useful to the designer during all the phases of the design process, and the manufacturer for the selection of optimum subsystems, which meet global market requirements. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a Multiple-Attribute Decision Making (MADM) approach used for selection of subsystems for a composite product development in order of preference for a given application. Two graphical methods of the MADM approach for evaluation and comparison are also introduced by the authors. It is recommended in this paper that the manufacturer of a composite product should develop attribute-based specifications in the form of a proposed coding scheme. This will directly help industry in carrying out SWOT (Strength– Weakness–Opportunities–Threats) analysis from the point of view of its manufacturing and business strategies.

R.K. Garg et al. (2006) developed a deterministic quantitative model based on graph theoretical methodology to compare various technical and economical features of wind, hydro and thermal power plants and also used to evaluate and rank the power plants in ascending or descending order in accordance with the value of their suitability index. It is concluded by the authors that the methodology present in this paper allows a decision maker to perform, not just a general analysis, but also other various focused analysis regarding his personal preferences.

R.K. Garg et al. (2007) presented a computational methodology for a computer-based solution to the problem of evaluation and selection of an optimum power plant. This methodology is named as multiple attribute decision making (MADM) methodology and consists of elimination search and technique for order preference by similarity to ideal solution (TOPSIS) approach. Authors have suggested a coding scheme based on 190 pertinent attributes for a given thermal power plant for the development of a large database of available plants, and their subsequent retrieval. The “technique for order preference by similarity to ideal solution” (TOPSIS) approach has provided a complete and thorough comparison and ranking of available power plants. Authors have also developed user friendly computer software for Elimination Search and TOPSIS approach.

R.T. D. Prabhakaran et al. (2007) developed an integrated systems model for the structure of the composite product system in terms of its constituents and interactions between the constituents and the modelling processes, curing kinetics etc. using graph theory and matrix algebra. This proposed systems methodology for developing a composite product considered all attributes responsible for design, production, and process parameters. The composite product is first modelled with the help of graph theory, then by variable adjacency matrix and then by a multinomial known as permanent functions. The permanent function has provided an opportunity to carry out structural analysis of the composite product in terms of strength, weakness, improvement, and optimization by correlating the properties of a composite with its structure.

Varinder Singh and V.P. Agrawal (2008) have presented a methodology that builds a flexible and comprehensive model of manufacturing system, which has the capability to consider the interdependencies between its various subsystems. After the identification of elements constituting a manufacturing system and the interactions between them, it has been represented by graph-based model. Also the matrix models and the variable permanent function models have been developed to carry out decomposition, characterization and the total analysis. Structural patterns and combination sets of subsystems interacting in various ways have been recognized as capabilities of manufacturing system in different performance dimensions. The permanent function of the manufacturing system matrix has been proposed as a systematic technique for structural analysis of manufacturing system.

C. Phaneendra Kiran et al. (2011) presented a methodology useful in optimal selection of a mechatronic system based on the Multi Attribute Decision Matrix (MADM) approach. A coding scheme which is a collection of 88 attributes which characterize a mechatronic system and is useful in differentiating mechatronic system alternatives is proposed. An illustrative

example of selecting a hard disk drive (HDD), a mechatronic system, for the up-gradation of consumer's office desktops is given to explain the methodology. Authors also identified 3-stage selection procedure, which includes elimination search, TOPSIS based evaluation and ranking, other graphical methods (linear graph and spider diagram), works on the information of the pertinent attributes. This procedure ranks the mechatronic system alternatives based on the Euclidian distance of alternatives from hypothetically best and hypothetically worst mechatronic systems.

C.P. Kiran et al. (2011) presented a novel methodology which combines all the design aspects together to generate a useful form of solution for the mechatronic industry. This methodology concurrently considered all the x-abilities/design aspects along with interactions without missing any useful information and hence led to a high quality product. The methodology presented in this paper consists of graph theory, matrix algebra, and permanent multinomial. Eight x-abilities namely, miniaturization, intelligence, integration, environment, quality, reliability, manufacturing, and assembly for concurrent design of a mechatronic system and the design parameters under each x-ability are identified. Also a colour graph is proposed for visual analysis.

2.3) Tabular form of Literature Review:

The below table shows the area of research of different authors and their contributions and applications of the research. This information about the research work concentrated to the PTSC system, MADM approach and Graph Theory is represented in a tabulated form.

Table.2 Research contributions of different authors:

Sr.no	Author	Area of research	Contributions and applications of research
a) Performance Based:-			
1	Ari Rabl (1976)	Comparison of solar concentrators	Combination of different parameters like acceptance angle, concentration ratio, etc. for the development of a new solar concentrator.
2	Soteris Kalogirou et al. (1997)	Performance of PTSC system	Modelling with PTCDES program and performance evaluation of PTSC system for steam generation application

3	M J Brookes et al.(2006)	Performance of parabolic trough Solar collector(PTSC)	The glass-shielded element offered superior performance at maximum test temperature reducing the overall heat loss coefficient by half.
4	George C. Bakos(2006)	Tracking system	Collected solar energy on the moving surface is much larger in comparison with the fixed surface.
5	Ming Qu et al.(2006)	Performance of PTSC	Effects of glass cover, vacuum, pressure drop, incident angle, flow rate, and wind speed are calculated.
6	Amirtham Valan Arasu et al. (2006)	PTSC for hot water generation	Calculation of thermal and instantaneous efficiency of PTSC system with water recirculating from the storage tank for water heating application.
7	N. Naeeni et al.(2007)	Receiver tube	The effects of variation of collector angle of attack, wind velocity are studied and its distribution. The wind flow structure around a receiver tube is completely different than cross flow around a horizontal cylinder.
8	S.K. Tyagi et al. (2007)	Exergy Analysis	Variation of different parameters like mass flow rate, exergy output inlet temperature stagnation temperature etc. with the hourly thermal efficiency.
9	K. Ravi Kumar et al.(2008)	Solar parabolic trough receiver	The porous inclusions in the receiver improves its heat transfer characteristics but with a pressure drop as penalty.

10	P. Rhushi Prasad et al. (2008)	Comparison of fixed flat plate collector with that having tracking mechanism	There is an average increase of 4°C in the outlet temperature and an increase of about 21% in the percentage of efficiency.
11	Najla El Gharbi et al.(2011)	Comparison of Fresnel reflector and parabolic trough	The collector efficiency of parabolic trough is more than Fresnel reflector
12	M.J. Montes et al.(2011)	Integrated Solar Combined Cycle	Hybrid scheme is a cheaper way to exploit concentrated solar energy. The analysis also shows that the marginal cost of solar electricity is strongly influenced by the goodness of coupling
13	Ricardo Vasquez Padilla et al. (2011)	Receiver tube	Heat transfer and optical analysis of the receiver and partial differential and non-linear algebraic equations are solved.
b) Design, Materials, And Economics Based:-			
14	Soteris Kalogirou et al. (1994)	Method for low-cost PTSC production	Low cost method for mass-production of parabolic surfaces with fibreglass and plastic conduits.
15	George C. Bakos et al. (2001)	Simulation	Variation of collector's efficiency as a function of heat transfer fluid flux, pipe diameter, solar radiation intensity and area of collector.
16	Hank Price et al.(2002)	Cost Reduction	The various alternative technologies are given for the tracking mechanisms, reflector materials, heat collection elements thermal characteristics, heat transfer fluids and power cycle to reduce the cost of the plant
17	Michael Geyer et al.(2002)	Cost efficiency	Cost reduction by simplification of the design, by improvement of the optical performance of the collector, by extension of collector length per drive unit. 14% solar field cost reduction are observed due to weight reduction and collector extension to 150 meters
18	Daniel M. Blake et al.(2002)	Heat transfer fluid	An ionic fluid is used for both heat collection and storage requires a very low vapour pressure at the hot side operating temperature. Inorganic nitrate salts are

			used that can meet or exceed the 400°C limit because they are ionic in nature. The imidazolium salts are found in the above respect
19	Maria Brogren et al.(2004)	Properties of aluminium-polymer-laminated steel reflector	The optical properties, durability, and reflector performance is calculated and most importantly the cost-effectiveness of the reflector
20	A. Nasir(2004)	Design and performance of PTSC	Design, construction and performance of parabolic cylindrical trough air heater
21	F Mammadov et al.(2008)	Crude oil treatment using parabolic trough	Use of parabolic trough solar collector for the treatment of crude oil in the oil fields for economical, ecological, and energy efficient advantages.
22	Michael Di Grazia et al. (2009)	Lab test result of Reflectech mirror film	Mechanical stability and mechanical resistance to moisture, stability under ultra violet light.
23	Rafael Almanza et al. (2009)	Reflector surface	Aluminium- surface solar mirrors have a reflectance decrease of only 3% and is a good alternative material for parabolic troughs.
24	David Barlev et al. (2011)	Innovation in CSP technologies	Advancements in reflector and collector design and materials, heat absorption and transport, power production and thermal storage for better performance.
25	Silverio García-Cortés (2011)	Intercept factor	Greatest deviations are at the borders of the collector and are higher for the collector in a horizontal position rather than in a vertical position. Nearly 10% of the incidents rays do not reach the absorber.
c) Applications Based:-			
26	Soteris A. Kalogirou (2004)	Survey of different solar collectors	Description of the various types of collectors and their optical and thermal analysis and environmental problems and their performance

27	A. Scrivani et al.(2007)	Applications of PTSC	Waste water treatment, solar distillation, refrigeration without electrical power
28	Hazim Mohameed Qiblawey et al. (2008)	Desalination technologies	Use of different concentrated solar collectors in various desalination technologies.
29	M. M. Alkilani et al.(2009)	Heat transfer properties using phase change material	Output air temperatures due to a discharge process in a solar air heater integrated with a phase change material have been predicted for different values of mass flow rate and hence the maximum value of outlet air temperature is calculated at a given mass flow rate.
30	A. El Fadar et al.(2009)	Solar adsorption refrigeration systems	The numerical results show a great sensitivity of the performance coefficient of the machine to the radius of the absorber and the aperture width of collector. System is efficient when coupled with a heat pipe
d) Systems Approach (MADM-TOPSIS, Graph Theoretical Approach)			
31	Ashish Bhateja et al. (1996)	MADM approach on Springs	Evaluation, comparison, ranking of springs.
32	P.P. Bhangale et al. (2004)	MADM approach on robots	Evaluation, comparison, ranking and optimum selection of different robot designs.
33	R.T.Durai Prabhakaran et al. (2006)	MADM approach on composite system	Evaluation, coding, ranking, and optimum selection of subsystems for composite product
34	R.T. D. Prabhakaran et al. (2007)	Graph theory on composite system	Evaluation, coding, ranking, and optimum selection of subsystems for composite product.
35	Varinder Singh and V.P. Agrawal (2008)	Graph theory on manufacturing systems	Development of permanent function for structural analysis of manufacturing systems.

2.4) GAP Analysis:

From the above literature review it is seen that a lot of research work has been done in the field of parabolic trough solar collector system by different researchers. The following work has been observed after analysing all the literature work:

- **What has been done:** Performance analysis of PTSC system with the use of different materials for receiver tube, reflector surface, heat transfer fluid, support structure, and also the modifications in them. The experimental and theoretical analysis of the whole system under varying conditions i.e. winds speed, different climatic conditions, ambient temperature etc. It is observed that the main application of a parabolic trough solar collector is in the power generation with small use in water heating, air heating, waste water treatment and other applications. A lot of research has been done on the reduction of the overall cost of the PTSC system.
- **What has not been done:** The use of systems approach (MADM, Graph theoretical) for the evaluation, ranking and selection of the PTSC system has not been attempted before. Also no one has considered the structural constituents for analysing a PTSC system along with their interactions at design stages. Also consideration of all the factors i.e. performance, cost, design, materials, cost, quality, reliability etc. are not collectively evaluated and analysed before in a single research work. The research work regarding the use of glass cover tubes of different diameters over the copper tube and their performance evaluation with the comparison between them to select the best design of the absorber tube has not been done before.
- **Proposed work:** Use of the systems approach (MADM Approach, Graph theoretical) for this system will be extremely beneficial as it provides a lot of information and knowledge about the PTSC system to the users. It also gives the optimal design out of the alternative designs available in the global market. It can help in getting good benefits, high overall performance and good quality of the product in shorter time. Also it has not been attempted earlier so it's a new concept and it is hoped that system approach (MADM, Graph theoretical) will be a very useful technique to carry out the proposed study. Also on the basis of the knowledge gained from the system approaches a PTSC system is fabricated and an experimental investigation of the PTSC system with the use of glass cover tubes of different diameters is done to find out the best design of the absorber tube with glass cover tube for optimum performance of the system.

Chapter-3

System Approach (MADM-TOPSIS, Graph Theoretical) for PTSC system

3.1) Introduction:

Solar energy is utilized to fulfil our daily needs like water heating, space heating and power generation. A PTSC system is used for all the above applications. This system is mainly used for the steam and power production throughout the world but its use in the water and air heating applications is very limited. Flat plate collectors are generally used for the hot water production because they are comparatively cheaper than the PTSC system and also are easily available in the market. But they are less efficient than PTSC system which justifies their use for the water heating applications. The major problem with this technology is its unawareness amongst the people as they do not know what the best options are and which PTSC is to select from the global market. So there arises a need of PTSC system to be reached to the common man. In this respect the selection of parabolic trough solar collector becomes very important this as well as a very difficult task as there are a large number of parabolic trough solar collectors available in the global market. So different considerations such as performance, availability, maintainability, and economics concerned with the parabolic trough solar collector are considered during the selection. The identification of the maximum number of attributes results into the maximum amount of information about the system making it more exhaustive in nature. This is very helpful in the comparison of all the designs available in the global market and further selection of the PTSC. Every system is defined by its attributes and hence the attributes for the PTSC system are identified taking into account all the components and measuring instruments used in the system. A step by step procedure is followed in this approach which is:

- i.** The attributes defining the whole system are identified and categorized under different parameters affecting the system.
- ii.** A cause and effect diagram is also made for an optimized PTSC system which is very helpful in identification of attributes as well.
- iii.** The attributes are given codes on the basis of an n-digit coding scheme taking into account all the quantitative and qualitative attributes.
- iv.** The lot of information is thus arrived after coding of the attributes which is further very useful in the evaluation and selection procedure.

- v. A 3-stage selection procedure consisting of elimination search, evaluation by TOPSIS procedure, and final selection is used.
- vi. The methodology is explained with the help of an example in which 4 different alternative PTSC designs with four different attributes are used.
- vii. Ranking is done on the basis of a mathematical TOPSIS procedure, line graph representation, and the spider graph representation.
- viii. SWOT analysis is done and the according to which final selection of the PTSC.

This step by step procedure is followed in the selection of parabolic trough solar collector design.

3.2) Parabolic trough solar collector system- Characteristics and Attributes:

The first and the foremost step in MADM approach is the identification of the attributes which defines the whole PTSC system. The identification of attributes is done in a broad manner taking into account all the parameters affecting the system. A lot of information is gathered if the attributes are identified exhaustively.

3.2.1) Attributes identification:

Parabolic trough solar collector system consists of various subsystems such as reflector, supporting structure, tracking system, receiver etc. all of these subsystems are interrelated and dependent on each other. The most critical way of evaluating the parabolic trough solar collector system is the identification of the attributes affecting its performance characteristics and defining the physical parameters of the system. Proper identification of the attributes is very important because all the identified attributes will define the whole system and if it is done carefully then the selection of the parabolic trough solar collector system will become very precise and easy. The selection of the parabolic trough solar collector system on the basis of a few numbers of attributes is highly incorrect as it results in the improper and inaccurate selection. So the process of identification of the attributes should be highly exhaustive in nature. As far as the PTSC system is concerned the main emphasis is on reducing the cost of the system with the use of alternate materials and on increasing the efficiency of the system so as to make it a cost efficient system with the use by the common man as well. For e.g. instead of using parabolic mirror as a reflector one can use Aluminium foil on stainless steel sheet or polished aluminium as a reflector material to reduce the cost of the system. So a lot more alternate materials are identified to reduce the overall cost so as to make parabolic trough solar collector system affordable, compatible, and useful for the people throughout the world. The attributes are identified and classified under different

categories to make them easily understandable. The classification is done on the basis of different parameters such as:

- a) General
- b) Physical
- c) Performance
- d) Structure
- e) Application
- f) Cost parameters
- g) Control system

Table.3 Categorization of the attributes:

Sr.no	Name of Attribute	29	Aperture area
a) General Parameters:		30	Piping schedule (no of pipes)
1	Type of PTSC	31	Insulation material for pipes
2	Price range	32	Thickness of insulation
3	Region of installation	33	Supply piping length
4	Required application	34	Return piping length
b) Physical parameters:		35	Material for glass cover tube
5	Tracking system	36	Type of coating films
6	Receiver tube material	37	Weather resistance of the film on the reflector
7	Reflector material	38	Reflectance of the film
8	Weight of parabolic trough	39	Aperture width
9	Diameter of receiver tube	40	Focal length
10	Glass cover tube thickness	41	Length per collector module
11	Type of receiver	42	Location of centre of gravity
12	Reflectance of different reflector Materials	43	Size of storage tank
13	Type of heat transfer fluid used	44	Heat capacity of storage tank
14	Type of heat exchanger used	45	Material of storage tank
15	Material for heat exchanger	46	Thermal conductivity of storage tank
16	Material for insulation	47	Insulation for storage tank
17	Type of solar radiation	c) Performance parameters:	
18	Absorber coating material	48	Thermal losses
19	Length of parabolic trough	49	Solar intensity of the region
20	Thickness of parabolic trough	50	Incident angle
21	Length of receiver tube	51	Concentration ratio
22	Thickness of receiver tube	52	Collector efficiency
23	Annulus gap between the receiver tube and the glass cover tube	53	Operating temperature
24	Thickness of receiver tube	54	Heat transfer characteristics of HTF
25	Reflectance of the glass cover tube	55	Boiling point of HTF
26	Orientation of the parabolic trough	56	Viscosity of HTF
27	Transmittance of glass envelope	57	Density of HTF
28	Absorbance of absorber material	58	Thermal Conductivity of HTF

59	Heat carrying capacity of HTF	78	Steam/power generation
60	Reflective loss	79	Water heating
61	Focussing error	80	Space heating
62	Tracking error	81	Process heating
63	Alignment error of the mirror surface	82	Refrigeration & air conditioning
64	Wind speed	83	Waste water treatment
65	Inlet temperature of HTF	f)	Cost parameters:
66	Outlet temperature of HTF	84	Reflector material
67	Temperature of ambient air	85	Type of absorber
68	Humidity of ambient air	86	Material of absorber
69	Air pressure in the annulus area	87	Insulation on the pipe and storage tank
d) Structure parameters:		88	Support structure material
70	Support Structure material	89	Type of Heat transfer fluid
71	Weight of support structure	90	Type of tracking system
72	Type of foundation	g)	Control system:
73	Size of an array of the tracking structure	91	Temperature sensors
74	Length of tracking structure	92	Pressure gauge
75	Area of tracking structure	93	Pyranometer
76	Stiffness of the tracking structure material	94	Electric motor /battery
77	Strength of tracking material	95	Type of bearings used
e) Application:		96	Type of drive

The identification of the attributes and their categorization shown above covers approximately all the factors which will affect the PTSC system. As per the use of PTSC system for different applications is concerned more attributes are added to the above identification. The above classification of the attributes can be restructured depending upon the author's mind set.

3.2.2) Quantification and measurement of the attributes:

The PTSC system is expressed in a detailed manner by the attributes which are quantitative in nature e.g. power output 34 MW, length of the collector 150m etc. These attributes are expressed in the form of numerical values like 0, 1, 2, 3n. There are some attributes which only gives information about the subsystem or the component of the system e.g. type of drive used is hydraulic, and reflector material used is glass, are called as informative attributes. These attributes do not assign any numerical value and are only represented by alphabets A, B, C, D..... etc. Generally the quantification of many of the attributes is not

provided by the manufacturers. But if the manufacturer identifies and provides these attributes by itself then it will become very useful to the User, Designer, Maintenance personnel etc. so that they can design and manufacture the parabolic trough solar collector system by themselves.

A cause and effect diagram is also made for the optimized PTSC system which represents all the causes related to the general, cost, physical, application, structure etc. and their effect on the performance of the system.

3.3) CAUSE & EFFECT diagram:

Cause and Effect Diagram is a technique which is very helpful in identifying and displaying all the possible causes of a particular problem. In this diagram the relationship between the optimized PTSC system and all the factors that are affecting and are responsible for the optimisation of the PTSC system are represented graphically. The biggest advantage of this diagram is that it is easy to read and understand the relationships between different parameters. The cause and effect diagram for an optimized PTSC system is shown in figure.15. It represents the various factors affecting the optimized PTSC system. The main causes here are explained under different categories such as performance parameters, cost, and physical parameters etc. which are further sub-divided into different causes affecting the optimized PTSC system. The cause and effect diagram plays a very important role in the identification of attributes as it constitutes nearly all the factors affecting the PTSC system.

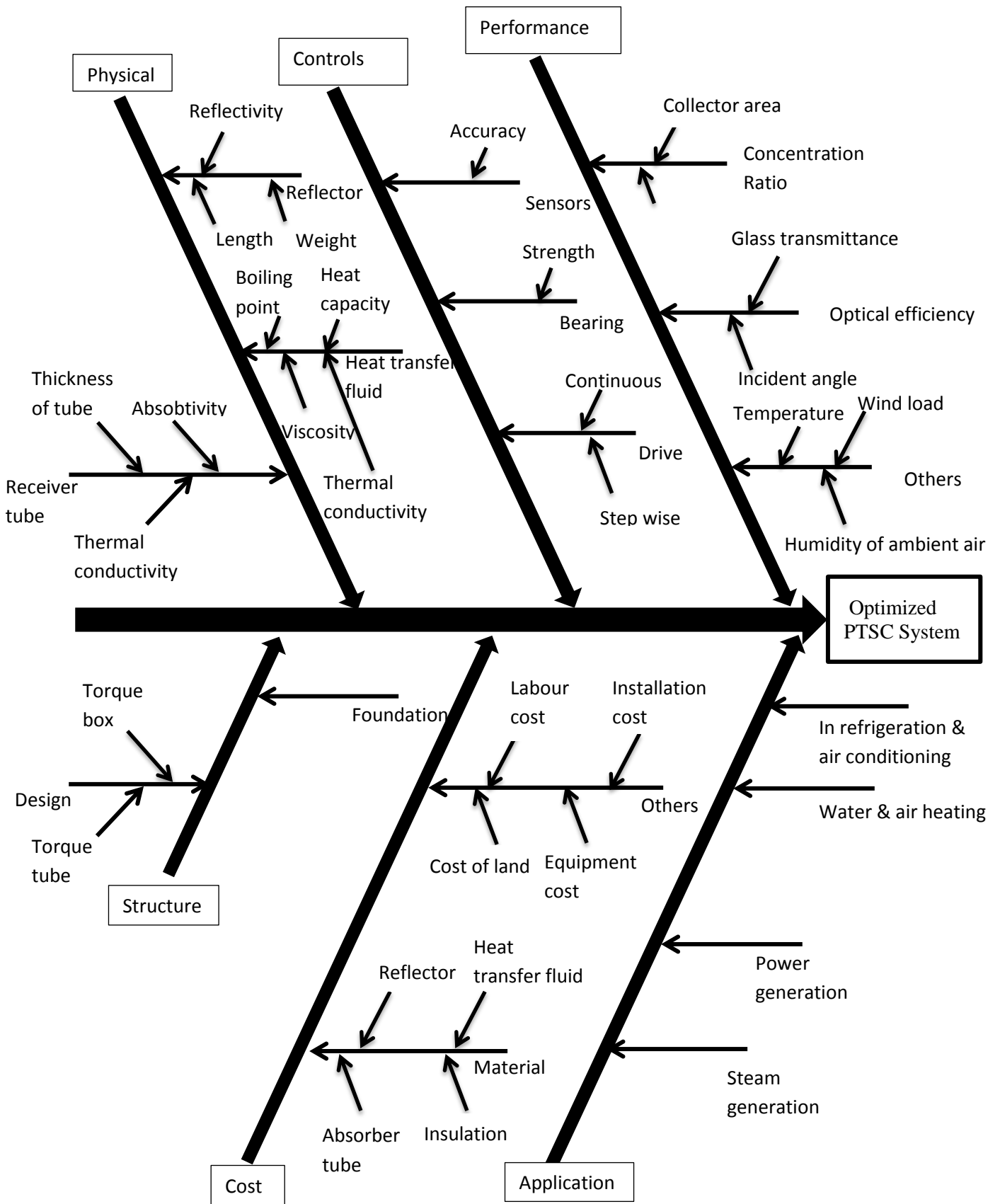


Fig.15 Cause and effect diagram of cost efficient PTSC system

3.4) Usefulness:

- i. The identification of the attributes is very useful for a well-established industry and for the one who is starting an industry. With the use of the entire informative database available a lot of information is gathered and from which very precious knowledge is gained which is highly beneficial for the one who is planning to start an industry in this area.
- ii. It is also useful for an industry which is already established. In this case the sensitivity analysis can also be performed on a single or multiple number of attributes. This is considered very important as by working and concentrating on one or two attributes rather than working on all of them the product is made different and attractive than the other products present in the global market. So by making changes in one attribute the whole system as a product will become different and better than the other products, this attribute will become a unique selling point (USP) of the product. The USP of the system is then highlighted during the advertisement of the product.
- iii. Also in case of a sick unit a critical analysis is done on the above identified attributes. By this the loop holes present in the system are identified and removed hence making it a healthy and effective unit for use.

3.5) Coding scheme:

After the identification of the attributes the next step is to assign codes to the attributes which is either a numerical value or an alphabet. This is done under the coding scheme which is very important as it gives all the detailed information about the attributes. The attributes are qualitative and quantitative in nature. The qualitative attributes are non-deterministic and are of subjective or fuzzy type whereas the quantitative attributes are deterministic in nature. In this paper the quantitative attributes are given codes on an interval scale of 0-6, where 0 indicates that no information is available about the attribute and 6 indicates the best information and alternative present in the attribute.

The coding scheme described above is better explained with an example. Suppose we want to give codes to the attribute number 12 shown above which is the reflectance of the different reflector materials. Now different materials which have good reflectance and are commercially useful are identified. These materials are then assigned numerical values as codes. Now the materials are assigned codes on an increasing order of their reflectance. The material with the lowest reflectance is coded with the lowest value and the material with the

highest reflectance is coded with the highest value. The information given in the table below is very useful for the user as he/she has a database of all the reflector materials available in the global market. This is very helpful as one can choose the best possible option according to the use. For e.g thick mirror is used for the power generation, but aluminium foil, stainless steel sheet is used for the water heating and air heating applications because these materials are cheaper and easily available in the market.

This is done as follows:

Table.4: Reflectance of different reflector materials:

Material	Reflectance	code
White enamel	.65	0
White paint	.80	1
Aluminium foil	.83	2
Fresh snow	.87	3
Stainless steel	.90	4
White plaster	.93	5
Thick mirror	.96	6

Here the reflector material under consideration has the reflectance of .96 which is coded as 6. Similarly all the identified quantitative attributes are assigned numerical values as codes.

Now a PTSC named Flagsol SKAL-ET 150 available in the global market is taken as an example and all the attributes are given codes on the basis of the information available for Flagsol SKAL-ET 150 PTSC. All the codes assigned are represented in the table below.

Table.5: Coding of attributes

Sr.no	Attribute	Information	Code
1	Type of parabolic trough solar concentrator	Linear	L
2	Price range	-	0

3	Region of installation (Solar intensity)	-	0
4	Required application	Steam generation	2
5	Tracking system	-	2
6	Receiver tube material	-	0
7	Reflector material	Glass Mirror	6
8	Weight of parabolic trough	-	0
9	Diameter of receiver	-	0
10	Glass cover tube thickness	-	0
11	Type of receiver	Evacuated tube	4
12	Reflectance of different reflector materials	-	6
13	Type of heat transfer fluid used	-	0
14	Type of heat exchanger used	-	0
15	Material of heat exchanger	-	0
16	Material of insulation	-	0
17	Type of solar radiation	Beam	B
18	Absorber coating material	-	0
19	Length of parabolic trough	148.5m	5
20	Thickness of parabolic trough	-	0
21	Length of receiver tube	-	0
22	Thickness of receiver tube	-	0
23	Annulus gap between the receiver tube and the glass cover tube	-	0
24	Coating on the glass cover tube from inside	-	0
25	Reflectance of the glass cover tube	-	0
26	Orientation of the parabolic trough	-	0
27	Transmittance of glass envelope	-	0
28	Absorbance of absorber material	-	0
29	Aperture area	-	0
30	Piping schedule(no of pipes)	-	0
31	Insulation material for pipes	-	0
32	Thickness of insulation	-	0
33	Supply piping length	-	0

34	Return piping length	-	0
35	Material for glass cover tube	-	0
36	Type of films	-	0
37	Weather resistance of the film on the reflector	-	0
38	Reflectance of the film	-	0
39	Aperture width	5.77m	3
40	Focal length	1.71m	3
41	Length per collector module	12m	2
42	Location of centre of gravity	3.5m	3
43	Size of storage tank	-	0
44	Heat capacity of storage tank	-	0
45	Material of storage tank	-	0
46	Thermal conductivity of storage tank	-	0
47	Insulation for storage tank	-	0
48	Thermal losses	-	0
49	Solar intensity of a particular Region	-	0
50	Incident angle	-	0
51	Rim angle	80 ⁰	4
52	Concentration ratio	82	6
53	Collector efficiency	80%	3
54	Operating temperature	-	0
55	Heat transfer characteristics of the heat transfer fluid	-	0
56	Boiling point of heat transfer fluid	-	0
57	Viscosity of heat transfer fluid	-	0
58	Density of heat transfer fluid	-	0
59	Conductivity of heat transfer fluid	-	0
60	Heat carrying capacity of Heat transfer fluid	-	0
61	Reflective losses	-	0
62	Focussing error	-	0

63	Tracking error	-	0
64	Wind speed	31.5m/s	4
65	Inlet temperature of heat transfer fluid	-	0
66	Outlet temperature of heat transfer fluid	-	0
67	Temperature of ambient air	-	0
68	Humidity of ambient air	-	0
69	Air pressure in the annulus area	-	0
70	Support structure material	galvanized steel	G
71	Weight of support structure	-	0
72	Type of foundation	pile	P
73	Size of an array of the tracking structure	-	0
74	Length of tracking structure	-	0
75	Area of tracking structure	-	0
76	Stiffness of the tracking structure material	-	0
77	Strength of the tracking structure Material	-	0
78	Steam/power generation	large scale	L
79	Water heating	-	0
80	Process heating	-	0
81	Space heating	-	0
82	Waste water treatment	-	0
83	Refrigeration & air conditioning	-	0
84	Reflector material	-	0
85	Type of absorber	-	0
86	Material of absorber	-	0
87	Insulation on the pipe and storage tank	-	0
88	Material of support structure	-	0
89	Type of Heat transfer fluid	-	0
90	Type of tracking system	-	0
91	Temperature sensors	-	0
92	Pressure gauge	-	0

93 Pyranometer	-	0
94 Electric motor /battery	-	0
95 Type of bearings used	-	0
96 Type of Drive	hydraulic	H

The above table shown here is the information provided by the manufacturer to the user. The information presented here is for the better understanding of the PTSC system. Here most of the cells have been given code 0. This is because only PTSC rather than the whole system including absorber tube, heat transfer fluid, storage tank etc. is taken into consideration here. This indicates that the information regarding a particular attribute is not available to the authors. The information about such attributes should be provided so as to make the database more exhaustive which results in a more précised and accurate selection. It will also be an easier and faster process to compare the different parabolic trough collector systems.

3.6) Selection Procedure:

The selection of the best possible PTSC design which is available in the global market for a given application is extremely important. The main emphasis is to select a PTSC design which is less in cost and effective for use in different applications and hence is cost efficient. So after consideration and evaluation of all the attributes of the different designs of the PTSC available throughout the world market, the design which is best suited for a particular area and application is selected.

The selection procedure consists of three stages which are as follows:

- i. Elimination search
- ii. Evaluation by TOPSIS procedure
- iii. Final Selection

3.6.1) Elimination search: After the identification of 97 attributes, the attributes which are not important in the selection of parabolic trough solar collector are eliminated and the attributes which have direct effect on the selection procedure are separated out. These attributes are called as pertinent attributes. According to their applicability some values are assigned to these attributes by obtaining information from the user and the group of experts. These values are called as the threshold values. Hence the main focus is on the pertinent attributes by scanning the database of a parabolic trough solar collector system and leaving out the rest.

3.6.2) Evaluation by TOPSIS procedure: A mini-database is formed which comprises of all the satisfying solutions. Now one has to find out the best solution out of all. These solutions are ranked in order of merit in the selection procedure.

Step 1: All of the information available from the database about these satisfying solutions is represented in the matrix form. This matrix is called as decision matrix ‘**D**’. Each row of the matrix is allocated to the different parabolic trough solar collector system and each column to one attribute. Therefore an element d_{ij} where,

d_{ij} = value of j^{th} attribute for i^{th} parabolic trough solar collector system. The order of the decision matrix is $m \times n$, where

m = number of shortlisted parabolic trough solar collector system.

n = number of pertinent attributes.

Step 2: This step includes the construction of Normalized Specification Matrix, ‘**N**’ from the decision matrix. This matrix ‘**N**’ is represented on a common scale of 0 to 1. An element n_{ij} of the normalized matrix **N** can be calculated as

$$n_{ij} = \frac{d_{ij}}{\sqrt{\sum_{i=1}^m d_{ij}^2}} \quad [15] \quad (3)$$

where d_{ij} is an element of the decision matrix.

Step 3: In this step the relative importance matrix ‘**A**’ is formed for the relative importance of the attributes over other. Element a_{ij} of the relative importance matrix represents the relative importance of the i^{th} attribute over the j^{th} attribute i.e (w_i/w_j) where w_i, w_j are the weight vectors. The relative importance of one attribute over other is decided by the user itself or the group of experts.

Step 4: Now by using Eigen vector method the maximum Eigen value λ is to be obtained by the use of the equation shown below:

$$(A - \lambda I)W = 0 \quad [15] \quad (4)$$

Where $W = \{w_1, w_2, w_3, \dots, w_n\}^T$, where $\sum_{i=1}^n w_i = 1$ [15] (5)

Step 5: In this step the weighted normalized specification matrix ‘**V**’ is obtained by the following expression:

$$V = [V_{ij}], \text{ where } V_{ij} = w_j \times n_{ij}, \text{ where } i=1,2,3,\dots,m \quad [15] \quad (6)$$

3.6.3) Final selection:

After the elimination search the finite number of attributes which are sufficient to evaluate the system are shortlisted. On the basis of these attributes a number of designs are developed and after that the ranking of the parabolic trough solar collector system is done mathematically by TOPSIS method.

3.6.3.1) TOPSIS method:

The above matrix V is used to obtain the positive and negative benchmark parabolic trough solar collector system which is supposed to have best and worst possible attribute magnitudes. Now the optimum design should be the one which is the closest to the positive benchmark PTSC system and farthest from the negative benchmark PTSC system. Now the separation from the positive and negative benchmark PTSC is calculated by the following formulae:

$$S_i^* = \left[\sum_{j=1}^n 1(v_{ij} - v_1^*)^2 \right]^{1/2} \quad (i = 1, 2, 3, \dots, m) \quad [15] \quad (7)$$

$$S_i^- = \left[\sum_{j=1}^n 1(v_{ij} - v_1^-)^2 \right]^{1/2} \quad (i = 1, 2, 3, \dots, m) \quad [15] \quad (8)$$

Where,

S_i^* = Positive benchmark PTSC

S_i^- = Negative benchmark PTSC

3.3.2) Determination of suitability index

The suitability index, 'C*' is a measure of the suitability of the PTSC system for the chosen application on the basis of attributes considered. It is defined as the relative closeness to the HBS, and is expressed as

$$C^* = S_i^- / (S_i^* + S_i^-), \quad i = 1, 2, \dots, m \quad [15] \quad (9)$$

Where, C^* = relative closeness to the positive benchmark PTSC.

Now the ranking is done with the decreasing value of C^* .

Illustrative example:

The above mentioned theory of the MADM-TOPSIS approach will be easily understood with the help of an illustrative example. Four alternative PTSC designs which are commercially

available and are used for different applications are selected from the global market. The names of the collectors are shown in the table below:

Table.6 Alternative PTSC designs from the global market

Sr.no	Name of PTSC
1	Flagsol SKAL-ET 150
2	Sener
3	IST Solucar PT-2
4	Acciona Solar Power SGX 2

The example is as follows:

Suppose we want to select a parabolic trough solar collector for the Indian conditions. It is to be noted that here only parabolic trough collector which is a part of PTSC system is taken into account and is illustrated just to explain the methodology. The minimum requirement is as follows:

Table.7: Minimum requirements

1. Concentration ratio	more than 70
2. Power Output	≤ 25 MW
3. Optical efficiency	at least 75%
4. Type of drive used	hydraulic
5. Tracking system	two axis
6. Reflector material	thick mirror

After analysing the global market the 4 best possible PTSC designs are selected and are compared and ranked with the use of the MADM-TOPSIS methodology. According to their use for different application areas the best suited design is selected. The values of the quantitative attributes of different PTSC designs are shown in the table mentioned below:

Table.8: Attributes for the candidate PTSC

Sr. No.	PTSC	Concentration ratio	Focal length	Optical efficiency	Length
1	Flagsol SKAL-ET 150	82	1.71	80	148.5
2	Sener	80	1.7	76	150
3	IST Solucar PT-2	63	1.73	75	149
4	Acciona Solar Power SGX 2	81	1.72	77	130

Now the procedure for the selection of the PTSC is as follows:

Step-1: Formation of the decision matrix ‘**D**’, in which the rows of the matrix are candidate PTSC and the columns are their attribute values.

$$D = \begin{bmatrix} 82 & 1.71 & 80 & 148.5 \\ 80 & 1.70 & 76 & 150 \\ 63 & 1.73 & 75 & 149 \\ 81 & 1.72 & 77 & 130 \end{bmatrix} \quad (10)$$

Step 2: Construction of relative importance matrix from decision matrix. A group of experts and the user will determine the importance of one attribute over the other. The relative importance matrix which is formed from the decision matrix is shown here.

$$A = \begin{bmatrix} 1 & 2 & 0.5 & 2 \\ 0.5 & 1 & 0.33 & 1 \\ 2 & 3 & 1 & 2 \\ 0.5 & 1 & 0.33 & 1 \end{bmatrix} \quad (11)$$

Step 3: Now the maximum eigen value of the relative importance matrix R is to be found out. Therefore $(A - \lambda_{\max}I)$ is equal to

$$\begin{bmatrix} 1 - \lambda & 2 & 0.5 & 2 \\ 0.5 & 1 - \lambda & 0.33 & 1 \\ 2 & 3 & 1 - \lambda & 2 \\ 0.5 & 1 & 0.33 & 1 - \lambda \end{bmatrix} \quad (12)$$

Also, $(A - \lambda_{\max}I) = 0$, On solving the above matrix we have $\lambda_{\max} = 3.93$ (13)

Therefore, Now $(A - \lambda_{\max}I) =$

$$\begin{bmatrix} -2.93 & 2 & 0.5 & 2 \\ 0.5 & -2.93 & 0.33 & 1 \\ 2 & 3 & -2.93 & 2 \\ 0.5 & 1 & 0.33 & -2.93 \end{bmatrix} \quad (14)$$

Step 4: In this step the weights for each attribute using the eigen vector associated with the maximum eigen value are calculated. This can be represented by the equation,

$$(A - \lambda_{\max}I)w = 0 \quad (15)$$

$$\begin{bmatrix} -2.93 & 2 & 0.5 & 2 \\ 0.5 & -2.93 & 0.33 & 1 \\ 2 & 3 & -2.93 & 2 \\ 0.5 & 1 & 0.33 & -2.93 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = 0 \quad (16)$$

Also we know that,

$$w_1 + w_2 + w_3 + w_4 = 1 \quad (17)$$

On solving this above matrix we have,

$$w_1 = 0.2732 \quad w_2 = 0.1457 \quad w_3 = 0.4352 \quad w_4 = 0.1457$$

Step 5: In this step the normalized specification matrix is calculated which helps to provide the dimensionless elements of the matrix. It is denoted by 'N'.

$$n_{ij} = \frac{d_{ij}}{\sqrt{\sum_{i=1}^m d_{ij}^2}} \quad (18)$$

therefore, normalized specification matrix **N** is equal to

$$N = \begin{bmatrix} 0.533 & 0.498 & 0.519 & 0.513 \\ 0.520 & 0.495 & 0.493 & 0.518 \\ 0.409 & 0.504 & 0.486 & 0.515 \\ 0.526 & 0.501 & 0.499 & 0.449 \end{bmatrix} \quad (19)$$

Step 6: In this step the weighted normalized specification matrix is calculated. It is denoted by ‘**V**’.

$$V = \begin{bmatrix} 0.1456 & 0.0726 & 0.2260 & 0.0748 \\ 0.1421 & 0.0722 & 0.2147 & 0.0755 \\ 0.1119 & 0.0735 & 0.2119 & 0.0750 \\ 0.1439 & 0.0731 & 0.2175 & 0.0654 \end{bmatrix} \quad (20)$$

The weighted normalized matrix involves both the attribute values and their relative importance to each other. So this matrix provides a very good basis for the comparison of the attributes with each other and with the benchmark PTSC.

3.6.3.2) TOPSIS method for ranking:

The weighted normalized attributes for the positive and negative benchmark PTSC’s are obtained which are as follows:

$$V^* = (0.1456, 0.0735, 0.2260, 0.0755)$$

$$V^- = (0.1119, 0.0722, 0.2119, 0.0654)$$

Now from the formulas above mentioned in the explanatory part of the TOPSIS method and relative closeness to the ideal solution can be calculated and the values for the same are as follows:

$$S_1^* = 0.0011$$

$$S_1^- = 0.0377$$

$$C_1^* = 0.9707$$

$$S_2^* = 0.0119 \qquad S_2^- = 0.0319 \qquad C_2^* = 0.7284$$

$$S_3^* = 0.0365 \qquad S_3^- = 0.0096 \qquad C_3^* = 0.2087$$

$$S_4^* = 0.0132 \qquad S_4^- = 0.0324 \qquad C_4^* = 0.7096$$

As the C^* value of the first PTSC is the highest therefore it is the best design available from the global market. Also the C^* value of third PTSC is the lowest, so it is the worst design available amongst all the four designs.

Table.9 Evaluation and ranking of four alternatives PTSC:

Sr.no.	Name of collector	Area under the curve	Rank
1	Flagsol SKAL-ET 150	0.9707	1 st
2	Sener	0.7284	2 nd
3	IST Solucar PT-2	0.2087	4 th
4	Acciona Solar Power SGX 2	0.7096	3 rd

As shown in the above table the **Flagsol SKAL-ET 150** is the highest ranked PTSC amongst all the four alternative designs on the basis of TOPSIS procedure and is hence the best option for the users.

3.7) Graphical technique:

After using the TOPSIS procedure for the ranking and selection of the PTSC the two graphical techniques i.e. Line graph and Spider graph are used for the ranking and thus final selection of the system.

3.7.1) Line Graph: A graph is drawn for the weighted normalized matrix between the weighted normalized values and the attributes for different parabolic trough solar collectors as shown in fig.18. The area under the curve in the line diagram for each system is calculated to compare the systems. The system with the least value of area is ranked last and the system with the highest value of area under the curve is ranked highest. The area under the curve for the line diagram is calculated by the following formulae:

$$\text{Area} = (d_{i,1} + 2(d_{i,2} + \dots + d_{i,j} + \dots + d_{i,n-1}) + d_{i,n})/2 \qquad (21)$$

Where, $d_{i,j}$ – The weighted normalized value of j^{th} attribute in i^{th} system

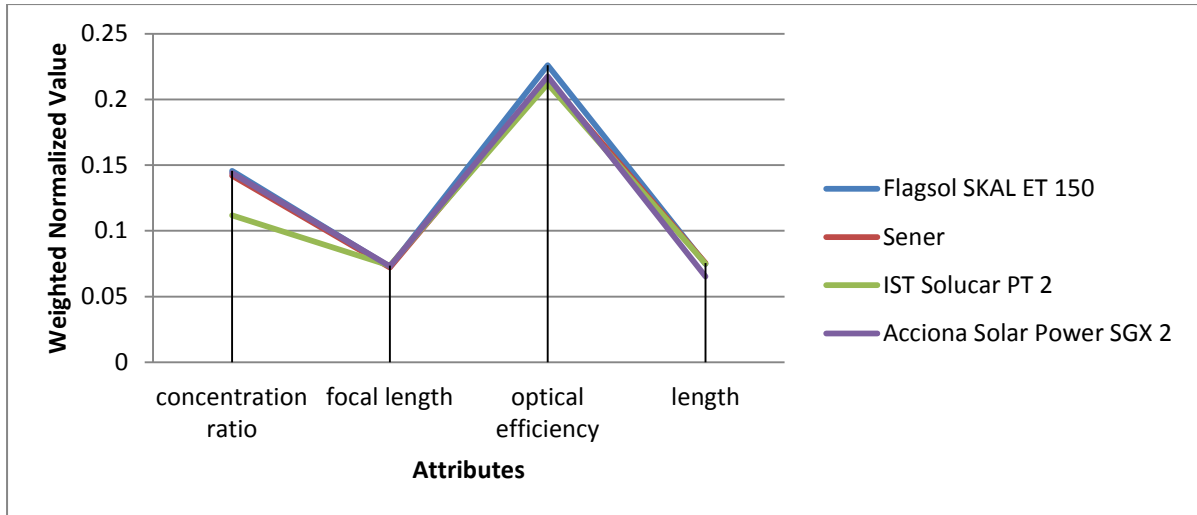


Figure.16 Line graph of different PTSC

On the basis of the line diagram shown above the area under the curve for every PTSC is calculated and hence ranking of the four different collectors is done.

Ranking based on line graph:

Table.10: Ranking of PTSC designs based on the area under the curve in line diagram

Sr.no.	Name of collector	Area under the curve	Rank
1	Flagsol SKAL-ET 150	0.8176	1 st
2	Sener	0.7914	2 nd
3	IST Solucar PT-2	0.7577	4 th
4	Acciona Solar Power SGX 2	0.7905	3 rd

As shown in the above table the **Flagsol SKAL-ET 150** is the highest ranked PTSC amongst all the four alternative designs and is hence the best option for the users.

3.7.2) Spider graph representation:

The area under the curve for different PTSC's in a spider graph representation is calculated by the following formulae:

$$\text{Area} = (\sin \theta / 2) \sum_{j=1}^n d_{i,j} \times d_{i,j+1}, \text{ Where, } d_{i,n+1} = d_{i,1} \text{ and } \theta = 360/n \quad (22)$$

The spider diagram representation of all the alternative designs and their attribute values is shown in figure.17.

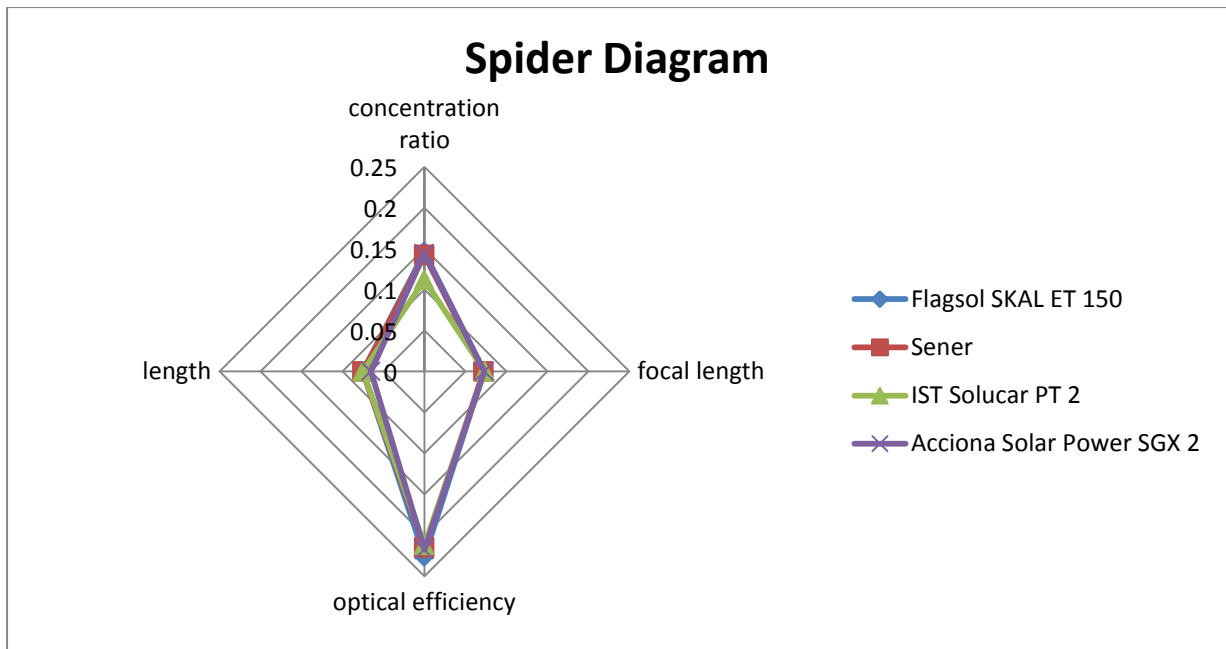


Figure.17 Spider graph for different PTSC

Similarly on the basis of the spider diagram shown above the area under the curve for every PTSC is calculated and hence ranking of the four different collectors is done.

Ranking based on spider graph:

Table.11 Ranking of PTSC designs based on the area under the curve in spider diagram

Sr.no.	Name of collector	Area under the curve	Rank
1	Flagsol SKAL-ET 150	0.0273	1 st
2	Sener	0.0263	2 nd
3	IST Solucar PT-2	0.0240	4 th
4	Acciona Solar Power SGX 2	0.0250	3 rd

As shown in the above table the **Flagsol SKAL-ET 150** is the highest ranked PTSC amongst all the four alternative designs and is hence the best option for the users.

3.8) SWOT Analysis:

The SWOT analysis is done for the use of parabolic trough solar collector technology in India. As we all know that there is a lot of power crisis in our country and less use of solar energy creates an opportunity for the PTSC technology for the power production and other solar energy applications. Here the strength of the PTSC technology, its weakness, the various opportunities for PTSC technology in India, and the threats from the surroundings are presented below. In the above SWOT analysis it is observed that there is lot of scope of

PTSC technology in India. As the operating temperature of the PTSC system is very high which can be used for the steam/power generation. But for the water heating applications the PTSC system is rarely used due to its high cost. But with the use of alternate materials the overall cost of the system will be reduced so as to make it affordable for the water heating. . The solar water heating installations in India are distributed across the following market-segments: households (residential sector) in both urban and rural areas, commercial and institutional buildings (e.g., hotels, hospitals, hostels, and religious complexes), and industries. Also due to a rapid increase in the power demands there is a huge scope of the installation of the PTSC power plant in India.

Table.12[57]: Estimated breakdown of solar water heating applications in India

Sector	Percentage Distribution	Area (Million m²)
Residential	80%	2.108
Hotels	6%	0.158
Hospitals	3%	0.079
Industries	6%	0.158
Others (Railway, Defence, Hostels, Religious places etc.)	5%	0.132
Total	100%	2.635

The above table shows the percentage distribution of different sectors in India with the solar collecting area. It is clearly seen from the above figure that the major use of solar water heating is in residential complexes. If the tracking and focussing errors are reduced and with the use of suitable materials the PTSC technology can overpower flat plate collectors for water heating applications.

<p>Strength</p> <ol style="list-style-type: none"> 1) Operating temperature potential Of upto 500⁰C 2) Can be used for approximately every Solar energy application 3) Commercially available. 4) Best land use. 5) Storage capability 	<p>Weakness</p> <ol style="list-style-type: none"> 1) Use of thermal oil as heat transfer media restricts the operating temperature to 400⁰C which results in moderate steam qualities 2) Huge water demand for power Production. 3) land availability
<p>Opportunity</p> <ol style="list-style-type: none"> 1) Small use of PTSC technology In India. 2) Can be used for water heating if alternative materials are used to reduce the cost of the system 3) Generally Flat plate collectors Are used for water heating. 4) Flat plate collectors cannot produce steam for domestic purposes 	<p>Threat</p> <ol style="list-style-type: none"> 1) For water heating applications Flat plate collectors are very well established and a proven technology 2) Dish type and power tower collectors can produce much Higher temperatures than PTSC. A slight modification in their design can also be very useful.

Figure.18 SWOT Analysis for the use of PTSC system for water heating

Considering the SWOT analysis and by the use of TOPSIS procedure, line and spider graph representation the best and the worst design possible are selected so as to make it easier for the buyer to choose the design which is closest to the best possible design. The identification of the attributes is done in an exhaustive way which includes all the components of the PTSC system. It is done by applying the coding scheme to all the attributes so that even the smallest of the information and parameters affecting the PTSC system are presented. This is very useful as it allows even the common man to assemble the PTSC system by himself. The overall work done and presented here is very useful for the user, designer, manufacturer and the maintenance personnel in the industry. The SWOT analysis of the PTSC technology for water heating applications is shown in figure.18.

3.9) Graph Theoretic Representation:

3.9.1) Structural Constituents Identification with Their Interactions:

In order to achieve very high temperature of steam, water, air etc. for power generation, water heating, air heating and other applications with the use of PTSC system, it is very important to select the best suitable material for all the structural constituents or subsystems of the parabolic trough solar collector system. So the identification of structural constituents of PTSC system with all the interactions between them should be done in a comprehensive way. A PTSC system is considered as a collection of a number of structural constituents e.g. reflector, absorber tube, support structure, etc. as shown in the figure.19.

These constituents are interconnected with each other through some bonding and interactions. The constituents with the interactions and connectivity between them are shown in figure.20. The schematic directional diagram shown in figure.19 gives the better understanding of the structure of the PTSC system. But it is impossible to derive different results as it not a mathematical entity and so no mathematical operations can be carried out from this representation. For this, a mathematical representation of the PTSC system and a model for analysis and synthesis of the PTSC system is developed. This is very useful for the analysis of an existing product for modifications and hence the cost reduction of the system. Five subsystems are identified in this regard which constitutes the PTSC system. All the structural attributes are identified and arranged under five different subsystems.

Each subsystem and sub-subsystem is shown in a tree diagram above in figure.19. As shown in the figure.20 the PTSC system consists of five subsystems with the influence of one subsystem over the other is also shown. The figure.20 is represented by a mathematical entity called as a PTSC system digraph. If we do not consider the directional interactions between the subsystems i.e. $P_{ij} = P_{ji}$.

Where, P_{ij} represents the interaction of the i th subsystem with the j th attribute then it will become undirected. The five subsystems shown below gives only the interaction and connectivity between the subsystems. The one way or two way interactions and the degree of influence are not considered in the undirected graph because of $P_{ij} = P_{ji}$.

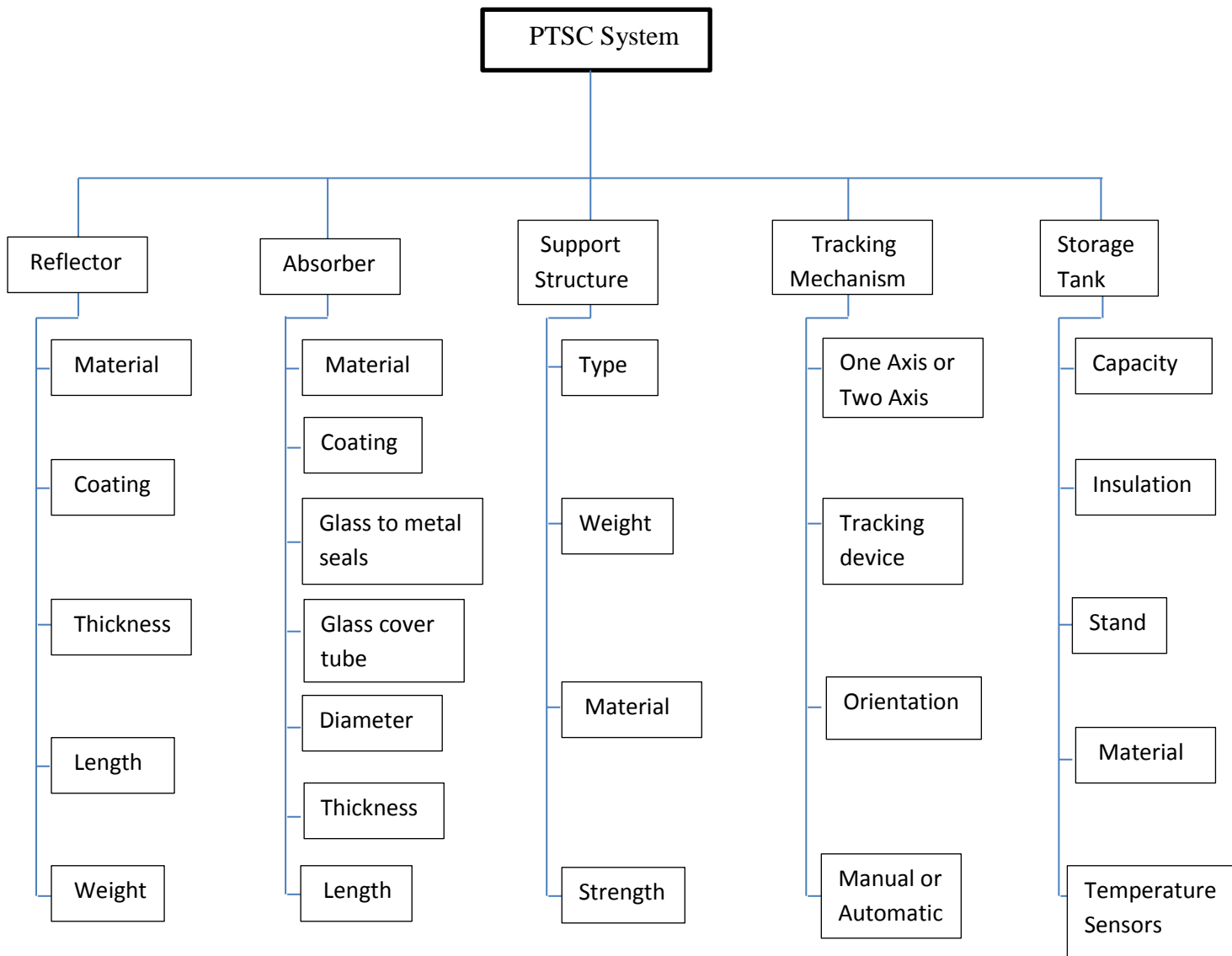


Figure.19 Structural constituents of PTSC system

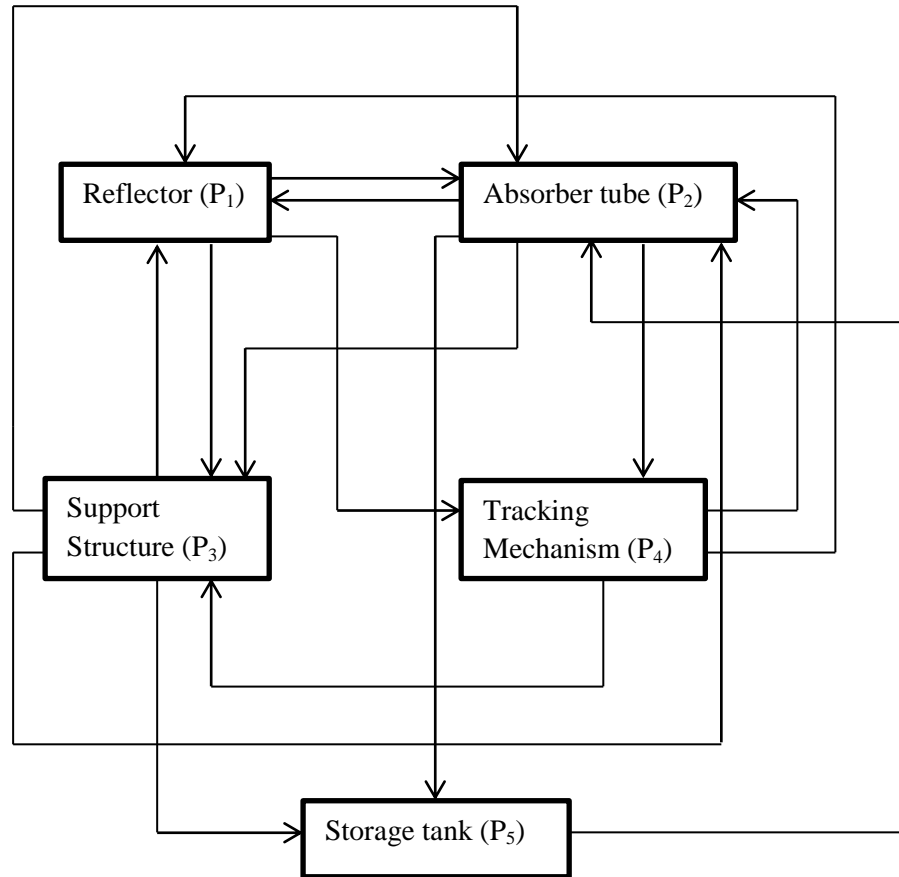


Figure.20 PTSC system digraph

3.10) Matrix Representation:

Since the digraph is a visual representation and is very useful in the visual analysis of the PTSC system. So the matrix representation of the digraph becomes very important in establishing a computer friendly representation for the PTSC system which is very helpful for the users. The directional graph is represented in the matrix form which is convenient in computer processing and in the mathematical analysis of the PTSC system. The digraph shown in figure.20 consists of 5 subsystems leading to a 5th order symmetric (0, 1) matrix $\mathbf{A} = [P_{ij}]$ where P_{ij} represents the interaction of the i th subsystem with the j th attribute.

$$P_{ij} = \begin{cases} 1 & \text{If subsystem } i \text{ is connected to subsystem } j \\ 0 & \text{Otherwise} \end{cases} \quad (23)$$

It is supposed that the subsystem is not interacted with itself therefore $P_{ii} = 0$ and also $P_{ij} \neq P_{ji}$ as the PTSC attributes are directional. So the PTSC system matrix represented by 'A' which is square and symmetric in nature representing the digraph is written as:

$$A = \begin{matrix} & \begin{matrix} 1 & 2 & 3 & 4 & 5 \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{matrix} & \begin{bmatrix} 0 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \end{matrix} \quad (24)$$

In the above matrix 'A' the values of P_{ii} , P_{15} , P_{34} , P_{45} , P_{51} , P_{53} , P_{54} are zero as there are no interactions between these subsystems. The off-diagonal elements with values 0, 1 show the interdependency and connectivity between the subsystems of the PTSC system.

3.10.1) PTSC System Characteristic Matrix:

To characterize the PTSC system matrix 'A' a PTSC System Characteristic Matrix 'B' is introduced which may be expressed as $[PI - A]$.

Where, A = PTSC system matrix,

P = Variable representing the PTSC system,

I = Identity matrix of order 5.

Therefore

$$B = \begin{bmatrix} P & -1 & -1 & -1 & 0 \\ -1 & P & -1 & -1 & -1 \\ -1 & -1 & P & 0 & -1 \\ -1 & -1 & -1 & P & 0 \\ 0 & -1 & 0 & 0 & P \end{bmatrix} \quad (25)$$

In the above matrix the value of all the diagonal elements are same. Interdependencies between the subsystems have been assigned values of 0 and 1 depending on whether it is there or not. This does not represent varying degree of influence of one subsystem over the other subsystems.

3.10.2) PTSC System Variable Characteristic Matrix:

To consider this, another matrix called the PTSC system variable characteristic matrix is proposed. PTSC system variable characteristic matrix takes into account the effect of

different parabolic trough solar collector subsystems and their varying degree of interactions.

The PTSC system variable characteristic matrix is expressed as $\mathbf{H} = [\mathbf{D} - \mathbf{C}]$.

\mathbf{D} = Diagonal matrix with diagonal elements representing five different subsystems,

\mathbf{C} = Square matrix with off-diagonal elements representing varying interactions between the PTSC subsystems.

Therefore,

$$H = \begin{bmatrix} P_1 & -P_{12} & -P_{13} & -P_{14} & 0 \\ -P_{21} & P_2 & -P_{23} & -P_{24} & -P_{25} \\ -P_{31} & -P_{32} & P_3 & 0 & -P_{35} \\ -P_{41} & -P_{42} & -P_{43} & P_4 & 0 \\ 0 & -P_{52} & 0 & 0 & P_5 \end{bmatrix} \quad (26)$$

This matrix represents characteristic features of the subsystems and their interactions. Thus the matrix \mathbf{H} gives the complete structural representation of the PTSC system capturing all the data related to the PTSC system including the interactions. The determinant of the above matrix gives the variable characteristic PTSC multinomial which has positive and negative signs with some of its terms. The multinomial contains the complete information of the PTSC system. If the symbols like P_i , P_{ij} in the above are replaced by numerical values information will be lost.

3.10.3) PTSC system variable permanent matrix:

To avoid the loss of structural information during mathematical calculations a PTSC system variable permanent matrix ' \mathbf{P} ' is introduced and this matrix of five subsystems is expressed as:

$$P = \begin{bmatrix} P_1 & P_{12} & P_{13} & P_{14} & P_{15} \\ P_{21} & P_2 & P_{23} & P_{24} & P_{25} \\ P_{31} & P_{32} & P_3 & P_{34} & P_{35} \\ P_{41} & P_{42} & P_{43} & P_4 & P_{45} \\ P_{51} & P_{52} & P_{53} & P_{54} & P_5 \end{bmatrix} \quad (27)$$

PTSC system variable permanent matrix as shown in the digraph in figure is expressed as:

$$E = \begin{bmatrix} P_1 & P_{12} & P_{13} & P_{14} & 0 \\ P_{21} & P_2 & P_{23} & P_{23} & P_{25} \\ P_{31} & P_{32} & P_3 & 0 & P_{35} \\ P_{41} & P_{42} & P_{43} & P_4 & 0 \\ 0 & P_{52} & 0 & 0 & P_5 \end{bmatrix} \quad (28)$$

This above matrix is formed when negative signs of the PTSC system variable characteristic matrix are converted into the positive ones. This model allows the representation of the contribution of each subsystem and interaction quantitatively without any loss of information in multinomial representation.

3.11) Variable Permanent Function Representation:

The determinant of the PTSC system variable permanent matrix \mathbf{P} is calculated and the values of P_{15} , P_{34} , P_{45} , P_{51} , P_{53} , P_{54} are entered into it as zero which means the interactions are absent between the respective subsystems. This gives the Variable Permanent Function for the PTSC system.

3.11.1) Permanent function representation:

The expression for a Permanent Function is as follows:

$$\begin{aligned}
 per(P) = & P_1 P_2 P_3 P_4 P_5 + (P_1 P_2 P_4 P_{35}^2 + P_1 P_3 P_4 P_{25}^2 + P_1 P_3 P_5 P_{24}^2 + P_1 P_3 P_5 P_{23}^2 + \\
 & P_2 P_3 P_5 P_{14}^2 + P_2 P_4 P_5 P_{13}^2 + P_3 P_4 P_5 P_{12}^2) + (2P_1 P_4 P_{23} P_{35} P_{52} + 2P_3 P_5 P_{12} P_{24} P_{41} + \\
 & 2P_4 P_5 P_{12} P_{23} P_{31} + (P_1 P_{24}^2 P_{35}^2 + P_2 P_{14}^2 P_{35}^2 + P_3 P_{14}^2 P_{25}^2 + P_4 P_{12}^2 P_{35}^2 + P_4 P_{13}^2 P_{25}^2 + \\
 & P_5 P_{15}^2 P_{24}^2 + P_5 P_{14}^2 P_{23}^2) + (2P_1 P_{24} P_{43} P_{35} P_{52} + 2P_5 P_{13} P_{32} P_{24} P_{41} + 2P_{14}^2 P_{23} P_{35} P_{52} + \\
 & 2P_{35}^2 P_{12} P_{24} P_{41} + 2P_{13} P_{35} P_{52} P_{24} P_{41})
 \end{aligned} \tag{29}$$

The above equation represents the PTSC system of figure.20. The numerical index is developed based on the permanent multinomial terms in above equation by giving numerical value to individual structural elements can be considered a composite score of the PTSC system in any performance dimension depending upon the one selected for giving values to individual structural elements. This score can prove as a powerful tool for comparison, ranking and optimum selection of different PTSC system designs. This function gives a unique representation of a PTSC system. If numerical values are given as inputs then it gives results in the same. The permanent function carries the whole information about the system and no information is lost. Thus a permanent function is proposed to be a complete tool for the total structural analysis of the PTSC system.

3.12) Usefulness of the methodology:

- i. This procedure helps in the comparison and ranking of different PTSC designs for different applications.
- ii. This methodology is dynamic in nature as its constituents and bonding between them can be easily changed without any difficulty.
- iii. The proposed methodology is very useful for the user and designer as they generate a number of alternative PTSC designs and can select the optimum design amongst all.
- iv. Graph theory is flexible in nature to expand the analysis, can be quickly built based on a simple logic, is mathematical in nature and it can integrate the analysis over the total PTSC system.
- v. This methodology gives a lot of knowledge to the user which helps in the optimum selection at the right time and more importantly at the right cost.

3.13) Conclusion:

Both the system approaches (MADM, Graph Theoretical) used in this chapter are very helpful in the evaluation, comparison, ranking and optimum selection of the PTSC system. As MADM Approach deals with the exhaustive identification of the attributes which are used to define the overall PTSC system. On the other hand the Graph theoretical approach deals with the structural modelling and analysis of the PTSC system with the identification of different constituents/subsystems and the bonding and interactions between them. Both approaches uses mathematical tools for the comparison and ranking of the PTSC system with TOPSIS method used in MADM approach and the formation of a permanent function in graph theoretical approach. Both methodologies are very useful for the designer and the user for the evaluation, comparison and optimum selection of the PTSC system from the different alternate designs available in the global market.

Chapter - 4

Experimental Set up- Design and Fabrication

4.1) Design and Fabrication of PTSC:

The design of Parabolic trough collectors are structurally simpler than other types of concentrated collectors but it requires continuous tracking so as to make sure that solar radiations are concentrated on the absorber tube throughout the day. The design of a PTSC should be precise and the dimensions on x, y directions must be accurate to ensure the better optical efficiency of the PTSC design and hence to improve the overall thermal efficiency of the system.

4.1.1) Design Parameters:

The design parameter of a parabolic trough collector can be classified as geometric and functional. The geometric parameters of a PTSC are its aperture width and length, rim angle, focal length, diameter of the receiver, diameter of the glass envelope and the concentration ratio. The functional parameters of a PTSC are optical efficiency, instantaneous and overall thermal efficiency and receiver thermal losses. These parameters are largely influenced by the absorptivity of the absorber. The errors are due to the defects in reflector material, support structure, location of the receiver with respect to the focal plane of PTSC and misalignment of PTSC with respect to the sun caused by the tracking errors.

Following parameters shown in figure are needed to specify the parabola.

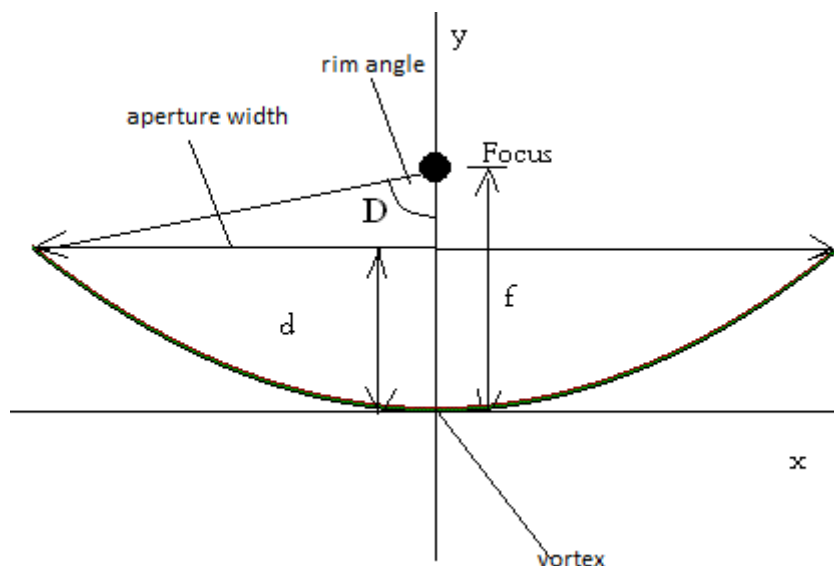


Fig.21[57] Design Specifications of a parabolic reflector

Where, f- Focal Lenth, d- Depth of Parabola, D- Aperture Width

4.1.2) Design of prototype PTSC:

The design of the parabolic trough solar collector is done by the use of software called as PARABOLA CACULATER 2.0 which is easily available on the internet. The initial specification for the design of Parabolic Trough Solar Collector is obtained by considering parabolic equation: $X^2=4aY$ (30)

Where,

Y = Distance along vertical axis

a = Focal length

X = Distance along horizontal axis.

Corresponding points are obtained by the use of this software and hence we get a parabolic shape at different values of x and y. The initial design of the prototype parabolic trough solar collector by the use of PARABOLA CACULATOR 2.0 software is shown below and the values of different parameters obtained is shown in Table 13 and Table 14.

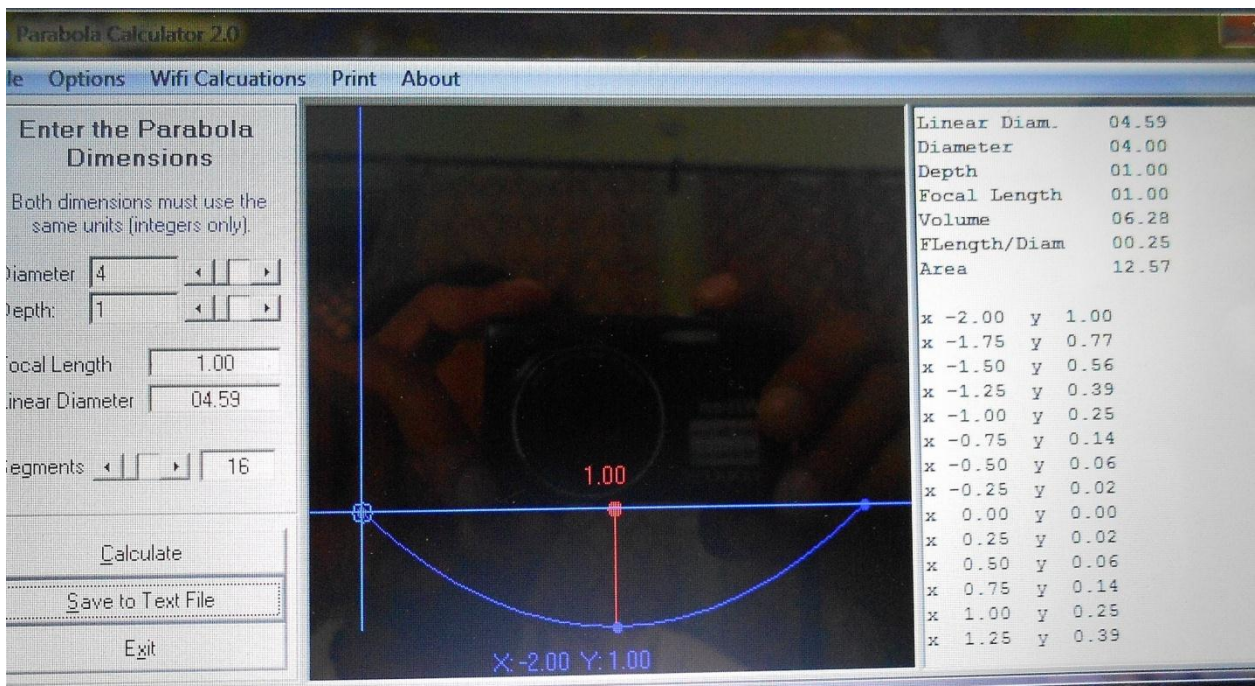


Fig.22. Parabola dimensions from Parabola Calculator 2.0 software

Table.13: Different parameters with their design values:

Parameter	Design Value (in ft)
Linear diameter.	04.59
Diameter	04.00
Depth	01.00
Volume	06.28
Focal length	0.25
Area	12.57

Table.14: Values of x, y calculated with the help of the Parabola Calculator 2.0 software:

X- axis	Y-axis	X- axis	Y-axis
-2.00	1.00	.50	.06
-1.75	0.77	.75	.14
-1.50	.56	1.00	.25
-1.25	.39	1.25	.39
-1.00	.25	1.50	.56
-.75	.14	1.75	.77
-.50	.06	2.00	1.00
-.25	.02		
.00	00		
.25	.02		

4.1.3) Fabrication of Prototype Parabolic Trough Solar Collector System:

After finalizing the design of the parabolic trough solar collector the main task is to fabricate this PTSC system with the use of different materials which are easily available and are of less cost. The main emphasis is on reducing the cost of the PTSC system by the use of different alternate materials without compromising on the quality of the material and hence performance of the system. The trough should be made capable of withstanding different loads like wind load, stress loads etc. So these things are kept in mind during the fabrication of the PTSC system. The overall fabricated PTSC system is shown in figure below.

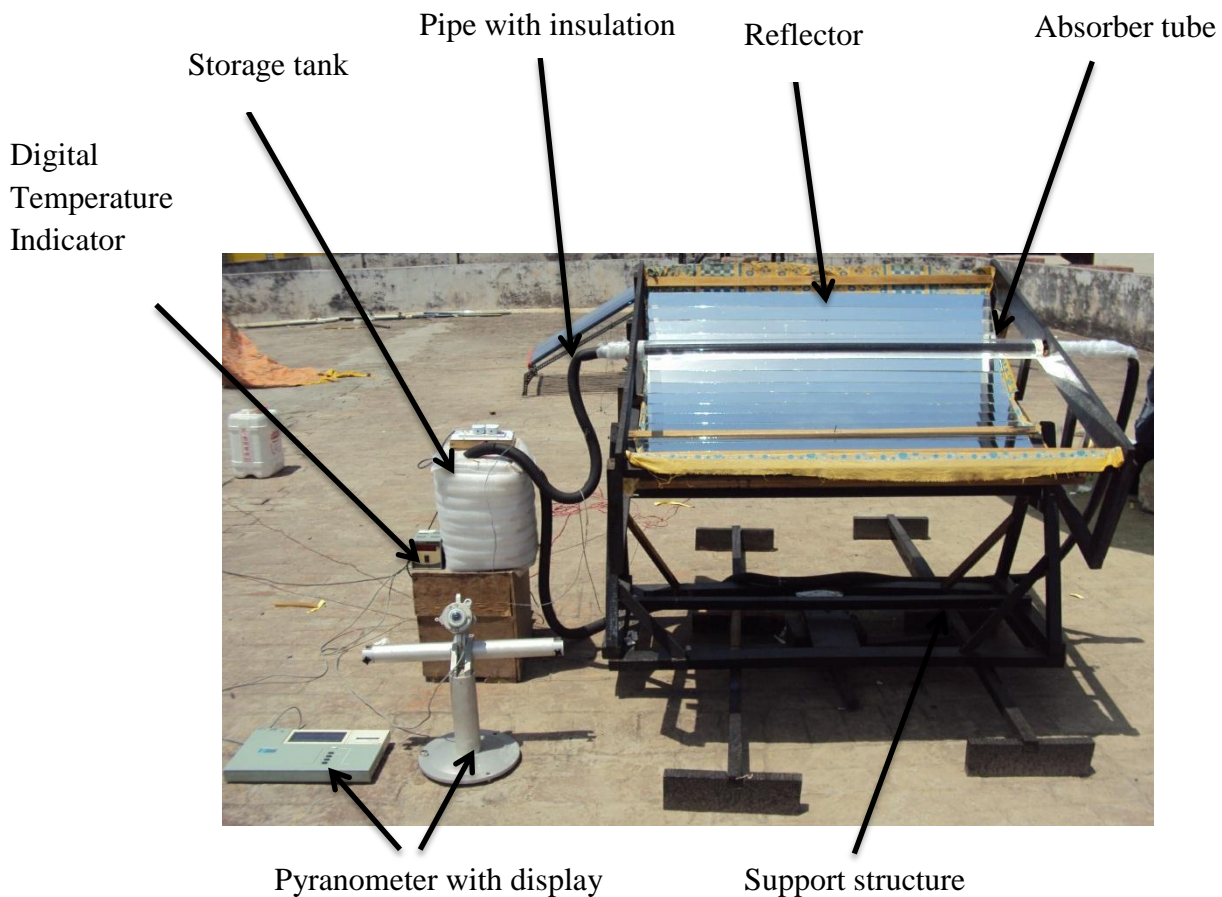


Figure.23 Fabricated PTSC system with different components

4.2) **Components of the Prototype PTSC system:** The main Components of the above fabricated PTSC system are explained as follows:

- 1) **Reflector:** A Stainless steel sheet of dimensions (4ft x 5ft) is used to form the parabolic shape in prototype with the use of all the dimensions calculated from the software above. The stainless steel sheet is used to provide the mechanical strength to the parabolic trough. A piece of cotton cloth is then pasted on the sheet over which

the mirror stripes which are 25 in number with dimensions (2in x 48in) are pasted over the cloth. The mirror stripes are pasted in such a way that they do not affect the curve of the parabola. The mirror stripes are used because they have a very high reflectivity of 96%. The reflector made up of mirror stripes pasted on a stainless steel substrate is shown in figure 24.



Fig.24 Reflector with absorber tube

- 2) **Absorber Tube:** A copper tube with the glass cover tube on it joined by the glass to metal seals on both sides of the copper tube is used as an absorber tube. The glass cover tube is used so as to reduce the conductive, convective, and radiative losses from the copper tube. A bare copper tube and Aluminium tube with length 5ft and with inside and outside diameter of 31.5mm and 32.5 mm are used. Four glass cover tubes with diameters of 45mm, 55mm, 65mm, and 75mm respectively are used. A copper tube with the glass cover tube over it is shown in figure.24.
- 3) **Storage Tank:** A container made up of steel of 15 litres capacity filled with water which is working fluid is used as a storage tank. The water is circulated from the container with the help of a small pump of power 24 W to the inlet of the absorber tube. Water after gaining heat from the absorber tube is dropped in the same container and is re-circulated again with the help of a pump. The inlet and outlet to the absorber tube is from the storage tank. The storage tank is insulated with glass wool and then wrapped in a thermo Cole sheet. Figure.25 shows the picture of storage tank used in the experiment.



Fig.25 Storage Tank



Fig.26 Support structure

4) **Support Structure:** The support structure for the PTSC is made up of wood. The selection of wood as a material for the support structure is because it is cheap, easy to maintain, lighter in weight and also it is very flexible to the changes if necessary. The support structure which is made up of wood is black painted. The support structure is fabricated in such a way that it could withstand wind loads, stress loads etc. It is also designed so that it could not affect the shape of the parabola and also to minimize the alignment errors. The provision of manual tracking is also there in the support structure. Figure.26 shows the support structure used in the experiment. The drawing of the PTSC with copper absorber tube with glass cover tube, and the wooden support structure is made by designing software CATIA is shown in figure 27 and figure 28.

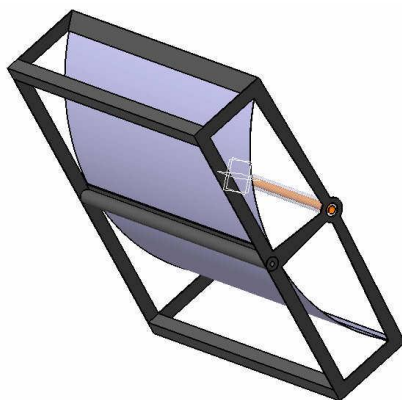


Figure.27 Support Structure Design

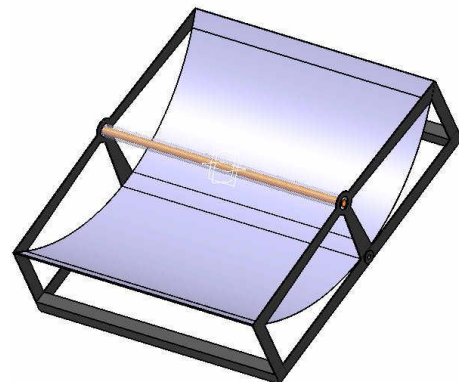


Figure.28 Reflector and Absorber Design

- 5) **Insulation:** The SOFLON insulation is used on the pipes so as to minimize all the heat losses during the transport of working fluid from inlet to the outlet which is from the storage tank. This insulation is easily available from the market in the Air Conditioners and Refrigerators spare parts shop. Also glass wool is used for insulating the storage tank which is also easily available. The insulation on the pipe and on the Storage tank is shown in figure.25



a

Figure.29 Manual Tracking



Figure.30 Pyranometer

- 6) **Tracking Mechanism:** In this experiment manual tracking is done because it is comparatively cheaper than automatic tracking as automatic tracking requires a motor and gear mechanism. Manual tracking is done by rotating the parabolic trough by 10 degrees after every 1 hour by creating holes in a wooden ply of semi-circular shape. A proper observation of the sun's trajectory in kurukshetra is done with $29^{\circ} 58'$ (latitude) North and $76^{\circ} 53'$ (longitude) east and proper angle measurement (approx. 10°) of tracking is observed. Also one axis tracking system is used because the use of two axis tracking system will make the PTSC system complicated to use. Manual tracking is shown in figure.29.

4.3) Prototype PTSC system specifications after fabrication: The dimensions of PTSC system model fabricated above is shown in figure.31 in a CATIA drawing of the parabolic trough solar collector with absorber tube.

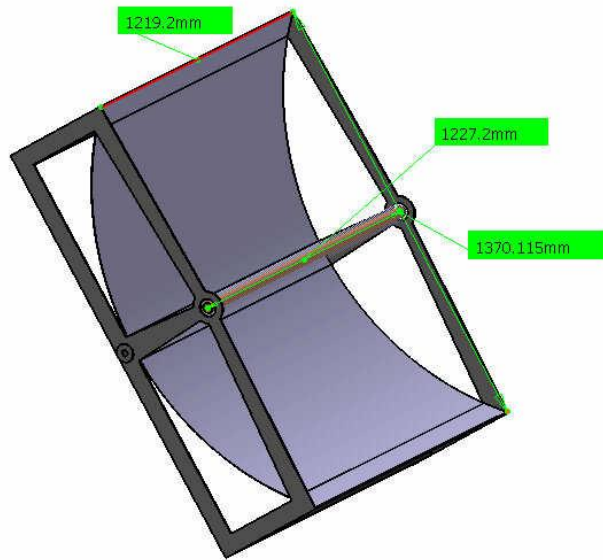


Figure.31 Drawing of fabricated PTSC with absorber tube

Table.15: Different parameters and their values for the fabricated PTSC

Parameters	Value
Collector aperture	1.2m
Collector length	1.2m
Aperture area	1.44 m ²
Rim angle	90 ⁰
Focal distance	.30m
Receiver diameter	.0325
Concentration ratio	11.04
Water flow rate	.09kg/s
Storage tank capacity	15lt
Tank material	Stainless steel
Tank insulation material	Glass wool
Water pump	25W
Insulation on the pipes	Soflon, Superlon

4.4) Measuring instruments and devices:

There are some instruments which are used to measure the temperature of the working fluid and the amount of solar intensity. These are:

4.4.1) Pyranometer with digital display:

The Pyranometer is used to measure the solar intensity coming from the sun. It is used to measure both the beam and diffused radiations. There is a digital display which shows the amount of solar intensity in (W/m^2). The Pyranometer and the digital display used in this experiment are shown in figure.30 and figure.32.

4.4.2) Thermocouple with DTI(Digital Temperature Indicator):

The temperature of the working fluid i.e. water is measured by the use of a thermocouple which is completely dipped in the container. The measured temperature is shown on the digital temperature indicator (DTI) which is called as RTPTD-100. Figure.33 shows the RTPTD-100 used to indicate the temperature of water in ($^{\circ}C$) in the storage tank.



Fig.32 Digital display of Pyranometer



Fig.33 RTPTD 100 display

4.5) **Working Principle:** The working of the above experimental set up is better explained with the help of a line diagram of the experimental set up. The line diagram is shown in figure.34.

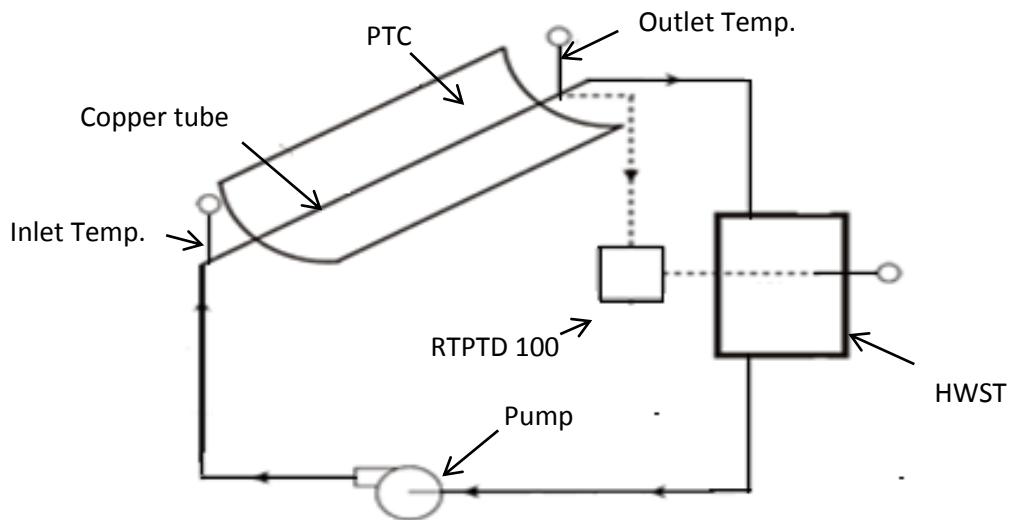


Fig.34 Line diagram of the fabricated PTSC

Where, HWST- Hot water storage tank, PTC- Parabolic Trough Concentrator

The HWST used in the experimental set up is of 15 litres capacity is filled with the water which is used as a working fluid. Water is circulated to the absorber tube with the help of a water pump which is located inside the storage tank. The mass flow rate of water through the absorber tube is 0.09kgps. During circulation it gains heat in the absorber tube and comes back in the storage tank. The water is then recirculated again and again through the absorber tube throughout the whole day. A glass cover tube is used over the copper tube to reduce the conduction, convection, and radiation losses. Two insulated pipes one from storage tank to the inlet of the absorber tube and other from the outlet of the absorber tube to the storage tank are used to carry the water from storage tank to the absorber tube. It is noted that in the experimental set up the peak temperature of the water is obtained at 01:00 PM and after that the temperature started decreasing due to the thermal losses from the absorber tube. The temperature at inlet and outlet to the absorber tube is measured by a thermocouple and is indicated by RTPTD 100. The temperature of the water in the storage tank is measured by a thermocouple which is completely dipped in water.

Chapter – 5

Results and discussions of Experimental investigation

5.1) Performance testing of hot water generating PTSC with formulas used:

The performance of this fabricated PTSC hot water generation system is determined by obtaining the values of collector instantaneous efficiency, overall thermal efficiency, and the hourly thermal efficiency for different combinations of solar intensity of radiations, ambient temperature and the inlet water temperature. The storage tank water temperature, ambient temperature, and collector water outlet temperature were recorded with the help of thermocouple and are indicated by RTPTD-100. The solar radiation intensity is measured by pyranometer. All parameters are measured as a function of time over one hour period under steady state conditions.

5.1.1) Overall Thermal Efficiency: The overall thermal efficiency, $\eta_{overall}$ of a concentrating collector operating under steady-state conditions can be described by:

$$\eta_{overall} = \frac{Q_u}{A.I} = \frac{m.c_p(T_0 - T_i)}{A.I} \quad [18] \quad (31)$$

Where,

Q_u = Useful Heat Gain (in watt), A = Aperture area(in m^2), I = Solar Radiation Intensity (in W/m^2), m = Mass flow rate(in Kg/hr), c_p = Specific heat capacity of water (in $JKg^{-1}K^{-1}$), and T_0 , T_i = Outlet and inlet temperature of water (in $^{\circ}C$)

5.1.2) Useful Heat Gain: The experimental work is done and operated in a closed loop mode. The rate of energy gained by the water in the storage tank for a time interval of 1 hour is given by:

$$Q_s = m_w c_p (T_0 - T_i) \quad [18] \quad (32)$$

Where, Q_s = Energy stored in the storage tank (in KJ/hr), m_w = Mass of water in the storage tank (in kg)

5.1.3) Thermal efficiency: The hourly efficiency of the PTSC hot water storage system is calculated by the following equation:

$$\eta_{thermal} = \frac{Q_s}{A.I_h} = \frac{m_w.c_p(T_0 - T_i)}{A.I_h} \quad [18] \quad (33)$$

$$\text{The effective aperture area} = (W - d_{co})L \quad [1] \quad (34)$$

5.1.4) Concentration ratio: It is the ratio of the effective aperture area of the collector to the absorber area. It is denoted by C_R .

$$C_R = \frac{\text{Aperture area}}{\text{Absorber area}} = \frac{(W-d_{co})L}{\pi D_o L} = \frac{W-d_{co}}{\pi D_o} \quad [1] \quad (35)$$

(Where, d_{co} is the outer diameter of glass cover tube), W = width of the reflector,

These are the formulas which are used in the calculation of overall thermal efficiency, hourly thermal efficiency, and instantaneous efficiency.

5.2) Problem Formulation: The fabricated PTSC has different components e.g reflector, absorber tube, tracking system, support structure, etc. The research work is mainly concentrated on the experimental investigation and comparison of different absorber tube made up of Aluminium and Copper and also the use of glass cover tubes of different diameters. The following are the absorber tubes with different glass cover tubes are used in the experiment:

- 1) Bare Aluminium tube
- 2) Bare Copper tube
- 3) Copper tube with glass cover tube of 45mm in diameter
- 4) Copper tube with glass cover tube of 55mm in diameter
- 5) Copper tube with glass cover tube of 65mm in diameter
- 6) Copper tube with glass cover tube of 75mm in diameter

5.2.1) Specifications: The absorber tube made up of copper with the glass cover tube of different diameters on it separated by glass to metal seals of the following specifications are used throughout the experiment. The following are the specifications of all absorber tubes used in the experiment:

Reflective material	=	Glass Mirror
Reflectivity of mirror	=	0.96
Absorber tube material	=	Copper, Aluminium
Outside Diameter of Cu tube	=	32.5 mm
Inside Diameter of Cu tube	=	31.5 mm
Glass cover tubes diameter	=	45 mm, 55mm, 65mm, 75mm
Corresponding Aperture Area	=	1.38m ² , 1.374m ² , 1.362m ² , 1.35m ²

5.3) Experimental Procedure: The stepwise experimental procedure which is followed during the experiment is as follows:

Step 1: Cleaning of the reflector surface and absorber tube to remove dust particles. The fresh water is filled in the storage tank. The collector is exposed to the sun at least 30 min before start of the experiment.

Step 2: Setting and tracking of the reflector towards the sun. The pump is started at 7:30 A.M.

Step 3: In each experiment, for 30 min duration, the water flow rate passing through the absorber was maintained constant rate.

Step 4: Start taking readings of the solar intensity from the pyranometer and inlet and outlet temperatures of the working fluid from thermocouple from 8:00 A.M onwards.

Step 5: The readings shown in below table are taken after every hour up to 5:00 P.M and are noted down in a tabular form.

Step 6: The pump is switched off and the whole set up is covered up. This procedure is repeated again for the next readings.

The experimental procedure explained above is followed during the whole experiment.

5.4) Experimental Results: The following results are obtained with the experimental analysis of the fabricated PTSC system for hot water generation. The results are shown in the tabulated form and the variation of useful heat gain, hourly thermal efficiency, instantaneous efficiency and overall thermal efficiency with temperature of water in storage tank, time and intensity are represented graphically.

5.4.1) Aluminium absorber tube: Firstly Aluminium is used as an absorber tube material for the performance evaluation of the fabricated PTSC system. The below table gives the measured values of the inlet and outlet temperature of water, intensity of solar radiations, with respect to the time. The Outlet Temperature here is the temperature of water in storage tank. Solar Intensity is measured every hour with the use of a Pyranometer. The experimental readings are as follows:

Table.16: Experimental readings with Aluminium tube as an absorber

Sr.No	Time(hours)	Intensity (W/m ²)	Inlet Temp(°C)	Outlet Temp(°C)
1	8-9	404	25.0	37.9
2	9-10	507	37.9	45.6
3	10-11	612	45.6	53.0
4	11-12	750	53.0	59.2
5	12-1	826	59.2	63.0
6	1-2	900	63.0	65.9
7	2-3	816	65.9	61.2
8	3-4	721	61.2	57.1
9	4-5	600	57.1	53.2

The below table gives the calculated values of useful heat gain and the values of instantaneous efficiency, system efficiency, and the overall thermal efficiency with the help of the formulas shown above in equation 31, 32, 33. In this case the effective aperture area is calculated as 1.40.

Table.17: Calculated values of Useful Heat Gain and efficiencies

Time (hours)	Useful heat gain Q_u (W)	Instantaneous efficiency/ $(\Delta T^{\circ}C)$ $\eta_{\text{instantaneous}}$	System efficiency η_{thermal}	Overall thermal efficiency η_{overall}
8-9	225.75	13.36	35.40	12.78
9-10	134.75		17.20	
10-11	129.50	8.82	13.58	
11-12	68.50		9.83	
12-1	66.50	3.26	5.50	
1-2	50.75		4.22	

5.4.1.1) Graphical representation: From the above readings the relationship between different parameters are observed and analysed. These relationships and variations of different parameters with respect to one another are better explained with the help of a graphical representation. The variation is represented in 4 different ways:

- a) Variation of time and intensity with temperature:
- b) Variation of time and intensity with instantaneous efficiency:
- c) Variation of time and intensity with useful heat gain:
- d) Variation of time and intensity with thermal efficiency

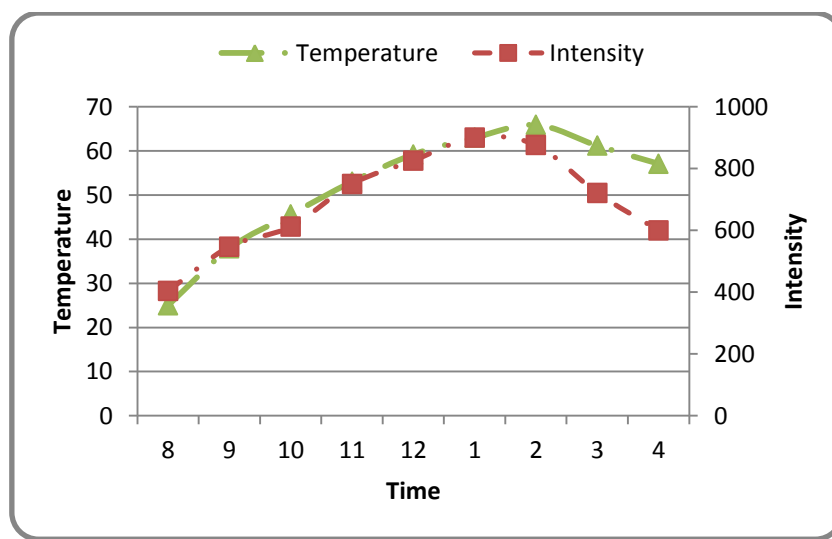


Figure.35 Variation of time and intensity with temperature (Al tube)

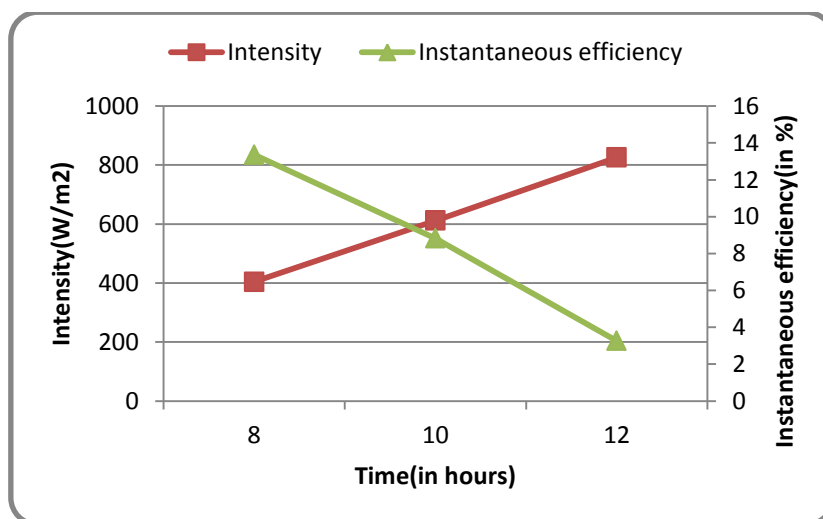


Figure.36 Variation of time and intensity with instantaneous efficiency

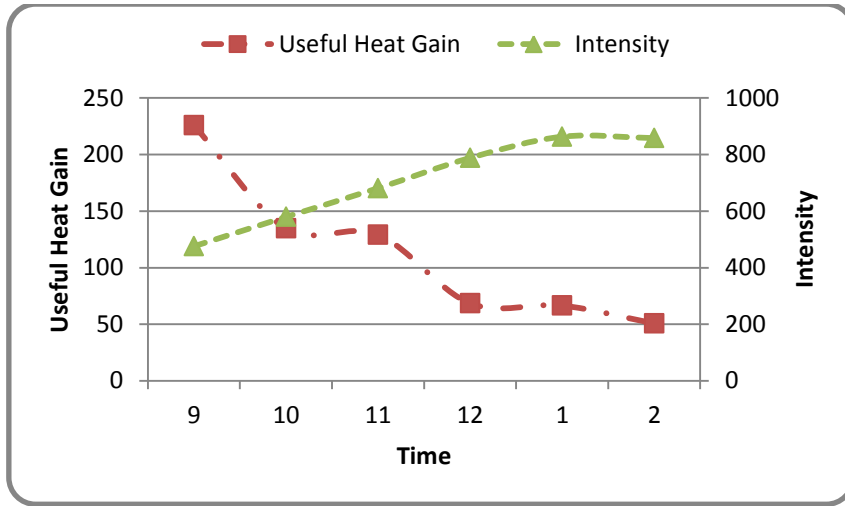


Figure.37 Variation of time and intensity with useful heat gain

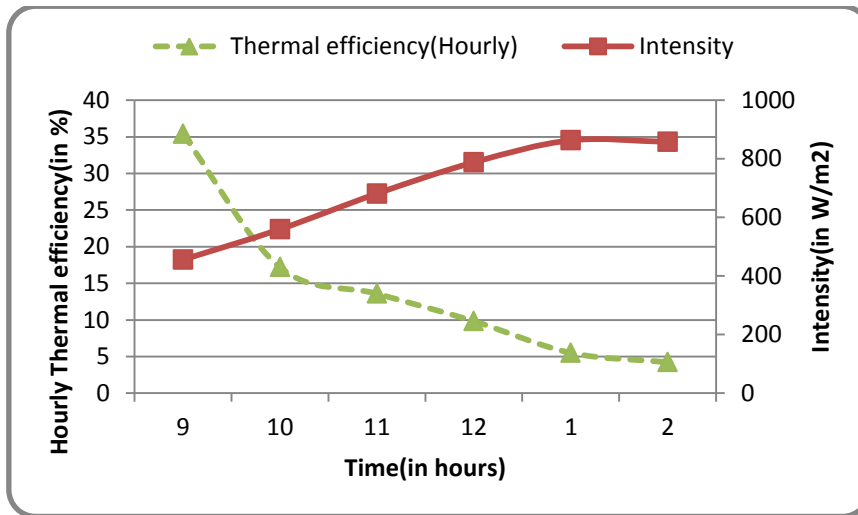


Figure.38 Variation of time and intensity with hourly thermal efficiency

5.4.1.2) Discussion: It is observed from the graphical representations of the Aluminium absorber tube that:

- As the time increases the temperature of the water increases from 25 °C at 8:00 A.M to the peak temperature of 65.9 °C at 2:00 P.M as shown in figure.35.
- Due to increase in thermal losses the temperature of water decreases after 2:00 P.M and the solar intensity also decreases with the increase in time. The temperature of water decreases more rapidly than the solar intensity as shown in figure.35.
- The maximum increase in temperature of water is between 8:00 A.M to 9:00 A.M and the minimum increase is between 1:00 P.M to 2:00 P.M as shown in figure.35.

d) As the time and solar intensity increases the instantaneous efficiency and thermal efficiency decreases up to the peak temperature. Both the efficiencies are at their maximum values between 8:00 A.M-9:00 A.M as shown in figure.36 and figure.38.

e) The useful heat gain also decreases with an increase in time.

5.4.2) Copper absorber tube: Now instead of Aluminium, an absorber tube made up of copper is used and the same readings are performed as in the case of Aluminium tube. The below table gives the measured values of the inlet and outlet temperature of water, intensity of solar radiations, with respect to the time.

Table.18 Readings with copper absorber tube

Sr.No	Time(hours)	Intensity (W/m ²)	Inlet Temp(°C)	Outlet Temp(°C)
1	8-9	395	25.0	39.8
2	9-10	526	39.8	48.7
3	10-11	657	48.7	57.6
4	11-12	788	57.6	65.4
5	12-1	892	65.4	72.6
6	1-2	810	72.6	72.2
7	2-3	734	72.2	68.1
8	3-4	662	68.1	65.4
9	4-5	590	65.4	61.8

The below table gives the calculated values of useful heat gain and the values of instantaneous efficiency, system efficiency, and the overall efficiency. The effective aperture area is 1.40.

Table.19 Calculated values of useful heat gain and efficiencies

Time (hours)	Useful heat gain Q _u (W)	Instantaneous efficiency/(ΔT°C) η _{instantaneous}	System efficiency η _{thermal}	Overall thermal efficiency η _{overall}
8-9	259.0	20.5	40.17	17.75
9-10	173.25		20.92	
10-11	173.25	12.32	17.12	
11-12	154.0		13.09	
12-1	108.50	6.05	9.10	

5.4.2.1) Graphical Representations: The values of the useful heat gain, hourly thermal efficiency, and instantaneous efficiency are calculated by the use of formulas given in eqn. as it is done in the previous case of Aluminium tube. The relationships between different parameters with solar intensity and time are shown graphically in the figures below:

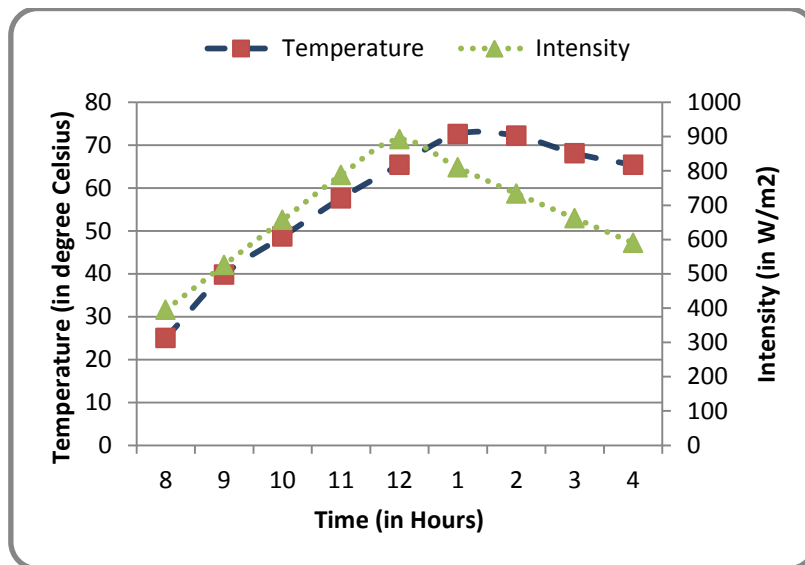


Figure.39 Variation of time and intensity with temperature (Cu tube)

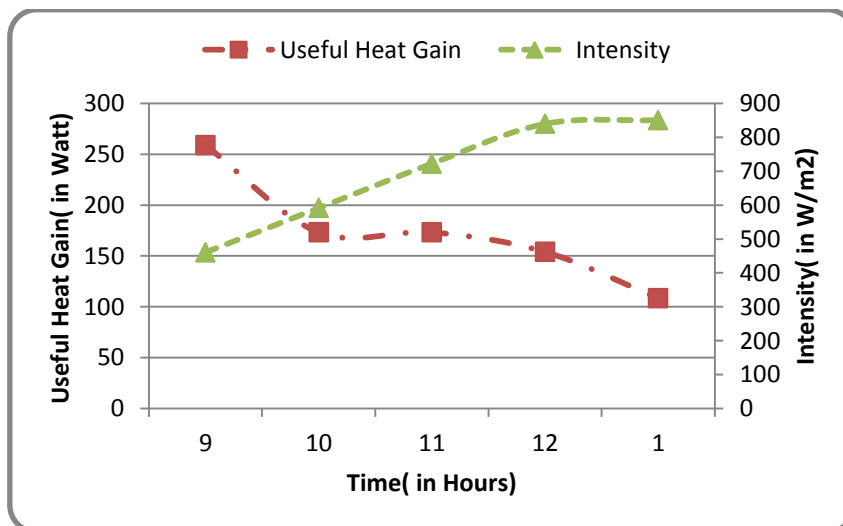


Figure.40 Variation of useful heat gain with time and intensity

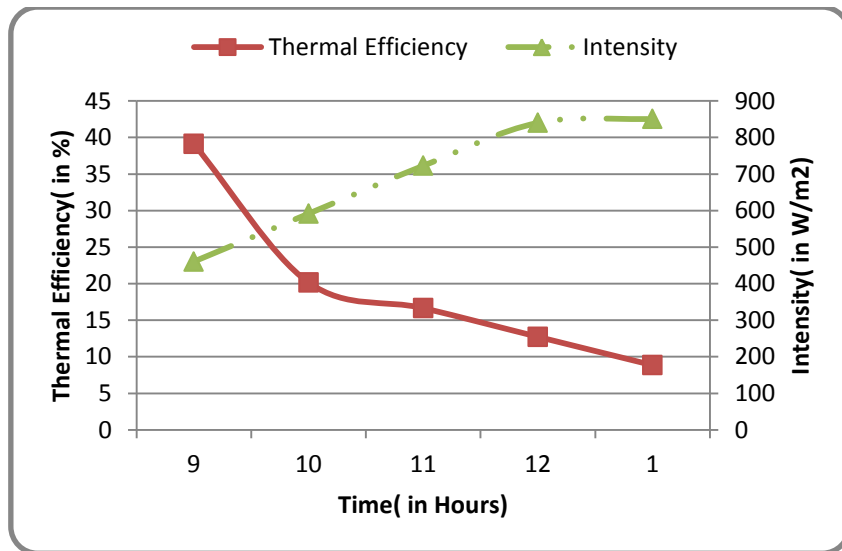


Figure.41 Variation of hourly thermal efficiency with time and intensity

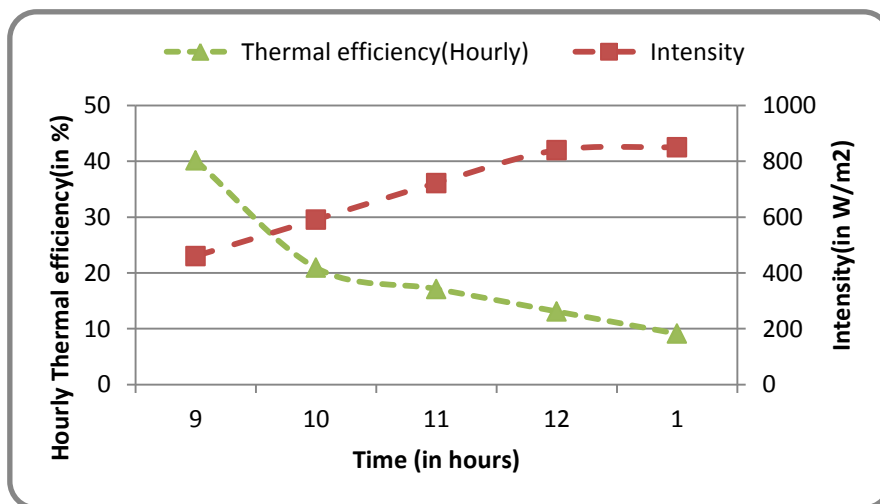


Figure.42 Variation of instantaneous efficiency with time and intensity

5.4.2.2) Discussion: It is observed from the above figures that:

- a) The storage tank water temperature increases steadily from an initial temperature of 25 °C at 8:00 A.M to a peak temperature of 72.6 °C at 1:00 P.M, as no energy is withdrawn from the storage tank during the collection period and after that it decreases to 61.8 °C due to thermal losses. This is shown in figure.39. The solar intensity also increases with time to a maximum value of 892 W/m² at 12 Noon after which it decreases.
- b) From figure.40 it is observed that the useful heat gain is maximum between 8:00 A.M to 9:00 A.M and it then decreases with the increase in time and solar intensity.

- c) Hourly thermal efficiency and instantaneous efficiency decreases with the increase in time and solar intensity as shown in figure.41 and figure.42. Maximum value of thermal efficiency is between 8:00 A.M-9:00 A.M. It firstly decreases to a large amount and then slowly to the lowest value at 5:00 P.M.

5.4.3) Comparison of Aluminium tube with Copper tube:

The above results are compared with that of an Aluminium absorber tube and it is observed that the maximum temperature of water in the storage tank is higher when copper tube is used. The hourly thermal efficiencies and instantaneous efficiency is also higher in case of copper tube. Also the values of the useful heat gain taken hourly are higher in comparison to the Aluminium tube. As the thermal conductivity of copper is higher than Aluminium therefore the peak temperature of the water in the storage tank is attained at 1:00 P.M which is earlier than that in case of Aluminium tube. So the use of copper tube gives the better performance and results than the Aluminium tube and hence it is used further in the experiment with the glass cover tubes of different diameters.

Now copper tube with the same inside and outside diameter as used above is now used with glass cover tubes of different outside diameters. The glass cover tube is fixed over the copper tube with the help of rubber cork seals at both ends. This arrangement with different outside diameters of the glass cover tubes are used as an absorber tube. The performance analysis is done for all the absorber tubes and comparison is done between them. Thus four different cases arises which are:

- 1) Copper tube with 45 mm glass cover tube
- 2) Copper tube with 55 mm glass cover tube
- 3) Copper tube with 65 mm glass cover tube
- 4) Copper tube with 75 mm glass cover tube

5.4.4) Copper tube with 45 mm glass cover tube: The copper tube with 45 mm glass cover tube is used as an absorber tube and the below table gives the measured values of the inlet and outlet temperature of water in the storage tank, intensity of solar radiations, with respect to the time.

Table.20: Readings of Copper tube with 45 mm glass cover tube

Sr.No	Time(hours)	Intensity (W/m ²)	Inlet Temp(°C)	Outlet Temp(°C)
1	8-9	410	25.0	40.6
2	9-10	540	40.6	50.2
3	10-11	670	50.2	59.2
4	11-12	790	59.2	68.3
5	12-1	898	68.3	75.7
6	1-2	792	75.7	73.7
7	2-3	732	73.7	70.0
8	3-4	681	70.0	68.3
9	4-5	605	68.3	66.5

The below table gives the calculated values of useful heat gain and the values of instantaneous efficiency, system efficiency, and the overall efficiency. The effective aperture area is 1.38.

Table.21 Calculated values of useful heat gain and efficiencies

Time (in hours)	Useful heat gain Q_u (W)	Instantaneous efficiency/ $(\Delta T^{\circ}\text{C})$ $\eta_{\text{instantaneous}}$	System efficiency η_{thermal}	Overall thermal efficiency η_{overall}
8-9	273.0	20.04	41.64	19.43
9-10	168.0		20.12	
10-11	157.5	6.17	18.11	
11-12	159.25		13.67	
12-1	129.5	6.10	11.10	

5.4.4.1) Graphical Representations: The values of the useful heat gain, hourly thermal efficiency, and instantaneous efficiency are calculated by the use of formulas given in eqn. as it is done in the previous two cases. The relationships between different parameters are shown graphically in the figures below:

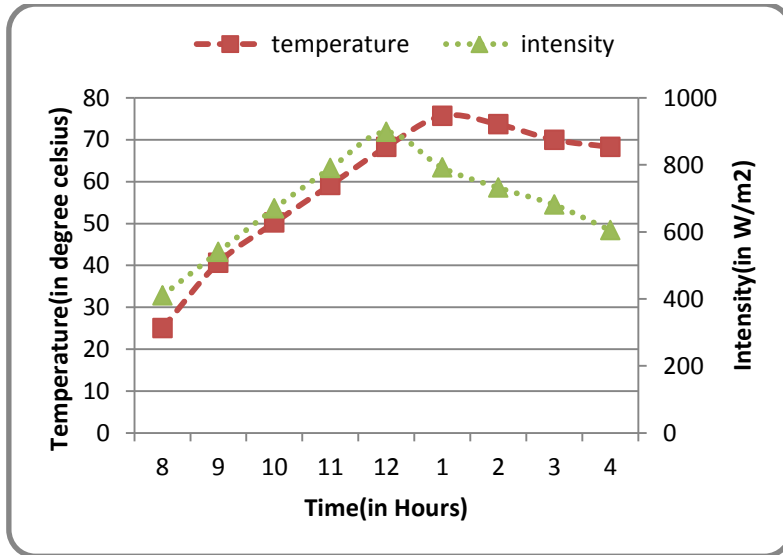


Figure.43 Variation of storage tank water temperature with time and intensity

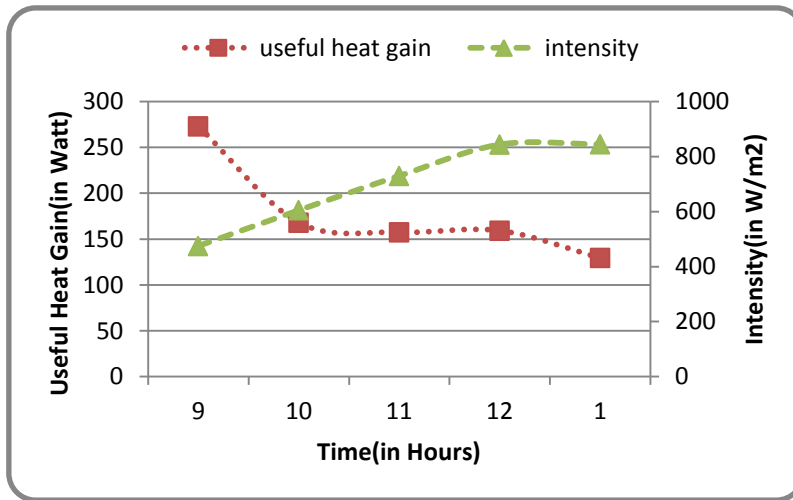


Figure.44 Variation of useful heat gain with time and intensity

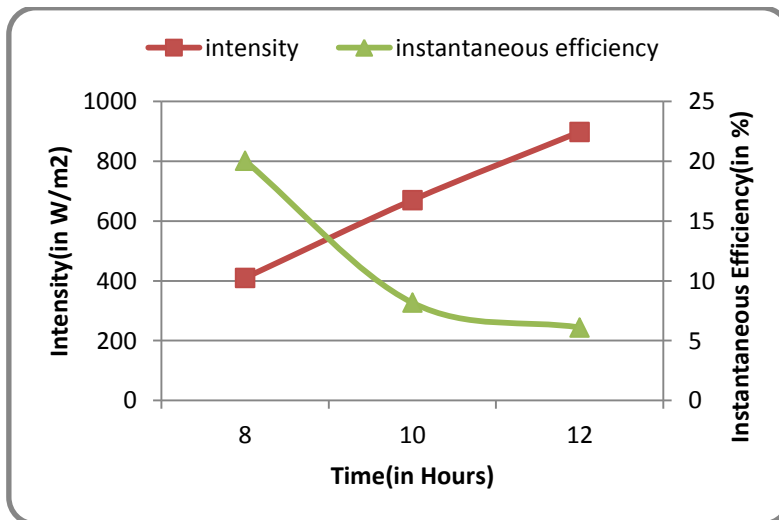


Figure.45 Variation of instantaneous efficiency with time and intensity

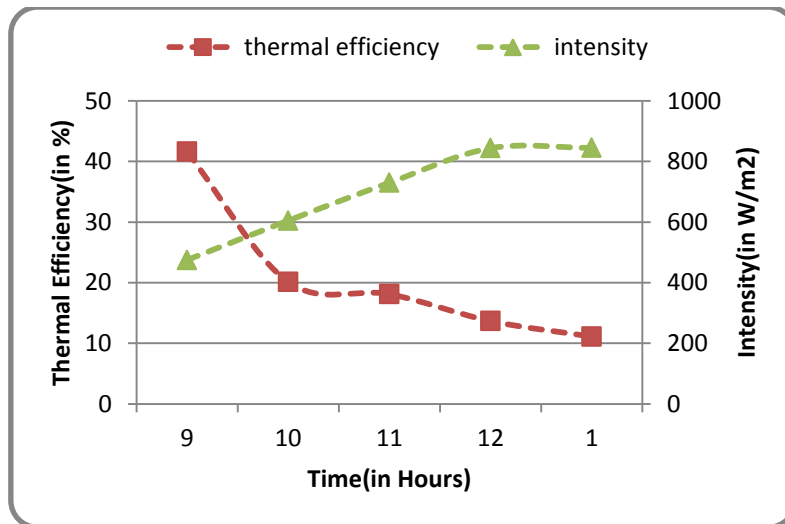


Figure.46 Variation of hourly thermal efficiency with time and intensity

5.4.5) Copper tube with 55 mm glass cover tube: The copper tube with 55 mm glass cover tube is used as an absorber tube and the below table gives the measured values of the inlet and outlet temperature of water in the storage tank, intensity of solar radiations, with respect to the time.

Table.22 Readings of Copper tube with 55 mm glass cover tube

Sr.No	Time(hours)	Intensity (W/m ²)	Inlet Temp(°C)	Outlet Temp(°C)
1	8-9	402	25.0	41.0
2	9-10	546	41.0	52.3
3	10-11	650	52.3	61.2
4	11-12	800	61.2	70.8
5	12-1	910	70.8	77.4
6	1-2	805	77.4	75.7
7	2-3	745	75.7	73.6
8	3-4	636	73.6	71.1
9	4-5	597	71.1	69.8

The below table gives the calculated values of useful heat gain and the values of instantaneous efficiency, system efficiency, and the overall efficiency. The effective aperture area is 1.374.

Table.23 Calculated values of useful heat gain and efficiencies

Time (in hours)	Useful heat gain Q_u (W)	Instantaneous efficiency/ $(\Delta T^\circ\text{C})$ $\eta_{\text{instantaneous}}$	System efficiency η_{thermal}	Overall thermal efficiency η_{overall}
8-9	280.0	27.37	42.98	20.17
9-10	197.75		24.13	
10-11	155.75	12.69	15.63	
11-12	168.0		14.30	
12-1	115.5	6.04	9.80	

5.4.5.1) Graphical Representations: The values of the useful heat gain, hourly thermal efficiency, and instantaneous efficiency are calculated by the use of formulas given in eqn. as it is done in the previous two cases. The relationships between different parameters are shown graphically in the figures below:

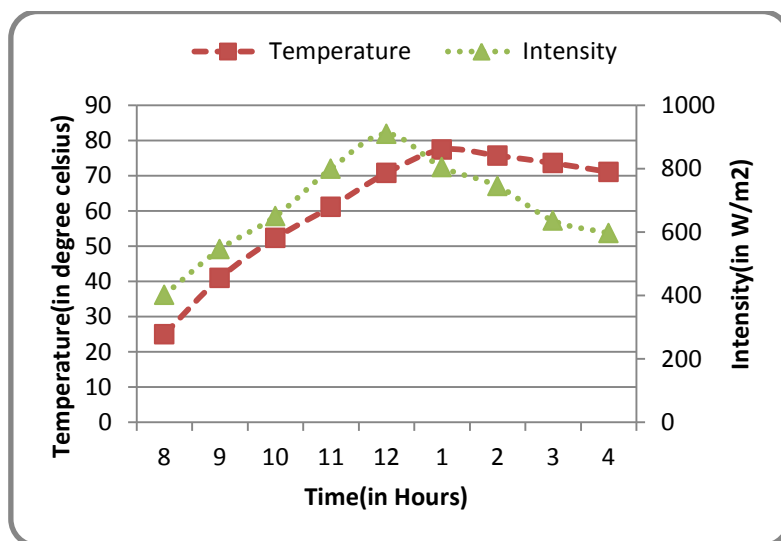


Figure.47 Variation of water temperature with time and intensity (55mm)

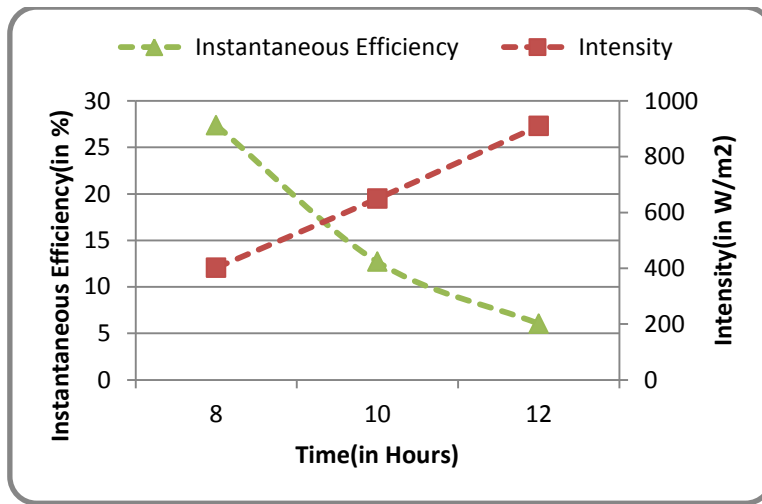


Figure.48 Variation of instantaneous efficiency with time and intensity

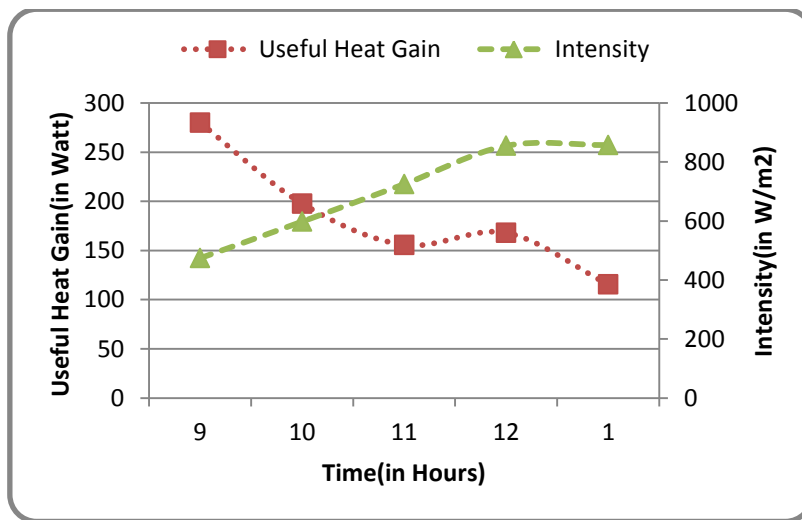


Figure.49 Variation of useful heat gain with time and intensity

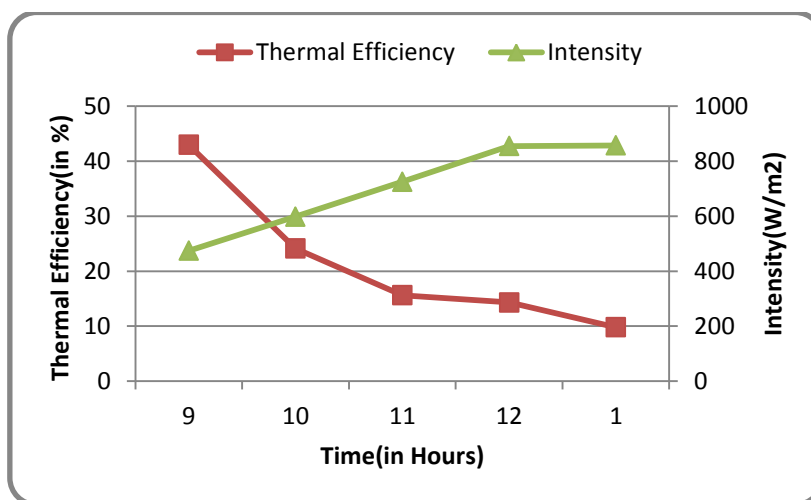


Figure.50 Variation of hourly thermal efficiency with time and intensity

5.4.6) Copper tube with 65 mm glass cover tube: The copper tube with 45 mm glass cover tube is used as an absorber tube and the below table gives the measured values of the inlet and outlet temperature of water in the storage tank, intensity of solar radiations, with respect to the time.

Table.24 Readings of Copper tube with 65 mm glass cover tube

Sr.No	Time(hours)	Intensity (W/m ²)	Inlet Temp(°C)	Outlet Temp(°C)
1	8-9	388	25.0	39.8
2	9-10	559	39.8	51.2
3	10-11	688	51.2	61.7
4	11-12	821	61.7	70.1
5	12-1	915	70.1	76.4
6	1-2	857	76.4	72.2
7	2-3	751	72.2	69.1
8	3-4	683	69.4	67.1
9	4-5	601	67.1	65.8

The below table gives the calculated values of useful heat gain and the values of instantaneous efficiency, system efficiency, and the overall efficiency. The effective aperture area is 1.362.

Table.25 Calculated values of useful heat gain and efficiencies

Time (in hours)	Useful heat gain Q_u (W)	Instantaneous efficiency/ $(\Delta T^{\circ}\text{C})$ $\eta_{\text{instantaneous}}$	System efficiency η_{thermal}	Overall thermal efficiency η_{overall}
8-9	259.0	28.60	40.16	19.50
9-10	199.5		23.49	
10-11	163.75	12.10	17.88	
11-12	147.0		12.43	
12-1	110.25	9.09	9.13	

5.4.6.1) Graphical Representations: The values of the useful heat gain, hourly thermal efficiency, and instantaneous efficiency are calculated by the use of formulas given in eqn. as

it is done in the previous two cases. The relationships between different parameters are shown graphically in the figures below:

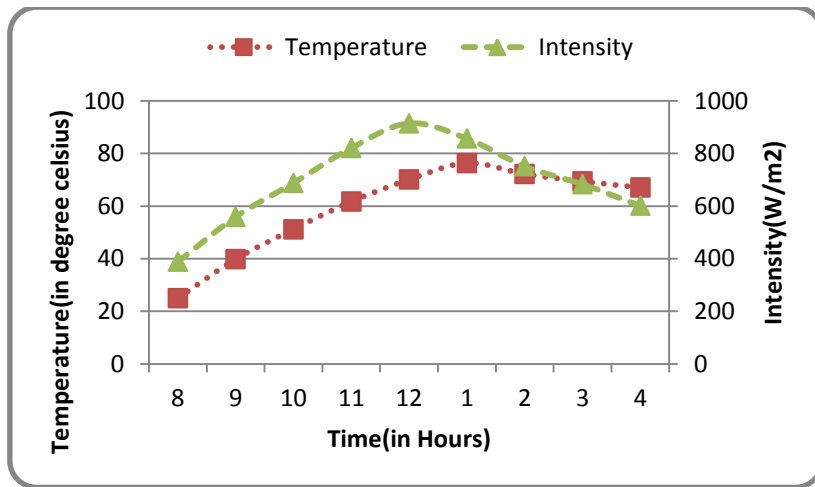


Figure.51 Variation of water temperature with time and intensity (65mm)

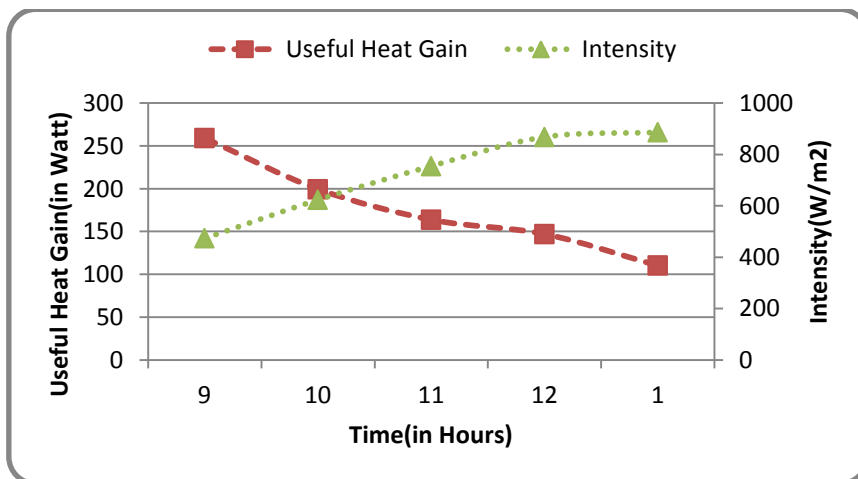


Figure.52 Variation of useful heat gain with time and intensity

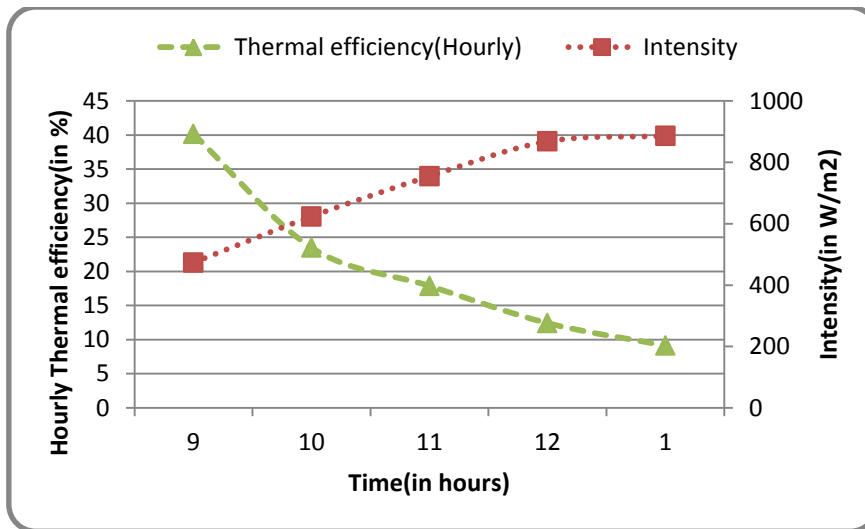


Figure.53 Variation of instantaneous efficiency with time and intensity

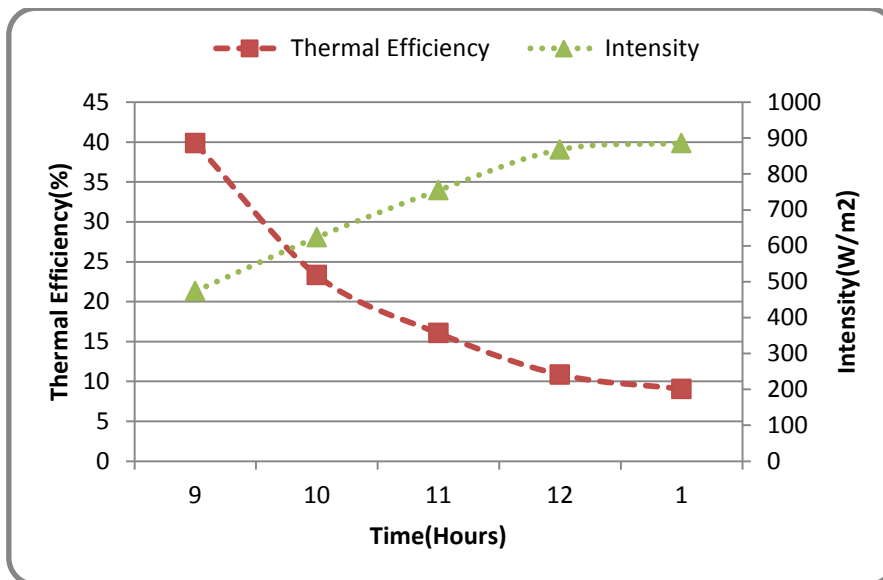


Figure.54 Variation of hourly thermal efficiency with time and intensity

5.4.7) Copper tube with 75 mm glass cover tube: The copper tube with 45 mm glass cover tube is used as an absorber tube and the below table gives the measured values of the inlet and outlet temperature of water in the storage tank, intensity of solar radiations, with respect to the time.

Table.26 Readings of Copper tube with 75 mm glass cover tube

Sr.No	Time(hours)	Intensity (W/m ²)	Inlet Temp(°C)	Outlet Temp(°C)
1	8-9	421	25.0	38.8
2	9-10	592	38.8	49.1
3	10-11	697	49.1	58.9
4	11-12	783	58.9	67.3
5	12-1	895	67.3	74.7
6	1-2	817	74.7	71.6
7	2-3	723	71.6	69.0
8	3-4	655	69.0	66.1
9	4-5	590	66.1	63.4

The below table gives the calculated values of useful heat gain and the values of instantaneous efficiency, system efficiency, and the overall efficiency. The effective aperture area is 1.35.

Table.27 Calculated values of useful heat gain and efficiencies

Time (hours)	Useful heat gain Q_u (W)	Instantaneous efficiency/ $(\Delta T^{\circ}C)$ $\eta_{\text{instantaneous}}$	System efficiency η_{thermal}	Overall thermal efficiency η_{overall}
8-9	241.50	19.95	35.31	19.01
9-10	180.25		20.73	
10-11	171.50	12.05	17.16	
11-12	147.0		12.97	
12-1	129.50	6.25	11.20	

5.4.7.1) Graphical Representations: The values of the useful heat gain, hourly thermal efficiency, and instantaneous efficiency are calculated by the use of formulas given in eqn. as it is done in the previous two cases. The relationships between different parameters are shown graphically in the figures below:

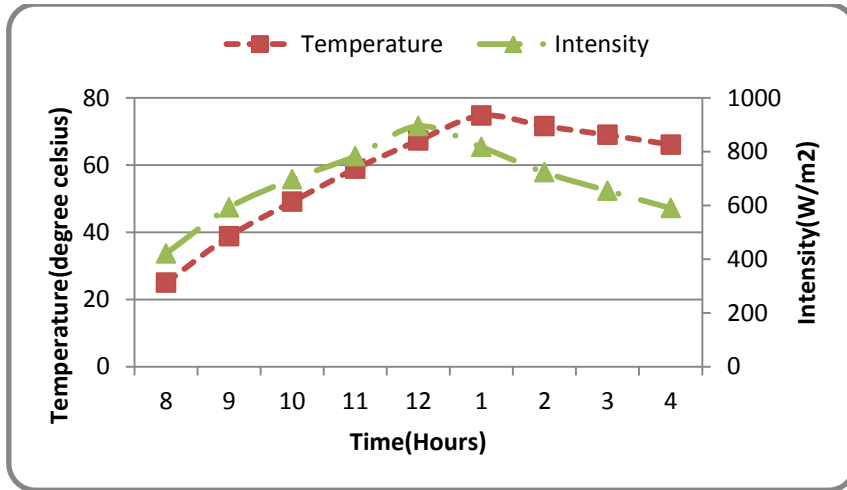


Figure.55 Variation of water temperature with time and intensity (75mm)

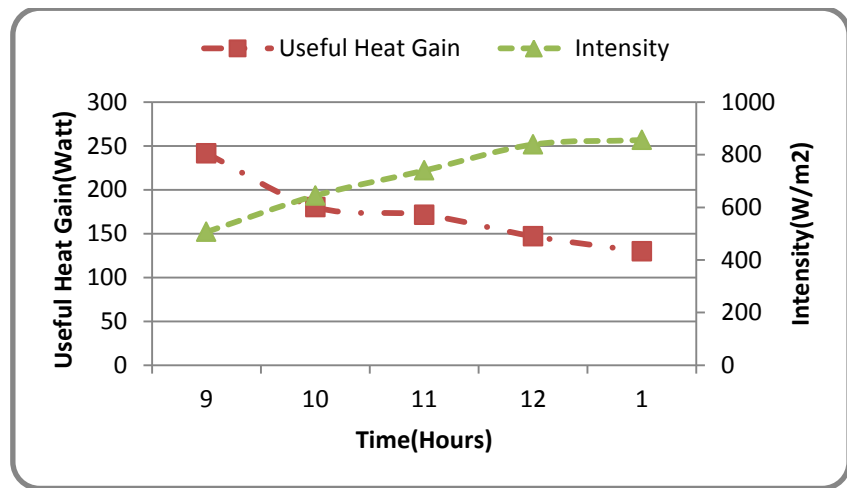


Figure.56 Variation of useful heat gain with time and intensity

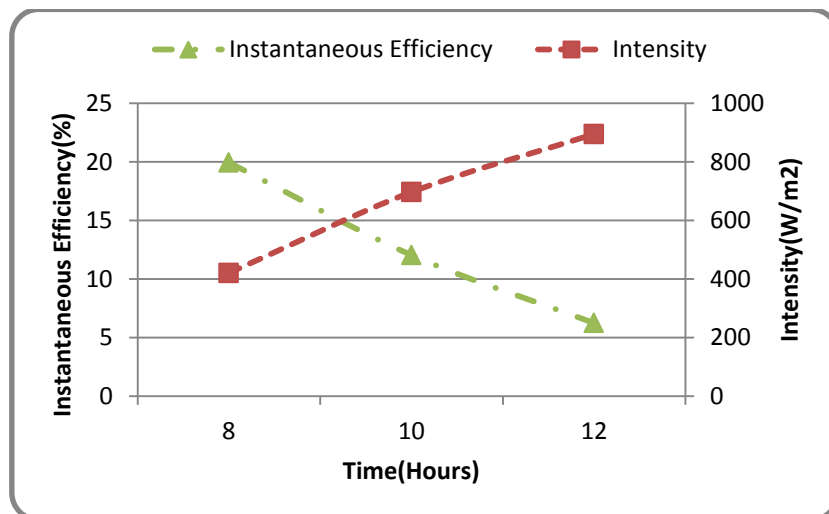


Figure.57 Variation of instantaneous efficiency with time and intensity

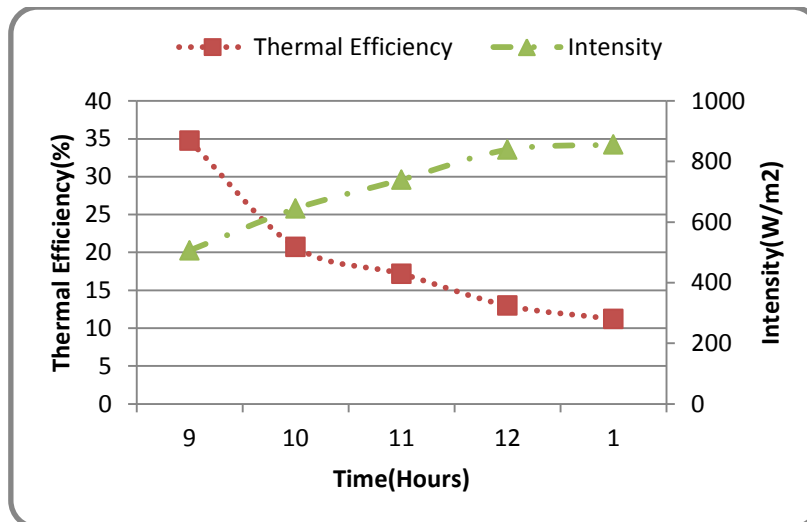


Figure.58 Variation of hourly thermal efficiency with time and intensity

5.5) Results and Discussion: From all the above results it is observed that the maximum peak temperature of water in the storage tank is **77.4°C** in case of 55 mm glass cover tube and minimum peak temperature attained is 74.7°C in case of 75 mm glass tube. The maximum useful heat gain is in case 2 and minimum in case 4. The maximum value of hourly thermal efficiency is **42.98%** in case of 55 mm glass tube which is **1.34%**, **2.82%**, and **7.67%** more than the maximum hourly thermal efficiencies in case 1, case 3, and case 4 respectively. The instantaneous efficiency in case of 65 mm glass cover tube is **28.6%** which is maximum and is **1.23%** more than in case of 55mm glass cover tube. The overall thermal efficiency in case of glass tube with 55 mm diameter is 20.17% which is maximum amongst all the cases. The maximum useful heat gain in case of 55 mm glass tube is **280 watt** which is also the highest. It is observed from the graphical representation that as the time increases the useful heat gain, overall thermal efficiency, instantaneous efficiency, and hourly thermal efficiency decreases, but solar intensity increases to its peak value and then decreases. The optimum results are obtained in case of copper tube with glass cover tube of 55 mm diameter. So it is the best option amongst all the cases.

Chapter - 6

Results, Conclusion and Future Scope

6.1) Results and Conclusion: The parabolic trough solar collector system is mainly used for the power production as the temperature of steam coming from it is very high. It is also used for water heating, air heating and other applications as well. The PTSC technology can be very useful for the water heating applications if cost of the system is reduced to some extent. In this proposed work there is a use of systems approach (MADM, Graph Theoretical approach) for the evaluation, comparison, ranking and optimum selection of the PTSC system. MADM approach involves the identification of different attributes affecting a PTSC system forming an exhaustive database from which a lot of information and knowledge can be gathered. A mathematical tool named TOPSIS procedure is used for the ranking and optimum selection of the PTSC design which is explained with an example. Four different PTSC designs from the global market are taken which are ranked and the best design amongst all four is selected. The PTSC named **Flagsol SKAL ET 150** is proved to be the best possible design according to the requirement. In the graph theoretical approach a systems methodology for developing a PTSC system by considering all the attributes responsible for design, production etc. along with interactions between the constituents is proposed using a digraph and various matrix models. The structural constituents of PTSC system along with the interactions between them are identified and represented in a tree diagram and a digraph respectively. The PTSC system permanent function is thus formed which is a mathematical model used to determine the PTSC system index. The numerical index of PTSC system derived from a multinomial is used for the comparison, ranking and optimum selection of the PTSC system. The overall work done and presented here in this thesis is very useful for the user, designer, manufacturer and the maintenance personnel in the industry.

The temperature of water in the storage tank, useful heat gain, hourly thermal efficiency, instantaneous efficiency and overall thermal efficiency are calculated for each case and the results from the experimental investigation of the fabricated PTSC system are shown in the table below.

Table.28 Maximum values of different parameters in all cases

Sr. no.	Type of absorber tube	Temperature of water in storage tank(°C)	Useful heat gain Q_u (W)	Overall thermal efficiency $\eta_{overall}$	System efficiency $\eta_{thermal}$	Instantaneous efficiency/(ΔT °C) $\eta_{instantaneous}$
1	Bare Aluminium tube	65.9	225.75	12.78	35.40	13.36
2	Bare Copper tube	72.6	259.0	17.75	40.17	20.5
3	Copper tube with 45 mm glass cover tube	75.7	273.0	19.43	41.64	20.04
4	Copper tube with 55 mm glass cover tube	77.4	280.0	20.17	42.98	27.37
5	Copper tube with 65 mm glass cover tube	76.4	259.0	19.50	40.16	28.60
6	Copper tube with 75 mm glass cover tube	74.7	241.5	19.01	35.31	19.95

When the experimental results of bare Aluminium absorber tube and bare copper absorber tube with same outer and inner diameter of 32.5 mm and 31.5 mm are compared then the copper tube showed the better results. The maximum temperature of water in the storage tank is **72.6°C** in case of copper absorber tube and **65.9°C** in case of Aluminium absorber tube. The overall thermal efficiency in case of copper absorber tube is 4.97% more than in case of Aluminium absorber tube. The above table shows that performance with glass tube of different diameters are compared the optimum results comes out in case of copper tube with

glass cover tube of 55 mm outside diameter on it. The values of temperature of water in the storage tank, overall thermal efficiency, useful heat gain, and hourly thermal efficiency, i.e. **77.4°C, 20.17%, 280.0 watt, 42.98%** respectively are maximum amongst all the cases. The maximum useful heat gain is in case 2 and minimum in case 4. The maximum value of hourly thermal efficiency is **1.34%, 2.82%, and 7.67%** more than the thermal efficiencies in case 1, case 3, and case 4 respectively. The instantaneous efficiency in case of 65 mm glass cover tube is maximum and is **1.23%** more than in case of 55mm glass cover tube. The results of overall thermal efficiency are as follows:

$$\eta_{\text{overall } 2} > \eta_{\text{overall } 3} > \eta_{\text{overall } 1} > \eta_{\text{overall } 4}$$

Where, $\eta_{\text{overall } 1}$ = Overall thermal efficiency when 45 mm glass cover tube is used,

$\eta_{\text{overall } 2}$ = Overall thermal efficiency when 55 mm glass cover tube is used,

$\eta_{\text{overall } 3}$ = Overall thermal efficiency when 65 mm glass cover tube is used,

$\eta_{\text{overall } 4}$ = Overall thermal efficiency when 75 mm glass cover tube is used.

The overall thermal efficiency when copper tube with 55mm glass cover tube is used as an absorber tube is **20.17%** which is highest amongst all the four cases. After analysing all the results it is concluded that the copper tube with 55 mm glass cover tube which is to be used as an absorber tube has got the best results amongst all the other cases. Hence the best performance of the PTSC system comes out in this case. The reasoning behind all these results is that when the 45mm glass cover tube is used then the gap between the metal surface and the glass tube is less which results in heat losses through the glass cover tube. As the outside diameter of glass tube increases the volume of air in between also increases which decreases the heat losses from the glass tube to some extent. But when the diameter of glass tube increases further the volume of air also increases to greater extent which results into the increase in heat losses to air trapped in between copper and glass tube. There might be human error, tracking error, and experimental error which also affect the performance of the system. The optimum results are achieved when 55mm glass tube is used. When the annulus gap is increased to 65mm and 75mm then the heat losses to air increases and hence performance of the system decreases.

6.2) Future Scope: There is a lot of scope of future investigation as well which is as follows:

- i. The sensitivity analysis can be done on a single or multiple number of attributes e.g. thickness of the absorber tube to make it different and better than the other competitive products present in the global market.
- ii. The comparison and evaluation of different PTSC designs on the basis of some other attributes like quality, reliability etc. as the permanent function is formed by the structural constituents and their interactions.
- iii. This fabricated PTSC system can be used for steam generation if length of the collector and the effective aperture area is increased.
- iv. We can do further work on the tracking mechanism of the parabolic solar collector by the use of automatic tracking (gears, motors) with the help of sensors or relays.
- v. Experimental investigation can be done by considering the different materials for the reflector and with that the performance of parabolic trough solar collector system is evaluated.

References:

- 1) Ari Rabl, "Comparison of Solar Concentrators Solar Energy", vol.18. Pp.93-111, pregamon press 1976.
- 2) Jaideep Ahluwalia, Sumit Kumar Gupta and V.P. Agrawal, "Computer-aided optimum selection of roller bearings", Computer-Aided Design 25 (1993) 493-499.
- 3) A. Thomas and H. M. Guven, "Parabolic Trough Concentrators---Design, Construction and Evaluation", Energy Convers, Mgmt Vol. 34, No. 5, pp. 401-416, 1993.
- 4) Soteris Kalogirou, Polyvic Efeetheriou, Stephen Llyod And John Ward, "Low Cost High Accuracy Parabolic Troughs Construction and Evaluation", Renewable Energy, Vol. 5,Part 1,Pp, 384-386,1994.
- 5) Ashish Bhateja, V.P. Agrawal and K. Athre, "Total Design Concept of springs-A Novel Approach Using MADM, "Methodology, Advances in Mechanical Engineering (1996) 401-424.
- 6) Soteris Kalogirou, Stephen Llyod and John Ward, "Modelling, Optimisation and Performance Evaluation of a Parabolic Trough Solar Collector Steam Generation System", Solar energy Vol. No.1, pp. 49-59, 1997.
- 7) G.C. Bakos, I. Ioannidis, N.F. Tsagas, I. Seftelis "Design, Optimisation and Conversion-Efficiency Determination of A Line-Focus Parabolic-Trough Solar-Collector (PTC)" Applied Energy 68 (2001) 43-50.
- 8) Hank Price, Eckhard Lu'pfert, David Kearney, Eduardo Zarza, Gilbert Cohen, Randy Gee, Rod Mahoney, "Advances in Parabolic Trough Solar Power Technology", Journal of solar Energy Engineering MAY 2002, Vol. 124 / 111.
- 9) Michael Geyer, Eckhard L'upfert, Rafael Osuna, Antonio Esteban, Wolfgang Schiel, Axel Schweitzer, Eduardo Zarza, Paul Nava, Josef Langenkamp, Eli Mandelberg, "Eurotrough - Parabolic Trough Collector developed for Cost Efficient Solar Power Generation", 11th Int. Symposium on Concentrating Solar Power and Chemical Energy Technologies, September 4-6, 2002.
- 10) P.Naidoo, T.I. van Niekerk and M.Brooks, "Intelligent Control and Tracking of a Parabolic Trough Solar Collector", Copyright 2002 IFAC.
- 11) Daniel M. Blake, Luc Moensa, Mary Jane Halea, Henry Pricea, David Kearney, and Ulf Herrmann "New Heat Transfer and Storage Fluids for Parabolic Trough Solar Thermal Electric Plants", September 4-6, 2002.

- 12) Maria Brogren, Anna Helgesson, Bjorn Karlsson, Johan Nilsson, Arne Roosa “Optical properties, durability, and system aspects of a new aluminium-polymer-laminated steel reflector for solar concentrators”, *Maria Solar Energy Materials & Solar Cells* 82 (2004) 387–412.
- 13) Soteris A. Kalogirou “Solar thermal collectors and applications”, *Progress in Energy and Combustion Science* 30 (2004) 231–295.
- 14) A.Nasir “Design, Construction and Experimental Study of the Thermal Performance of a Parabolic Cylindrical Trough Solar Air Heater”, Department of Mechanical Engineering, Federal University of Technology Minna, Niger State, Nigeria” *AU J.T.8* (1): 21-26 (Jul. 2004).
- 15) P.P. Bhangale, V.P. Agrawal, S.K. Saha, “Attribute Based Specification, Comparison and Selection of a Robot, Mechanism and Machine Theory 39 (2004) 1345–1366.
- 16) George C. Bakos “Design and construction of a two-axis Sun tracking system for parabolic trough collector (PTC) efficiency improvement”, *Renewable Energy* 31 (2006) 2411–2421.
- 17) R.K. Garg, V.P. Agrawal and V.K. Gupta, “Selection of power plants by evaluation and comparison using graph theoretic methodology”, *Electrical Power and Energy Systems* 28 (2006) 429-435
- 18) Amirtham Valan Arasu and Samuel Thambu Sornakumar, “Performance Characteristics of the Solar Parabolic Trough Collector with Hot Water Generation System”, *BIBLID: 0354-9836*, 10 (2006), 2, 167-174.
- 19) M J Brooks, I Mills, T M Harms, “Performance of a parabolic trough solar collector”, *Journal of Energy in South Africa* Vol. 17 No 3 August 2006.
- 20) Ming Qu, David H. Archer, Sophie V. Masson, “A Linear Parabolic Trough Solar Collector Performance Model”, *Renewable Energy Resources and a Greener Future* Vol.VII-3-3, 2006, *ESL-IC-06-11-267*.
- 21) R. T. Durai Prabhakaran, B. J. C. Babu & V. P. Agrawal (2006): “Optimum Selection of a Composite Product System Using MADM Approach, Materials and Manufacturing Processes”, 21:8, 883-891
- 22) N. Naeeni, M. Yaghoubi, “Analysis of wind flow around a parabolic collector heat transfer from receiver tube”, *Renewable Energy* 32 (2007) 1259–1272.
- 23) A. Scrivani, T. El Asmar, U. Bardi “Solar trough concentration for fresh water production and waste water treatment”, *Desalination* 206 (2007) 485-493.

- 24) S.K. Tyagi, Shengwei Wang, M.K. Singhal, S.R. Park, “Exergy Analysis and Parametric Study of Concentrating Type Solar Collectors”, *International Journal of Thermal Sciences* 46 (2007) 1304-1310.
- 25) R.T. D. Prabhakaran and V.P. Agrawal, *Structural Modeling and Analysis of Composite Product System: A Graph Theoretic Approach*, *Journal of Composite Materials* 40:22 (2006) 1987-2007.
- 26) R.K. Garg, V.P. Agrawal, and V.K. Gupta, “Coding, evaluation and selection of thermal power plants – A MADM approach”, *Electrical Power and Energy Systems* 29 (2007) 657–668.
- 27) F Mammadov, U Samadova, O Salamov “Experimental results of using a parabolic trough solar collector for thermal treatment of crude oil”, *Journal of Energy in Southern Africa* Vol 19 No 1 February 2008.
- 28) Hazim Mohameed Qiblawey, Fawzi Banat “Solar thermal desalination technologies” *Desalination* 220 (2008) 633–644.
- 29) Varinder Singh and V.P. Agrawal, “Structural modelling and integrative analysis of manufacturing systems using graph theoretic approach”, *Journal of Manufacturing Technology Management* 19/7 (2008) 844-870.
- 30) M. Petrakis, G. Barakos and S. Kaplanis, “Roof Integrated Mini-Parabolic Solar Collectors. Comparison between Simulation and Experimental Results”, *the Open Fuels & Energy Science Journal*, 2009, Vol. 2, 71-81.
- 31) K. Ravi Kumar, K.S. Reddy “Thermal analysis of solar parabolic trough with porous disc receiver”, *Applied Energy* 86 (2009) 1804–1812.
- 32) Milton Matos Rolim, Naum Fraidenraich and Chiguera Tiba, “Analytic Modeling of a Solar Power Plant with Parabolic Linear Collectors”, *Solar Energy* 83 (2009) 126-133.
- 33) A. Fadar, A. Mimet, A. Azzabakh, M. Pérez-García, J. Castaing, “Study of a new solar adsorption refrigerator powered by a parabolic trough collector”, *Applied Thermal Engineering* 29 (2009) 1267–1270.
- 34) Michael DiGrazia, R. Gee, and G.Jorgensen “ReflecTech mirror film attributes and durability for CSP applications”, ASME conference, proceedings of Energy Sustainability 2009, July 19-23, 2009, San Francisco, California.
- 35) Rafael Almanza, Perla Hernandez, Ivan Martinez, Marcos Mazari “ Development and mean life of aluminium first-surface mirrors for solar energy applications” *solar energy materials & solar cells* 93 (2009) 1647-1651.

- 36) M. M. Alkilani, K. Sopian, Sohif Mat, "Output Air Temperature Prediction in a Solar Air Heater Integrated with Phase Change Material", ISSN 1450-216X Vol.27 No.3 (2009), pp.334-341.
- 37) P. Rhushi Prasad H.V. Byregowda P.B. Gangavati, "Experiment Analysis of Flat Plate Collector and Comparison of Performance with Tracking Collector" ISSN 1450-216X Vol.40 No.1 (2010), pp.144 -155.
- 38) Abhishek Kumar, Shibu Clement and V.P. Agrawal, "Attribute based design specification, comparison and selection of electroplating waste treatment system using MADM approach" Journal of Tribology and Surface Engineering 1 (2010) 1-30.
- 39) Najla El Gharbi,, Halima Derbal, Sofiane Bouaichaoui, Noureddine Said "A comparative study between parabolic trough collector and linear Fresnel reflector technologies" Energy Procedia 6 (2011) 565–572.
- 40) Heinz Marty and Elimar Frank, "Investigations on Solar Thermal Process Heat Integration with Parabolic Trough Collectors", ISES Solar Word Congress, 28. August - 2. September 2011, Kassel, Germany.
- 41) M.J. Montes, A. Rovira, M. Muñoz, J.M. Martíne, "Performance analysis of an Integrated Solar Combined Cycle using Direct Steam Generation in Parabolic Trough Collectors" Applied Energy 88 (2011) 3228–3238.
- 42) Ricardo Vasquez Padilla, Gokmen Demirkaya, D. Yogi Goswami, Elias Stefanakos, Muhammad M. Rahman, "Heat transfer Analysis of Parabolic Trough Solar Receiver", Applied Energy 88 (2011) 5097–5110.
- 43) David Barlev, Ruxandra Vidu, Pieter Stroeve "Innovation in concentrated solar power", Solar Energy cells & solar cells 95 (2011) 2703-2725.
- 44) C.P. Kiran, Shibu Clement and V.P. Agrawal, "Design for X-Abilities of a Mechatronic System- A Concurrent Engineering and Graph Theory Based Approach, Concurrent Engineering: Research and Applications", 19:1 (2011) 55-69.
- 45) C. Phaneendra Kiran, Shibu Clement, and V.P. Agrawal, "Coding, evaluation and optimal selection of a mechatronic system", Expert Systems with Applications 38 (2011) 9704-9712.
- 46) Claudia Vannoni, Riccardo Battisti and Serena Drigo, "Potential for Solar heat in Industrial processes", Department of Mechanics and Aeronautics, University of Rome "La Sapienza", Italy.
- 47) G.N. Tiwari "Solar Energy- Fundamentals, Design, Modelling And Applications" ISBN No- 81-7319-450-5.

- 48) G.D Rai “Non-Conventional energy sources” ISBN No: 81-7409-073-8.
- 49) H.P. Garg, J Prakash “Solar Energy fundamentals and applications”, Tata Mcgraw Hill ISBN No-07-463631-6.
- 50) http://en.wikipedia.org/wiki/Solar_power_in_India#Installed_capacity.
- 51) http://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations.
- 52) http://www.analyzemath.com/parabola/parabola_work.html.
- 53) www.google.com
- 54) India Energy Portal. <http://www.indiaenergyportal.org>. Accessed August 2010.
- 55) <http://www.google.co.in/imgres?q=flat+plate+collector&um=1&hl=en&safe=active&sa=N&biw=1366&bih=667&tbn=isch&tbnid=byMcsIInmLO4BM:&imgrefurl=http://www.adamsolarresources.com/solarthermal.html&docid=KhULFKUJhZIAMM&imgurl=http://www.adamsolarresources.com/pictures/flatplate.jpg&w=500&h=307&ei=q9nZTtSuGcbhrAej5LjtDQ&zoom=1&iact=hc&vpx=947&vpy=305&dur=52&hovh=176&hovw=287&tx=89&ty=105&sig=110898329299467212791&page=2&tbnh=120&tbnw=195&start=18&ndsp=19&ved=1t:429,r:17,s:18>
- 56) http://www.google.co.in/imgres?q=flat+plate+collector&um=1&hl=en&safe=active&sa=N&biw=1366&bih=667&tbn=isch&tbnid=fNQDA_tvZI_hNM:&imgrefurl=http://www.daviddarling.info/encyclopedia/A/AE_air_collector.html&docid=h2f_vh2KBsNikM&imgurl=http://www.daviddarling.info/images/air_flatplate_collector.gif&w=235&h=223&ei=q9nZTtSuGcbhrAej5LjtDQ&zoom=1&iact=hc&vpx=198&vpy=151&dur=10&hovh=178&hovw=188&tx=100&ty=103&sig=110898329299467212791&page=4&tbnh=134&tbnw=144&start=59&ndsp=21&ved=1t:429,r:14,s:59
- 57) http://www.analyzemath.com/parabola/parabola_focus.html.