PARAMETRIC ANALYSIS OF A PARABOLIC TROUGH SOLAR COLLECTOR

A

THESIS

Submitted in the partial fulfilment of the requirement for the award of degree of

Master of Engineering

In

Thermal Engineering

Submitted By:

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Declaration

I, Bharat Gupta, declare that this thesis report entitled **"Parametric Analysis of Parabolic trough solar collector"**, submitted towards fulfillment of the requirements for the award of Master's Degree in Thermal Engineering, in Mechanical Engineering Department of Thapar University, Patiala, is entirely my own work. This document has not been submitted for any degree in any other institution.

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Abstract

The solar parabolic trough collector technology is one of the most reliable technology in the field of solar thermal. This is due to the fact that temperatures as high as 300^oC can be achieved using this technology. This technology is used for hot water production, process steam requirement, power generation and many more. In the present study a parametric analysis on a parabolic trough collector is performed. Different parameters of the system such as receiver tube diameter, material of the receiver tube and heat transfer fluid are chosen for the study and evaluating the performance of the system. In the present work stainless steel with mirror finish is taken as the reflecting material for the trough. Stainless steel and copper are taken as the material for the receiver tubes. Bare tubes of three different diameters i.e. 19.05mm, 25.4mm and 31.75mm are used for both the tube materials. All the six test sections are fabricated and then electroplated with nickel and chromium in order to increase their absorptivity and reduce losses. Water and Mythol Therm 500 are used as heat transfer fluid. Four mass flow rates are used for both the fluids. Temperature are recorded using RTD sensors and Pyranometer is used for measuring intensity of solar radiation. On the basis of recorded parameters efficiency of the system was calculated and its variation with time of day and mass flow rate for different conditions is represented graphically. Overall heat loss coefficient (U_L) and Heat removal factor (F_R) also calculated and represented in tabular form.

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Chapter 1

Introduction

The worldwide requirement of energy is persistently increasing and makes it ineluctable to make the use of unconventional resources. The sun is one of the substantial energy sources that has the potential to fulfil this rising energy need. Sun is inexhaustible and cleaner source of energy. Solar thermal technology is inevitable in growth of the community as well as the nation. Also, it is important to the nation and to the Earth. Sun is an enormous pool of clean energy and this clean power reaches earth in the form of its rays is known as Solar Energy. Solar energy is an abundant source of energy and is available in plenty. Conversion of these incoming solar radiations can be done directly or indirectly in other useful forms of energy as heat and electricity which can be utilized further as per the requirement of the mankind. The sun is providing an incredible supply of solar energy for over 4 billion years. Solar energy was used by the ancient people to warm their homes and dry clothes but their uses were mostly primitive. Drastic increase in global oil prices, extensive use of fossil fuels, threatening rise in pollution and greenhouse effect have led a large number of countries around the globe to carry out extensive research in this area.

1.1) The sun and the earth

The sun is at the centre of the solar system and contains about 99% mass of the solar system making it the largest member. The diameter of the sun is about 864,938 miles which is about 109 times to that of earth. There is a continuous conversion of helium atom into hydrogen at the center through a fusion process and its surface temperature is about 550^0c. It takes about 8 minutes 20 seconds to reach the light from the sun to the earth and the energy radiated can be calculated by Stefan Boltzman law of radiation which is

$\mathbf{E = \varepsilon\sigma T^4}$, where [2]

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

The earth is the third planet from the sun and its diameter is about 7.926 miles. The planet rotation cause it to bulge at the center due to which there is difference of 40 miles in equatorial and pole diameter. About 70% of the earth's surface is covered by water due to which it is known as the blue planet. Earth is inclined at an angle of 23.5^0c on its axis.

1.2) Solar spectrum and solar radiation

Sun's radiation is in the form of electromagnetic radiation which is categorized further into infrared radiation, ultra violet radiation and white light.

1.2.1) Solar Spectrum:

Sun's radiation is a combination of different layers which absorb and emit radiations that differ in wavelengths. Harmful portion of these wavelengths i.e. is the Gamma and X-rays are filtered out by the atmosphere. About 48% of the sun's radiation falls in visible region, whereas about 45.6% is in the infrared region [2] and the rest is in ultraviolet spectrum. The solar spectrum is shown in the figure 1.1 [2].

1.2.2) Direct and Diffuse solar radiation

The solar energy that reaches the earth is further categorized in the form of direct and diffuse radiations.

Diffuse: As the white light passes through the sun's atmosphere it gets scattered, reflected and absorbed by various elements such as the clouds, pollutants, dust, air molecules etc. This radiation is known as diffuse radiation.

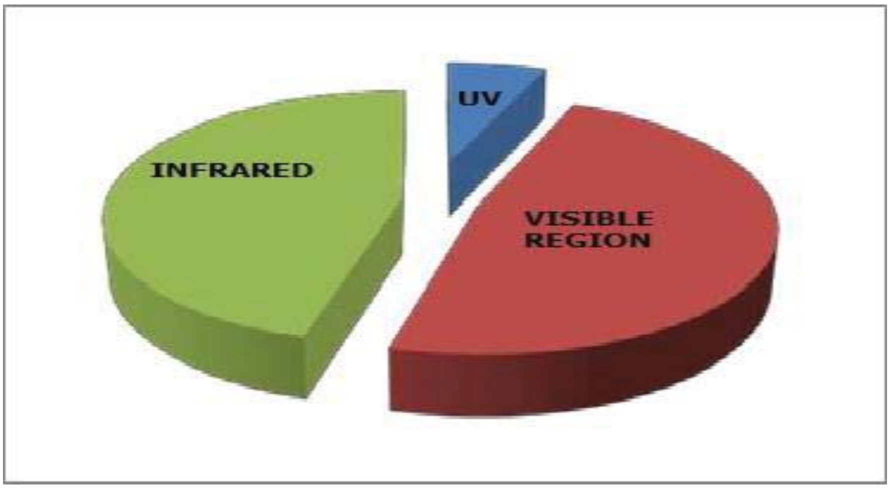

Figure 1.1: Solar Spectrum

Direct: The portion of the sunlight which does not diffused and reaches the earth is known as direct radiation or Beam radiation. On a clear, dry sunny day the atmosphere can block up to 10% of beam radiation whereas this can reach up to 100% on very thick cloudy day. The solar flux registered per sec by a surface having unit area and kept perpendicular to the sun rays is known as Solar constant (Isc) which is a constant throughout the year. The Solar constant is having a value of 1367W/m^2 [2].

1.3) Sun and Earth angles

Various important sun and earth angles are shown in the figure 2 below are as follows:

Altitude angle (α): Angle formed between a horizontal surface and sun rays.

Zenith angle (θ): Angle formed between a line which is perpendicular to the horizontal plane and the sun rays.

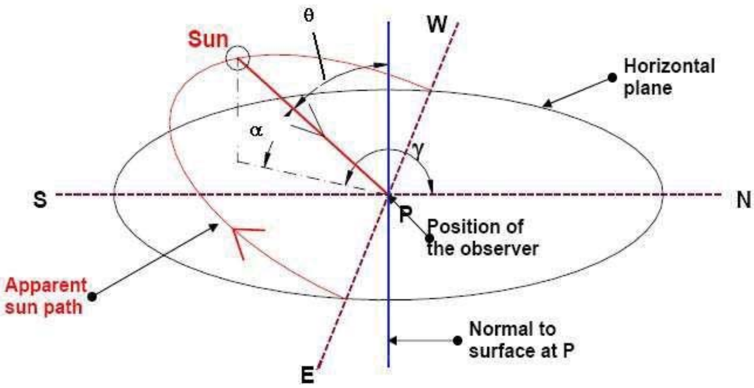

Figure 1.2: Solar Angles

Surface Azimuth angle (γ): This angle is measured in a horizontal plane and is formed between the line due south and the projection of the normal surface on the horizontal plane.

Latitude (ϕ): The latitude angle of a location is the formed between the radial line connecting that location to the earth's centre with line's projection on equatorial plane.

Hour angle (ω): It is the angle through which the earth must be rotated to bring the meridian of the plane directly under the sun.

Declination (δ): It the angle which is formed between the line joining the earth centers of sun and earth and projection of this line on the equatorial plane.

Angle of incidence (θ_i): It is the angle between the beam radiation on the surface and normal to the surface.

1.4) Solar Energy in India:

India is blessed with a huge potential of solar power. India receives an estimated hourly radiation of 200 MW/km^2 with approximately 300 sunny days per year. The theoretical reception of solar power on the land area is about 5 trillion KWh/yr. At present India is having about 3 GW of installed capacity which is just over 1% of the total installed capacity and about 0.5% of the estimated potential. As estimated by the National Institute of solar energy the current potential of solar energy in India is about 750 GW[1]. The estimates suggest that Rajasthan and Jammu Kashmir have the highest potential in this regard. Thar Desert in Rajasthan has massive potential of about 142GW of solar power[1]. Currently Gujarat is the leading state when it comes to installed solar power and has installed capacity of about 900 MW and is also developing utility-scale power project over various canals and rooftops throughout the state. Indian government is expanding its wings to become one of the largest producers of solar power in the world and plans to install 100 GW by the end of 2022 which includes about 20 GW of ultra-mega solar power projects across 12 different states[1].

1.5) Application of solar energy:

Solar energy has wide variety of applications which are classified as follows:

- Urban planning and architecture
- Horticulture and agriculture
- Steam Cooking/ Heating
- Process Heating
- Chip and timber drying

[1] http://cleantechnica.com/2014/11/29/indias-solar-power-potential-estimated-750-gw/

- Cooling and refrigeration
- Desalination of water
- Power/ Electricity generation

Solar energy is a fantabulous source for meeting our electricity requirements. Solar PV (photovoltaic) possesses the ability of direct conversion of incoming solar radiations into electricity. This energy can tapped using PV cells and can be stored using battery which can be further used as per the demands. These can be used for such puposes:

- Village electrification
- Water pumping
- Street lighting
- Domestic lighting
- Mini grid

1.6) Solar energy collectors

The purpose of a solar energy collector is to gather the radiant energy falling on its surface and then transfer this energy to fluid which is in contact with the collecting surface. These are classified as:

- Concentrating
- Non-concentrating

The basic difference between these is that of the absorber area. In a non-concentrating collector absorber area is nearly same as that the recipient area but on the other hand the energy falling on a large recipient area is focused on a small absorber area.

1.6.1) Non-concentrating

1.6.1.1) Flat Plate type solar collector

The chief components are

Absorber plate – These are made of highly conducting materials so as to absorb as much heat as possible.

Fins or Tubes – They carry heat transfer fluid, and are made from good conducting material.

Glazing – These are very thin sheets of glass or plastic to prevent heat loss.

Insulation – This is used minimize heat loss from the non-receiving end.

Casing or Cover – It surrounds the other entire component and prevents them against weather, moisture, dust etc.

Flat plate collectors are further categorized into two types:

Water type – They use water as the fluid for heat transfer.

Air type – They use air as the fluid for heat transfer.

Advantages and Uses:

- It is easy to fabricate and install.
- It utilizes both the direct beam and diffused radiations.
- It does not require sun tracking.
- They are mechanically simpler to construct than other collectors.
- They can be used as domestic water heaters or for offices and hotels as they easily reach the temperature range of 40^0C to 70^0C.

- The flat plate collector for air and water heating is shown in figure 1.3[2] and figure 1.4[3] below.

1.6.1.2) Evacuated Tube collectors

This is another type of non-concentrating collectors which is generally made from glass tube that held parallel to each other. The glass tube is fabricated in such a way that the space between the tubes is vacuumed and each glass tube possesses a metal absorber. This metal absorber is attached to a fin and is coated so as to increase its absorptivity and cut down the losses. The vacuum between the layers of the glass

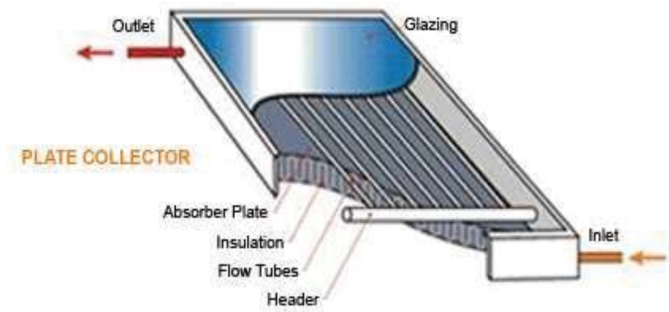

Figure1.3: Flat plate collector for water heating

tube also helps in minimizing the convective, conductive and radiation losses. An evacuated tube collector is shown in the figure 1.5 [20].

[2] https://www.google.co.in/search?site=imghp&tbm=isch&source=hp&biw=1366&bih=667&q=flat+plate+collector+for+water+heating&oq=flat+plate+collector+for+water+heating&gs_l=img.3...5546.17734.0.18330.48.22.5.21.26.0.290.3416.0j13j5.18.0....0...1ac.1.64.img..28.20.3414.LGEecPqph2M#imgrc=PB6ioXq9Ei73LM%3A

[3] http://www.google.co.in/imgres?q=flat+plate+collector&um=1&hl=en&safe=active&sa=N&biw=1366&bih=667&tbm=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

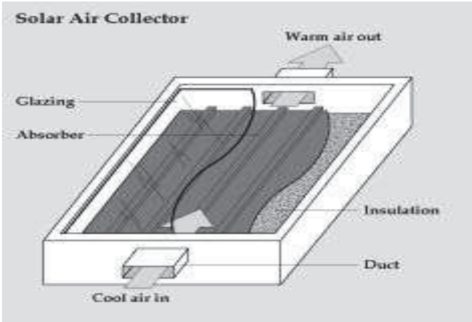

Figure1.4: Flat plate collector for air heating

Advantages:

- Their operating temperatures are higher when compared with the flat plate collector.
- The heat losses in this type are less compared to flat plate collector.
- They have a compact design.

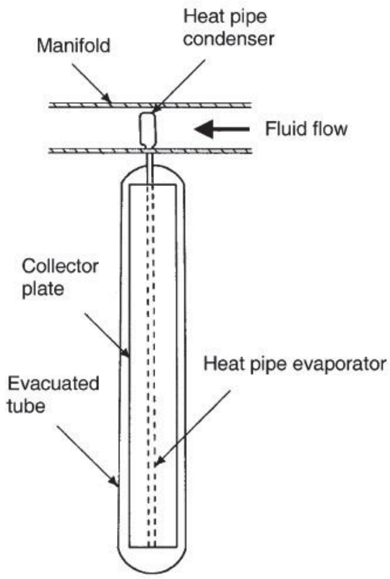

Figure1.5: Evacuated Tube Collector

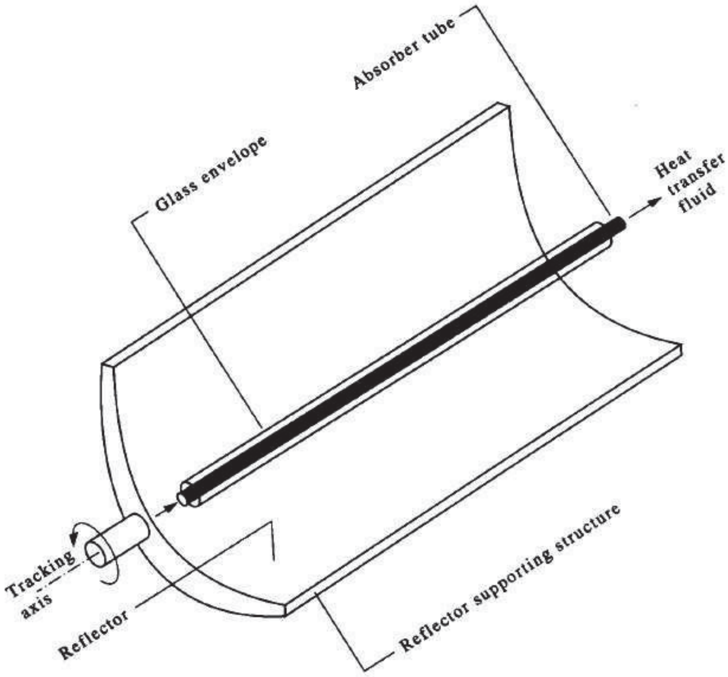

Figure1.6: Parabolic Trough Collector system

1.6.2) Concentrating

These are basically of four types:

- Parabolic Trough solar collector
- Linear Fresnel Reflector
- Parabolic Dish
- Power tower

1.6.2.1) Parabolic Trough Collector

A parabolic trough collector system consists of a reflecting surface which resembles a parabolic shape. This reflecting surface is mostly made of reflecting mirrors or anodized aluminium sheets. The solar radiations falling on the reflecting surface is concentrated on the focal line of the parabola where a receiver tube carrying the heat transfer fluid is placed. Absorber tube either painted black or electroplated with nickel or chromium in order to increase the absorptivity of the tube. The heat transfer fluid picks up the heat from the absorber tube which is utilized later in the desired way. The temperature in this type of system can reach as high as 400^0c, depending upon the type of reflecting surface, absorber tube materials and heat transfer fluid.

A parabolic trough collector system must be positioned in agreement with the sun's position so that it can reflect the incoming beam radiations to the absorber tube. Concentrating ratio is an important term when talking about concentrating collectors. It is defined as the ratio of the area aperture area of collector and absorber tube's area. Its value ranges from 20 to 70. Increase in concentration ratio corresponds to higher working temperatures. Various components of the system are shown in the figure 1.6 [25]. Design specifications are shown in figure 1.7[4].

Some of the chief components of the system are:

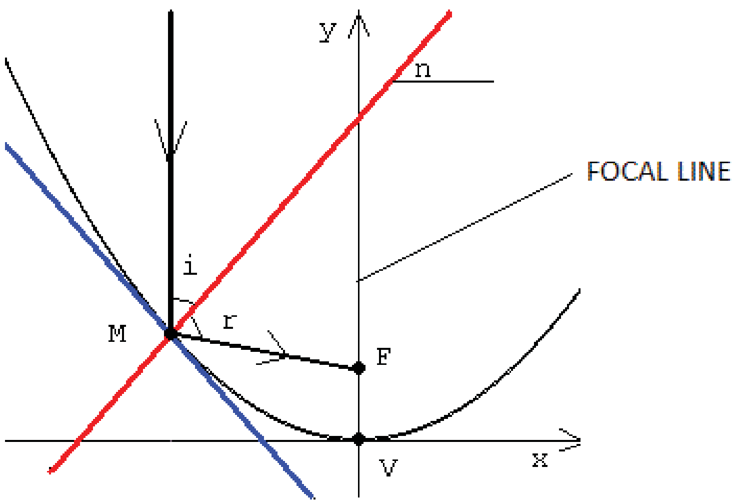

Figure1.7: Design specification of a reflector

[4] http://www.analyzemath.com/parabola/parabola_work.html.

Reflector: The purpose of the reflector is to reflect and concentrate the incoming direct radiation to the focal line. This is generally made from a material of very high reflectivity such as polished mirrors, anodized aluminium etc.

The reflectivity is as high as 90%.

Absorber tube: It acts as receiver and transporter of the energy which is being concentrated at focal line of the reflecting surface. It is made of good

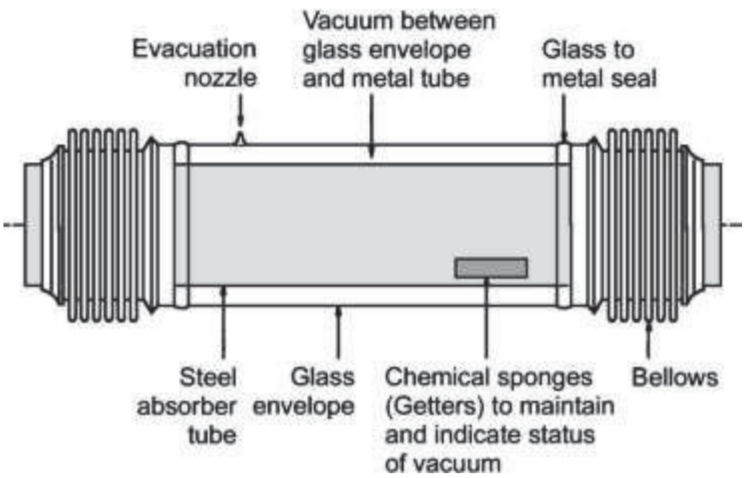

Figure1.8 Absorber Tube

absorbing materials such as copper and is coated with black paint or other metal for increased absorptivity. It carries the heat transfer fluid to which the energy is transferred. Figure1.8[12] shows a type of absorber tube.

Glass cover tube: Absorber tube may contain a glass envelope which can evacuated on non-evacuated. The impetus of this tube is minimizing the various heat losses due to convection, conduction and radiation. Evacuated tubes are more efficient in minimizing these losses but are difficult to fabricate.

Support structure: It is a mechanical frame which gives the required support to sustain the weight and provide robustness against wind loads.

Tracking mechanism: The function of this device is to keep the collector in agreement with the position of the sun so as to keep it in focus as the soon moves from east to west.

Various subsystem of the parabolic trough collector system is shown in figure1.9 [25]

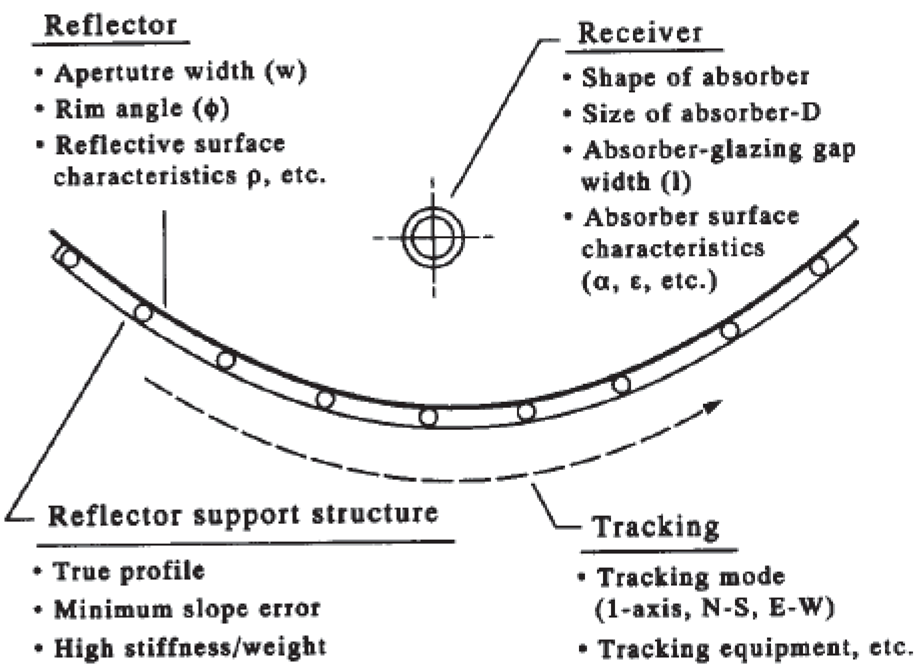

Figure1.9 Subsystems of Parabolic trough collector system

Advantages:

- System has high conversion efficiency.
- It can be used for power generation and steam generation.
- It can be used for community cooking purposes.

- Temperatures as high as 400^0C are achievable.
- It can also be utilized for thermal energy storage.

1.6.2.2) Fresnel Reflector:

It is another type of concentrating collector where the collector is in the form of an array of plane mirror strips. These mirrors concentrate beam radiation on a fixed absorber tube which is positioned in such a way that it lies at focus of all the mirror strips. The absorber is fixed the mirrors are moved as the sun changes its position. Fresnel Reflector is shown in figure1.10 [20].

Advantages:

- The reflectors have low cost as they are linear and not in a parabolic shape.
- The structure requirement is minimum as they are placed close to the surface.

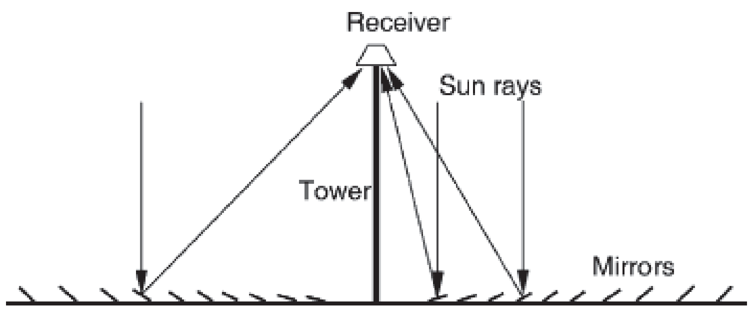

Figure1.10: Fresnel Reflector

1.6.2.3) Parabolic dish:

A parabolic dish collector is a type point focusing concentrating collector. The incoming beam radiations falling on the surface parallel to the axis of the dish concentrated at the focal point of the dish. This system uses a dual axis tracking which clearly means that it had to follow sun throughout the day in order for high efficiency. This system can attain temperature as high as 1500^0C. A parabolic dish is shown in figure1.11 [20].

Advantages:

- They have the highest efficiency of all the concentrating system as they always points the sun.
- The system has got very high concentration ratios of about 600-2000.
- Each dish has its own focal point which makes it an independent unit and this can also be used in array of dishes.

1.6.2.4) Power tower:

A power tower is a different form of concentrating collector system. In this system a number of small tracking mirrors concentrate the beam radiations onto a large tower

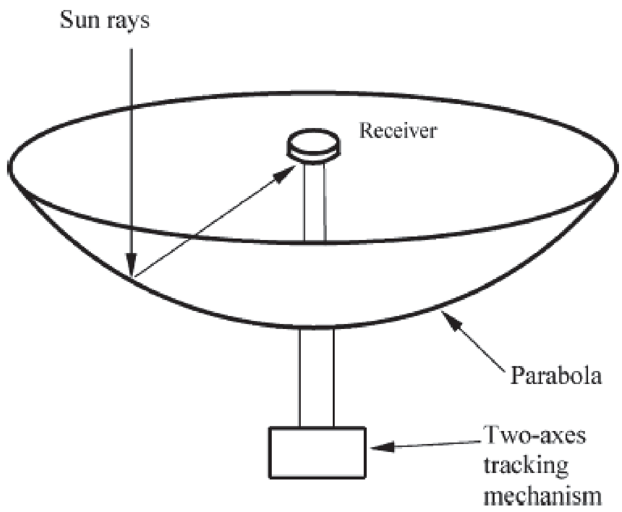

Figure1.11: Parabolic Dish

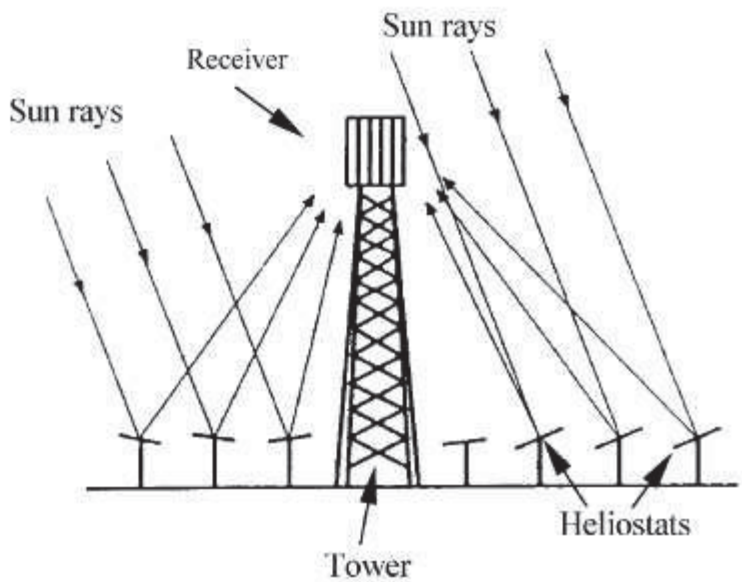

Figure1.12: Power Tower

which is placed at centre. The tracking mirrors are aligned and rotated in such a way that it always reflects the light to the top of tower. The average value of the concentrated solar flux that falls on the tower is about 200 to 1000 kw/m^2

which allows working at very high temperature of about 1500^0C. A power tower is shown is figure 1.12 [20].

Advantages:

- They can be economically used for power generation as the working temperature is very high.
- They are very good for thermal energy storage using molten salts.

1.7) Objectives of the study

The present study has been carried out to achieve the following objectives.

1. To determine the effect of mass flow rate of working fluid on thermal performance of the concentrating collector.
2. To determine the effect of absorber tube diameter on the thermal performance of the concentrating collector.
3. To determine the performance of concentrating collector with i) water and ii) Mythol Therm 500 as working fluid.

Chapter-2

Literature Review

Cheng *et al.* investigated the heat transfer characteristics of absorber tube of a parabolic solar trough collector using three-dimensional numerical simulation. Monte Carlo Ray-Trace Method (MCRT Method) was adopted to calculate the distribution of solar irradiance on the outer walls of the receiver tube. It was observed that there is very large non-uniformity of flux distribution. The data of the experiment performed on LS2 solar parabolic trough collector using Syltherm 800 as the heat transfer fluid was analysed by combining MCRT method and Fluent software. Various properties of oil that were temperature dependent as well as the radiations between the glass cover and inner tube were also taken into consideration. Three typical test conditions were taken and model was validated. It was observed that the radiation losses were maximum in model 3 which was about 153.7 W/m^2.

Khanna *et al*. studied the effect of incidence angle of the rays of sun on the banding and deflection of absorber tube. It was observed that due to non-uniform distribution of flux on the absorber tube causes the development of circumferential temperature gradient causing the induction of bending moment in the tubes leading to their deflection. It was concluded that if somehow the incidence angle is made zero the absorber tube will not deflect. However due to non-zero incidence angle deflection of tubes takes place which is due to the fact that the end of the tube facing the sun does not receive any concentrated flux. Dimensions from LS3 parabolic collector used with a Schott 2008 PTR 70 receiver was used for the study.

Lupfert *et al.* experimentally investigated thermal properties of receivers of a parabolic trough. In this study different methods to calculate the thermal loss from a receiver tube were presented based on their operating temperature. Two different receiver tubes which are Solel UVAC and Schott PTR 70 were used for the purpose of experiment. A single receiver tube of 4m length was heated up using a 4m long quartz heating element which was placed inside the tubes. The temperature measurements were done using 14 thermocouple placed accordingly at different places on the tube. It was observed that the solar parabolic trough plants which are having a temperature range of about 390^{o}C were having an energy loss of about 300 W/m of receiver length.

Padilla *et al* performed the exergy analysis on a parabolic trough solar receiver. The purpose of the study was to know the effects of various environmental and operational parameters on the performance of the parabolic trough collectors. Different parameters whose effect was seen on the performance were mass flow rate of heat transfer fluid, inlet temperature, pressure in annulus, wind speed and solar irradiance. The study was based on heat transfer models which have been used before by other authors. It was observed that vacuum in the annulus between the glass and the tube along with the intensity of solar radiation have significant effects on thermal and exergetic performance of the collector whereas other parameters were not affecting the performance significantly. Pressure less than 1 Torr is maintained in vacuum and solar irradiance varied between 250 to 1000 W/m^2.

Manikandan *et al.* had done the parametric analysis of a parabolic trough collector. Various parameters were chosen for the study which is mass flow rate of the heat transfer fluid, different heat transfer fluid, solar insolation and concentration ratio. It was observed that rise in inlet temperature of the heat transfer fluid caused a decrease in efficiency due to an increase in convective and radiation losses to the surroundings. Water and Castor oil were used as the heat transfer fluid for comparison. It was also observed that the effective heat gain was more with water than with castor oil. This was due to the fact that water was having more specific heat than castor oil. It was also observed that the effective heat gain increased with an increase in irradiance of sun rays.

Bakos *et al.* performed the simulation study of a large solar line focusing power plant in Greece. The literature deals with the technical feasibility of the plant that is to be set up some-where at island of Rhodes. This simulation study was carried out using TRNSYS software (STEC library). STEC library is based on 1st and 2nd law of thermodynamics (steady state energy conservation) formulated in other thermodynamic quantities such as pressure, temperature, enthalpy etc. It also consists of other models which are suitable for parabolic trough collector and Rankine cycles. It was calculated that for having an output of 8.55MW the total field area of the collector should be about 60,000 m^2 and a total of 60 loops with each loop having 12 solar collector in a row are required.

Brooks *et al.* investigated the performance of a solar parabolic trough collector. An evacuated glass shielded absorber and an unshielded absorber tube were used for the purpose of study. Water is used as the heat transfer fluid with both type of absorber tube. It was observed that the maximum thermal efficiencies for both the evacuated glass shielded and unshielded were 53.8% and 55.2% respectively. It was also observed that the absorber tube with evacuated glass shield was superior under maximum test temperatures also reducing the overall heat loss coefficient by half.

Cheng *et al.* performed a comparative and sensitive analysis of a solar parabolic trough collector using Monte Carlo Ray Trace model. In this study different solar parabolic trough collector systems were tested under different operating conditions in order to make a comparison as well as expecting to optimize PTC system for better performance. It was assumed that the average solar irradiance falling on the system is 1000 W/m^2. Various combinations of seven different types of solar parabolic trough collectors which are LS-2, LS-3, Sky Trough, Euro Trough, LAT 73, Helio Trough and Ultimate Trough along with four different receivers which are LS-2 receiver, LS-3 receiver, Siemens UVAC 2010 receiver and Schott PTR 70 receiver were used for the study. It was found that UVAC 2010 receiver had the largest absorbed solar energy whereas LAT73 has the best optical efficiency.

Chengmu *et al.* studied on the compensation of the end loss effect of solar parabolic trough collector. The study was carried out on PTC-HNSA which is placed horizontally along the north-south axis. It was observed by analysis that the compensation method was very much applicable for the regions which are having a latitude angle more than 25^o and also for short parabolic trough collectors. The length of the system used for the purpose of study is 5m. The literature provides a compensation method for minimizing the end loss caused due to the single axis tracking. As the sun-earth line is not vertical to earth's axis, the incident rays are generally oblique, therefore, it is becomes impossible for the system to avoid end losses. The end loss effect decreases with the increase of trough length L, and varies significantly in the range of $L < 15$ m. Also the available energy at the absorber can also be increased by employing a plane mirror at the end of the collector.

Meyer *et al.* investigated the heat transfer characteristics and performance of a parabolic trough absorber with centrally placed perforated plate inserts. Different perforated plate geometry was used for the analysis. Reynolds number was kept in the range $1.02\times10^4 \leq Re \leq 7.38\times10^5$ which was according to temperature of the heat transfer fluid. There were four different fluid temperatures used for the analysis i.e. 400K, 500K, 600K and 650 K. Plate porosity was having a fixed value of 0.65. The assembly of the perforated plate was supported on a thin rod that was placed axially inside the tube. It was observed that the placing of the perforated plate helped in increasing the thermal efficiency in the range from 1.2% to 8% depending upon the plate spacing and size.

Morrison *et al* done the optimization of a solar parabolic trough collector system. The purpose of the study was to tackle the problem of fluctuation in system temperature during unsteady state radiation condition associated with process heat applications using solar energy. For this a transient model was developed so as to analyze the performance of an industrial water heating solar parabolic system. The most important finding was that thermal storage tank size should be more than 14.51 m^{-2} of the collector area in order to provide stability process heat system during transition radiation period. It was also observed that the radiation instability having a period of 30 min or lower does not affect the system operation significantly.

Srinivas *et al.* performed numerical and experimental analysis on the performance of the absorber tube of a parabolic trough collector system with and without insertion. Commercially available code Ansys CFX 12.0 had been used for the numerical analysis. Water was used as the heat transfer fluid and three different mass flow rates had been used which were 33Kg/hr, 63 Kg/hr and 85 Kg/hr. It was seen that presence of inserts gave a higher rise in the outlet temperature when compared with the one without insertion which was due to the fact the area of heat transfer was increased with the insertion. It was also observed that the thermal stresses on the tube with insertion were less than that without insertion.

Sornakumar *et al.* carried out the performance characteristics of a solar parabolic trough collector system which was used for hot water generation. This analysis was carried out in accordance with ASHRAE Standard 93, 1986. Simulation were carried out using a MATLAB code and parabolic trough collector system was designed with 90^{o} rim angle and a reflector material having a reflectance of 0.974 was used for the analysis. It was observed that the time constant of the collector was 67 seconds which gives a clear indication about the response of the system for maintaining quasi-steady conditions.

Wang *et al.* carried out a detailed parametric study on the comprehensive characteristics and on the performance of a parabolic trough collector system. A theoretical analysis is performed on the association between geometric parameters of the system and the focal shape formed by the defocusing phenomenon. A three dimensional model in which Monte Carlo Ray Trace (MCRT) method coupled along with Finite Volume Method (FVM) was used for the analysis. It was found the performance and comprehensive characteristics were very much different for some critical points as determined by the coupled technique. For these critical points some ranges of geometric parameters were determined for optimizing performance.

Zhiyong *et al.* performed the structural reliability analysis of solar parabolic trough receiver. As the absorber tubes accounts for about 30% of the cost of a solar parabolic field this study was focused on the reason behind the bending of the receiver tubes used for carrying heat transfer fluids causing the failure of the system. An indoor experiment was carried out using 4m long stainless steel tube on a heat loss test rig. Numerical simulations were carried out using ANSYS software and MCRT code. Field measurements were also performed on 36m long parabolic trough collector system. The study also showed that the important causes for the failure of the receiver tubes are improper installations along with operational practices of the system. The maximum working temperature of the system was kept about 700K.

Barriga *et al.* performed analysis on selective coatings for the parabolic trough collectors. The study was focused on selective coating that was used on the absorber tube in order to increase its absorptivity so as to enhance its performance. Typical coatings have an absorbance > 95% and emittance < 10 % at about 400^{o}C. For a new system design that will be working at a temperature of about 600^{o}C and low vacuum pressure of about 10-2 mbar new selective coatings was to be tested. For this purpose a 4m long receiver tube was chosen and test were performed on a test rig. Semi-conductors metal tandems, multilayer spectral selective absorbers (MSSA) and metal dielectric composite coatings (Cermets) were types of approaches that can withstand such high temperatures and pressures. A different kind of selective absorber coating was designed and deposited on the absorber reaching an absorbance value of 95.2% having.

Yaghoubi *et al.* analyzed the heat losses of a receiver tube of a solar parabolic trough collector. Experimental measurement along with numerical modelling is carried for the fulfilling the purpose of study. Three different absorber tubes i.e. vacuum tube, glass cover with air and bare tube were used for comparing the heat losses from them. The length of the tubes used was 4m. The working fluid reaches a maximum temperature of about 265^{o}C. An infrared thermograph (IR) camera was used for measurement of temperature around the glass tube. It was observed that convective losses reduces significantly in vacuum tubes when compared with bare and tubes with air in glass. It was also observed that the heat loss form air in glass tube is 40% higher than vacuum tube that reduces the collector performance by 3-5%. The increment in the amount of heat loss in a bare tube were considerably higher than others.

Natarajan *et al.* carried out the numerical simulations of characteristics of heat transfer of the receiver tube with internal flow obstructions. The experiments were carried out using water as the heat transfer fluid and Copper was taken as the material of the receiver tube. Inserts of different cross-sections were placed inside the receiver tube in the flow path of fluid to study the slow characteristics and numerical simulations were performed using ANSYS CFX 12.1 software. The modelling of turbulence was done using SST k-ω model. The heat transfer characteristics and pressure drop was calculated for a mass flow rate of 85 Kg/hr and solar irradiance of 850 W/m^2. The inserts that were used for the study possess a triangle, an inverted triangle and semi-circular shapes. It was also observed that the triangular shape inserts gave more uniform heat transfer than others and reduced thermal fatigue. Also the pressure drop was considerably high when compared with tube without insertion.

Munoz *et al.* analyzed the performance of internally finned helical tubes for solar parabolic troughs. CFD tolls were used for the analysis of the absorber tube. Four different fin configurations differing in number of starts and helix angle were used for the analysis. The outer diameter of each tube was taken as 70 mm each with a thickness of about 2 mm. The fin height is kept same i.e. 2 mm for all the tube configurations. The main drawback of the finned design that was pressure drop that was around 10% to 50% depending upon helix angle and number of pins. It was also observed that temperature gradient and thermal losses were reduced due to which exergetic and thermal efficiency of the collector increased.

Muhlen *et al.* performed a sensitivity analysis on the effect of various parameters on the performance of the solar parabolic trough collector. A one dimensional finite element model was used for simulating solar parabolic trough and then validated using available experimental data. A sensitivity analysis was later carried out to see the effect of change of type of heat transfer fluid and varying Reynolds number on the system performance. It was observed that the temperature of the heat transfer fluid and the receiver tube was close to a linear increase along the length of the trough. The simulation results also showed that at low vacuum pressure of around 10^{-4} torr heat losses from the receiver tube to the cover were negligible. The losses through the support bracket were observed to be the highest.

Ghadirijafarbeigloo *et al.* carried out a three dimensional numerical simulation of heat transfer characteristics and turbulent flow of a absorber tube with louvered twisted-tape inserts. In this literature a perforated louvered twisted tape insert was placed inside a receiver tube and was numerically studied. Three different twist ratios i.e. 2.67, 4 and 5.33 were used for the study. Flow inside the receiver tube was to be turbulent keeping in view the shape of the inserts. Absorber tube used for the study was having a length of 1000 m and 17 mm inner diameter. Remarkable growth in heat transfer were observed because of the swirling flow provided by the twisted tape increasing the turbulence and the vortex that was generated due to louvered on it. Also the efficiency of the louvered twisted tape was found out to be 26% higher than twisted tape.

Chapter 3

Experimental setup and Parameters

A parabolic trough is a concentrating solar collector in which the reflecting surface is bent in the form of a parabola. This reflecting surface is either fabricated from polished mirrors or from polished Aluminium sheets. The energy of beam radiation falling on the trough which enters the collector parallel to its plane of symmetry is concentrated along its focal line, where a receiver tube is held. The mirror is oriented so that sunlight which it reflects is concentrated on the tube, which contains a heat transfer fluid to which heat is transferred and its get heated to a high temperature by the energy of the sunlight. In the present work various parameters of the system such as reflector material, absorber tube material and diameter and mass flow rate are varied to study their effects on Overall heat transfer Coefficient, Heat removal factor and efficiency.

Figure 3.1 Parabolic trough collector

Figure 3.1 is a picture of the solar parabolic trough collector used in the present study.

3.1) Reflector:

In the present work a parabolic trough collector made with stainless steel sheet having 1.219m length is used. The arc length (perimeter) of the reflector is 1.829m. Its depth is 0.207m and the focal length is 0.607m.

A single axis east west tracking is used by the help of a sun tracker which is controlled by a micro-controller. The micro-controller gives signals to a stepper motor which is having a step of 0.004^o. The tracker provides a span of 80^o for sun tracking which means that if we have started tracking sun 40^o east we can go up to 40^o west. The movement of the tracker is in accordance with the speed of sun which means it covers a span 15^o in one hour which is also the speed of the sun.

3.2) Absorber tube:

3.2.1) Material of the Tube

Material of the absorber tube affects its performance and its ability to transfer heat. In the present work absorber tube of two different materials that is stainless steel and copper are used so its effect can be studied in the overall performance of the system. The absorber tubes are electroplated using black nickel and chromium in order to increase their absorptivity and decrease losses. The tubes are bare and are not covered with any type of glass material.

3.2.2) Diameter of the tube

The diameters of the tube are also an important parameter along with its material. In the present work the diameter of the tubes are also varied to study its effect on the efficiency of the system. The diameters that are chosen for the study are 2.54cm, 1.905cm and 3.175cm.

The six test sections that are fabricated and used for experimental investigation in the present study is shown in figure 3.2 and figure 3.3.

Figure 3.2 Copper tubes of different diameters

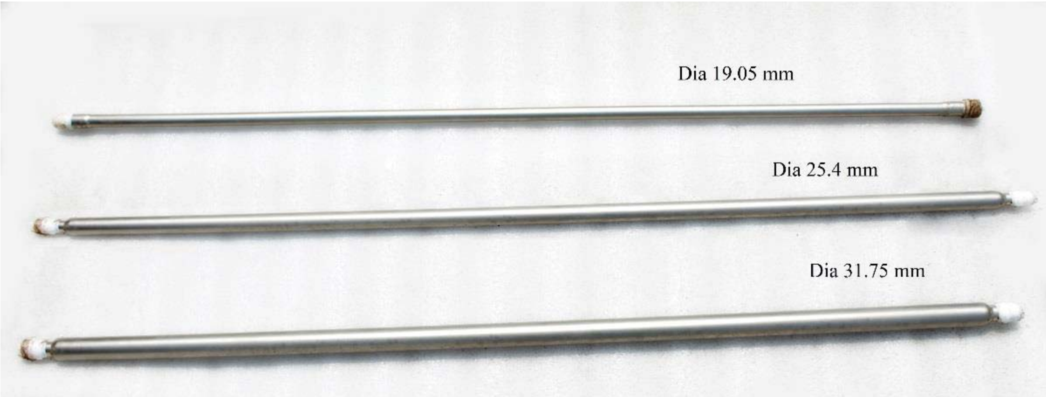

Figure 3.3 SS tubes of different diameters

3.3) Heat Transfer Fluid:

Heat transfer fluid carries the heat that falls on the receiver tube. In the present study two different heat transfer fluids i.e. water and Mythol Therm 500 oil are used. Both the fluids have different physio-chemical properties which will help in understanding how properties of the fluid affect the performance of the system. Water is used in combination with the Stainless steel tube whereas Therm 500 oil is used in combination with copper tube.

3.4) Mass flow rate:

Mass flow rate of the heat transfer fluid plays an important role when it comes to the parabolic trough collector system. In the present work four different mass flow rate

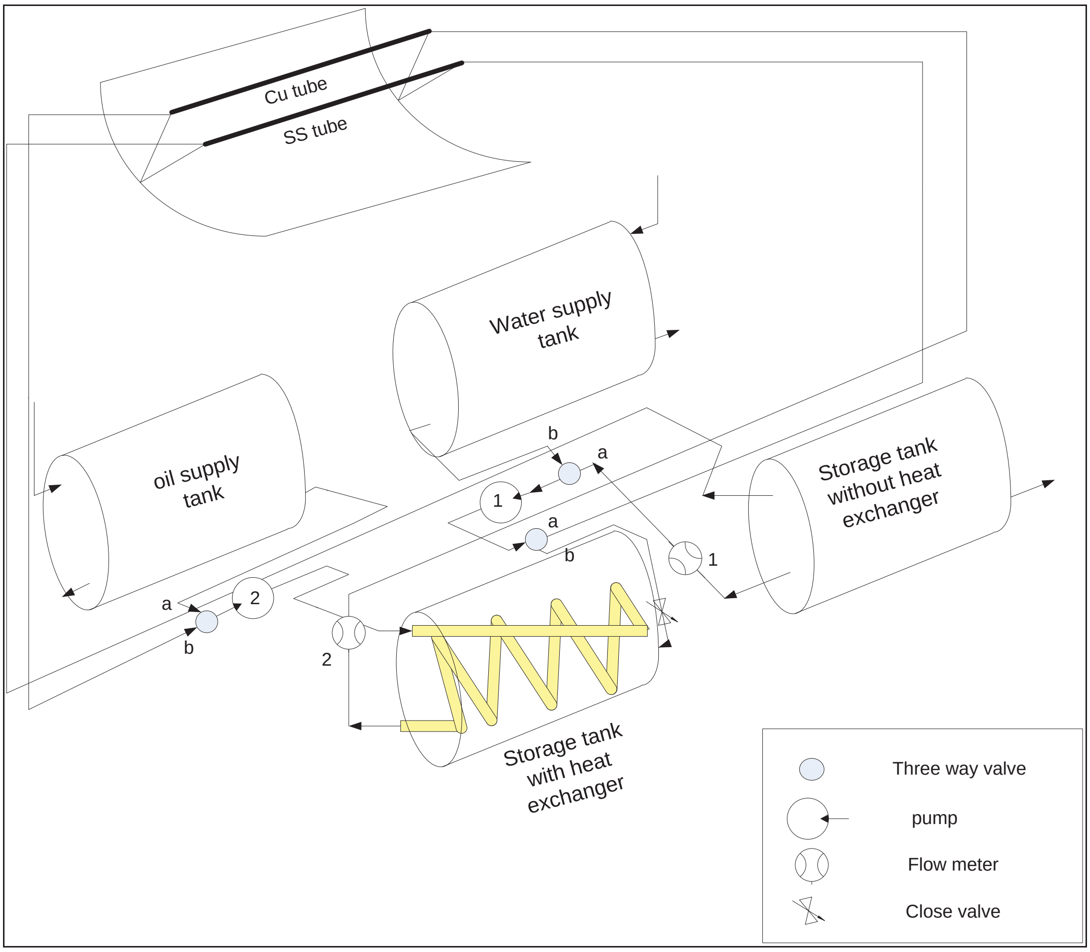

Figure3.4: Schematic diagram of Experimental Setup

have been taken too realize the effect of Reynolds number of the performance of the system. The mass flow rate is varied by variable flow oil and water pumps.

A schematic diagram of the experimental setup with its various components is shown in the figure3.4.

3.5) Overall Heat Loss Coefficient (U_L)

U_L is the overall heat transfer coefficient from the receiver tube to the ambient air. This is very important and complex factor which tells us the heat loss per unit area per

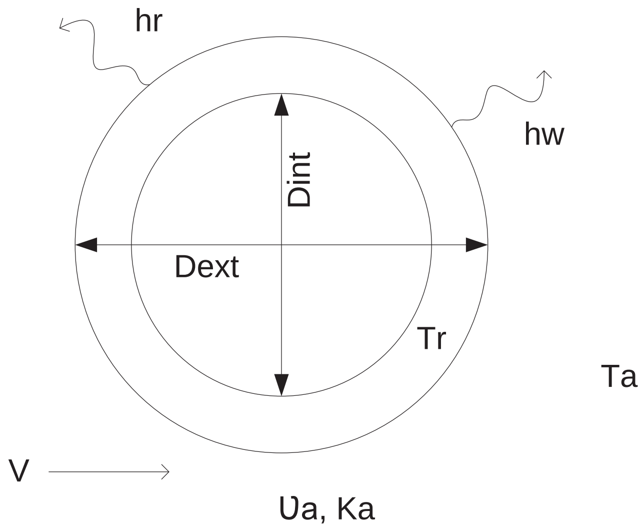

Figure3.5 Cross-sectional view of tube

unit temp difference from receiver tube to ambient. In the present study there is no glass glazing therefore, U_L can be expressed in two terms only as shown in figure 3.5. The total heat loss from tube to ambient is calculated by multiplying the overall heat loss coefficient with tube area and temperature difference between tube and ambient.

$$\mathbf{U_L = h_w + h_r}$$

Where,

h_w: Convective heat transfer coefficient between tube and atmosphere

h_r: Radiative Heat transfer coefficient of radiation

h_w and h_r can be expressed by using following expression

$$h_w = Nu_a * \frac{K_a}{D_{ext}}$$

where, Nu_a can be calculated by using following expression

For $0.1<Re_a<1000$, $Nu_a = 0.4 + 0.54 \times Re_a^{0.6}$

For $1000<Re_a<50000$, $Nu_a = 0.3 \times Re_a^{0.6}$

where $Re_a = V * D_{ext} / \upsilon_a$

$h_r = \varepsilon * \sigma * (T_r + T_a) * (T_r^2 + T_a^2)$

3.6) Heat removal factor

Heat removal factor is constant for any collector design and fluid flow rate. This represents the ratio of actual useful energy gain to the useful energy gain that would result if the receiver tube surface temperature had been at the fluid inlet temperature.

$$F_R = \frac{Actual\ usefull\ energy\ gain}{useful\ energy\ gain\ if\ the\ entire\ collector\ were\ at\ the\ fluid\ inlet\ temperature}$$

Mathematically,

F_R can be calculated as follows

$$F_R = \frac{\dot{m}C_p}{A_{int}U_L}\left[1 - \exp\left(-\frac{U_L F/A_{int}}{\dot{m}C_p}\right)\right]$$

Where

C_p represents specific heat and,

Specific heat of water = 1000 J/kg/^oK

Specific heat of oil = 2061 J/kg/^oK

$A_{int} = 3.14*(0.0125)^2 = 0.00049m^2$

3.7) Thermal Efficiency of the collector (η)

It is the ratio of the Useful heat gain to the Total input solar energy. It defines how well the system is working which in turn defines its effectiveness.

Mathematically,

$$\eta = \dot{m} * Cp * \frac{T_o - T_i}{A_a * I_b}$$

3.8) Table showing overall specifications of the system

S.No.	**Components**	
1	**Heat generating unit with tracking system**	**Specifications**
	Parabolic Reflector	
	Length	1.219 m
	Arc Length	1.829 m
	Depth	0.207 m
	Focal Length	0.607 m
	Material	SS with mirror film
	Sun Tracker	Single axis
	Absorber Tube	
	Length	1.219 m
	Diameter	0.019 m, 0.025 m, 0.031 m
	Absorber Material	Copper and SS
	Insulation Material	PUF
	Piping Material	GI and Copper
2	**Storage Unit**	**Specifications**

	Storage Tank	2(one with heat exchanger and one without heat exchanger)
	Capacity	28 L
	Material	SS
	Insulation Used	Glass Wool with rexene
	Working Fluid	Water and mythol Therm 500 oil
3	**Control Unit**	**Specification**
	Pump(for water)	
	Power Rating	0.1 HP
	Head	6 m
	Pump(for oil)	
	Power Rating	0.5 HP
	Head	10 m
4	**Different Meters**	**Specifications**
	RTD sensors	To measure temperature
	Flow meter	To measure flow rate
	Pyranometer	To measure radiation intensity
	Anemometer	To measure wind velocity

Table 3.1: Overall Specifications of the system

Chapter 4

Results and discussions of Experimental Investigation

4.1) Problem Formulation

Parametric analysis of a parabolic trough solar collector having stainless steel reflector with mirror finish was carried out with different combinations of receiver tube material, heat transfer fluid, mass flow rate and diameter of the receiver tube. The temperature of the fluid at inlet and outlet of the receiver tube along with the surface temperature of the tubes were recorded with the help of RTD (Resistance Temperature Detectors) sensors. The intensity of solar radiations were measured using a digital pyranometer and the wind velocity using an ammeter. On the basis of data recorded system various properties of the system such as the thermal efficiency, heat removal factor and overall heat loss coefficient were evaluated.

4.2) Experimental Procedure

Steps that were followed during the experimental investigation are as follows:

Step 1: To clean the reflecting surface in order to remove the accumulated dust.

Step 2: Setting and positioning the reflector according to the sun’s position. Switching on the pump and tracker mechanism and running the system for 30 min prior to recording the first reading.

Step 3: The time gap between each reading is set to 30 min. Flow rate of the heat transfer fluid was maintained constant to ensure proper reading.

Step 4: The system was started 9:30 AM and the reading was taken from 10:00 AM to 02:30 PM by recording the data every half an hour.

Step 5: The pump and tracker mechanism were switched off and the whole set up was covered.

Step 6: The receiver was changed after readings of four different mass flow rates were recorded.

The same procedure was repeated for other readings.

The experimental procedure as mentioned above was followed throughout the experimental investigation.

4.3) Experimental Results

The following results are gathered by the parametric analysis of the solar parabolic trough collector system.

4.3.1) Variation of efficiency with time

The efficiency of the system was evaluated for various combinations of parameters which are as follows:

4.3.1.1) Varying diameters of Cu tube when oil is flowing at 0.0603 Kg/s

It can be observed that from figure 4.1 that the thermal performance of the collector first starts to increase as the time changes from till it reaches a maximum value at around 12 p.m. and then starts to decrease slowly as the time passes. The reason behind is that the solar insolation increases as the time reaches 12 p.m. and the collector attains the best thermal efficiency. It can also be seen that the as the diameter of the tube increases efficiency increases which is due to an increase in area of heat transfer. The values of overall heat loss coefficient and heat removal factor are shown in table 4.1.

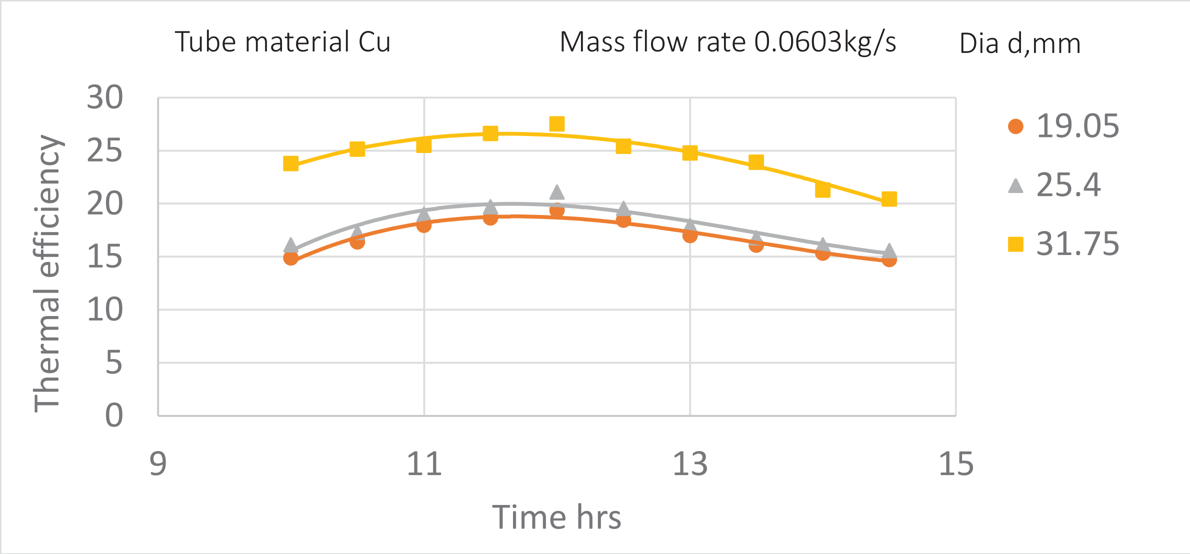

Figure4.1: Efficiency VS time graph for mass flow rate 0.0603 kg/s

Mass flow rate is 0.0603 kg/s				
Diameter in mm	Absorber tube temperature in K	Air velocity in m/s	Overall heat loss coefficient (U_L)	Heat Removal factor (F_R)
19.05	338.45	0.9	47.74	0.88
25.4	328.55	3.5	222.04	0.588
31.75	333.42	2	76.59	0.748

Table 4.1 Values of U_L and F_R for mass flow rate 0.0603 kg/s

4.3.1.2) Varying diameter of Cu tube when oil is flowing at 0.0675 Kg/s

Figure 4.2 shows a steady increase in the efficiency as the time passes reaching to maximum and then declining till the end of the readings. The curve reaches to a maximum at about noon where the solar insolation reaches its maxima. As the area of heat transfer increases which is due to increase in tube diameter higher efficiencies were obtained. The values of overall heat loss coefficient and heat removal factor are shown in table 4.2.

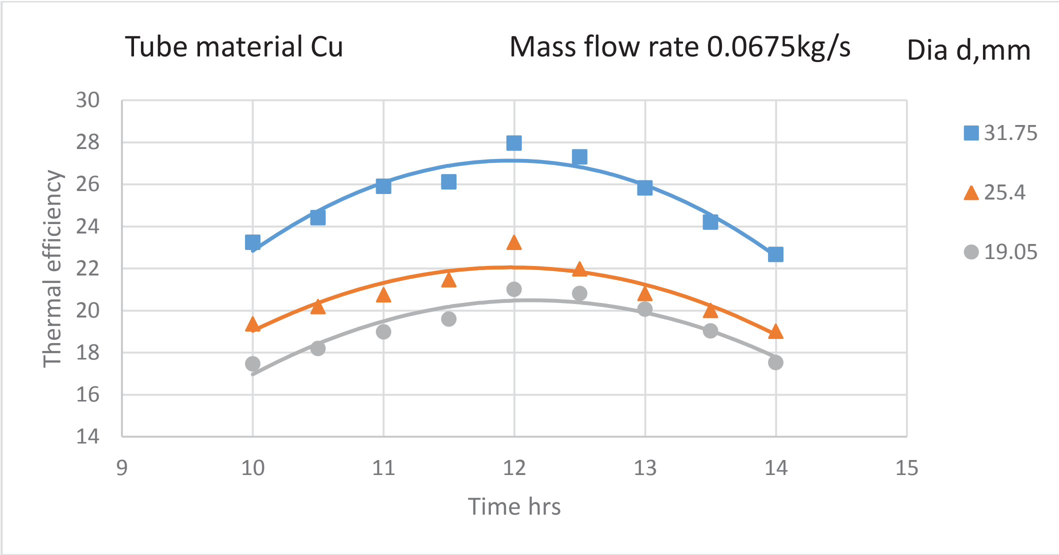

Figure4.2: Efficiency VS time graph for mass flow rate 0.0675 kg/s

Mass flow rate is 0.0675 kg/s				
Diameter in mm	Absorber tube temperature in K	Air velocity in m/s	Overall heat loss coefficient (U_L)	Heat Removal factor (F_R)
19.05	340.45	0.6	38.62	0.915
25.4	309.35	1.2	80.67	0.751
31.75	344.34	1	42.27	0.857

Table 4.2 Values of U_L and F_R for mass flow rate 0.0675 kg/s

4.3.1.3) Varying diameter of Cu tube when oil is flowing at 0.0828 Kg/s

It can be observed from figure 4.3 that the thermal efficiency of the collector increases as the time passes and reaches to a maximum value at noon. It then shows a decreasing trend. It can also be seen that the performance of the collector increases as the tube diameter increases. This trend is due to an increase in solar intensity as well as the area available for heat transfer. The values of overall heat loss coefficient and heat removal factor are shown in table 4.3.

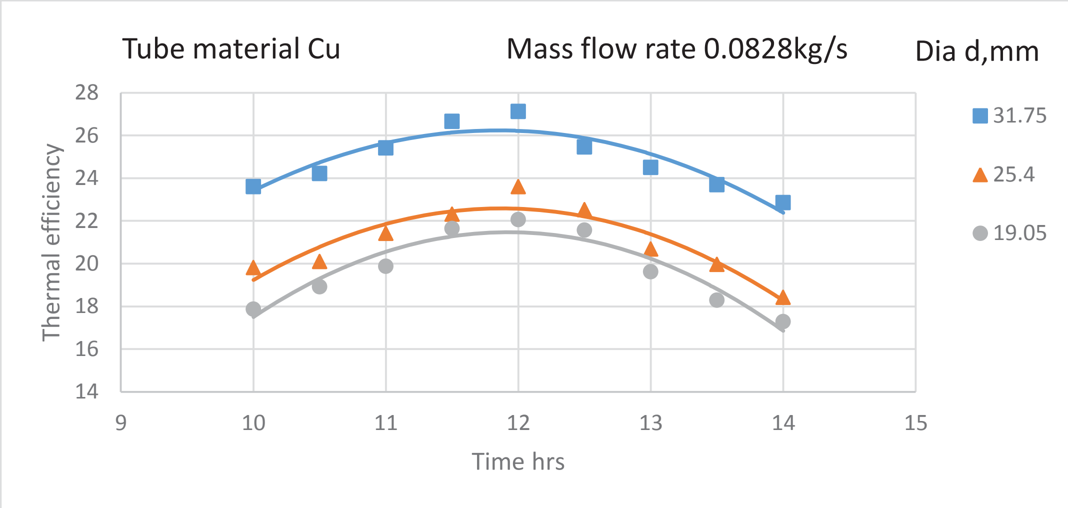

Figure 4.3 Efficiency VS time graph for mass flow rate 0.0828 kg/s

Mass flow rate is 0.0828 kg/s				
Diameter in mm	Absorber tube temperature in K	Air velocity in m/s	Overall heat loss coefficient (U_L)	Heat Removal factor (F_R)
19.05	337.95	1.2	55.77	0.901
25.4	347.55	0.5	72.87	0.813
31.75	352.38	0.1	14.72	0.954

Table 4.3 Values of U_L and F_R for mass flow rate 0.0828 kg/s

4.3.1.4) Varying diameter of Cu tube when oil is flowing at 0.0972 Kg/s

Figure 4.4 shows that as the tube diameter increases performance of the collector increases due to an increase in the area of heat transfer. It can also be seen that the efficiency increases with time of day to a maximum value around 12 p.m. and then follows a decreasing trend due to a lower solar intensity. The values of overall heat loss coefficient and heat removal factor are shown in table 4.4.

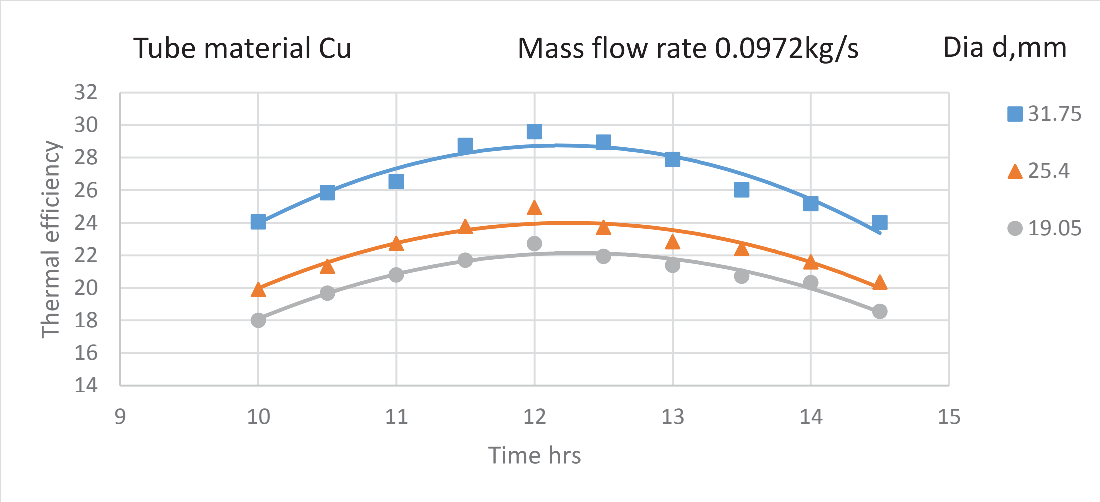

Figure 4.4 Efficiency VS time graph for mass flow rate 0.0972 kg/s

Mass flow rate is 0.0972 kg/s				
Diameter in mm	Absorber tube temperature in K	Air velocity in m/s	Overall heat loss coefficient (U_L)	Heat Removal factor (F_R)
19.05	338.12	1.4	60.69	0.907
25.4	363.65	0.7	88.40	0.850
31.75	368.62	1.7	56.79	0.865

Table 4.4 Values of U_L and F_R for mass flow rate 0.0972 kg/s

4.3.1.5) Varying diameter of SS tube when water is flowing at 0.067 Kg/s

It can be observed from figure 4.5 that the performance of the collector increases with an increase with tube diameter which due to an increase in the area of heat transfers. It can also be seen that the maximum efficiency is observed at the noon time, before and after which the efficiency decreases. This is due to maximum incident solar radiation at this time. The values of overall heat loss coefficient and heat removal factor are shown in table 4.5.

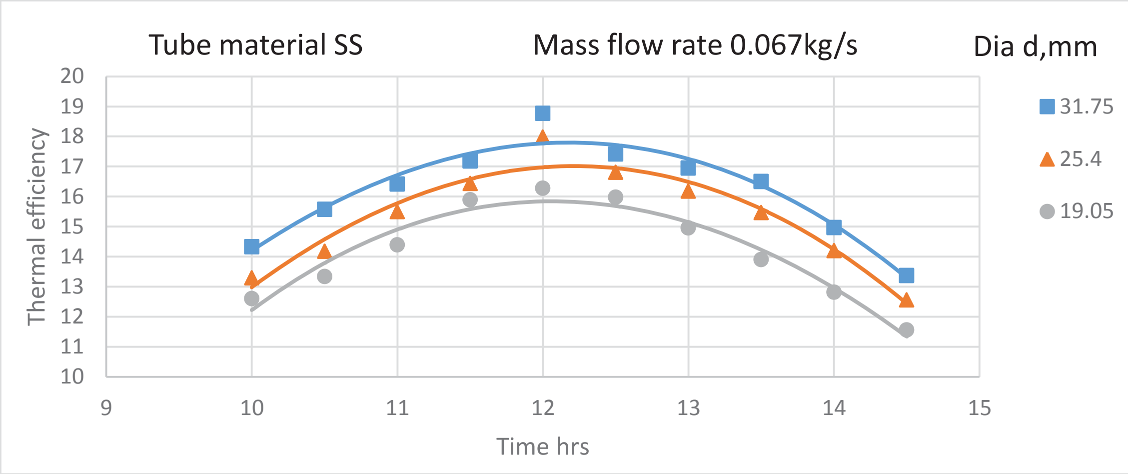

Figure 4.5 Efficiency VS time graph for mass flow rate 0.067 kg/s

Mass flow rate is 0.067 kg/s				
Diameter in mm	Absorber tube temperature in K	Air velocity in m/s	Overall heat loss coefficient (U_L)	Heat Removal factor (F_R)
19.05	335.15	0.1	16.40	0.971
25.4	327.25	1.7	145.63	0.833
31.75	343.64	0.9	39.98	0.907

Table 4.5 Values of U_L and F_R for mass flow rate 0.067 kg/s

4.3.1.6) Varying diameter of SS tube when water is flowing at 0.083 Kg/s

Figure 4.6 shows increasing trend of the performance of the collector as the time of the day passes till it reaches a maximum value about 12 p.m. It is due to increase in solar intensity till this time after which it starts to decrease. It also shows that the performance of the collector increases with increase in tube diameter which is due to increase in available area of heat transfer. The values of overall heat loss coefficient and heat removal factor are shown in table 4.6.

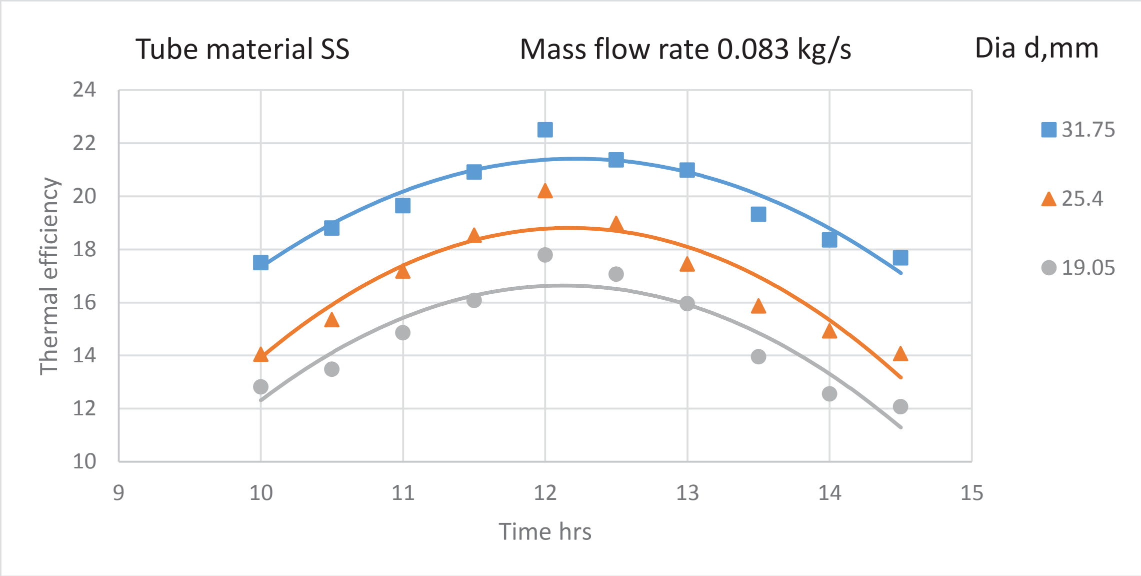

Figure 4.6 Efficiency VS time graph for mass flow rate 0.083 kg/s

Mass flow rate is 0.083 kg/s				
Diameter in mm	Absorber tube temperature in K	Air velocity in m/s	Overall heat loss coefficient (U_L)	Heat Removal factor (F_R)
19.05	335.22	1.3	58.202	0.916
25.4	337.82	0.6	80.44	0.915
31.75	344.47	0.9	40.01	0.919

Table 4.6 Values of U_L and F_R for mass flow rate 0.083 kg/s

4.3.1.7) Varying diameter of SS tube when water is flowing at 0.1 Kg/s

It can be observed from figure 4.7 that thermal performance of the collector increases as the diameter of the tube increases which is due to the fact that as the diameter increases area available for heat transfer increases and hence the performance. It can also be seem that as the time changes and noon approaches the thermal efficiency of the collector also increases due to increase in intensity of solar radiation. Efficiency

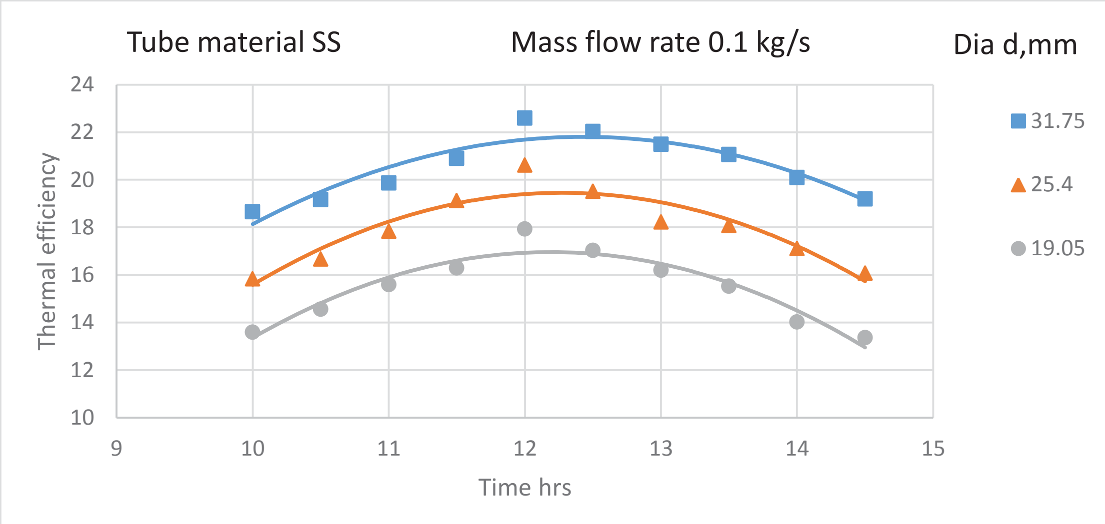

Figure 4.7 Efficiency VS time graph for mass flow rate 0.1 kg/s

Mass flow rate is 0.1 kg/s				
Diameter in mm	Absorber tube temperature in K	Air velocity in m/s	Overall heat loss coefficient (U_L)	Heat Removal factor (F_R)
19.05	338.75	0.8	52.08	0.923
25.4	343.12	1.2	119.45	0.895
31.75	337.1	0.7	35.82	0.928

Table 4.7 Values of U_L and F_R for mass flow rate 0.1 kg/s

decreases afterwards. The values of overall heat loss coefficient and heat removal factor are shown in table 4.7.

4.3.1.8) Varying diameter of SS tube when water is flowing at 0.117 Kg/s

It is evident from figure 4.8 that as the time of day increases thermal efficiency of the collector increases due to an increase in intensity of beam radiations. It shows a decreasing trend afterwards. The performance of the collector also increases with an increases in the diameter of receiver tube. This is due to increase in area of heat

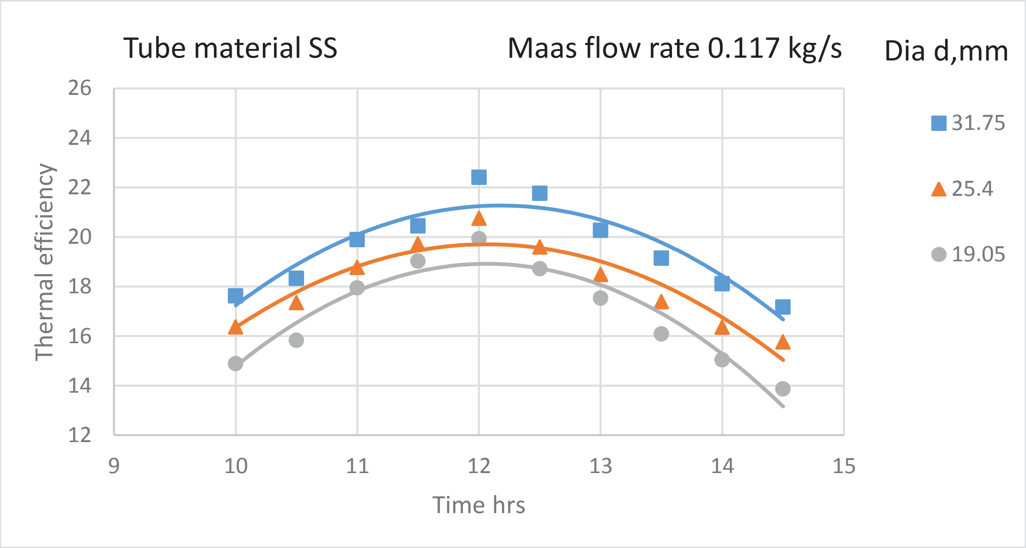

Figure 4.8 Efficiency VS time graph for mass flow rate 0.117 kg/s

Mass flow rate is 0.117 kg/s				
Diameter in mm	Absorber tube temperature in K	Air velocity in m/s	Overall heat loss coefficient (U_L)	Heat Removal factor (F_R)
19.05	335.45	1.3	58.20	0.929
25.4	343.92	0.5	72.78	0.941
31.75	359.06	1.7	56.30	0.911

Table 4.8 Values of U_L and F_R for mass flow rate 0.117 kg/s

transfer. The values of overall heat loss coefficient and heat removal factor are shown in table 4.8.

4.3.2) Variation of efficiency with Mass flow rate with varying tube diameter

The variation of efficiency is observed with change in mass flow rate for different absorber tube materials.

4.3.2.1) Copper as tube material

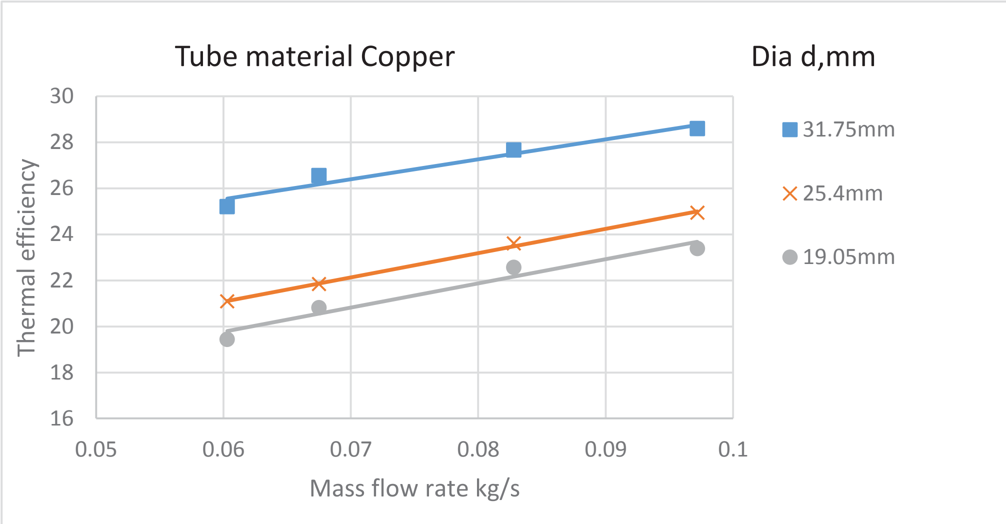

Figure 4.9 Efficiency VS mass flow rate graph when tube material is Cu

It can be observed from figure 4.9 that as the mass flow rate of the heat transfer fluid is increasing, efficiency of the collector increases and it almost follows a linear trend. This is due to an increase in the Reynolds number which in turn increases the rate of heat transfer. It can also be seen that the as the diameter of tube increases performance of collector increases due to an increase in available area of heat transfer.

4.3.2.2) SS as tube material

Figure 4.10 shows the performance of the collector increases following a linear trend as the mass flow rate of heat transfer fluid increases. Performance

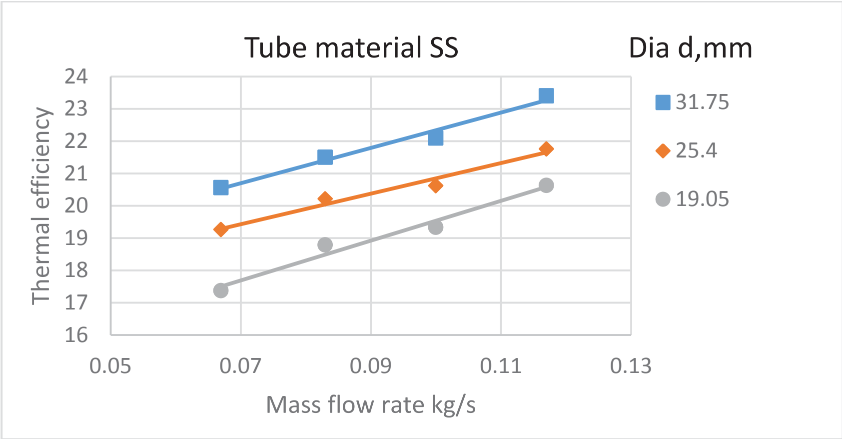

Figure 4.10 Efficiency VS mass flow rate graph when tube material is SS

of the collector also increases with an increase in tube diameter. An increase in the Reynolds number with mass flow rate and increase in area of heat transfer with increasing tube diameter increases the performance of the collector.

4.3.3) Variation of efficiency with mass flow rate with different tube material

4.3.3.1) Tube diameter is 19.05mm

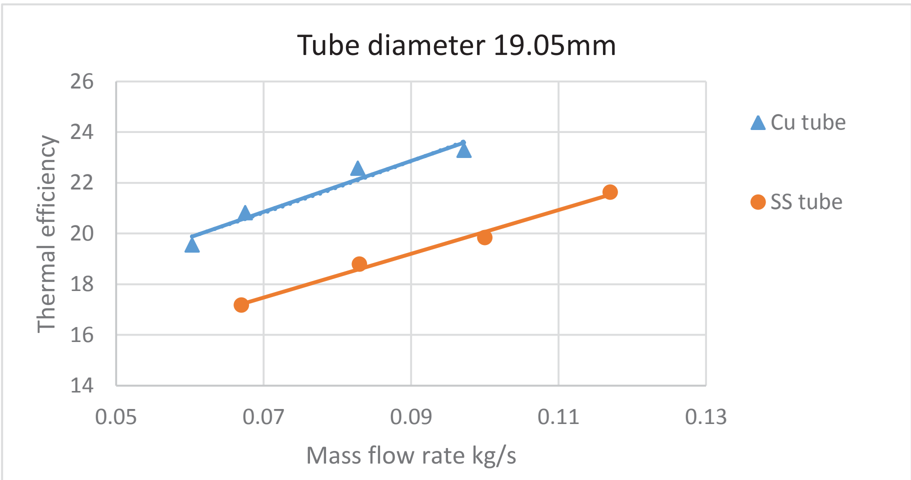

Figure 4.11 Efficiency VS mass flow rate graph for diameter 19.05mm

It can be observed from figure 4.11 that the performance of the collector increases with mass flow rate of the heat transfer fluid. It can also be seen that the performance of the system is better with copper tube rather that stainless steel tube for the same tube diameter. This is due to high thermal conductivity of copper than the conductivity of stainless steel tube.

4.3.3.2) Tube diameter is 25.4mm

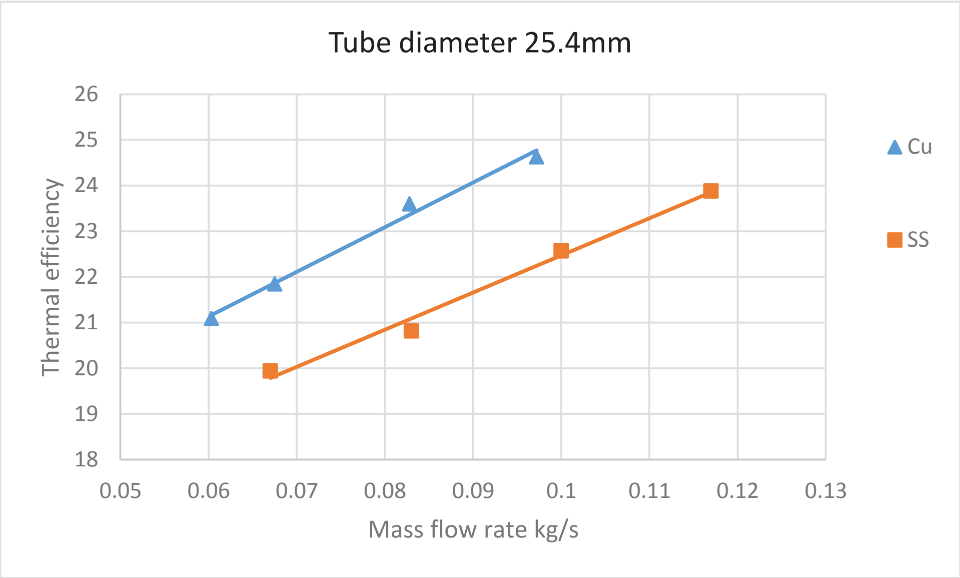

Figure 4.12 Efficiency VS mass flow rate graph for diameter 25.4mm

Figure 4.12 shows that the performance of the collector is better with copper tube rather than a stainless steel tube diameter. The high thermal conductivity of copper which is more than stainless steel tube is the reason behind this. The thermal efficiency follows a linear trend and increases with increase with mass flow rate.

4.3.3.3) Tube diameter is 31.75mm

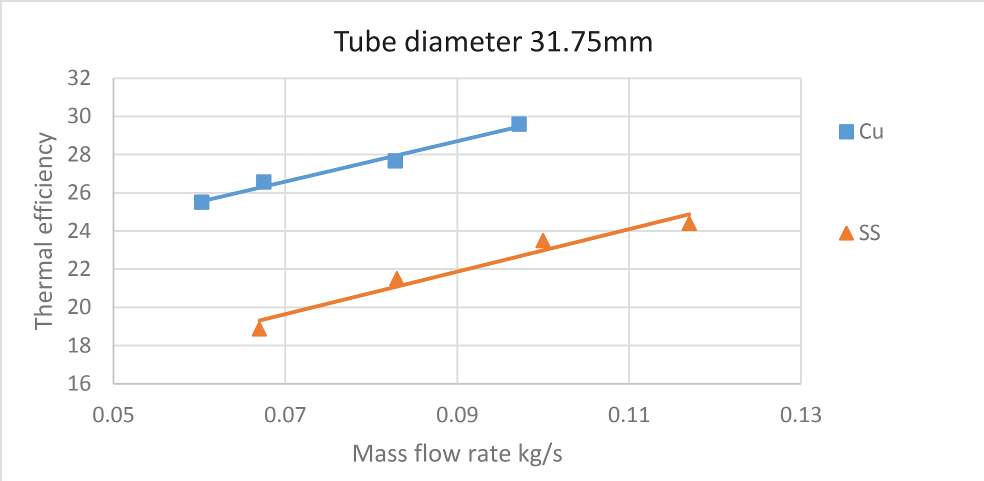

Figure 4.13 Efficiency VS mass flow rate graph for diameter 31.75mm

It can be observed from figure 4.13 that the system exhibits a better thermal efficiency with copper tube than a stainless steel tube of same diameter. This is due to a high thermal conductivity of copper which is considerably higher than the thermal conductivity of stainless steel.

Chapter 5

Conclusions and Future Scope

5.1) Conclusion

The solar parabolic trough collector system is used for generation of power as the system is capable of producing high temperature. This system is also employed for water heating, process steam application and air heating as well. In this present study a parabolic trough collector with stainless steel reflecting surface is used for the parametric analysis is used. During the experimental investigation receiver rubes of three different diameters and two different materials are used. In the present study various parameters such as inlet temperature, outlet temperature, receiver tube temperature, solar intensity etc. were measured. Performance of the collector is calculated on the basis of the recorded parameters.

The following are the conclusions of the present study.

i.) The performance of the concentrating collector with Copper receiver tube having diameter 31.75mm is 19.47% higher than the Copper receiver tube having diameter 25.4mm when the mass flow rate is 0.0603 kg/s. Also the performance of the concentrating collector with Copper tube of 31.75mm diameter is 36.65% higher than the Copper tube of 19.05mm diameter at the same mass flow rate.

ii.) The performance of the concentrating collector with Copper receiver tube having diameter 31.75mm is 14.67% higher than the Copper receiver tube having diameter 25.4mm when the mass flow rate is 0.0972 kg/s. Also the performance of the concentrating collector with Copper tube of 31.75mm diameter is 22.28% higher than the Copper tube of 19.05mm diameter at the same mass flow rate.

iii.) The performance of the concentrating collector with Stainless steel receiver tube of 31.75 mm diameter is 9.04% higher than the Stainless steel receiver tube having diameter 25.4mm when the mass flow rate is 0.067 kg/s. Also the performance of the concentrating collector with Stainless steel tube of 31.75mm diameter is 20.8% higher than the Stainless steel tube of 19.05mm diameter at the same mass flow rate.

iv.) The performance of the concentrating collector with Stainless steel receiver tube of 31.75 mm diameter is 7.55% higher than the Stainless steel receiver tube having diameter 25.4mm when the mass flow rate is 0.117 kg/s. Also the performance of the concentrating collector with Stainless steel tube of 31.75mm diameter is 13.44% higher than the Stainless steel tube of 19.05mm diameter at the same mass flow rate.

v.) The performance of the collector with Copper receiver tube of 19.05mm diameter was on an average 11.5% higher than that with Stainless steel tube of the same diameter.

vi.) The performance of the collector with Copper receiver tube of 25.4mm diameter was on an average 4.61% higher than that with Stainless steel tube of the same diameter.

vii.) The performance of the collector with Copper receiver tube of 31.75mm diameter was on an average 24.4% higher than that with Stainless steel tube of the same diameter.

5.2) Future scope

There is a lot of future investigation that can be carried out which are as follows:

1. Parametric analysis can be performed on the fabricated system with a different type of reflecting surface.
2. Receiver tubes having outer glass coating with and without vacuum can be used for the evaluation purposes.
3. Different absorber coating materials can be tested to see their effects on the performance of the system.
4. Receiver tubes with centrally placed inserts of different shapes can also be tested with the system to see their effects on the performance.

Appendix A

Readings on Copper Tubes

Time	Inlet Temperature(in K)	Outlet Temperature (in K)	Absorber Tube Temp (in K)	Tank Inlet (in K)	Hot Water (in K)	Solar Insolation (in W/m^2)	Air flow (in m/s)	efficiency
10:00	312.53	315.63	346.22	317.05	302.25	784.089	1.3	23.7598
10:15	318.03	321.37	347.32	321.85	305.55	798.98	2.2	25.1221
11:15	318.43	322.12	340.32	322.05	309.75	869.76	1-1	25.4961
11:45	322.53	326.56	349.62	326.25	313.15	910.74	0.8	26.5924
12:15	322.63	326.32	333.42	325.35	314.65	806.45	3.5	27.4976
12:45	323.13	326.9	346.62	323.45	315.75	892.11	0.7	25.3962
01:15	324.53	328.3	349.62	327.65	316.55	915.21	2.5	24.7552
01:45	323.63	327.13	347.72	325.75	318.65	880.94	2	23.8763
02:15	325.63	328.63	350.52	328.85	319.05	847.41	1.5	21.2752
02:45	327.73	330.47	351.62	330.45	320.45	806.44	1.2	20.4185

Table A.1 Diameter: 31.75mm Flow Rate: 0.0603kg/s

Time	Inlet Temperature(in K)	Outlet Temperature (in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	305.91	308.67	322.24	309.05	297.35	799	1.2	23.2378
10:30	311.51	314.43	342.24	315.65	299.45	772.91	1	25.4148
11:00	314.51	317.92	341.34	318.05	303.45	852.63	1.5	26.9046
11:30	315.51	318.97	338.84	318.65	306.35	858.59	2	27.1096
12:00	319.41	323.07	344.34	322.25	309.35	862.31	1	28.5529
12:30	320.01	323.57	346.34	322.85	310.95	877.21	3	27.3010
01:00	321.41	324.53	347.84	324.15	312.45	880.94	0.9	23.8254
01:30	322.11	324.87	348.34	324.65	314.55	836.24	0.7	22.2029
02:00	323.11	325.45	346.84	325.55	314.55	761.74	2	20.6653

Table A.2 Diameter: 31.75mm Flow Rate: 0.0675 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	317.76	320.12	345.38	320.95	304.05	791.54	0.1	24.6036
10:30	321.06	323.57	347.78	324.45	309.25	821.34	0.9	25.218
11:00	325.36	328.18	351.18	328.05	313.95	880.94	0.5	26.4157
11:30	322.76	325.62	332.98	324.25	317.05	853.24	0.5	27.6601
12:00	327.06	330.15	352.38	329.45	318.65	884.66	0.1	28.8231
12:30	330.86	333.78	361.48	333.35	320.95	910.739	0.3	26.4575
01:00	333.66	336.52	363.98	336.35	323.75	925.64	0.1	25.4966
01:30	336.26	338.98	365.38	338.75	326.55	909.25	0.2	24.685
02:00	335.96	338.42	363.18	338.25	328.15	851.14	0.1	23.8503

Table A.3 Diameter: 31.75mm Flow Rate: 0.0828 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	319	320.98	349.32	321.35	305.95	765.464	2	25.05742
10:30	321	323.32	343.72	323.25	310.45	837.729	0.3	26.82751
11:00	326.1	328.63	355.62	328.65	314.85	890.624	1.4	27.51832
11:30	329.4	332.23	361.32	331.75	318.35	921.914	1.7	29.73664
12:00	333.1	336.24	368.62	335.45	321.45	962.889	0.7	31.58998
12:30	335.1	338.02	368.52	337.55	324.65	914.464	0.6	30.93229
01:00	336.5	339.31	371.72	338.85	326.35	1220	0.1	910.739
01:30	336.6	339.13	373.02	338.85	327.55	1215	0.5	907.014
02:00	337.7	340.12	370.42	340.15	328.15	1200	0.4	895.839
02:30	338	340.33	369.52	339.55	329.75	1190	0.7	888.389

Table A.4 Diameter: 31.75mm Flow Rate: 0.0972 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	311.55	313.65	341.35	317.05	302.25	784.089	1.3	16.09537
10:15	317.05	319.35	342.45	321.85	305.55	798.98	2.2	17.29971
11:15	317.45	320.08	335.45	322.05	309.75	869.76	1	18.17202
11:45	321.55	324.49	344.75	326.25	313.15	910.74	0.8	19.39992
12:15	321.65	324.48	328.55	325.35	314.65	806.45	3	21.089
12:45	322.15	325.05	341.75	323.45	315.75	892.11	0.5	19.53559
01:15	323.55	326.28	344.75	327.65	316.55	915.21	2.5	17.92622
01:45	322.65	325.11	342.85	325.75	318.65	880.94	2	16.78169
02:15	324.65	326.92	345.65	328.85	319.05	847.41	1.5	16.09827
02:45	326.75	328.84	346.75	330.45	320.45	806.44	1.2	15.57475

Table A.5 Diameter: 25.4mm Flow Rate: 0.0603 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	304.55	306.85	317.55	309.05	297.35	799	1.2	19.36486
10:30	310.15	312.55	337.55	315.65	299.45	772.91	1	20.88890
11:00	313.15	315.78	336.65	318.05	303.45	852.63	1.5	20.75049
11:30	314.15	316.89	334.15	318.65	306.35	858.59	2	21.46832
12:00	318.05	320.85	339.65	322.25	309.35	862.31	1	21.84378
12:30	318.65	321.15	341.65	322.85	310.95	877.21	3	19.17210
01:00	320.05	322.12	343.15	324.15	312.45	880.94	0.9	15.80728
01:30	320.75	322.69	343.65	324.65	314.55	836.24	0.7	15.60645
02:00	321.75	323.45	342.15	325.55	314.55	761.74	2	15.01327

Table A.6 Diameter: 25.4mm Flow Rate: 0.0675 kg/s

me	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	316.35	318.25	340.55	320.95	304.05	791.539	0.1	19.80803
10:30	319.65	321.65	342.95	324.45	309.25	821.339	0.7	20.09405
11:00	323.95	326.15	346.35	328.05	313.95	880.939	0.5	20.60804
11:30	321.35	323.37	328.15	324.25	317.05	746.839	0.5	22.31949
12:00	325.65	328.18	347.55	329.45	318.65	884.664	0.1	23.59946
12:30	329.45	331.87	356.65	333.35	320.95	910.739	0.3	21.92711
01:00	332.25	334.57	359.15	336.35	323.75	925.639	0.1	20.68265
01:30	334.85	337.05	360.55	338.75	326.55	909.249	0.2	19.9664
02:00	334.55	336.45	358.45	338.25	328.15	851.139	0.1	18.42099

Table A.7 Diameter: 25.4mm Flow Rate: 0.0828 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	317.55	319.55	344.35	321.35	305.95	765.464	1.2	18.90175
10:30	319.55	322.02	338.75	323.25	310.45	837.729	0.3	21.32554
11:00	324.65	327.45	350.65	328.65	314.85	890.624	0.4	22.73597
11:30	327.95	330.98	356.35	331.75	318.35	921.914	1.7	23.76685
12:00	331.65	334.97	363.65	335.45	321.45	962.889	1.5	24.93126
12:30	333.65	336.65	363.55	337.55	324.65	914.464	0.6	23.72362
01:00	335.05	337.99	366.75	338.85	326.35	930.854	0.3	22.83898
01:30	335.15	338.01	368.05	338.85	327.55	922.659	0.4	22.41524
02:00	336.25	338.97	365.45	340.15	328.15	910.739	0.5	21.59757
02:30	336.55	339.05	364.55	339.55	329.75	888.389	0.8	20.35115

Table A.8 Diameter: 25.4mm Flow Rate: 0.0972 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	318.65	320.35	329.45	324.65	311.75	687.239	4.9	14.86579
10:30	321.35	323.42	336.65	327.55	315.05	759.504	1	16.37899
11:00	323.55	325.87	335.85	329.95	317.85	776.639	3.9	17.95212
11:30	323.75	326.24	337.55	329.85	320.15	802.714	1.1	18.6417
12:00	326.15	328.79	338.45	332.55	321.75	819.104	0.9	19.3692
12:30	326.73	329.25	343.15	333.45	323.25	821.339	0.9	18.43848
01:00	329.25	331.53	341.15	334.95	324.55	806.439	1.2	16.99066
01:30	331.95	334.08	344.15	335.45	326.55	796.754	1.3	16.0658
02:00	333.45	335.45	350.45	336.85	327.35	784.089	0.8	15.32892
02:30	332.35	334.25	345.75	337.55	327.45	775.149	0.9	14.73043

Table A.9 Diameter: 19.05mm Flow Rate: 0.0603 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	319.05	320.95	329.45	323.65	311.95	731.939	0.9	17.46273
10:30	321.75	323.78	336.65	326.75	315.75	750.564	1.2	18.19457
11:00	323.45	325.82	335.85	329.85	318.85	839.964	1.3	18.98109
11:30	324.15	326.27	337.55	328.25	320.85	746.839	0.4	19.09599
12:00	326.55	329.02	338.45	332.05	320.95	761.739	0.6	21.81344
12:30	327.13	329.71	343.15	333.75	322.75	821.339	0.8	21.13151
01:00	329.65	332.35	341.15	334.95	324.65	892.114	1.4	20.35995
01:30	332.35	335.05	344.15	339.05	325.45	907.014	0.5	20.02549
02:00	333.85	336.45	350.45	339.45	326.35	895.839	0.8	19.52436
02:30	332.75	335.19	345.75	338.15	326.95	880.939	0.9	18.63277

Table A.10 Diameter: 19.05mm Flow Rate: 0.0675 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	315.65	317.42	333.45	321.45	306.25	817.614	2	17.86425
10:30	320.55	322.45	340.65	325.45	310.85	828.789	0.7	18.91775
11:00	323.05	325.14	341.45	329.15	315.85	880.939	0.5	19.57764
11:30	326.65	328.99	344.15	331.95	319.35	892.114	0.6	21.64489
12:00	327.65	330.12	337.95	332.95	322.25	903.289	1.2	22.56473
12:30	329.85	332.23	341.05	336.25	324.65	910.739	2.3	21.56468
01:00	332.35	334.57	346.95	336.55	326.55	888.389	0.7	20.621
01:30	333.35	335.46	344.05	337.45	328.95	858.589	0.1	20.27949
02:00	335.05	336.87	349.55	339.85	330.15	839.964	0.1	17.88013
02:30	334.05	335.45	347.75	337.45	330.75	827.299	2.2	13.9645

Table A.11 Diameter: 19.05mm Flow Rate: 0.0828 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	315.95	317.53	333.62	320.55	306.45	810.164	1.2	18.89209
10:30	320.85	322.53	340.82	326.45	310.65	827.299	0.9	19.67173
11:00	323.35	325.16	341.62	329.25	315.45	843.689	0.3	20.78223
11:30	326.95	328.89	344.32	331.95	319.75	866.039	1.6	21.70002
12:00	327.95	330.07	338.12	333.45	321.95	888.389	1.2	23.11684
12:30	330.15	332.17	341.22	335.15	323.85	888.389	1.5	22.02643
01:00	332.65	334.57	347.12	336.55	326.15	869.764	0.9	21.38433
01:30	333.65	335.47	344.22	338.45	328.85	851.139	0.4	20.71413
02:00	335.35	337.1	349.72	339.35	329.35	834.749	0.2	20.30851
02:30	334.35	335.93	347.92	338.15	330.25	825.064	1.9	18.55091

Table A.12 Diameter: 19.05mm Flow Rate: 0.0972 kg/s

Appendix B

Readings on Stainless Steel Tubes

Time	Inlet Temperature(in K)	Outlet Temperature (in K)	Absorber Tube Temp (in K)	Tank Inlet (in K)	Hot Water (in K)	Solar Insolation (in W/m^2)	Air flow (in m/s)	efficiency
10:00	308.25	308.93	320.95	309.35	308.55	731.939	0.3	12.59851
10:30	312.85	313.61	325.95	314.25	312.05	772.914	0.3	13.33422
11:00	316.55	317.39	329.35	318.05	315.55	791.539	0.2	14.39104
11:30	320.25	321.23	332.15	321.75	318.35	836.239	1.9	15.89209
12:00	322.75	323.85	335.15	324.35	320.65	858.589	0.1	17.37371
12:30	324.65	325.67	336.15	326.35	322.35	866.039	2.5	15.97159
01:00	326.25	327.17	337.15	327.85	313.35	851.139	3.7	14.65793
01:30	327.35	328.18	339.15	328.95	324.25	839.964	2.9	13.39994
02:00	328.15	328.94	340.45	329.75	324.55	836.239	2.3	12.81097
02:30	329.05	329.75	341.75	330.45	325.55	821.339	1.5	11.55742

Table B.1 Diameter: 19.05 mm Flow Rate: 0.067kg/s

Time	Inlet Temperature(in K)	Outlet Temperature (in K)	Absorber Tube Temp (in K)	Tank Inlet (in K)	Hot Water (in K)	Solar Insolation (in W/m^2)	Air flow (in m/s)	efficiency
10:00	308.38	308.93	321.02	309.93	307.12	720.764	1.1	12.81912
10:30	312.98	313.60	326.02	314.96	311.34	772.914	0.3	13.47563
11:00	316.68	317.38	329.42	318.98	315.11	791.539	0.1	14.85643
11:30	320.38	321.18	332.22	323.12	320.44	836.239	0,5	16.07119
12:00	322.88	323.84	335.22	324.99	321.37	858.589	1.3	18.78341
12:30	324.78	325.67	336.22	327.12	323.43	866.039	1.5	17.26399
01:00	326.38	327.22	337.22	328.76	325.98	883.664	0.4	15.95106
01:30	327.48	327.19	339.22	328.54	325.98	854.864	0.5	13.95243
02:00	328.28	328.89	340.52	330.01	326.15	836.239	0.1	12.25429
02:30	329.18	329.77	341.82	332.12	328.37	821.139	0.6	12.06752

Table B.2 Diameter: 19.05mm Flow Rate: 0.083 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature (in K)	Absorber Tube Temp (in K)	Tank Inlet (in K)	Hot Water (in K)	Solar Insolation (in W/m^2)	Air flow (in m/s)	efficiency
10:00	308.57	309.07	324.55	311.35	308.25	744.604	0.3	13.59112
10:30	313.17	313.72	329.55	314.65	311.05	764.719	1.3	14.55698
11:00	316.87	317.48	332.95	318.45	314.35	791.539	1.2	15.59797
11:30	320.57	321.24	335.75	323.75	318.35	832.514	1.3	16.28898
12:00	323.07	323.89	338.75	325.25	321.25	858.589	1.5	19.33032
12:30	324.97	325.73	339.75	326.38	323.85	853.374	0.4	18.02539
01:00	326.57	327.29	340.75	328.55	323.65	847.414	0.7	17.19679
01:30	327.67	328.35	342.75	329.95	325.85	832.514	2.1	16.53209
02:00	328.47	329.12	344.05	331.65	327.35	821.339	0.7	16.01775
02:30	329.37	329.95	345.35	331.98	328.15	817.614	1.2	14.35788

Table B.3 Diameter: 19.05mm Flow Rate: 0.1 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	308.91	309.37	321.25	310.25	308.25	732.939	1.2	14.88262
10:30	313.51	314.02	326.25	315.35	312.75	773.914	1.3	15.62555
11:00	317.21	317.83	329.65	319.15	314.55	795.539	1.2	18.5488
11:30	320.91	321.61	332.45	322.95	318.45	832.239	1.7	19.82275
12:00	323.41	324.19	335.45	325.65	322.65	867.039	1.2	21.32817
12:30	325.31	325.98	336.45	327.15	323.35	859.099	0.5	18.51144
01:00	326.91	327.54	337.45	328.95	325.35	852.139	0.7	17.52816
01:30	328.01	328.65	339.45	329.95	325.95	838.964	0.9	18.04329
02:00	328.81	329.39	340.75	331.65	327.55	835.279	0.6	16.54247
02:30	329.71	330.19	342.05	332.45	328.75	820.849	1.2	13.86448

Table B.4 Diameter: 19.05mm Flow Rate: 0.117 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	309.15	310.02	328.34	311.65	308.15	806.439	0.1	14.62962
10:30	311.25	312.19	332.34	313.25	310.75	839.964	0.7	15.17583
11:00	315.15	316.21	338.34	317.55	314.25	880.939	1.0	16.31719
11:30	318.65	319.78	340.24	321.95	317.45	892.114	0.6	17.17685
12:00	321.35	322.61	343.64	323.85	319.15	910.739	0.9	18.76126
12:30	326.15	327.29	346.04	320.75	326.05	903.289	1.3	17.11447
01:00	329.15	330.22	348.34	332.35	328.15	889.879	0.1	16.30565
01:30	331.85	332.87	349.74	334.75	329.15	880.939	0.2	15.70145
02:00	334.55	335.51	351.24	336.55	332.75	869.764	0.5	14.9677
02:30	336.75	337.65	354.72	339.55	335.55	849.649	0.8	14.36443

Table B.5 Diameter: 31.75mm Flow Rate: 0.067 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	309.28	310.12	329.17	311.65	308.15	806.439	0.4	17.49832
10:30	311.38	312.32	333.17	313.55	310.55	839.964	0.4	18.79991
11:00	315.28	316.31	339.17	315.45	313.65	880.939	1.3	19.64174
11:30	318.78	319.89	341.07	318.55	317.45	892.114	0.2	20.90216
12:00	321.48	322.68	344.47	320.35	319.15	895.839	0.7	22.50297
12:30	326.28	327.41	346.87	324.75	324.15	888.389	1.2	21.368
01:00	329.28	330.38	349.17	327.35	327.45	880.939	0.3	20.97662
01:30	331.98	332.98	350.57	329.15	329.95	869.764	1.1	19.31466
02:00	334.68	335.61	352.07	332.65	332.05	851.139	0.1	18.3557
02:30	336.88	337.76	355.55	333.55	335.15	836.239	0.4	17.67831

Table B.6 Diameter: 31.75mm Flow Rate: 0.083 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	309.44	310.18	321.8	311.65	308.25	802.714	0.8	18.6587
10:30	311.54	312.34	325.8	313.55	310.25	836.239	0.5	19.36289
11:00	315.44	316.28	331.8	314.45	314.45	873.489	1.4	19.46401
11:30	318.94	319.84	333.7	321.55	317.55	888.389	0.6	20.50453
12:00	321.64	322.64	337.1	323.35	319.25	895.839	0.1	22.59335
12:30	326.44	327.42	339.5	329.65	324.45	892.114	1.4	22.23393
01:00	329.44	330.38	341.8	332.25	327.65	877.214	0.5	21.68866
01:30	332.14	333.06	343.2	335.25	329.75	867.529	1.1	21.46418
02:00	334.84	335.71	344.7	338.75	333.15	851.139	0.1	20.68851
02:30	337.04	337.84	348.18	339.95	334.55	843.689	0.1	19.19191

Table B.7 Diameter: 31.75mm Flow Rate: 0.1 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	309.65	310.25	332.36	311.65	308.25	806.439	0.2	17.61879
10:30	311.75	312.4	336.36	314.55	310.45	839.964	0.5	18.32521
11:00	315.65	316.39	342.36	318.45	314.45	880.939	1.2	19.89217
11:30	319.15	319.92	344.26	320.55	317.65	892.114	0.6	20.43933
12:00	321.85	322.75	347.66	324.35	320.75	910.739	0.3	23.40157
12:30	326.65	327.48	350.06	329.75	325.15	903.289	1.7	21.75944
01:00	329.65	330.41	352.36	332.35	327.25	888.389	0.5	20.25848
01:30	332.35	333.07	353.76	335.15	330.35	877.214	1.2	19.43673
02:00	335.05	335.75	355.26	337.65	332.35	858.589	0.2	19.30675
02:30	337.25	337.92	358.74	339.55	333.45	836.239	0.3	18.97321

Table B.8 Diameter: 31.75mm Flow Rate: 0.117 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	307.75	308.46	312.75	313.15	306.45	724.489	0.8	13.2896
10:30	313.25	314.07	317.95	314.95	311.35	784.089	0.5	14.18188
11:00	317.45	318.36	321.75	317.95	315.75	817.614	2.2	15.0931
11:30	321.55	322.55	326.25	321.45	321.05	825.064	0.5	16.43606
12:00	324.75	325.93	327.25	323.15	322.95	866.039	1.7	18.47693
12:30	326.35	327.47	329.35	324.45	325.15	882.429	1.4	17.21169
01:00	328.15	329.17	331.15	325.75	328.15	851.139	1.3	16.25118
01:30	330.15	331.11	334.45	328.55	329.95	836.239	1	15.56776
02:00	332.55	333.41	335.85	330.55	331.25	821.339	1.4	14.19912

Table B.9 Diameter: 25.4mm Flow Rate: 0.067 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	307.95	308.56	323.32	311.15	306.25	729.704	0.5	14.04338
10:30	313.45	314.17	328.52	315.95	312.35	787.814	0.6	15.35315
11:00	317.65	318.49	332.32	319.95	316.65	821.339	0.4	17.18088
11:30	321.75	322.67	336.82	323.45	321.15	834.004	1.2	18.5314
12:00	324.95	325.99	337.82	327.15	323.45	864.549	0.6	20.20842
12:30	326.55	327.52	339.92	329.45	325.75	858.589	1.5	18.97907
01:00	328.35	329.23	341.72	332.75	327.25	847.414	0.9	17.44519
01:30	330.35	331.14	345.02	334.55	328.55	836.239	1	15.87031
02:00	332.75	333.48	346.42	335.55	330.85	821.339	0.5	14.931

Table B.10 Diameter: 25.4mm Flow Rate: 0.083 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	305.65	306.26	318.82	308.15	305.15	810.164	1	15.23938
10:30	313.65	314.36	326.82	313.45	312.25	862.314	0.5	16.66493
11:00	320.65	321.47	333.62	322.55	320.45	880.939	0.2	18.8399
11:30	326.05	326.92	339.02	328.25	323.55	888.389	0.6	19.82105
12:00	330.65	331.57	343.12	333.75	328.15	903.289	1.2	20.61444
12:30	333.55	334.41	346.12	337.45	330.45	892.114	0.5	19.51141
01:00	334.65	335.43	348.12	338.25	332.55	866.039	1.3	18.2292
01:30	337.15	337.91	350.12	339.65	334.25	851.139	1.5	18.07272
02:00	339.25	340.05	352.32	342.55	339.85	821.339	0.8	19.71415
02:30	340.35	341.07	353.62	343.35	340.65	806.439	1	18.07055

Table B.11 Diameter: 25.4mm Flow Rate: 0.1 kg/s

Time	Inlet Temperature(in K)	Outlet Temperature(in K)	Absorber Tube Temp(in K)	Tank Inlet(in K)	Hot Water(in K)	Solar Insolation(in W/m^2)	Air flow(in m/s)	efficiency
10:00	305.95	306.51	319.62	307.15	304.15	810.164	0.3	16.3686
10:30	313.95	314.58	327.62	316.25	311.45	860.079	0.2	17.34597
11:00	320.95	321.63	334.42	322.55	318.65	871.999	0.1	18.4667
11:30	326.35	327.09	339.82	329.75	324.35	888.389	1.0	19.72536
12:00	330.95	331.78	343.92	333.35	328.65	903.289	0.1	21.75944
12:30	333.85	334.57	346.92	336.45	331.15	888.389	1.4	19.19224
01:00	334.95	335.63	348.92	339.25	332.35	871.254	0.4	18.48249
01:30	337.45	338.11	350.92	341.45	335.45	854.864	0.5	18.28282
02:00	339.55	340.12	353.12	343.55	337.55	825.064	0.3	16.36001
02:30	340.65	341.19	354.42	345.65	338.15	810.909	0.5	15.7695

Table B.12 Diameter: 25.4mm Flow Rate: 0.117 kg/s

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