Design of a Solar Collector for Heating Thermal Fluid For a Liquid Desiccant Dehumidifier Regenerator

Thesis Submitted in Partial Fulfillment For the Degree of M.Sc. in Renewable Energy Technology

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Jan 2010
ACKNOWLEDGMENTS

I gratefully acknowledge my indebtedness to

Dr. Salah a abdalla

For his guidance, valuable supervision and advice. He spared no time or effort in supporting me.

I wish to thank my family and colleagues for their help and support.
ABSTRACT

The objective of this research is to carry out a study on a solar liquid heater to heat thermal oil in flat plate collector and apply it in air conditioning system in the liquid desiccant dehumidifier to replace the standard electrical heater.

The research contains literature review on solar liquid heaters, explains the types of collector's devices and compare between them, and also storage tanks.

An experimental test were done on energy research institute, the objective of these test is to study the effect of the absorber radiation (in different time of the day) in the temperature of the thermal oil during constant parameter such as area of collector and specific heat of thermal oil. The results of the experiment were discussed and change in temperature versus the time and efficiency versus time curves was drawn.

From the experimental the efficiency of the collector was found to be above 40%.
المستخلص

الهدف من هذا البحث هو إجراء دراسة على المجمعات الشمسية، باستخدام مجمع مائع ذو لوحية مستقيمة لتسخين زيت حراري، وكيفية الاستفادة منه في نظام التبريد بواسطة مجفف أو نازع للرطوبة بدلاً عن الغلايات الكهربائية.

أشتمل البحث على عرض بعض للدراسات السابقة في مجال المجمعات الشمسية وأنواعها وعمل مقارنة بينها.

كما أشتمل البحث على تجربة تمث في معهد أبحاث الطاقة، وكان الهدف من هذه التجربة دراسة تأثير الطاقة الشمسية في تسخين الزيت الحراري، وذلك عند ثبات مساحة المجمع والحرارة النوعية للزيت الحراري.

تم عرض نتائج التجارب و مناقشتها، ومن ثم رسم مخططات توضح تغير درجة الحرارة مع الزمن، ومخططات كفاءة المجمع مع الزمن، ومن التجارب اتضح أن كفاءة المجمع أكثر من 40%.
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Nomenclature

\( A_c \): collector area \((m^2)\)
\( C_p \): specific heat \((J/Kg \cdot K)\)
\( D_p \): pipe diameter \((m)\)
\( D_a \): annulus diameter \((m)\)
\( G_t \): incident radiation \((W/m^2)\)
\( E \): energy absorbed by absorbed plate
\( g \): gravitational constant
\( h_c \): convective heat transfer coefficient \((W/m^2 \cdot k)\)
\( h_r \): radiation heat transfer coefficient \((W/m^2 \cdot k)\)
\( h_w \): convective heat transfer coefficient due to wind \((W/m^2 \cdot k)\)
\( K \): thermal conductivity of insulation \((W/m \cdot K)\)
\( L \): length of the collector \((m)\)
\( m \): mass flow rate \((kg/s)\)
\( N_u \): nusselt number
\( n \): number of days
\( N \): number of glass covers
\( q_l \): heat loss \((W)\)
\( R \): thermal resistance
\( R_b \): Rayleigh number
\( R_b \): Ratio of beam radiation flux
\( R_e \): Reynolds number
\( r_1 \): Perpendicular reflection
\( r_2 \): parallel reflection
\( T_a \): ambient temperature \((^\circ C)\)
\( T_b \): back insulator temperature \((^\circ C)\)
\( T_c \): cover temperature \((^\circ C)\)
\( T_i \): inlet temperature \((^\circ C)\)
\( T_o \): outlet temperature \((^\circ C)\)
\( T_p \): plate temperature \((^\circ C)\)
t: thickness of the insulator (m)
$U_{bot}$: bottom heat loss coefficient (W/m²K)
$U_{edg}$: edge heat loss coefficient (W/m²K)
$U_l$: overall heat loss coefficient (W/m²K)
$U_{top}$: top heat loss coefficient (W/m²K)
$\delta$: declination angle (°deg)
$\Phi$: latitude angle (°deg)
$\omega$: hour angle (°deg)
$\Psi$: azimuth angle (°deg)
$\beta$: tilt angle (°deg)
$\alpha$: solar altitude
$\theta$: angle of incidence (°deg)
$\theta_{ed}$: angle of incidence for diffuse radiation (°deg)
$\rho$: reflectivity
$\tau$: transmissivity
$\tau_r$: Reflection transmittance
$\alpha$: absorbtivity
$\tau\alpha$: transmissivity absorbtivity product
$\sigma$: Stefan-Boltzman constant
$\varepsilon_p$: emissivity of absorber plate
$\varepsilon_c$: emissivity of cover plate
$\alpha$: thermal diffusivity
$\eta$: collector efficiency
CHAPTER ONE

INTRODUCTION

1.1 GENERAL

Air conditioning is the process of treating air to control simultaneously its temperature, humidity, cleanliness, and distribution to meet the requirements of the conditioned spaces.

Conventional chilled water or direct expansion air conditioning that uses a coil to cool air below its dew point temperature has been achieved reliably and efficiently over the last years due to the popularity gained by vapor compression refrigeration. However, desiccant dehumidification, in which a desiccant extracts water vapour from process air, can be used to dehumidify the air and thus give a significant reduction in energy consumption.

Desiccant system used in air conditioning can be explained by (cooling/dehumidification psychometric chart Figure 1.1). During the summer time warm moist air, for example 40°C and 15.7 g/kg moisture content is drawn through the desiccant conditioner so that it comes off at, 57°C and 6.3 g/kg moisture content. The supply air stream then passes through the thermal wheel where it is sensibly cooled to, 28°C. The air then passes through a chilled water cooling coil and is sensibly cooled to the supply condition of; 17°C and 6.3 g/kg moisture content and its cool, dry ventilation delivered to the building.
A liquid desiccant dehumidifier, figure 1.2, consists basically of an absorber and a regenerator. The absorber and regenerator are air-to-solution heat and mass exchangers in which air and desiccant solution are brought into contact in counter-flow or cross-flow. Both types of equipment may be identical in structure, i.e., they have the same type of exchange surfaces and usually differ only in terms of their relative dimensions. Humidity is absorbed from the process air into the solution in the absorber; the desiccant solution is then regenerated so that the same initial concentration is always available. A relatively low temperature level heat at temperatures of about 60°C is sufficient to regenerate the solution (remove the absorbed water out of the dilute solution heat). A hot fluid flowing within the regenerator can be supplied by a solar thermal heating system. As the temperature of the desiccant increases, water evaporates into the air stream and then discharged outdoors.
1.2 **THESIS OBJECTIVES**

The main objectives of this research are:

1. Review the types of solar thermal collectors and some of the present techniques employed for heating.

2. Design a simple, direct, efficient and low cost solar thermal collector to be used as a thermal fluid heater to provide the heating required for a desiccant system.

1.3 **THESIS OUTLINE**

This thesis consists of five chapters

- Chapter 1 is an introduction concerned with air-condition and liquid desiccant dehumidifier system.

- Chapter 2 is concerned with solar liquid heaters theory, solar radiation, transmissivity - absorptivity product, the feasibility of solar heating systems, collector thermal analysis, useful energy delivered by a flat plate solar collector and the means of controlling thermal losses from storage systems.
- Chapter 3 concerned with solar collector heater theory and experimental work.
- Chapter 4 concerned with economical analysis and comparison between heating by solar and electric.
- Chapter 5 concerned with conclusion and recommendations.
CHAPTER 2
SOLAR LIQUID HEATERS THEORY

2.1 GENERAL:

Non conventional energy sources such as energy from the sun (an outstanding source of energy for mankind) are the sources to be utilized in future. Solar energy is abundant, inexhaustible, and environmentally clean source of energy; it is free and available in adequate quantities in almost all parts of the world where people live. However, solar energy is intermittent in nature.

2.2 SOLAR RADIATION

Solar radiation originates from the sun in the wavelength range of 0.3-3.0 \( \mu \text{m} \) and is divided into beam radiation and diffuse radiation. Long wave radiation originates from sources at or near ambient temperature and contains wavelengths over 3 \( \mu \text{m} \). The geometric relationship between a plane of any orientation and the incoming beam of solar radiation depends upon several angles, namely, the latitude \( \phi \), declination \( \delta \), Slope \( \beta \), surface azimuth angle \( \Psi \), the hour angle \( \omega \), and the angle of incidence \( \theta \).

Total solar radiation is the sum of the beam and diffuse solar radiation on a surface, the receiving surface orientation (usually horizontal, sometimes inclined at a fixed slope, or normal to the beam radiation). Most of the data on
solar radiation received on the surface of the earth are measured by a
solarimeter, which gives readings for instantaneous measurements at rate
throughout the day for total radiation on a horizontal surface [1].
The solar altitude \( \alpha \) or angle of incidence on a horizontal surface \( \theta_z \) is
given by:

\[
\sin \alpha = \cos \phi \cos \delta \cos \theta + \sin \phi \sin \delta = \cos \theta_z
\]  
(2.1)

For general surface of any orientation and slope \( \beta \) the angle of incidence \( \theta \) is
given by:

\[
\cos \theta = \cos(\phi - \beta) \cos \delta \cos \omega + \sin(\phi - \beta) \sin \delta
\]  
(2.2)

The solar declination \( \delta \) is given by:

\[
\delta = 23.45 \sin \left[ \frac{360(n-80)}{370} \right]
\]  
(2.3)

The hour angle \( \omega \) is zero at solar noon, negative in the morning and positive
in the afternoon, for northern hemisphere.
To express \( \omega \) in degrees, multiply the hours from solar noon by \( (360/24) \):

\[
\omega = (LST - 12) \times 15
\]  
(2.4)

AST is the apparent solar time used for calculating solar noon

\[
AST = LCT + TZ - \text{longitude/15} + \text{EQT}
\]  
(2.5)

Where:

\[
\text{ACT} = \text{apparent solar time.}
\]

\[
\text{LCT} = \text{the local clock time.}
\]

\[
\text{TZ} = \text{time zone (for Khartoum = -3).}
\]

\[
\text{EQT} = \text{equation of time.}
\]

\[
= [18.6 \left( \sin \left( N - 242 \right)/0.685 \right)] 2.5
\]

(for \( N > 259 \))
i) The tilt factors:
The tilt factor for beam radiation \( r_b \) is ratio of the beam radiation flux
falling on a tilted surface to that falling on horizontal surface

\[
r_b = \cos \theta / \cos \theta_z
\]  
(2.6)

For diffuse radiation it is the ratio of the diffuse radiation flux falling on
tilted surface to that falling on horizontal surface
\[ r_d = \frac{1 + \cos \beta}{2} \]  

for tilt angle of 30, \( r_d = 0.933 \)

for reflect radiation \( r_r = \rho \frac{(1 - \cos \beta)}{2} = 0.0134 \)

ii) Transmissivity Based on Absorption:

\[
\tau_a = \frac{I_{\text{transmitted}}}{I_{\text{incident}}} = \exp \left( -\frac{KL}{\cos \theta_2} \right)
\]

Now the transmittance of a single cover becomes:

\[
\tau = \tau_a \tau_r
\]

Where:

\( \theta_i \) and \( \theta_r \) = angles of incidence and refraction.

\( n_1 \) and \( n_2 \) = refractive indices of the two media.

\( \rho_{1r} \) \( \rho_{11} \) = reflectivity of the perpendicular and parallel components of polarization of incoming radiation.

Subscript ‘r’ indicates that only reflection loss has been considered for transmission of radiation.

Subscript ‘a’ indicates that the transmission is due to absorption only.

\( K \) is proportionality constant (the extinction coefficient). \( K \) is a property of the cover material. It varies from about 4 to 32 m\(^{-1}\) for different types of glass (a low value is desirable).

\( L \) = total thickness of cover material in (m).

Average refractive index \( n_r \) of glass in solar spectrum = 1.526
\[
\frac{1}{n_r} = \frac{\sin \theta_r}{\sin \theta_o}
\]  
(2.10)

Perpendicular reflection \( r_1 = \frac{\sin^2(\theta_r - \theta_o)}{\sin^2(\theta_r + \theta_o)} \)  
(2.11)

Parallel reflection \( r_2 = \frac{\tan^2(\theta_r - \theta_o)}{\tan^2(\theta_r + \theta_o)} \)  
(2.12)

Reflection transmittance \( \tau_r = \frac{1}{2} \left[ \frac{1-r_1}{1+(2N-1)r_1} + \frac{1-r_2}{1+(2N-1)r_2} \right] \)  
(2.13)

### 2.2.1 Absorptivity - Transmissivity Product

The transmissivity - absorptivity product is defined as the ratio of the flux absorbed in the absorber plate to the flux incident on the cover system and is denoted by the symbol \((\alpha\tau)\).

The net fraction absorbed,

\[
(\alpha\tau) = \frac{\alpha\tau}{1-(1-\alpha)\rho_d}
\]  
(2.14)

A reasonable approximation for most practical solar collectors is:

\[
(\alpha\tau)_b = 1.01(\alpha\tau)_d
\]

\[
(\alpha\tau)_b = \frac{\tau(\theta_b)\alpha}{1-(1-\alpha)\rho_d}
\]

\[
(\alpha\tau)_d = \frac{\tau(\theta_d)\alpha}{1-(1-\alpha)\rho_d}
\]  
(2.15)

Where:

- \((\alpha\tau)_b\) for beam radiation falling on the collector.
- \((\alpha\tau)_d\) for diffuse radiation (for sky and ground) falling on the collector.
- \(\rho_d\) = diffuse reflectance of the cover system (at an angle of 30°)
  
  \((0.15, 0.22, 0.24\) for a one, two, and three glass cover system).

### 2.2.2 Absorbed Solar Radiation

Incident radiation on a tilted surface at a given hour is given by:

\[
I_r = I_b R_b + I_d \left( \frac{1 + \cos \beta}{2} \right) + (I_d + I_b) \left( \frac{1 - \cos \beta}{2} \right) \rho_d
\]  
(2.16)
To determine the absorbed radiation in the absorber plate, each of the terms in the above equation must be multiplied by the term \((\tau\alpha)\), so the absorbed radiation \((I_T)\) by tilted collector at a given hour is given by:

\[
I_T = I_b R_b \left( \tau\alpha \right) + \left[ I_d \left( \frac{1 + \cos \beta}{2} \right) + \left( I_d + I_b \right) \left( \frac{1 - \cos \beta}{2} \rho_g \right) \right] \left( \tau\alpha \right) \quad (2.17)
\]

To fit the need of the user, solar energy must be gathered when it is available and stored until it is needed. Solar energy can be utilized by converting it into electric energy using photovoltaic devices or converted into thermal energy using a solar thermal system to be used for space heating and cooling. A solar thermal system, Fig (2.2), consist of the following main component:

i- Solar collector.

ii- Storage system.

iii- Pumping system.

iv- Heat exchanging system.

![Fig 2.2: Solar thermal system components](image)

1. solar collector
2. Thermal fluid out.
3. Storage tank.
5. Valve (Control valve).
6. Cold storage tank (storage system).
7. Pump & piping (distribution system).

2.3 THE SOLAR COLLECTOR

A solar collector is a special kind of heat exchanger that transforms solar energy into heat. It consists of a black surface, that transfers the absorbed thermal energy to a fluid, a transparent envelope over the absorber surface to reduce convection and radiation losses to the atmosphere; and back insulation to reduce conduction losses.

There are several types of solar collectors: concentrating collector, evacuated tube collector, and flat plate collector.

2.3.1 A concentrating collector

A concentrating collector utilizes reflective parabolic-shaped surface to reflect and concentrate the sun's energy to a focal point where the absorber (receiver) is located. The receiver contains a heat-transfer fluid (fig. 2.3). A concentrating type solar collector can achieve very high temperatures up to 250 °C [9]

(Fig 2.3): A concentrating collector [9]

2.3.2 Evacuated tube collectors

Evacuated tube collectors are constructed of a number of glass tubes inside which vacuum is created. Each tube is made of annealed glass and has an absorber plate within the tube. The vacuum creates
excellent insulation, allowing higher temperatures to be achieved at the absorber plate. (Fig 2.4).

**Fig (2.4) Evacuated tube collector [7]**

There are several types of evacuated tubes:

- **Glass-Glass** tube consists of two glass tubes fused together at one end. The inner tube is coated with a selective surface that absorbs solar energy well but inhibits radiative heat loss.

- **Glass-Metal** tubes consist of a single glass tube. Inside the tube is a flat or curved aluminum plate which is attached to a copper heat pipe or water flow pipe. The aluminum plate is generally coated with Tin ox, or similar selective coating.

- **Glass-glass - fluid flow path** tubes incorporate a fluid flow path into the tube itself.[7][9]

### 2.3.3 Flat plate collector:

The flat plate collector consists of the following basic components. A large plate of blackened material oriented in such a manner that the solar energy falls on the plate is absorbed and converted to thermal energy by heating the plate. Tubes or ducting are provided to remove heat from the plate, transferring it to a liquid or gas, and carrying it away to the load. One (or more) transparent (glass or plastic) plates are often placed in top of the absorber plate to reduce heat loss to the atmosphere. Likewise, opaque insulation is placed around the backside
of the absorber plate for the same purpose. Operating temperatures up to 70 °C are typical. (Fig 2.5)
Flat plate collectors have the advantage of absorbing not only the energy coming directly from the disc of the sun (beam normal radiation) but also the solar energy that has been diffused into the sky and reflected from the ground. Flat plate thermal collectors are seldom tracked to follow the sun's daily path across the sky; however their fixed mounting usually provides a tilt by angle 30° toward the south to minimize the angle between the sun's rays and the surface at noontime. Tilting flat-plate collectors toward the south provides a higher rate of energy at noontime and more total energy over the entire day. [9]

**Fig (2.5): A flat plate collector**

1. Outer cover.
2. Inner cover.
4. Insulation.
5. Collector bottom.
6. Fluid conductor.
2.4 Thermal analysis of a solar collector:

2.4.1 Utilizability methods of active system

This method should provide the means for estimating the long-term average performance of a specific system, while requiring relatively little calculation effort and utilizing readily available input data. Design methods for active solar systems have been classified as correlations, simplified simulations, or utilizability-based methods:

1. Correlations methods are the most widely used since they are easy to apply, easy to understand, and amenable to hand calculations. Their main disadvantages are that they are highly empirical and unreliable for systems that differ in any respect from those for which the method was derived.

2. Simplified simulation methods are at an early state of development. Although they require fewer calculations than do simulation methods. Unfortunately, reducing the calculations induces large errors. The main advantage of simplified simulation methods is that they are very flexible, and with the vast growth of computers, they could in the near future become the primary method of design.

3. Utilizability-based methods require more computation than correlation methods but less than simplified simulation ones. These methods consist of a statistic of solar weather that provides a correlation between the radiation and its effect on solar collectors. Since these methods provide a means of accounting for the dependence of system performance on locations and weather conditions through the utilizability factor, they tend to provide more accurate results than correlation methods. This factor is based on long-term average conditions. The major disadvantages of these methods are their dependence on average solar radiation data, which could cause error in output, and their limited suitability to specific applications. The utilizability is divided to:-
(i) Hourly utilizability can be defined as a fraction of the incident solar radiation that can be converted to useful heat. It is the fraction utilized by a collector having $F_R = (\tau \alpha) = 1$, and operating at ambient temperature difference.

(ii) Daily utilizability defined as the sum for a month over all hours and days of radiation on a tilted surface that is above a critical level divided by a monthly radiation described in the equation

$$\phi = \frac{\sum_{\text{days hours}} (I_T - I_{TC})}{H_T N}$$

(2.18)

The monthly utilizability energy is

$$H_T N = \frac{F_R U_i (T_i - T_a)}{F_R (\tau \alpha)}$$

(2.19)

the critical level $I_{TC}$ defined by the following equation

$$I_{TC} = \frac{F_R U_i (T_i - T_a)}{F_R (\tau \alpha)} \frac{(\tau \alpha)_n}{(\tau \alpha)_n}$$

(2.20)

the daily useful energy gain is then given by

$$\sum Q_u = A_i F_R (\tau \alpha) H_T \phi$$

(2.21)

The monthly average critical radiation ratio $\overline{X}$ is the ratio of the critical radiation to the noon radiation level for a day of the month in which the total radiation for the day is the same as the monthly average. For the noon hour

$$\overline{X}_c = \frac{I_c}{r_{i,n} R_n H_o} = \frac{F_R U_i (T_i - T_a)}{r_{i,n} R_n K_i H_o}$$

(2.22)

where

$$\phi = \exp \left[ \left( a + b \left( \frac{R_n}{R} \right) \right) \left( \overline{X}_c + c \overline{X}_c^2 \right) \right]$$

(2.23)

where

$$a = 2.943 - 9.271 \overline{K}_R + 4.031 \overline{K}_R^2$$

$$b = -4.345 + 8.853 \overline{K}_R - 3.602 \overline{K}_R^2$$
\[ c = -0.170 - 0.306 \bar{K}_r + 2.936 \bar{K}_r^2 \]

Where:

- \( \bar{K}_r \) = monthly average hourly clearness index
- \( U_e \) = utilizable energy for month
- \( R \) = monthly ratio of radiation on tilted surface to that on horizontal surface \( H_t/H_h \)
- \( R_n \) = ratio for the hour centered at noon of radiation on the tilted surface to that on horizontal surface for an average day of the month.
- \( R_t \) = the ratio of the hourly total to daily total radiation \( I/H \)

The useful energy delivered by a solar collector is the difference between the absorbed incident radiation and the total heat losses from the collector. From an energy balance on a flat plate solar collector \([4]\) the total heat losses can be calculated using the following formula:

\[ Q_i = U_i(T_p - T_a) \quad (2.24) \]

Considering one glass cover system, the energy balance will estimate the heat loss through the top, the bottom, and the edges of the collector individually and give in terms of the overall heat loss coefficient for the collector.

(i) **Heat loss through the top:**

Due to both convection and radiation, the energy loss from the absorber plate to the ambient through the top cover:-

The heat transfer between the absorber and cover \( = \) The heat transfer between cover and the ambient

Therefore, the heat loss through the top \( (q_{i,t}) \) per unit collector area is the sum of the heat loss due to radiation and to convection. Considering the heat transfer between the absorber plate and the glass cover and noting that:
$h_{c,p-c}$ Convective heat transfer coefficient between the plate and the cover.

The heat loss through the top of the collector \( (q_{i,t}) \) is given by

\[
q_{i,t} = h_{c,p-c} (T_p - T_c) + \frac{\sigma (T_p^4 + T_c^4)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1}
\]  
(2.25)

\[
= h_{c,p-c} (T_p - T_c) + h_{r,p-c} (T_p - T_c)
\]  
(2.26)

\[
= (T_p - T_c) (h_{c,p-c} + h_{r,p-c})
\]  
(2.27)

\[
h_{r,p-c} = \frac{\sigma (T_p^4 + T_c^4)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1}
\]  
(2.28)

Where, \( h_{r,p-c} \) radiation heat transfer coefficient between the absorber and cover

\[
(h_{c,p-c} + h_{r,p-c}) = \frac{1}{R_1}
\]  
(2.29)

Where \( R_1 \) is the resistance to heat transfer between the absorber plate and cover. Then the heat loss through the cover is expressed by:

\[
q_{i,t} = \frac{(T_c + T_p)}{R_1}
\]  
(2.30)

By a similar analysis, the heat loss from cover to the ambient is given by:-

\[
q_{i,t} = h_w (T_c + T_a) + \sigma \varepsilon_c (T_c^4 + T_s^4)
\]  
(2.31)

Where \( h_w \) is the convective heat transfer coefficient due to wind

\( T_a \) is the ambient temperature and

\( T_s \) is the sky temperature

Simplifying,
\[ q_{1,s} = h_w (T_c - T_a) + \frac{\alpha \epsilon_c (T_c + T_s)(T_c - T_s)(T_c^2 + T_s^2)}{(T_c - T_a)} \] (2.32)

We have
\[ q_i = \frac{(T_c - T_a)}{R_2} \] (2.33)

where,
\[ R_2 = \frac{1}{h_w + h_{rc1-a}} \] is the resistance between cover and the ambient. Taking
\[ h_{rc1-a} = \frac{\alpha \epsilon_c (T_c + T_s)(T_c - T_s)(T_c^2 + T_s^2)}{(T_c - T_a)} \] (2.34)

the heat loss through the cover for this one cover system is,
\[ q_{c,t} = \frac{T_p - T_a}{R_{top}} \] (2.35)

Where, \( R_{top} \) is the sum of the two resistances
\[ R_{top} = R_1 + R_2 = \frac{1}{U_{top}} \] (2.36)

\[ \therefore q_{c,t} = U_{top} (T_p - T_a) \] (2.37)

This gives the heat loss through the top of the collector.

(ii) **Heat loss through the bottom:**

The heat loss from the absorber plate to the ambient through the bottom is due to conduction through the insulation and then by a combination of convection and radiation from the insulator to the ambient. At steady state, the heat loss from plate to insulator is equal to the heat loss from insulator to ambient \((q_{l,b})\).

Considering the heat transfer through the insulation (due to conduction), the rate of heat transfer \((q_{l,b})\) is given by
\[ \therefore q_{l,b} = \frac{k}{l} (T_p - T_b) \]
\[ q_{l,b} = \frac{(T_p - T_b)}{R_4} \] (2.38)
Where, \( k \) is the thermal conductivity of the insulator, \( l \) is the thickness of the insulator, \( T_b \) is the temperature at the back of the insulator and \( R_4 = \frac{l}{k} \).

The heat transfer from the bottom (or back) of the insulator to the ambient is due to both convection and radiation and is given in terms of the convective and radiative heat transfer coefficients \( h_{c,b-a} \) and \( h_{r,b-a} \) respectively as

\[
q_{1,5} = h_{c,b-a}(T_b - T_a) + h_{r,b-a}(T_b - T_a)
\]  

(2.39)

But, since the temperature at the bottom of the casing will be low, the radiation loss could be neglected. Therefore, the above equation reduces to

\[
q_{1,5} = h_{c,b-a}(T_b - T_a) = \frac{(T_f - T_a)}{R_3}
\]  

(2.40)

Where, \( R_3 = \frac{1}{h_{c,b-a}} \) is sometimes neglected in comparison with \( R_4 \).

Therefore, the loss through the bottom is given by,

\[
q_{1,5} = \frac{(T_f - T_a)}{R_{bot}},
\]  

(2.41)

Where, \( R_{bot} \) is the sum of the two resistances as shown in the following

\[
R_{bot} = R_4 + R_5
\]  

\[
\therefore q_{1,5} = U_{bot}(T_f - T_a)
\]

Where,

\[
U_{bot} = \frac{1}{R_{bot}}
\]  

(2.42)

(iii) Heat loss through the Edge:

The edge losses also need to be referenced per collector area and can be estimated as
\[ Q_{\text{le}} = \frac{T_p - T_a}{R_{\text{edge}}} \]  \hspace{1cm} (2.43)

\[ R_{\text{edge}} = \frac{1}{U_{\text{edge}}} \quad \text{and} \quad U_{\text{edge}} = \frac{U}{\frac{1}{A_p} \cdot \frac{A_p}{A_c}} \]  \hspace{1cm} (2.44)

Where, \( k_e \) is thermal conductivity of edge insulation

L_e is the insulation thickness.

A_p is the outside perimeter area of collector = 2t (l+b)

Where, l, b and t are the length, breadth and thickness of the collector respectively

\[ A_c \]

A_c is the collector area \( U_{\text{edge}} \) is given by \( \frac{k_e}{l_e} \)

Therefore,

\[ Q_{\text{le}} = U_{\text{edge}} (T_p - T_a) \]  \hspace{1cm} (2.45)
(iv) Total heat loss coefficient

Combining equations 2.3, 2.4 and 2.5, we get the total heat loss occurring between the mean plate temperatures ($T_p$) and the ambient ($T_a$). These three heat losses can be combined and given in terms of a single parameter called the overall heat loss coefficient ($U_i$) as shown below:

\[
q_{tot} = q_{l,t} + q_{l,h} + q_{l,e} \tag{2.46}
\]
\[
q_{tot} = U_{tot} (T_p - T_a) + U_{bot} (T_p - T_a) + U_{edge} (T_p - T_a) \tag{2.47}
\]
\[
q_{tot} = (U_{tot} + U_{bot} + U_{edge}) (T_p - T_a) \tag{2.48}
\]
\[
q_{tot} = U_i (T_p - T_a) \tag{2.49}
\]

Since the solar radiation absorbed by the collector $H_a = \text{incident solar radiation - optical losses}$

Where the thermal losses are due to convection, conduction, and radiation to the surrounding ($U_i$) and the difference between the mean plate temperature $T_p$ and the ambient temperature $T_a$ the useful energy gain of a collector with area $A_c$ is

\[
Q_u = A_c \cdot h - U_i (T_p - T_a) \tag{2.50}
\]

The top loss heat coefficient and be estimated directly by the following equation

\[
U_i = \left[ \frac{N}{C \left( \frac{T_{pot} - T_a}{N + f} \right)} + \frac{1}{h_w} \right]^{-1} + \frac{\sigma (T_{pot} + T_a) (T_{pot}^2 + T_a^2)}{(e_p 0.00591N h_w)^{-1} + \frac{2N + f - 1 + 0.133e_p}{e_s}} - \frac{N}{e_s} \tag{2.50}
\]

Where:
\[
f = (1 + 0.089 h_w - 0.1166 h_w \varepsilon_p) (1 + 0.07866 N)
\]
\[
C = 520 (1 - 0.000051 \beta^2) \quad \text{for } 0 < \beta < 70, \text{ for } 70 < \beta < 90 (\text{use } \beta = 70)
\]
\[
e = 0.43 \left( \frac{1}{1 - \frac{100}{T_{\text{set}}} \epsilon} \right)
\]

(v) **Collector efficiency**

The performance of the collector is evaluated in terms of efficiency, which is defined as the ratio of the useful energy delivered by the collector during a specified time period (instantaneous, hourly or daily) to the incident solar radiation on the collector during the same time period. The efficiency of the collector is given by

\[
\eta = \frac{\int Q_u \, dt}{A_c \int H \, dt}
\]  
(2.51)

Where \( Q_u \) is the useful energy delivered by a collector of area \( A_c \) in time \( t \) during which it received a solar radiation \( H \).

2.5 **STORAGE SYSTEM**

The storage system stores energy when the collected amount is in excess of the requirement of the application and discharges energy when the collected amount is inadequate. There are three basic methods of storing thermal energy:

(I) Using a liquid or a solid which does not change phase, this is called sensible heat storage. The amount of energy stored is dependent on the temperature change of material.

(II) Using material which undergoes a phase change (usually melting). This called latent heat storage. The amount of energy stored in this case depends upon the mass and the latent heat of fusion of material.

(III) Using heat, the energy to be stored is used to produce a certain endothermic chemical reaction and the products of the reaction
are stored. The heat is released when the reverse reaction is made to occur. The storage operates essentially exothermally during the chemical reactions, however the temperature at which the forward reaction occurring is higher than the temperature of the reverse reaction. [10]

The choice of storage media depend on the nature of the process, the major characteristics of a thermal energy storage system are:-

1. Capacity per unit volume.
2. The temperature range over which it operates
3. Power requirement for addition or removal of heat.
4. The means of controlling thermal losses from the storage system.

A well mixed liquid storage (Fig 2.6) connected to the heat exchanger the collector inlet temperature $T_c$ is not the same as the storage temperature $T_s$. The rate of charging is given by

$$Q_c = \{m_{cp}\}(T_{c0} - T_{cl})$$

Where $(m_{cp})$ is the product of specific heat and the fluid mass flow rate through the collector.

![Figure 2.6 A well mixed liquid storage](image)

The energy balance for an elemental length $d_x$ of the heat exchanger can be written as
\[
(m_c) \frac{dT_c}{dx} = (U2r)(T_c - T_s)
\]  
(2.52)

\[
\frac{dT_c}{T_c - T_s} = \frac{(U2r)dx}{(m_c) - c}
\]

After integrating

At \(x = 0\), \(T_c = T_{co}\), at \(x = l\), \(T_c = T_{ci}\)

\[
T_c - T_{ci} = (T_c - T_s) \left( 1 - \exp\left(\frac{(UA)}{m_c} \right) \right)
\]

(2.53)

Hence

\[
Q_c = (m_c) \left( T_c - T_{ci} \right) = (m_c) \left( 1 - \exp\left(\frac{(UA)}{m_c} \right) \right) (T_c - T_s)
\]

Similarly the energy withdrawn by the load is

\[
Q_l = (m_c) \left( T_{li} - T_{lo} \right)
\]

And \(T_{li} - T_{lo}\) is obtained from

\[
\frac{T_{li} - T_{lo}}{T_{is} - T_{lo}} = \left( 1 - \exp\left(\frac{(UA)}{m_c} \right) \right)
\]

(2.54)

Where \((UA)\) is the product of surface area and the overall heat transfer coefficient for the liquid in store.

### 2.6 PUMPING SYSTEM

The solar heating system uses a pump to circulate fluid through the solar collector. The circulating fluid is commonly controlled by a differential temperature-sensing controller. The controller generally turns on if the water inlet temperature to the collector is less than the collector fluid outlet temperature.

A photovoltaic (PV) powered pump can be used to replace the standard electrical pump. The PV driven pump provides some advantages; first the PV pumping system can eliminate the need for a controller since the PV pump will only respond to solar radiation and
will only pump at times the solar collector is receiving radiation. The PV pump also eliminates the need for an auxiliary power source.

The photovoltaic pumping system include a PV panel directly coupled to a DC motor and pump, a battery buffered pumping system where a battery is connected across the PV panel to feed the DC motor driving a pump [Fig 2.7], and a maximum power point tracker where the system will always operate at the PV panel’s maximum power point.

![Fig (2.7) A photovoltaic powered pumping system](image)

PV panel is composed of Photovoltaic cells, and the PV cells function is to convert solar radiation into electrical energy. Photovoltaic cells are made of a semiconductor material such as single-crystal silicon or amorphous (non-crystalline) silicon. Semi-conductors normally behave electrically like an insulator that inhibits the transfer of electrical energy however, when sufficient energy, such as sunlight is incident on these materials they act like electrical conductors. PV pumping systems require minimum radiation to start the pumping. The minimum radiation is called the threshold radiation and it is dependent on the characteristics of the system components. As the radiation increases, the PV pump will circulate fluid at an increasing rate.

One type of pumps is the centrifugal pumps which require less torque to start and produce more head than other pumps. Simplicity, low cost, low maintenance and availability of designs for a wide range of flow rates and heads make centrifugal pumps an appropriate choice for the system.
centrifugal pump operated at constant speed delivers any capacity from zero to the pumps maximum.

2.7 **CONTROL SYSTEM**

Two types of controls are used on solar collectors: first on-off controller, a decision should be made to turn the circulating pump on or off depending on whether or not useful output is available from the collector. The second type of control is the proportional controller, where the pump speed is varied in an attempt to maintain a specified temperature level at the collector outlet.

The most common control requires two temperature sensors, one on the bottom of the storage tank and one on the pipe near to the plate collector. When fluid is flowing; the collector transducer senses the exit fluid temperature. When the fluid is not flowing, the mean plate temperature is measured. A controller receives this temperature and the temperature at the bottom of the storage unit. When the pump turns on, the temperature of the bottom at storage will equal the inlet fluid temperature.

2.8 **PIPING SYSTEM**

The type of pipe used is a pre insulated corrugated stainless steel water flexi pipe, which is encased with insulation. Designed to cope with the extremely high water temperatures which Solar collectors produce, the unique design of flexi pipe ensures a leak free installation since there are no joints in the flexi pipe run[8].

The flexi pipe is encased within an insulation material, which is molded around the flow and return pipe to form a one piece extrusion. The two encased pipes can easily be separated if required, when we connect them to the solar collector or the hot water storage cylinder. The resulting fit of this pipe system is extremely neat and tidy.
CHAPTER 3
SOLAR COLLECTOR HEATER DESCRIPTION AND EXPERIMENTAL WORK

This chapter deals with the solar heating system adopted in this research and the design of solar collector heater.

3.1 HEATER DESCRIPTION

The primary components of a solar heating system are a flat plate collector, storage tank, circulating pump and heat exchanger. The function of the solar collector is to absorb solar radiation and convert it into thermal energy; the storage tank is used as storage media for storing the heated thermal fluid. The components of the solar heating system are as shown in Figure (3.1)

![Figure (3.1) solar heater system]

1) Flat plate collector.
2) Storage tank.
3) Heat Exchanger.
4) Pump.
5) Valve.

A cylindrical storage tank 1.24 m diameter 1 m high made from sheet metal (\( \rho = 7800 \text{ kg/m}^3, \ C_p = 0.46 \text{ kJ/kg-k} \)) 6 mm thickness is used in this system.
The tank is suitably insulated with glass wool; the thickness of insulation used is 10 cm.

3.2 **DESIGN PARAMETERS**

The collector design parameters include operational parameters such as efficiency, mass flow rate, constructive parameters such as area of the collection (m²), and specific heat of the thermal fluid (J/kg°C) consistency.

3.3 **DESIGN METHODOLOGY**

The methodology adopted for design of the solar collector heater in this research depends on the following steps:

1. Knowing the value of the monthly mean total radiation of the geographical place in which the collector is settled (Meteorological Department, Khartoum).

2. Calculating the heat loss and efficiency from the load and the dimension of the collector.

3. Calculating the specific output power in kw.

4. Calculating the efficiency of the solar collector by the following equation:

\[
\eta = \frac{m c_p (T_a - T_i)}{A_c I_t}
\]  

(3.1)

3.4 **DESIGN OUTPUT**

There are three parts explaining the output results of the design:

3.4.1 **Heater component sizes**

The structure of a solar collector is fabricated from steel, surround by (1x1x0.1) m insulation, a rectangular steel stand with the same dimensions as the box, and steel legs at the corners of the collector, the two front legs shorter than the others so as to hold the collector inclined at the tilt angle.
Flat plate collectors are normally fixed in one position and don’t track the sun, the most efficient orientation for the collectors is facing south at angle 30°

(I) The cover:
The cover of the collector consists of a single layer of glass. The specifications of the glass cover are:
- 3 mm thickness with dimension 1 x 1 m.
- Index of refraction = 1.1518
- Solar radiation transmission 92%.
- Solar radiation absorption 2%.
- Cover glass emittance ($\lambda=2.5 - 40 \ \mu m$) = 0.88
- Specific heat = 0.754 x 103 J/kgK.
- Density = 2.489 x 103 kg/m3.

The spacing between the absorber plate and cover is selected to minimize the convective heat transfer coefficient. Since the collectors are designed to operate at one location and constant tilt the best spacing is chosen as 10 cm.

(II) The selective surface:
The selected absorber plate surface is of high absorptivity for incident solar radiation and low emissivity for outgoing radiation. Mild steel has high absorptivity with the following properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7833 Kg/m³</td>
</tr>
<tr>
<td>Specific heat</td>
<td>0.465 KJ/Kg°C</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>54 W/m °C</td>
</tr>
</tbody>
</table>
(III) The insulation
Because of its low thermal conductivity, stability at high temperature (up to 200 °C), ease of application, no contribution in corrosion. (10 cm thick, 3 m²) of glass wool was used as an insulating material to reduce the losses from the absorbing plate and pipe, with the properties
Thermal conductivity at 200 °C = 0.044 W/m°C.
Density = 48 kg/m³.

3.4.2 The outlet temperature
Based on the weather records the collections of solar energy occur between 9.00 am and 2.00 pm. As the fluid inlet temperature is estimated as 40 °C, the value of the $T_{out}$ is calculated; the temperature of the outlet fluid from the collector is 69 °C.

3.4.3 The energy requirement
The energy absorbed by the absorber plate calculated per unit area:-

$$E = I_b r_b (\tau \alpha)_b + [I_d r_d + (I_b + I_d) \tau \alpha] (\tau \alpha)_d$$  \hspace{1cm} (3.2)
3.5 **EXPERIMENTAL SETUP**

The experiments were carried out on the 8th, 9th, 12th of April. The experimental solar collector was placed on the Energy Research Institute.

**3.5.1 Objective of the experiments:**
To test the possibility of using thermal oil as heat transfer
To predict the performance of the system during the day and record the peak temperature reached.

**3.5.2 Instruments used**

1- Solar radiation meter used to measure solar radiation in W/m².
   
   [Solar sensor ss-100 (100-W/m² +100 mv)]
   
   Dodgt Products, Houston Texas

2- Electronic thermometer to measure Tin, Tout, Tg, Tp.

**3.5.3 Procedure**

- The pipe of the system was filled by thermal oil.
- The oil in the pipes of solar collector was heated by the absorbed solar radiation.
- Natural circulation took place due to change of density of oil caused by absorbed heat.
- All data were measured.
3.5.4 Results and discussion

Experimental work was carried out in three days.

Collected data during days 8th, 9th, 12th of April on table (3.1)

Table (3.1) the results of recorded radiation and measured temperature by using thermal oil

(i) Date 08/04/2009

<table>
<thead>
<tr>
<th>Time</th>
<th>( T_a ) (°C)</th>
<th>( T_{in} ) (°C)</th>
<th>( T_{out} ) (°C)</th>
<th>( T_p ) (°C)</th>
<th>( T_g ) (°C)</th>
<th>( I_t ) (W/m²)</th>
<th>( I_d ) (W/m²)</th>
<th>( I_b ) (W/m²)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00</td>
<td>30</td>
<td>30</td>
<td>37</td>
<td>73</td>
<td>43</td>
<td>450</td>
<td>190</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>10:00</td>
<td>35</td>
<td>39</td>
<td>49</td>
<td>83</td>
<td>50</td>
<td>620</td>
<td>210</td>
<td>410</td>
<td></td>
</tr>
<tr>
<td>11:00</td>
<td>40</td>
<td>45</td>
<td>67</td>
<td>88</td>
<td>56</td>
<td>740</td>
<td>215</td>
<td>525</td>
<td>Clear day</td>
</tr>
<tr>
<td>12:00</td>
<td>44</td>
<td>47</td>
<td>75</td>
<td>93</td>
<td>56</td>
<td>840</td>
<td>230</td>
<td>610</td>
<td></td>
</tr>
<tr>
<td>13:00</td>
<td>45</td>
<td>49</td>
<td>80</td>
<td>100</td>
<td>60</td>
<td>875</td>
<td>225</td>
<td>650</td>
<td></td>
</tr>
</tbody>
</table>
Fig (3.3.a) Ambient and outlet temperature against time of the day

(ii) Date 09/04/2009

<table>
<thead>
<tr>
<th>time</th>
<th>$T_a$ (°C)</th>
<th>$T_{in}$ (°C)</th>
<th>$T_{out}$ (°C)</th>
<th>$T_p$ (°C)</th>
<th>$T_g$ (°C)</th>
<th>$I_t$ (W/m²)</th>
<th>$I_d$ (W/m²)</th>
<th>$I_b$ (W/m²)</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00</td>
<td>31</td>
<td>31</td>
<td>36</td>
<td>63</td>
<td>35</td>
<td>575</td>
<td>195</td>
<td>380</td>
<td>dusty day</td>
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<tr>
<td>10:00</td>
<td>35</td>
<td>35</td>
<td>41</td>
<td>70</td>
<td>39</td>
<td>640</td>
<td>200</td>
<td>440</td>
<td>With Wind Speed 4 m/s</td>
</tr>
<tr>
<td>11:00</td>
<td>37</td>
<td>38</td>
<td>51</td>
<td>83</td>
<td>41</td>
<td>755</td>
<td>210</td>
<td>545</td>
<td></td>
</tr>
<tr>
<td>12:00</td>
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<td>40</td>
<td>64</td>
<td>93</td>
<td>45</td>
<td>830</td>
<td>230</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>13:00</td>
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<td>42</td>
<td>74</td>
<td>95</td>
<td>45</td>
<td>890</td>
<td>220</td>
<td>670</td>
<td></td>
</tr>
<tr>
<td>14:00</td>
<td>42</td>
<td>45</td>
<td>75</td>
<td>102</td>
<td>49</td>
<td>890</td>
<td>220</td>
<td>670</td>
<td></td>
</tr>
</tbody>
</table>
Fig (3.3.b) Ambient and outlet temperature against time of the day

(iii) Date 12/04/2009

<table>
<thead>
<tr>
<th>time</th>
<th>$T_a$ (°C)</th>
<th>$T_{in}$ (°C)</th>
<th>$T_{out}$ (°C)</th>
<th>$T_p$ (°C)</th>
<th>$T_g$ (°C)</th>
<th>$I_t$ (W/m²)</th>
<th>$I_d$ (W/m²)</th>
<th>$I_b$ (W/m²)</th>
<th>remarks</th>
</tr>
</thead>
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<td>33</td>
<td>49</td>
<td>33</td>
<td>480</td>
<td>190</td>
<td>290</td>
<td></td>
</tr>
<tr>
<td>10:00</td>
<td>35</td>
<td>35</td>
<td>42</td>
<td>68</td>
<td>40</td>
<td>660</td>
<td>200</td>
<td>460</td>
<td></td>
</tr>
<tr>
<td>11:00</td>
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<td>42</td>
<td>53</td>
<td>81</td>
<td>41</td>
<td>815</td>
<td>225</td>
<td>585</td>
<td>Clear day</td>
</tr>
<tr>
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<td>45</td>
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<td>42</td>
<td>860</td>
<td>220</td>
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<tr>
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<td>97</td>
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<td>660</td>
<td></td>
</tr>
<tr>
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<td>46</td>
<td>75</td>
<td>96</td>
<td>47</td>
<td>780</td>
<td>220</td>
<td>680</td>
<td></td>
</tr>
</tbody>
</table>
Fig (3.3.c) Ambient and outlet temperature against time of the day

As shown from fig (3.1.a), (3.1.b), (3.1.c) from 9 O’clock to 14:00 O’clock the ambient temperature at (energy research institute) where the collector was put ($T_a$) increased slightly. Oil temperature in the pipe increased gradually between 9 to 12 O’clock, after 12 O’clock a significant increase noticed and temperature difference reached 8$^\circ$C to 10$^\circ$C. The highest increase after 12 O’clock occurred due to the highest intensity of solar radiation during that period.

### 3.5.5 Solar angle and tilt factor

The value of incident angle ($\theta$), altitude angle ($\alpha$), zenith angle ($\theta_z$), and the ratio of beam radiation flux ($R_b$) are calculated by using equations (2.1), (2.2), (2.6), respectively. The value were tabulated below
Table (3.2) the calculated values of solar angles and tilt factor

For day 08/04/2009
For N= 97 days, \(\Phi=15, \beta=30, \delta = -6.68\)

<table>
<thead>
<tr>
<th>time</th>
<th>(\omega_{(hr)})</th>
<th>(\omega^0)</th>
<th>(\Theta^0)</th>
<th>(\alpha^0)</th>
<th>(\Theta_z^0)</th>
<th>(R_b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00</td>
<td>-4</td>
<td>-60</td>
<td>59.35</td>
<td>26.715</td>
<td>63.28</td>
<td>1.134</td>
</tr>
<tr>
<td>10:00</td>
<td>-3</td>
<td>-45</td>
<td>44.89</td>
<td>40.41</td>
<td>49.59</td>
<td>1.093</td>
</tr>
<tr>
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<td>-30</td>
<td>30.58</td>
<td>53.20</td>
<td>36.80</td>
<td>1.075</td>
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<tr>
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<td>-1</td>
<td>-15</td>
<td>16.91</td>
<td>63.71</td>
<td>26.29</td>
<td>1.067</td>
</tr>
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<td>8.32</td>
<td>68.32</td>
<td>21.68</td>
<td>1.064</td>
</tr>
<tr>
<td>14:00</td>
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<td>15</td>
<td>16.92</td>
<td>63.71</td>
<td>26.29</td>
<td>1.067</td>
</tr>
</tbody>
</table>

For day 09/04/2009
For N= 98 days, \(\Phi=15, \beta=30, \delta = -7.06\)

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<th>(\alpha^0)</th>
<th>(\Theta_z^0)</th>
<th>(R_b)</th>
</tr>
</thead>
<tbody>
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<td>59.26</td>
<td>26.58</td>
<td>63.42</td>
<td>1.142</td>
</tr>
<tr>
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<td>-45</td>
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<td>40.24</td>
<td>49.76</td>
<td>1.109</td>
</tr>
<tr>
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<td>-30</td>
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<td>53.97</td>
<td>37.03</td>
<td>1.080</td>
</tr>
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<td>-15</td>
<td>16.71</td>
<td>62.45</td>
<td>26.60</td>
<td>1.071</td>
</tr>
<tr>
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<td>67.94</td>
<td>22.06</td>
<td>1.069</td>
</tr>
<tr>
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<td>15</td>
<td>16.71</td>
<td>63.40</td>
<td>26.60</td>
<td>1.071</td>
</tr>
</tbody>
</table>

For day 12/04/2009
For N= 101 days, \(\Phi=15, \beta=30, \delta = -8.19\)

<table>
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<th>(\omega^0)</th>
<th>(\Theta^0)</th>
<th>(\alpha^0)</th>
<th>(\Theta_z^0)</th>
<th>(R_b)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-60</td>
<td>59.00</td>
<td>26.19</td>
<td>63.81</td>
<td>1.167</td>
</tr>
<tr>
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<td>-45</td>
<td>44.53</td>
<td>39.73</td>
<td>50.27</td>
<td>1.115</td>
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<tr>
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<td>-2</td>
<td>-30</td>
<td>30.13</td>
<td>52.29</td>
<td>37.71</td>
<td>1.093</td>
</tr>
<tr>
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<td>-1</td>
<td>-15</td>
<td>16.18</td>
<td>62.45</td>
<td>27.55</td>
<td>1.083</td>
</tr>
<tr>
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<td>66.81</td>
<td>23.19</td>
<td>1.080</td>
</tr>
<tr>
<td>14:00</td>
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<td>15</td>
<td>16.18</td>
<td>62.45</td>
<td>27.55</td>
<td>1.083</td>
</tr>
</tbody>
</table>
In tables (3.2.a), (3.2.b), (3.2.c)

- $\Theta^o$ and $\Theta_z^o$ decreased gradually till the peak point at 13:00 o'clock after that they increased.
- $\alpha^o$ increased gradually till the same peak point and then deceased.
- $R_b$ did not change because it is the ratio between $(\cos \Theta_z^o / \cos \Theta^o)$.

3.5.6 The transmissivity

The value of $\Theta_r^o$, $r_1$, $r_2$, $\tau_r$, $\tau_a$, $\tau_b$, $(\tau \alpha)_b$, are calculated by using equations (2.10), (2.11), (2.12), (2.13), (2.8), (2.14)

Tables (3.3) the values of transmissivity and transmissivity-absorbtivity

For day 08/04/2009

For N= 97 days, $\Phi = -6.68$

<table>
<thead>
<tr>
<th>time</th>
<th>$\Theta^o$</th>
<th>$\Theta_r^o$</th>
<th>$r_1$</th>
<th>$r_2$</th>
<th>$\tau_r$</th>
<th>$\tau_a$</th>
<th>$\tau_b$</th>
<th>$(\tau \alpha)_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00</td>
<td>59.35</td>
<td>34.32</td>
<td>0.180</td>
<td>8.97x10^{-4}</td>
<td>0.847</td>
<td>0.934</td>
<td>0.791</td>
<td>0.759</td>
</tr>
<tr>
<td>10:00</td>
<td>44.89</td>
<td>27.55</td>
<td>0.098</td>
<td>9.76x10^{-3}</td>
<td>0.902</td>
<td>0.939</td>
<td>0.847</td>
<td>0.813</td>
</tr>
<tr>
<td>11:00</td>
<td>30.58</td>
<td>19.47</td>
<td>0.063</td>
<td>0.0270</td>
<td>0.914</td>
<td>0.942</td>
<td>0.861</td>
<td>0.826</td>
</tr>
<tr>
<td>12:00</td>
<td>16.91</td>
<td>10.99</td>
<td>0.049</td>
<td>0.0384</td>
<td>0.9163</td>
<td>0.945</td>
<td>0.866</td>
<td>0.831</td>
</tr>
<tr>
<td>13:00</td>
<td>8.32</td>
<td>5.44</td>
<td>0.045</td>
<td>0.0422</td>
<td>0.9164</td>
<td>0.946</td>
<td>0.867</td>
<td>0.832</td>
</tr>
<tr>
<td>14:00</td>
<td>16.92</td>
<td>10.99</td>
<td>0.049</td>
<td>0.0384</td>
<td>0.9163</td>
<td>0.945</td>
<td>0.866</td>
<td>0.831</td>
</tr>
</tbody>
</table>

For day 09/04/2009

For N= 98 days, $\Phi=15$, $\beta=30$, $\Phi = -7.06$

<table>
<thead>
<tr>
<th>time</th>
<th>$\Theta^o$</th>
<th>$\Theta_r^o$</th>
<th>$r_1$</th>
<th>$r_2$</th>
<th>$\tau_r$</th>
<th>$\tau_a$</th>
<th>$\tau_b$</th>
<th>$(\tau \alpha)_b$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>8.31x10^{-4}</td>
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<td>0.791</td>
<td>0.759</td>
</tr>
<tr>
<td>10:00</td>
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<td>27.50</td>
<td>0.097</td>
<td>9.88x10^{-3}</td>
<td>0.9015</td>
<td>0.938</td>
<td>0.846</td>
<td>0.812</td>
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<td>19.40</td>
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<td>0.0272</td>
<td>0.9143</td>
<td>0.942</td>
<td>0.861</td>
<td>0.826</td>
</tr>
</tbody>
</table>
For day 12/04/2009
For N= 101 days, Φ=15, β=30, = -8.19

<table>
<thead>
<tr>
<th>time</th>
<th>Θ₀</th>
<th>Θ₀</th>
<th>r₁</th>
<th>r₂</th>
<th>rᵣ</th>
<th>rₐ</th>
<th>rₐ</th>
<th>(rα)ᵦ</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00</td>
<td>59.00</td>
<td>34.17</td>
<td>0.177</td>
<td>6.57x10⁻⁴</td>
<td>0.849</td>
<td>0.936</td>
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<td>0.763</td>
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<td>27.36</td>
<td>0.096</td>
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<td>0.902</td>
<td>0.940</td>
<td>0.848</td>
<td>0.834</td>
</tr>
<tr>
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<td>19.20</td>
<td>0.063</td>
<td>0.0275</td>
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<td>0.943</td>
<td>0.862</td>
<td>0.827</td>
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<td>0.048</td>
<td>0.0388</td>
<td>0.916</td>
<td>0.946</td>
<td>0.867</td>
<td>0.832</td>
</tr>
<tr>
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<td>0.044</td>
<td>0.0424</td>
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<td>0.947</td>
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<td>0.833</td>
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<td>16.18</td>
<td>10.52</td>
<td>0.048</td>
<td>0.0388</td>
<td>0.917</td>
<td>0.946</td>
<td>0.867</td>
<td>0.832</td>
</tr>
</tbody>
</table>

From above three tables it was found that the transmissivity - absorptivity product from beam radiation increased gradually and reached its maximum value at 13:00 o'clock then decreased which is due to the variation of solar radiation intensity.

### 3.5.7 The useful energy and efficiency

The value of \( U_t \), \( U_l \), \( q_u \), \( I_T \), \( I_c \), \( \eta \) are calculated by using equations (2.50 ), (2.48 ), (2.49 ), (2.17 ), (2.51 )

#### Tables (3.4) the values of useful energy and efficiency

For day 08/04/2009

<table>
<thead>
<tr>
<th>time</th>
<th>( U_t )</th>
<th>( U_l )</th>
<th>( I_T )</th>
<th>( q_u )</th>
<th>( I_c )</th>
<th>( \eta )</th>
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</thead>
<tbody>
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</tr>
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<td>612.37</td>
<td>39.7</td>
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<td>734.89</td>
<td>40.6</td>
</tr>
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<td>(U_t)</td>
<td>(U_l)</td>
<td>(I_T)</td>
<td>(q_u)</td>
<td>(I_c)</td>
<td>(\eta)</td>
</tr>
<tr>
<td>-------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>-------</td>
<td>-------</td>
<td>--------</td>
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For day 09/04/2009

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<th>(I_T)</th>
<th>(q_u)</th>
<th>(I_c)</th>
<th>(\eta)</th>
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<td>44.52</td>
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<td>683.00</td>
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<td>739.57</td>
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For day 12/04/2009

<table>
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<th>(U_l)</th>
<th>(I_T)</th>
<th>(q_u)</th>
<th>(I_c)</th>
<th>(\eta)</th>
</tr>
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<td>522.13</td>
<td>40.84</td>
</tr>
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<td>708.34</td>
<td>41.64</td>
</tr>
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<td>5.71</td>
<td>675.21</td>
<td>364.78</td>
<td>860.18</td>
<td>42.89</td>
</tr>
<tr>
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<td>6.12</td>
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<td>43.01</td>
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<td>743.9</td>
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<td>43.87</td>
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<td>6.076</td>
<td>653.3</td>
<td>381.24</td>
<td>933.76</td>
<td>41.93</td>
</tr>
</tbody>
</table>
Fig 3.4 the collector efficiency against time

From figure 3.2 it was found that the maximum efficiency occurred at 12 o'clock. This value is considered to be low due to bad insulation.
3.6 **Calculation of overall heat loss coefficient and outlet temperature by using a program:**

For calculating the heat loss coefficient and outlet temperature the following data is applying to the equation

Collector area $A = 1 \times 1$ = 1 m$^2$
Plate to cover spacing \( = 0.1 \) m
Back insulation thickness \( L = 0.05 \) m
Edge insulation thickness \( = 0.05 \) m
Fluid conductor tube length \( = 10 \) m
Ambient air temperature \( = 35 \) °C
Plate emittance \( = 0.95 \)
Cover glass emittance \( = 0.88 \)
Effective transmittance-absorptance product \( = 0.52 \)
Collector tilt angle \( \beta = 30^\circ \)
Wind heat transfer coefficient \( = 8 \) W/m$^2$ K
Stefan-Boltzman constant, \( \sigma = 5.66 \times 10^{-8} \)
Thermal conductivity \( K = 0.029 \) W/m K
Thermal diffusivity \( \alpha = 2.69 \times 10^{-5} \)
Incident radiation \( = 620 \) W/m$^2$
\( T_p = 83^\circ\)C
\( T_c = 50^\circ\)C
From previous equations at chapter two and from data collected at the experiment the following equation is calculated

\[
h_{r,p-c} = \sigma \left(\frac{T_p + T_e}{r} \right) \left(\frac{T_p^2 + T_e^2}{r^2} \right) = \frac{5.66 \times 10^{-8} (133 + 2 \times 273) \left[(83 + 273)^2 + (50 + 273)^2\right]}{1/\varepsilon_p + 1/\varepsilon_c - 1} \frac{1}{0.88 + 1/0.95 - 1}
\]

\[
= 7.47 \text{ W/m}^2\text{c}
\]

\[
h_{r,c-a} = \varepsilon \sigma \left(\frac{T_c^2 + T_a^2}{r} \right) \left(\frac{T_c + T_a}{r^2} \right)
\]

\[
= 0.88 \times 5.66 \times 10^{-8} \left((50 + 273)^2 + (35 + 273)^2\right) \times 85 + 2 \times 273 = 6.261 \text{ W/m}^2\text{c}
\]

Raleigh number \( R_a = \frac{g \beta \Delta T L^3}{\nu \alpha} = \frac{9.81 \times 30 x (0.2)^3}{343 \times 1.88 \times 10^{-5} \times 2.69 \times 10^{-5}} = 4.58 \times 10^7 \)

\[
N_u = 1 + 1.44 \left[1 - \frac{1708 (\sin 1.8 \beta)^{1/6}}{R_a \cos \beta} \right] + \left[ \frac{R_a \cos \beta}{5830} \right]^{1/3} - 1
\]

\[
N_u = 1 + 1.44 \left[1 - \frac{1708 (\sin 1.8 \times 30)^{1/6}}{4.58 \times 10^7 \cos 30} \right] + \left[ \frac{3.05 \times 10^4 \cos 30}{5830} \right]^{1/3} - 1
\]

\[
= 3.095
\]

\[
h_c = N_u \frac{k}{l} = \frac{3.095 \times 0.029}{0.1} = 0.8975
\]

\[
U_t = \left(\frac{1}{h_{c,p-c} + h_{r,p-c}} + \frac{1}{h_{c} + h_{r,c-a}}\right)^{-1} = \left(\frac{1}{0.8975 + 7.47} + \frac{1}{8 + 6.261}\right)^{-1} = 5.273 \text{ W/m}^2\text{c}
\]

\[
T_c = T_p - \frac{U_t \left(T_p - T_a\right)}{h_{c,p-c} + h_{r,p-c}} = 51.71
\]

\[
U_h = \frac{0.029}{0.05} = 0.56 \text{ W/m}^2\text{c}
\]

\[
U_e = \frac{\left(\frac{0.029}{0.025}\right) \times (2) \times (0.1)}{1} = 0.232 \text{ W/m}^2\text{c}
\]

The collector overall loss coefficient \( U_l = 4.234 + 0.56 + 0.232 = 5.026 \text{ W/m}^2\text{c} \)
For a thermal fluid [Petrona's Danol XHT (density at 15 °C = 0.874 Kg/l, kinematics viscosity at 100 °C = 5.6 cst, C_p=2.006 kj/kgc, m = 0.9 kg/s)]

Dimensionless capacitance rate \( \frac{mc_p}{A U_f} \) = \( \frac{0.9 \times 2.006}{1 \times 7.661 \times 0.344} \) = 0.685

The collector flow factor = \( F'' = 0.685(1 - e^{-1/0.685}) \) = 0.526

The collector heat removal factor \( F_R \) = 0.344 x 0.526 = 0.181

The useful gain \( Q_u = 1 \times 0.181 (620 \times 0.52 - 5.026(39-35)) = 58.59 \)

The outlet temperature = \( T_i + \frac{Q_u}{mC_p} = 39 + \frac{58.59}{0.9 \times 2.006} = 69.9 \) °C

The mean plate temperature \( T_{pm} = 39 + \frac{69.9}{5.026 \times 0.181} (1 - 0.181) = 71.43^\circ C \)

And the mean fluid temperature \( T_{fm} = 39 + \frac{69.9}{5.026 \times 0.181} (1 - 0.684) = 52.8^\circ C \)

By using a program for flat plate collector to calculate heat loss coefficient the table are created [13]. Fig. 3.2
Fig (3.2) flat plate collector overall heat loss coefficient program [13]

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_c$, $^\circ$C</td>
<td>50</td>
<td>53.71</td>
<td>53.91</td>
<td>53.86</td>
</tr>
<tr>
<td>$h_{r,p-c}$</td>
<td>7.69</td>
<td>7.497</td>
<td>7.503</td>
<td>7.49</td>
</tr>
<tr>
<td>$h_{r,c-a}$</td>
<td>6.569</td>
<td>6.306</td>
<td>6.376</td>
<td>6.378</td>
</tr>
<tr>
<td>$R_a$</td>
<td>$3.05 \times 10^4$</td>
<td>$4.05 \times 10^4$</td>
<td>$4.02 \times 10^4$</td>
<td>$4.03 \times 10^4$</td>
</tr>
<tr>
<td>$N_a$</td>
<td>2.771</td>
<td>2.975</td>
<td>2.969</td>
<td>2.971</td>
</tr>
<tr>
<td>$h_{c,p-c}$</td>
<td>2.678</td>
<td>2.876</td>
<td>2.870</td>
<td>2.872</td>
</tr>
<tr>
<td>$U_f$</td>
<td>6.057</td>
<td>6.013</td>
<td>6.026</td>
<td>6.022</td>
</tr>
<tr>
<td>$T_c$</td>
<td>53.71</td>
<td>53.91</td>
<td>53.86</td>
<td>53.85</td>
</tr>
</tbody>
</table>

Table (3.5) calculation of temperature of the cover
CHAPTER FOUR
ECONOMIC ANALYSIS

4.1 GENERAL
This chapter shows the cost analysis of the solar flat plate collector compared to the cost of the electrical heater to heat a thermal fluid. Comparison between the high initial capital costs which will be associated with the solar thermal flat plate collector and the annual electricity consumption costs will also be shown.

4.2 COST ANALYSIS
The total cost of the plate collector is assumed to be composed of fixed costs and operating costs. The minimum annual rate of return (MARR) is assumed to be 5% and the salvage value (SV) of plate collector is estimated to be 10% of the first cost (P) and each plate collector is assumed to provide the same service during its life time.
The annual equivalent cost (AE) is used as a basis for comparison of the financial desirability of the plate collector. [10]

\[
TEA = CRWR + O & M
\]

(4.1)

Where:
TEA = Total Equivalent Annual Cost.
O & M = Annual operating and maintenance cost
CRWR = Capital Recovery with Return.

CRWR is determined by the following relation:

\[
CRWR = P \left( \frac{A}{F_{i,n}} \right) - sv \left( \frac{A}{F_{i,n}} \right)
\]

(4.2)

But

\[
\left( \frac{A}{F_{i,n}} \right) = \left( \frac{A}{P_{i,n}} \right) - i
\]

(4.3)

From equations (4.2) & (4.3) it follows that

\[
CRWR = (P - sv) \left( \frac{A}{P_{i,n}} \right) + sv(i)
\]

(4.4)

Where:
\( n \) = useful life of equipment  
\( i = \) interest rate = MARR = 5%  
\[
\left( \frac{A}{P_{i,n}} \right) = \text{functional symbol or designation for equal payment series capital recovery factor (to find } A \text{ given } P).
\]

\[
\left( \frac{A}{F_{i,n}} \right) = \text{functional symbol for equal payment series sinking fund factor (to find } A \text{ given } F).
\]

\[
\left( \frac{A}{P_{i,n}} \right) = \frac{i(1+i)^n}{(1+i)^n-1}
\]  
(4.5)

Therefore:

\[
CRWR = (P - Sv) \left[ \frac{i(1+i)^n}{(1+i)^n-1} \right] + sv(i)
\]

(4.6)

\[
TEA = (P - Sv) \left[ \frac{i(1+i)^n}{(1+i)^n-1} \right] + sv(i) + O \& M
\]

(4.7)

4.2.1 The Proposed Solar Thermal Plate collector

\( P = 400 \text{ SDG} \)

This is for 1 m\(^2\) plate collector

\( Sv = 0.1 \times 400 = 40 \text{ SDG} \)

\( O&\)M = 5\% of the total capital cost

\( = 20 \text{ SDG} \)

\[
TEA = (400 - 40) \left[ \frac{0.15(1.5)^n}{(1.5)^n-1} \right] + 40 \times 0.5 + 20
\]

\[
TEA = 40 + 360 \left[ \frac{0.15(1.5)^n}{(1.5)^n-1} \right]
\]

\( TEA_i = 94.04 \text{SDG} \)
4.2.2 The Electrical Heater

From local market the following heater from different type of the heaters are select.

Ariston GL2.5 Electric Heater with specification
(Voltage 120V, Amperage 12.5 amps, Temperature Range 40- 100°C, Connections ½" NPT, Heating Capacity 2.2 KW).

P=460 SDG
SV=46 SDG
Price = 27 SDG/kWh
Operating hours per day = 8
Operating cost, O=27x10x365x2.2= 216810 SDG/yr

Maintenance cost (M), is estimated as 1/3 of the capital cost over the useful life of the equipment. [8]

\[ M = \frac{P}{3n} = \frac{216810}{3 \times 10} = 7227 \text{ SDG/yr} \]

O&M= 361.35 SDG/yr
Figure 4.2 Cash flow diagram of the electrical heater

\[
TEA_2 = (460 - 46) \left( \frac{0.5(1.5)^n}{(1.5)^n - 1} \right) + 46 \times 0.5 + 361.35 \\
= 417.56 + 324 \left( \frac{0.15(1.5)^n}{(1.5)^n - 1} \right)
\]

\[TEA_2 = 595.42 SDG\]

Since TEA (solar thermal flat plate collector) for 25 years < TEA (electrical heater) for 10 years, then the solar thermal flat plate collector is preferable for heating fluid for air conditioning system
CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSIONS

From the previous discussion the following points emerge:

- This study investigates the performance of the flat plate collector, when used thermal oil as heat transfer media.
- In this study the system was tested for three days, the test result show that the outlet temperature of the thermal oil is high at 13:00 o'clock.
- The values of the efficiency of the flat plat collector obtained from the tests is low this may be due to not well insulation.
- The economic analysis was used to compare between the yearly cost of the solar thermal liquid heaters and heating using available electricity, It was determined that the solar thermal liquid heaters would be competitive to the electrical power, the solar thermal liquid heaters will have significantly lower yearly cost.

5.2 RECOMMENDATIONS

- Accurate measuring device are to be used for measuring solar radiation.
- Testing another oil with good specification and low cost than thermal fluid.
REFERENCES


(7) Principles of solar thermal conversion
www.jgsee.kmutt.ac.th/exell/2005

(8) Refrigeration & air conditioning.
http/www.imartinez.etsin.upm.es/bk3/default


(10) GN.Tiwari. (2002).Solar energy fundamentals, design, modeling and application.


(13) Flat plate collector over all heat loss coefficient program created by (Mohamed Elfatih), (U of K), faculty of engineering
# TABLE 1

Dimensions of seamless copper tubing

<table>
<thead>
<tr>
<th>Standard diameter</th>
<th>Outside diameter (in)</th>
<th>Internal diameter (in)</th>
<th>Flow area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4</td>
<td>0.375</td>
<td>0.02625</td>
<td>0.0005412</td>
</tr>
<tr>
<td>3/8</td>
<td>0.5</td>
<td>0.03563</td>
<td>0.9366</td>
</tr>
<tr>
<td>1/2</td>
<td>0.625</td>
<td>0.04542</td>
<td>0.00162</td>
</tr>
<tr>
<td>5/8</td>
<td>0.75</td>
<td>0.0555</td>
<td>0.002419</td>
</tr>
<tr>
<td>3/4</td>
<td>0.875</td>
<td>0.06542</td>
<td>0.003361</td>
</tr>
<tr>
<td>1</td>
<td>1.125</td>
<td>0.08542</td>
<td>0.00573</td>
</tr>
<tr>
<td>1.25</td>
<td>1.375(0.0349m)</td>
<td>0.1054(0.0328m)</td>
<td>0.008728</td>
</tr>
<tr>
<td>1.5</td>
<td>1.625</td>
<td>0.1254</td>
<td>0.01235</td>
</tr>
<tr>
<td>2</td>
<td>2.125</td>
<td>0.1654</td>
<td>0.02149</td>
</tr>
<tr>
<td>2.5</td>
<td>2.625</td>
<td>0.2054</td>
<td>0.03314</td>
</tr>
<tr>
<td>3</td>
<td>3.125</td>
<td>0.2454</td>
<td>0.0473</td>
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<tr>
<td>3.5</td>
<td>3.625</td>
<td>0.2854</td>
<td>0.6398</td>
</tr>
<tr>
<td>4</td>
<td>4.125</td>
<td>0.3254</td>
<td>0.08317</td>
</tr>
<tr>
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<td>5.125</td>
<td>0.4063</td>
<td>0.1296</td>
</tr>
<tr>
<td>6</td>
<td>6.125</td>
<td>0.4871</td>
<td>0.1886</td>
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<tr>
<td>8</td>
<td>8.125</td>
<td>0.6438</td>
<td>0.3255</td>
</tr>
</tbody>
</table>
### TABLE 2
Properties of saturated liquids
Methyl chloride, CH3CL

<table>
<thead>
<tr>
<th>$t$ (°C)</th>
<th>$\rho$ (Kg/m³)</th>
<th>$c_p$ (kJ/kg-°C)</th>
<th>$\nu \times 10^4$ (m²/s)</th>
<th>$K$ (W/m°C)</th>
<th>$\alpha \times 10^7$ (m²/s)</th>
<th>$\beta \times 10^3$ (1/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50</td>
<td>1052.58</td>
<td>1.4759</td>
<td>0.32</td>
<td>0.215</td>
<td>1.388</td>
<td>2.31</td>
</tr>
<tr>
<td>-40</td>
<td>1033.35</td>
<td>1.4826</td>
<td>0.318</td>
<td>0.209</td>
<td>1.368</td>
<td>2.32</td>
</tr>
<tr>
<td>-30</td>
<td>1016.53</td>
<td>1.4922</td>
<td>0.314</td>
<td>0.202</td>
<td>1.337</td>
<td>2.35</td>
</tr>
<tr>
<td>-20</td>
<td>999.39</td>
<td>1.5043</td>
<td>0.309</td>
<td>0.196</td>
<td>1.301</td>
<td>2.38</td>
</tr>
<tr>
<td>-10</td>
<td>981.45</td>
<td>1.5194</td>
<td>0.306</td>
<td>0.187</td>
<td>1.257</td>
<td>2.43</td>
</tr>
<tr>
<td>0</td>
<td>962.39</td>
<td>1.5379</td>
<td>0.302</td>
<td>0.178</td>
<td>1.213</td>
<td>2.49</td>
</tr>
<tr>
<td>10</td>
<td>942.36</td>
<td>1.56</td>
<td>0.297</td>
<td>0.171</td>
<td>1.166</td>
<td>2.55</td>
</tr>
<tr>
<td>20</td>
<td>923.31</td>
<td>1.586</td>
<td>0.293</td>
<td>0.163</td>
<td>1.112</td>
<td>2.63</td>
</tr>
<tr>
<td>30</td>
<td>903.12</td>
<td>1.616</td>
<td>0.288</td>
<td>0.154</td>
<td>1.058</td>
<td>2.72</td>
</tr>
<tr>
<td>40</td>
<td>883.1</td>
<td>1.6504</td>
<td>0.281</td>
<td>0.144</td>
<td>0.996</td>
<td>2.83</td>
</tr>
<tr>
<td>50</td>
<td>861.15</td>
<td>1.689</td>
<td>0.274</td>
<td>0.133</td>
<td>0.921</td>
<td>2.97</td>
</tr>
</tbody>
</table>
Table A 2.1 Monthly means total radiations in MJ / m² / day and wind speed for Shambat observatory

<table>
<thead>
<tr>
<th>Month</th>
<th>$I_{\text{total}}$ (MJ/m²)</th>
<th>Wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(knot)</td>
</tr>
<tr>
<td>January</td>
<td>18.45</td>
<td>06</td>
</tr>
<tr>
<td>February</td>
<td>21.58</td>
<td>06</td>
</tr>
<tr>
<td>March</td>
<td>22.74</td>
<td>07</td>
</tr>
<tr>
<td>April</td>
<td>24.01</td>
<td>08</td>
</tr>
<tr>
<td>May</td>
<td>22.35</td>
<td>06</td>
</tr>
<tr>
<td>June</td>
<td>20.78</td>
<td>05</td>
</tr>
<tr>
<td>July</td>
<td>20.42</td>
<td>07</td>
</tr>
<tr>
<td>August</td>
<td>20.72</td>
<td>07</td>
</tr>
<tr>
<td>September</td>
<td>20.52</td>
<td>06</td>
</tr>
<tr>
<td>October</td>
<td>19.59</td>
<td>05</td>
</tr>
<tr>
<td>November</td>
<td>19.63</td>
<td>06</td>
</tr>
<tr>
<td>December</td>
<td>18.71</td>
<td>06</td>
</tr>
</tbody>
</table>

Source: Meteorological Department, Khartoum - 1981

For Shambat: Latitude=15°04’ N, Longitude = 32°03’ E, Altitude = 380 m

For Khartoum: Latitude =15°03’ N, Longitude=32°30’ E, Altitude = 380m

Table A 2.2 Monthly dry (mean) bulb temperature, °C

<table>
<thead>
<tr>
<th>Element Month</th>
<th>0600 GMT</th>
<th>0900 GMT</th>
<th>1200 GMT</th>
<th>1500 GMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>19.8</td>
<td>26.6</td>
<td>30.0</td>
<td>31.4</td>
</tr>
<tr>
<td>February</td>
<td>20.2</td>
<td>27.8</td>
<td>31.5</td>
<td>32.0</td>
</tr>
<tr>
<td>March</td>
<td>23.2</td>
<td>30.1</td>
<td>34.2</td>
<td>34.4</td>
</tr>
<tr>
<td>April</td>
<td>29.0</td>
<td>37.1</td>
<td>39.6</td>
<td>38.8</td>
</tr>
<tr>
<td>May</td>
<td>31.3</td>
<td>37.6</td>
<td>40.5</td>
<td>40.0</td>
</tr>
<tr>
<td>June</td>
<td>31.5</td>
<td>36.1</td>
<td>39.2</td>
<td>39.1</td>
</tr>
<tr>
<td>July</td>
<td>28.5</td>
<td>32.8</td>
<td>35.9</td>
<td>35.7</td>
</tr>
<tr>
<td>August</td>
<td>27.6</td>
<td>32.0</td>
<td>34.5</td>
<td>34.0</td>
</tr>
<tr>
<td>September</td>
<td>29.8</td>
<td>34.4</td>
<td>37.5</td>
<td>36.8</td>
</tr>
<tr>
<td>October</td>
<td>30.9</td>
<td>36.1</td>
<td>39.1</td>
<td>37.8</td>
</tr>
<tr>
<td>November</td>
<td>25.9</td>
<td>33.0</td>
<td>35.8</td>
<td>34.3</td>
</tr>
<tr>
<td>December</td>
<td>20.7</td>
<td>28.0</td>
<td>32.1</td>
<td>30.9</td>
</tr>
</tbody>
</table>

Source: Meteorological Authority, Khartoum – 2003