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Solar Heating of Sudanese Fuel Oil

(Case Study of Bittar Soap & Oil Factory)

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Dedication

This research is dedicated to:

***My Mother** who takes care for me forever*

***My Father** who makes every effort to make me happy*

***My Colleagues** in the studying & labor*

To all friends

And to all home I lov

خلاصة البحث

بعد استخراج البترول السوداني في عدة حقول (أبوجابرة- هجليج- عدارييل)، صدر قرار وزاري باستخدام الفيرنس (زيت الوقود) السوداني بديلاً عن المستورد. يتصف زيت الوقود السوداني بأنه يحتوي علي نسبة عالية من شمع البرافين تتراوح مابين (8%- 22%)، والذي يتسبب في جعل الفيرنس يتجمد في درجة حرارة الغرفة العادية، مما يجعل ضخه عبر الأنابيب مستحيلاً.

هدا البحث يتناول حل المشكلة بتسخين الفيرنس حتي يصبح قابلاً للاستخدام. يستخدم التسخين الحالي في مصنع بيطار البخار المنتج في المصنع.

البحث يعمل علي استخدام الطاقة الشمسية لتسخين الفيرنس حتي يصبح قابلاً للضخ.

يقوم البحث اولا: علي دراسة مواصفات الفيرنس السوداني (الفيزيائية والكيمائية) ومقارنتها بالمواصفات العالمية ومواصفات الفيرنس المستورد، ومعرفة نقاط الانسكاب.

ثانيا: البحث يستقصي المشكلات الناتجة عن استخدام الفيرنس السوداني في مراحل النقل – التفريغ- المناولة.

ثالثاً: تقوم الدراسة بحساب الطاقة الحرارية المطلوبة لتسخين الفيرنس السوداني وحساب الفواقد والعمل على تقليلها بإستخدام العازل.

رابعاً: يقوم البحث بتصميم المجمع الشمسي المطلوب وحساب أبعاده ومساحته للحصول علي الطاقة الحرارية المطلوبة.

خامساً: يقوم البحث بعمل تحليل اقتصادي ودراسة جدوى للخيار المستخدم حالياً والخيارات البديلة والتفضيل بينها.

Abstract

It is known nowadays that the Sudan had stopped importing of crude after producing it in several fields (Abu Gabra, Adar Yale, Higlig……. ect.).Usage of the Sudanese fuel oil resulted in several problems in operation because of its high percentage of paraffin wax which reaches (8%- 22%) the Sudanese fuel oil freezes at temperature between (0 °C to 47 °C), which make it unpumpable.

The proposed solution for this problem is by heating the fuel oil to be pumpable. Present heating is carried out by using steam from the boiler. This research is a trial to use an alternative heating system by utilization of solar energy.

Firstly, about fuel oil chemical and physical properties were studied and compare them with the international properties of the imported fuel oil.

Secondly, the problems of using the Sudanese fuel oil in several stages; transportation, unloading, and handling were studied.

Thirdly, the required heat energy to heat the Sudanese fuel oil so as to be pumpable was calculated.

Fourth, the required solar collector was designed.

Fifth, economical analysis for the chosen heating system and the other alternatives were conducted

SYMBOLS

A_p**:** Area of the absorber plate.

A_c**:** The collector area m^2.

Cp : Specific heat of fuel oil (kJ/kg. K)

E: The equation of time (minutes).

h_A **:** Heat transfer coefficient of air ($W/m^2.K$).

h_F**:** Heat transfer coefficient of fuel oil (W/m^2. K).

h_w :Wind heat transfer coefficient (W/m^2K) = 2.8 + 3V.

H: The rate of incident beam or diffuse radiation on unit area of surface of any orientation.

HR: The solar energy received on the upper surface of the slopping collector structure W/m^2 or kcal/hr m^2.

I_b**:** Hourly beam radiation.

I_g**:** Hourly global radiation.

I_d**:** Hourly diffuse radiation.

I_{bn}**:** Beam radiation in the direction of the rays.

I_{sc}**T**he solar constant (= 1353 W/m^2).

I_{So}**:** The extraterrestrial radiation measured on the plane normal to the radiation on the nth day of the year.

I_d**:** Hourly difference radiation.

k **:**Thermal conductivity of tank wall material (w/m^2 .k).

k_1**:** Thermal conductivity of the tank material (50.5 W/m.K)

k_2**:** Thermal conductivity of the insulation.

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

K_i: Thermal conductivity of the insulation (W/mK) = 0.045

L: The total thickness of cover material.

L_b: Thickness of the back insulation.

L_1, L_2: The dimensions of the absorber plate.

L_3: Height of the collector casing.

L_s: Thickness of side insulation.

L_{Loc}: The longitude of the location.

L_{st}: The standard meridian for the local time zone (standard time longitude).

LST: The Local Solar Time used for calculating, ω.

m: Mass flow rate of fuel oil (kg/s).

n: Number of day in the year.

O & M: Operating and maintenance cost.

P: Present value.

***q**:* Rate of heat transfer per unit area (kW/m^2).

q_b: Rate at which heat is lost from the bottom

q_t: Rate at which heat is lost from the top.

q_s: Rate at which heat is lost from the sides.

Q_L: Rate of energy losses from the collector to the surroundings by re-radiation, convection and by conduction through supports for the absorber plate.

Q_S : Rate of energy storage in the collector.

Q_u: The useful energy delivered by collector, (watts or kcal/hr).

Q: The heat energy should be input to the fuel oil tank.

r' : Indicates that only reflection loss has been considered for transmission of radiation.

R: The factor to convert beam or diffuse radiation to that on the plane of collector.

R_b: The ratio of the beam radiation flux on a tilted surface.

R_d: The ratio of the diffuse radiation flux on a tilted surface.

R_t: The overall heat flow resistance (it is equal to 1/x of the overall heat transfer)

R_t : The ratio of the reflected radiation for tilted surface.

S: Incident solar flux absorbed in the absorber plate.

S.V: The salvage value

t_A **:**Temperature of fluid (air).

t_F: Temperature of fuel oil.

T_1: Fuel oil temperature (70°C).

T_2 : Ambient temperature degree (13°C) [the minimum temperature that the ambient temperature can be reached].

T_P, t_p: The average temperature of the upper surface of the absorber plate C°.

T_a, t_a: Atmospheric temperature °C or the ambient temperature.

TEA: Total Equivalent Annual Cost.

u **:** Overall coefficient of heat transfer factor ($W/m^2.K$).

U_L: The overall heat loss coefficient, (W/m^2 °C (kcal / hr m^2 °C)).

$(UA)_{edges}$: The edges loss coefficient – area product.

V: Velocity of wind ($0 \leq V \leq 10$) (m/s)

X: Wall thickness of the tank (m).

x_1**:** Thickness of the tank wall (5 mm).

x_2 : Thickness of the insulation (100 mm).

GREEK LETTERS

α: The fraction of solar energy reaching the surface that is bsorbed, absorptivity (dimensionless).

β : The collector inclination (+ve for surfaces sloping towards the south and –ve for surfaces sloping towards the north).

β : Collector tilt angle (deg) (=15.5°).

ε_g: Emissivity of the covers (0.88 for glass).

ε_p : Emissivity of the absorber plate (0.95).

η_c: The collector performance and is defined as the ratio of the useful gain over any time period to the incident solar energy over the time period.

θ_z : Angle of incidence on a horizontal surface, i.e. the zenith angle.

ρ_g: The reflection coefficient of the ground (= 0.2 and 0.6 for ordinary and snow covered ground respectively).

$\rho_\perp$, $\rho_{||}$: Reflectivities of the perpendicular and parallel components of polarization of incoming radiation.

τ : The fraction of incoming solar radiation that reaches the absorbing surface, transmissivity (dimensionless).

$(\tau.\alpha)_b$: Transmissivity-absorptivity product for beam radiation falling on the collector.

$(\tau.\alpha)_d$: Transmissivity-absorptivity product for diffuse radiation falling on the collector.

$(\tau.\alpha)_e$: Effective transmittance absorptance product of cover system for beam and diffuse radiation.

σ : Stefan – Boltzmann Constant.

ϕ : is the latitude angle.

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Chapter (1)
Introduction

Crude oil is a compound blend of hydrocarbons. It is found in liquid or solid or gas condition according to the temperature or pressure of the blend.

Sudanese crude oil is classified as paraffin base, for the high percentage of the paraffin wax in it. The percentage of the wax ranges between (8% to 22%).

Properties of Sudanese crude oil differ with different fields, but in general the main properties of Sudanese crude oil are similar to the light crude and it is classified under paraffin waxy crude. Wax is a natural component of crude chemical components. It is a good burning material.

The wax concentration in the Sudanese fuel oil has the adverse effect of raising the pour point to 48°C which leads to difficulties of handling (loading, unloading, transportation ,storing, and pumping through the pipes).This effect leads to extra costs by heating or by adding chemical components in order to decrease the pour point.

The Sudanese fuel oil viscosity and contaminants are having an adverse effect on the performance of the pumping system. For solving of this problem, some users tend to mix fuel oil with gasoline or imported fuel oil. Mixing of fuel results in a highly variable, stratified product of unreliable firing performance.

The perfect solution for this problem is by heating the fuel oil to be pumpable. At present, heating is carried out by using steam from the boiler which means extra running cost.

This research is a trial to use an alternative heating system by utilization of solar heat. Flat plate collectors were designed to provide the required heat for heating fuel oil. An economical analysis was performed to verify the feasibility of solar heating.

Sudan is one of the tropical countries, of high solar radiation intensity and relatively high temperature and with sunshine duration of about 10 hours.

The Objectives of the Research:

The research aims at:

1) Utilization of solar energy to heat the Sudanese fuel oil to be pumpable in the handling operations.
2) Show that it is possible to use solar energy to solve the problems of using the Sudanese fuel oil.
3) Conduct an economical analysis to determian the feasibility of solar heating of fuel oil.

Chapter (2)
Chemical and Physical Properties of The Sudanese Fuel Oil

2.1. General View on the Sudanese Crude Oil Properties:-

The properties of the Sudanese crude oil vary with variation of the fields even in the same field, they vary from well to well .But in general the producted is considered as medium to light density crude. It is classified as paraffiny or waxy crude, to for the high percentage of the wax in the crude, between (8%-22%) by weight. The wax concentration increases in the heavy products even further up to 30%.

The wax concentration in the Sudanese fuel oil has the adverse affect of raising the pour point to 48°C which means many problems in transportation, handling and storing .This effect leads to additional costs by heating or by adding chemical components in order to decrease the pour point.

On the other hand, the Sudanese crude oil has low percentage of sulfur components, Vanadium and Sodium which means less maintenance problems and longer engine life. Therefore, it does not pollute the environment and does not harm motors parts. Also wax concentration in the Sudanese fuel oil improves the ignition quality of the fuel. The calorific value is relatively high.

The viscosity at 100°C is 12.1 c St and at 80°C is 19.8 c St. But the measured viscosity at 50°C is 52 c St. The reason is probably because at low temperatures and slightly above the pour point is 48ºC the affect of the wax becomes dominant in the fuel.

2.2. What is the Wax:-

Paraffins are normal (Straight - Chain) or branched alkenes with relatively high molecular weight .This class of hydrocarbons is essentially inert to chemical reactions and is, therefore ,resistant to attack by bases and acids. Paraffin deposits chiefly contain alkenes having a carbon chain length from 20 melting point of 89 deg. F to 60 (melting point at about 215 deg F).

Crude paraffin deposits are mixture of these alkenes and consist of very small crystals that usually agglomerate to form granular particles. The wax varies in consistency from a soft much to a hard, brittle material. Paraffin deposits will be harder if long chain alkenes are prevalent. The most critical property of this blend, which will have certain implications on the transportation of the crude , is the high wax content .The pour point or the degree below which the crude will not flow is 48 degree C .This temperature is frequently encountered in the regions through which the pipeline routes .The design of the pipeline has resolved this transportation obstacle by adopting a certain treatment to keep the oil pumpable between the six pump stations .The procedure involves heating of the crude blend to 105 deg F. followed by rapid cooling (quenching) to 65 deg F. As a result of this thermal treatment, the wax comes out of solution and remains as flowing suspension in the rest of oil. Chemical additives (300-500 ppm) are deemed necessary to depress the pour point.

Wax is not harmful material and is a very good input for lubricating oil and wax industry .Pure wax is also a valuable material that can be used in different industries such as cosmetics, textile yarns, pharmaceutical industries, telecommunication optic fiber Etc.

2.3. Physical Properties of Sudanese Fuel Oil:-

2.3.1. Density:

Density is absolute relation between mass and volume at constant temperature .In SI system its unit is kg/m^3 and it is always taken at 15°C as a reference temp. Density is an important factor for choosing the suitable pumping equipment and moreover it gives indications about the internal energy and the type of fuel combustion. Density of Sudanese fuel oil ranges from (876.6-903.1) kg/m^3 (See tables from 2.2. to 2.8. and from 2.11. to 2.13).

2.3.2. API Gravity:

For the Sudanese fuel oil API Gravity ranges from (25.-29.9).

2.3.3. Kinematic Viscosity:

Kinematic viscosity is a property that explains the internal resistance of fluid beds against shear.

Always viscosity expressed by kinematic viscosity which is usually measured by stockes unit. Kinematic viscosity is the ratio of absolute viscosity or dynamic viscosity to the density at the same temperature [1 St = 100 c.St] [1 c.St = 1 mm^2/sec].

Viscosity of the Sudanese fuel oil varies according to the resource of crude (see tables from 2.1 to 2.13)

2.3.4. Flash Point:

It is the minimum temperature at which the fuel oil could produce quantity of vapour that combine with air producing mixture and flashes upon application of flame to it .The fuel oil has a low flash point is more easy in combustion operation .For diesel the flash point is 70°C, it reaches to 115°C for heavy fuel oil. There is a proportional relationship between the flash point and density of the fuel oil, while the contrary with Calorific value. For the Sudanese fuel oil flash point range from 47°C to 96°C (see tables 2.2 to 2.13).

2.3.5. Pour Point:

It is the minimum temperature at which the fuel oil could be pumped .It mainly depends on the quantity of wax in the crude oil or fuel oil. The pour point for the Sudanese fuel oil ranges from (35-48) °C. (See tables from 2.1 to 2.13).

2.3.6 Stability:

Stability of fuel oil can be defined as the ability of fuel oil to stay at stable condition when it is subjected to the factors that cause transformation.

2.3.7. Calorific Value:

The calorific value for the Sudanese fuel oil ranges from 43.5 to 48.516 MJ/kg (see tables 2.1 to 2.6).

2.4. Comparison of Tested Samples:

There is a clear difference in the properties of the tested samples in the Laboratories.

Adar Yale sample has flash point which is higher than those of all other samples, while El Obied trucks sample has a low flash point. Pour point of truck sample is the highest in comparison with other samples. There is a big difference in viscosity between truck sample and other samples.

2.5. Comparison between Local and Imported Samples:

There below are some local samples been compared with imported sample. Comparison is in flash point, pour point and viscosity. These samples were taken from Adar Yale field, Al Obied refinery (two samples) and AlObied refinery (from the truck).

2.5.1. Adar Yale Sample:

This sample is differs slightly from imported fuel oil in its properties. Flash point and viscosity are almost the same while its pour point is higher than that of imported fuel oil (see table 2.13)

2.5.2. Al Obied Sample [Land Turks]:

This sample differs from the imported sample since its flash point is much lower than that of imported fuel oil while its viscosity and pour point are higher than those of imported fuel oil.

2.5.3. Al Obied Samples (1&2):

From Al Obied refinery two samples were taken. The flash points of both samples are lower than that of imported fuel oil , while pour point are higher than that of imported fuel oil and also the viscosities of both samples are higher than that of imported fuel oil (see table 2.13).

2.6. Comparison between Tested Samples and the International Specifications:

There below general comparison between samples those had been tested in several laboratories (Dr.Mahmood Shareef Power Station, Thermodynamic Laboratory of Faculty Engineering, Central Petroleum Laboratories {LPC}).

2.6.1. Viscosity:

Viscosity of all samples is higher than international specifications; in addition to that, all samples were at solid phase at the room temperature (see table 2.13).

2.6.2. Flash point:

Adar Yale has a typical flash point of international specifications. Both samples of Al Obied (1, 2) have flash points lower than that of international specification. Al Obied truck samples have flash points very lower than international specifications.

2.7. Chemical Components of the fuel oil:

2.7.1. Sulfur:

Sulphur is a natural Component in the crude oil and it is mainly concentrated in the heavy crude. Increasing of Sulfur affects the specific energy and it affects in increasing the corrosion in diesel engines.Sulfur and Mercaptan compound in the Sudanese crude are relative moderate.

1.7.2. Vanadium and Sodium:

Vanadium is a mineral that is found in the Sudanese crude oil in liquid phase, its quantity in heavy fuel oil mainly depends on the resource of the crude .The actual amount of vanadium in the crude depends on the refining operation that is used in producing of heavy fuel oil. Most of heavy fuel oil contain amount of Vanadium less than 150 mg/kg, while some types of fuel oil contains amount of Vanadium more than 400 mg/kg. There is not an economic operation for separation of Vanadium from crude oil or heavy fuel oil.

Small quantity of Sodium is available in fuel oil content, that less than 50mg/kg, availability of seawater increases this quantity nearly to 100 mg/kg for every 1% seawater.

High amount of vanadium and Sodium in fuel oil at high temperature leads to corrosion and harming in valves.

The Sudanese crude is free from environmentally hazardous hydrogen sulfide gas .Heavy metals are comparable with most international oils .The oil water content and sediments appear to be in live with international crude oils .Light ends (gaseous) amount to be less than 0.27% by weight which minimizes gases release to the atmosphere during different activities.

Tables 2.1 to 2.16 show physical and chemical analysis of different samples taken from several units.

Table 2.1: Indigenous Crude Analysis

Test	**Heglig4**	**Unit 2**	**Unit 9**	**Talih**	**Nile Blend**
SP. Gravity (60/6F)	0.8850	0.8722	0.8570	0.8324	0.8544
Sulfur Content (%wt)	0.085	0.065	0.070	<0.07	0.04
Mercaptan Sulfur (%w)	-	-	-	-	0.0013
Total Nitrogen (wt %)	0.136	0.155	0.134	0.0265	0.074
RVP (Psi)	-	-	-	-	<0.1
Kinematics Viscosity @50ºC	48.92	33.34	19.73	5.589	20.95
Pour point (ºC)	18	24	27	30	36
Conradson Carbon Residue (wt %)	4.4	5.3	4.8	0.9	3.7
Metal by ICP (ppm wt)	-	-	-	-	-
Nickel	4.7	11	9.0	0.5	5
Vanadium	0.1	0.3	0.2	<0.07	<1.0
Salt (Ib/m bbl)	2000	2000	2200	2000	5282
Sediment & Water (vol %)	0	0	0	0	3.81
Total Acid (mg KoH/g)	-	-	-	-	<0.01
Wax @-30Cº (wt %)	-	-	-	-	10.9
Ash (wt %)	-	-	-	-	0.02
Sediments (vol %)	-	-	-	-	0.01
Organic Chloride (ppm wt)	-	-	-	-	10.7
Calorific Value (MJ/kg)	-	-	-	-	45.78

Table 2.2: Properties of Standard & Abu Gabra Fuel Oil:-

Property	P.S. Refinery Standard 1982	Abu Gabra fuel oil (1996)
Density @ 15 °C kg/L	Max 0.990	0.873
Viscosity	Max 180 C.St.	52 C.St.
Water %V	Max 0.75	0.1
Carbon Residue %m		3.3
Sulphur %m	Max 3	LT 0.20
Sediment %m	Max 0.15	0. 01
Ash %m	-	0.01
Vanadium mg/kg	-	LT 0.1
Sodium mg/kg	-	13
Aluminum mg/kg	-	2
Pour Point ºC	Max 21	48
Flash Point ºC	Min 62	68
Calorific value) Clac MJ/kg	Min 41.9 (grpss)	42.63 (net)
CCAL (cak)	-	75a

First, the analysis of fuel oil that taken from Dr. Sharif Thermal Power Station.

Table 2.3: Analysis of Adar Yale fuel oil* Sample** [1]:***

Test name	Result
Density @ 15 °C.	0.8782 kg/L
Viscosity Kin @40ºC (R.W.N).	350 sec
Viscosity Kin @100ºC (R.W.N).	73 sec
Flash Point.	48.8 °C
Pour Point.	39 °C
Calorific Value.	48.516 MJ/kg

Table 2.4: Analysis of Abu Gabra fuel oil Sample* [1]*:

Test name	Result
Density @ 15 °C.	0.878 kg/L
Viscosity Kin @40ºC (R.W.N).	406.43 sec
Viscosity Kin @100ºC (R.W.N).	55 sec
Flash Point.	47°C
Pour Point.	41°C
Calorific Value.	44.94 MJ/kg

Table 2.5: Analysis of AlObied fuel oil Sample [1]***:***

Test name	Result
Density @ 15 °C.	0.878 kg/L
Viscosity Kin @40ºC (R.W.N).	69.933 sec
Viscosity Kin @100ºC (R.W.N).	62 sec
Flash Point.	63°C
Pour Point.	37°C
Calorific Value.	43.5 MJ/kg

Table 2.6: Analysis of Imported fuel oil (Port Sudan) [1]***:***

Test name	Result
Density @ 15 °C.	0.935 kg/L
Viscosity Kin @40ºC (R.W.N).	1809.286 sec
Viscosity Kin @100ºC (R.W.N).	99 sec
Flash Point.	96°C
Pour Point.	25°C
Calorific Value.	42.8632 MJ/kg

Four samples were got from Dr. Sharif Thermal Power Station and were tested in the thermodynamic laboratory in the faculty of Engineering and got the following results.

Table 2.7: Analysis of Adar Yale fuel oil Sample [2]***:***

Test name	Result
Density @ 15 C°.	0.878 Kg/L
Viscosity Kin @60Cº (R.W.N).	197 sec
Viscosity Kin @80Cº (R.W.N).	123 sec
Viscosity Kin @100C°.	76C°
Flash Point.	96C°
Pour Point.	44C°

Table 2.8: Analysis of Al Obied fuel oil Sample (Land trucks) [2]***:***

Test name	Result
Viscosity Kin @60°C.	270 sec
Viscosity Kin @80°C.	176 sec
Viscosity Kin @100°C.	98 sec
Flash Point.	82°C
Pour Point.	48°C

Table 2.9: Analysis of Al Obied fuel oil Sample [2]***:***

Test name	Result
Viscosity Kin @60°C.	239 sec
Viscosity Kin @80°C.	139 sec
Viscosity Kin @100°C.	82 sec
Flash Point.	92°C
Pour Point.	40°C

Table 2.10: Analysis of Al Obied fuel oil Sample [2]***:***

Test name	Result
Viscosity Kin @40°C (R.W.N).	900 sec
Viscosity Kin @100°C.	74 sec
Flash Point.	73.9°C
Pour Point.	40°C

Certificate of quality of Central Petroleum Laboratories [CPL]

Table 2.11: Analysis of AlObied fuel oil Sample [3]***:***

Properties	Test Method	Unit	Result
Density @ 15 °C.	ASTMD 1298	kg/L	887.2
Viscosity Kin @60°C.	ASTMD 445	C.St	107.2
Viscosity Kin @100°C.	ASTMD 445	C.St	17
Viscosity Kin @120°C.	ASTMD 445	C.St	12
Power Point.	ASTMD 97	°C	47
Flash Point pmcc.	ASTMD 93	°C	180
Flash Point (COC).	ASTMD 92	°C	206
Water.	ASTMD 95	%V	<0.05
Sediment.	ASTMD 473	%m	0.01

Table 2.12: Certificate of quality of AlObied refinery fuel oil [3]***:***

Properties	Method(ASTM)	Result	Result
Density @ 15°C.	D1298	870.8	kg/m^3
Viscosity Kin @100°C.	D445	18.4	C.St
Viscosity Kin @40°C.	D445	245.0	C.St
Pour Point.	D97	42.0	°C
Flash Point (P.m).	D93	150	°C
Water Content.	D95	Nil	%vol
Sediment.	D473	0.1	%wt

Table 2.13: Fuel oil Comparison for different Samples

Test	Adar Yale	Imp. Fuel	Al Obied	Concorp	Result
Density @ 15°C.	0.879	0.958	0.901	0.920	kg/L
Sulphur Content.	0.067	3.29	0.21	1.94	%wt
Pour Point.	39	26	39	-	°C
Calorific Volume.	44.4	43.2	44.75	44.2	MJ/kg
Kin Viscosity.	65@50°C	66@50°C	237@50°C	35.5@50ºC	Main
Flash Point.	90	90	40	73.3	°C
Sediment.	0.1	0.1	0.001	0.3	%wt

At the following there are different analysis shows the chemical components in the Sudanese crude oil (sulfur content, water content, and sediment content and strong acid number).

Table 2.14: Analysis of fuel oil [Al Obied Refinery] [3]***:***

Test name	Method	Result	Unit
Sulphur content.	D1552	N.A	% wt.
Water Content.	D95	Nile	%vol
Sediment content.	D473	0.7	%wt
Strong Acid Number.	D974	-	Mg KOH/g

Table 2.15: Analysis of fuel oil (Abu Gabra Refinery) [3]

Test name	Method	Result	Unit
Sulphur Cont.	ASTM 1552	0.17	% wt
Water Content.	ASTM D95	Nil	%vol
Sediment Cont.	ASTM D473	0.003	%wt
Strong Acid Number.	ASTM D974	Nile	mg KOH/g

Table 2.16: Analysis of Top Sample of Abu Gabra
(Port Sudan Refinery) [3]

Test name	Result	Unit
Sulphur Cont	0.13	% wt
Bottom Water and Sediment	4.4	%v
Total Acid Number (tan)	-	mg KOH/g
Water Content D&S	1.75	%vol

Chapter (3)
Fuel Oil Handling System

3.1. Handling System Components of Fuel Oil:

Fuel oil applications system, in general, consists of the following components:-

1. Unloading area.
2. Forwarding area.
3. Operating area.

3.1.1. Unloading Area:

Fuel oil is transported from refineries to the factory by land trucks. Land trucks are weighted empty and full (before unloading and after unloading) to determine the quantity of fuel oil in the tuck and that after discharging water content from the truck which is accomplished by an unloading pump .The trucks are installed with internal heating coil.

3.1.1.1. Unloading Pumps:

Refering to figure 3.1, unloading area contains unloading pumps .The used pumps are designed in order to be easy in maintenance when they defected .Pumps are connected by an insulator and a chock return valve to facilitate pumping operation.

There are some criteria point should be taken into account at unloading operations:

a) The fuel oil should be free of water.
b) The flow rate should be maintained at the required level. This is done by:

i) Choosing appropriate motor and testing it at no load to determine the available power that the motor needs.

ii) Design filters with high specifications required. The unloading area contains two filters for protection of pumps from impurities and suspended matters.The impurities in the unloading pump may lead to defect in the pump which causes discontinuation of fuel oil flowing to the storage tank and that means more maintenance requirement for the pumps and decrease their life time.

3.1.1.2. Fuel Oil Storage Area:

The second stage of the system components is the storage area. The factory has several storage tanks which vary in their capacities from one to another. Storage tanks are usually made of cast iron .These storage tanks include heating coils that operate by electricity or steam. Heating coils are used for heating the fuel oil to facilitate its pumping by the pump where it is at a solid phase before heating it .In addition to the steam heaters, there may be an electric heater at the bottom of tanks; they are used when needed for completed discharging of the tank and that for maintenance or cleaning.

The storage tanks are equipped by pumps to pump the fuel oil from the storage tank and surging into the transportation pipeline .One pump could be used for all these storage tanks via a suitable piping system.The storage tanks are maintained and cleaned approximately every year.

3.1.1.3. The Transporting Lines:

References to figure (3.2) the pipelines are used in the fuel oil transportation from the storage tanks to the operating area. Fuel oil system includes pipeline that transport the fuel oil from the storage tank to small tank which called the feeding tank. The pipeline system includes a pump to pump the fuel oil from the tank and also includes a pipeline from the feeding tank passing an electric heater. There are two filters connected in parallel to purify the fuel oil from the impurities .Then the two parallel line are connected again, and then reachs the boiler or burner.

There should be heating of fuel oil in the pipeline by a superficial electric heaters overall the pipeline. The superficial heating of the pipeline should keep the fuel oil temperature from 60°C to 70ºC for continuing flowing of fuel oil and to prevent the fuel oil solidifying inside the pipe.

3.1.2. Forwarding Area:

As shown in figure (3.2) this is the stage that directly follows the storage area where the fuel oil is transported from the storage tank to the feeding tank .The advantage of this operation (transportation the fuel oil from the storage tank to the feeding tank) is to facilitate observeiuos of the actual quantity of fuel oil .The feeding tank is small tank having a capacity not more than 25 bbl, it is located near the boiler and provided by fuel oil from the storage tank. Forwarding Area Includes the following terms:

3.1.2.1. Pumps:

The pumps are designed to operate at known flow rate and known head.The viscosity of the fluid must not exceed 470 cp at temperature of 45°C. These pumps include an internal cover made of rubber.

3.1.2.2. Filters:

The filters operate to discard the small solid sediments that suspended in the fuel oil to get pure fuel oil.

3.1.2.3. Flow Meter:

Flow meter is a device that is used for measuring the fuel oil consumption rate. It is located on the pipe that is coming from the tank .It is a sensitive device which depends - in its accuracy - on the measured fluid viscosity.

3.1.2.4. Transportation Pipeline:

These are pipelines connected to the pumps to provide the operation area by the fuel oil .They contain an internal electrical heating line to maintain the temperature of fuel oil at (60 °C to 70 °C).

3.1.2.5. Interceptor:

The interceptor is a basin that is used to fluidize the fuel oil before the filtration from the water .The interceptor consists of:

i) Water and fuel oil collection basin.
ii) Pumps to pump the fuel oil to the storage tanks.
iii) Pumps to pump the water to the collection basin.
iv) Device of filtering the water from the fuel oil.

v) Heating lines inside the basin.
vi) Temperature measurement device.

All fuel oil falling from the trucks and that infiltrated from storage tanks is collected in the basin of separation of water from fuel oil. The used water of cleaning and maintenance is collected in the collection basin and then pumped to the interceptor.

3.1.3. Operating Area:

Operating area consists of three components as follows:

3.1.3.1. Heating and Pumping Area:

Heating and pumping area where fuel oil is pumped from the storage tank after heating up to the atomizing temperature .The heating and pumping area consists of:

a) Pumps.
b) Filters.
c) Heaters.
d) Heating Regulators.

3.1.3.2. Boilers and Burners:

Every boiler includes flaming burner in which fuel oil is mixed - at a suitable temperature - with air to produce flame .There are two types of burners, one of them is (The Nozzle) which includes a pump for provision of suitable pressure to the fuel oil .The fuel oil reaches the burners at pressure about 1.5 bar. The second type of the burners uses the rooter cup which includes vanes .These vanes are covered by covers .These vanes rotate to distribute the reached fuel oil from the pump .The vanes are connected to a column which rotate by strap and the strap is connected to the pump .This pump operates to rotate the column and also to operate another pump that provide the fuel oil by the suitable pressure.

The temperature of the coming fuel oil to this stage should be equal to the atomizing temperature.

3.1.5.3. Atomizing Operation:

a) Heating the fuel oil to atomizing temperature.
b) Provision of the required quantities of the heating air and guiding it by vanes.

The usefulness of atomizing operation is obtaining the required thermal energy to generate the steam and also to control the operating process.

There are two types of boilers:

a) Water – tube boiler. In this type the water flows into pipes while the thermal energy (fire) is inside steam generator.
b) Fire – tube boiler. This type of is apposite of the first type. The fire or the thermal energy is inside the pipes .The thermal energy pushed by air passing inside pipe respectively. The water inside the room should touch the pipes surfaces.

The boilers component should be strong enough to sustain high pressure and high temperature and they should have a high conductivity to avoid extreme heating or oxidation that destroys the manufactured material.

The water from the tank enters the generator after extracting the salts. The water is then pumped from the tank by pumps, then passes through internal pipes that forms internal wall of burning room. The temperature of the water raises and its fluid occurs between the generator cylinders and pipes where they roosted.

It should be ensured that the water provision to the generator must be continued at the operating condition, especially in the fire – tube boiler which the flame or thermal energy is inside the pipes and that to avoid explosion inside the generator which may happen as a result of the high temperature.

The fuel provision system in the boiler consists of the following:

a) The Main Tank:

The main tank is usually located far from the boiler, and it is connected to the daily tank.

b) The Daily Service Tank:

The daily service tank is usually located near to the boiler; it provides the boiler by the fuel oil directly.

c) The Pipes System:

The pipes system connects the main tank and the daily service tank and also connects the daily services tank and the boiler .It should have no infiltrate because the infiltrate leads to many problems in the draining systems and it increases the fuel oil consumption

d) Filters:

Their functions are to retard the strange and suspended materials from flowing inside the fuel pumps and other burning tools.

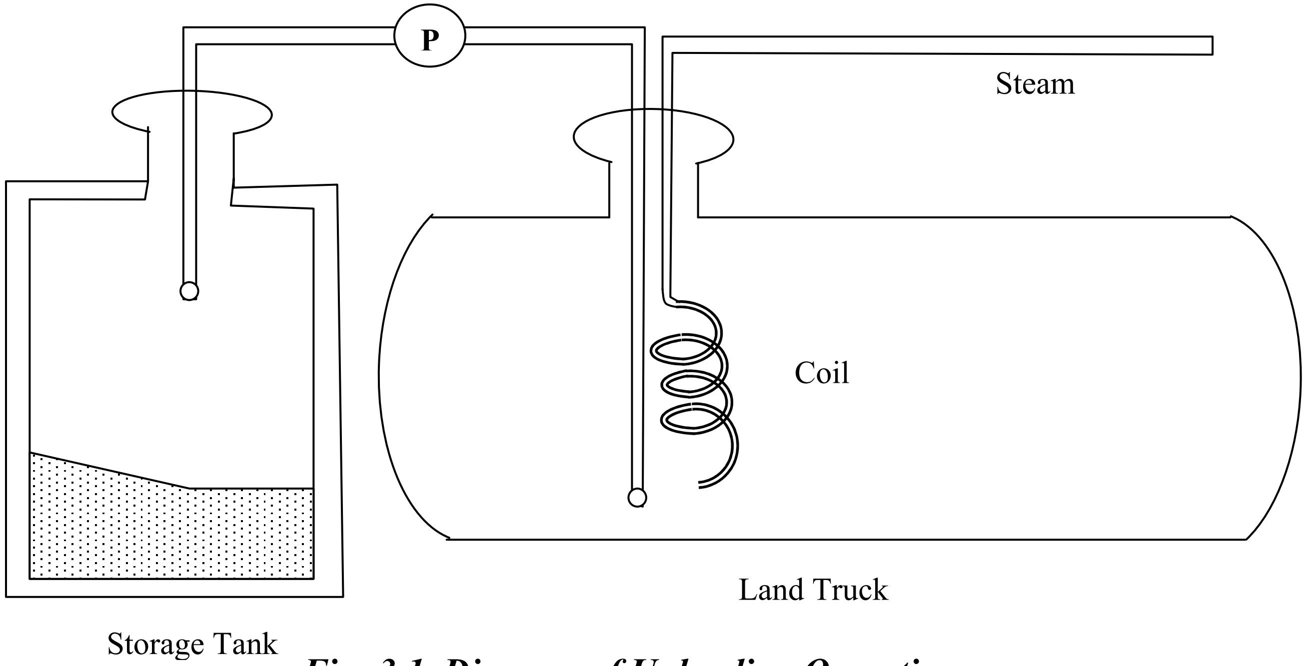


Fig: 3.1. Diagram of Unloading Operation

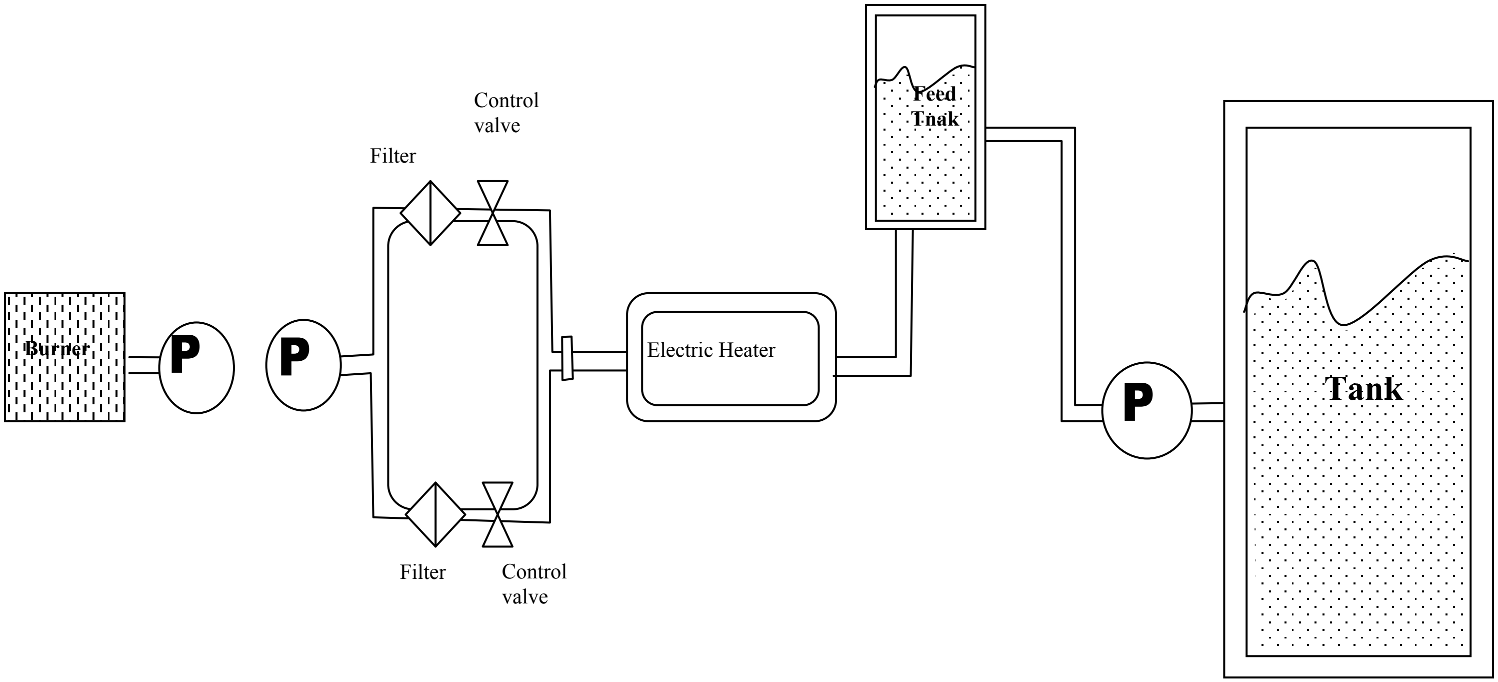


Fig: 3.2

Diagram of Fuel Oil Heating

Chapter (4)
The Problems of Using the Sudanese Fuel Oil

As a result using the Sudanese fuel oil in the boilers of power stations and factories, several operating problems could happen in the fuel oil systems in the unloading, forwarding and operating as follows:-

4.1. Unloading Problems:-

Unloading needs heating fuel oil up to (60ºC – 70ºC) of some heat energy. The unloading and waste problems are summerized below:

4.1.1. Transporting Trucks:

a) Few of transporting trucks have special system for unloading, they have heaters inside them. Those heaters were connected externally with steam hoses.
b) All the land trucks have not the required standards (internal heating).
c) Heating is done by using direct steam hose which enteres from the top of the truck and that leads to add water to the fuel oil.

4.1.2. The Resultant Problems:

a) Creation of much amounts of water that goes to the storage tank.
b) The heating inside the tank is not homogenious.
c) Creation of vacuums that effects the pumps life time.

d) Unhomogenized heating leads to closure of the unloading pipes.

4.1.3. The Proposed Solutions:

a) Preparing the transporting trucks (rail ways or land trucks) by an external heating system and this is doen by using a flange that is connected to the main steam line.

4.1.4. The Filters Problems:

As a result of wax solidification, filters closure happens, which leads to:

a) Increasing filters cleaning periods.
b) Some impurities such like sand could not be filtered.
c) More consumption of spare parts, which means more cost.

4.1.5. The Pumps Problems:

The specifications of original pumps are not suitable for the Sudanese fuel oil and that leads to following problems:

a) Continuous and quick decreasing of their efficiencies.
b) Decreasing of the life times of the pumps.
c) Increasing the spare parts consumption and so increase the cost.

4.1.6. The Collection Basins Problems:

They are basins used to collect the fuel oil that fell during the unloading operation. These basins are open which causes the collection of dust and impurities inside them.

The quick solidifying of fuel oil leads to the followings:

a) Solidification of fuel oil in these basins.

b) Stopping the transporting trucks for the time period of cleaning these basins.

4.1.6.1. Filters Problems:

a) Increasing the cleaning periods.
b) Continuous consumption of filters.

4.1.6.2. Pumps Problems:

a) The reduction of fuel oil viscosity and the increasing losses lead to reduction of the volumetric efficiency of the pumps and increment of the unloading time.
b) The high temperature leads to corrosion in side the pumps as a result of reduction of fuel oil viscosity.
c) The high heating operation leads to :
    i) Expansion of the internal parts which decreases the pumps efficiency and so increases the unloading time in the basin.
    ii) Much consumption of spare parts.

4.1.7. The Proposed Solutions:

a) Preparing filters spare parts.
b) Preparing spare parts for transporting pumps and basins pumps.
c) Design suitable heating system for land trucks.
d) Increasing filters cleaning periods.
e) Raising the vapour pressure of heating from 6 bars up to 12 bars.
f) Increasing the basins cleaning period.

4.1.8. Fuel Oil Storage Tanks Problems:

a) For difference of the fuel oil properties, different layers are created inside the tank, as a result of different of densities of the layers. Also water created as a result of the continuous heating. The Sudanese fuel oil solidifying phenomenon inside the storage tanks is a resultant of the high concentration of the paraffiny wax in the Sudanese crude. Paraffin is a long series of alkenes contains high percentage of wax. Wax percentage in the crude reaches 8% - 20% and may reach 30% in the heavy product. The wax concentration in the Sudanese fuel oil leads to raise the pour point up to 48°C.

b) The created water inside the tank leads to corrosion.

c) The heating inside the tank is not enough to heat the Sudanese fuel oil.

d) Sedimentation of quantity of squalors inside the tank.

4.1.9. Proposed Solutions:

a) Increasing the water discharging periods from inside the tank by draining.

b) A periodic cleaning for the tanks.

c) Cleaning the transporting lines.

4.1.10. The Transporting Lines (Pipe Line) Problems:

a) The superficial heating raises the temperature up to 40°C while the required is 60°C which requires high electrical consumption.

b) The created water -as a result of direct heating- leads to corrosion in the internal surface of the pipe then decrease its life time.

c) The the fuel oil flows inside the pipe is irregular and that leads to the following problems :
    i) Creation of air gaps inside the pipes.
    ii) Closing the unloading hoses and transporting lines.

4.2. The Forwarding Area Problems:

4.2.1. The Pumps Problems:

The pumps are not designed for the Sudanese fuel oil specifications. The pumps are designed for 47 cp at 45°C. The Sudanese fuel oil viscosity is not similar to the viscosity that the pumps are designed for, and that affects the pumps efficiencies.

The fuel oil needs extra heating for continuation the flow of the Sudanese fuel oil, and that affects the internal covers of the pumps.
This increases the maintenance periods.

4.2.2. The Filters Problems:

High content of wax in the Sudanese fuel oil leads to the following problems:

a) Increasing the filters cleaning periods and that may damage the filters
b) Increasing the pumps maintenance and spare parts requirements.

4.2.3. Water Collection Basins Problems:

High percentage of wax leads to the following problems:

a) Increasing the heating operation which affects the internal parts of the pumps leads to damage in the pumps. Damage of the pumps leads to pump a mount of water to inside the storage tanks or loosing quantities of fuel oil to the water collection basins.

b) Solidifying a mount of fuel oil on the interceptor device (the device that separates water from fuel oil) leads to infiltrate the water over the solidifying fuel oil and mix the water and fuel oil together.

c) Continuing and more consumption of spare parts.

4.2.4. The Proposed Solutions:

a) Increasing the filters cleaning periods and availing the required spare parts.

b) Increasing the pumps maintenance periods.

c) Frequent cleaning of basins.

d) Increasing the pumps pressure over the normal rate.

e) Raising the heating steam pressure from 6 bars up to 12 bars to reduce the unloading time.

4.3. The Operating Area Problems:

Unhomogeneity of the Sudanese fuel oil in the operating area affects the boilers. The fuel oil in the storage tanks is usually at the unhomogeneity layers with different properties, which lead to difficulty in determination the atomizing temperature. This leads to the following problems:

a) Difference in the flaming temperature as a result of the different in the atomizing temperature.

b) Creation of irregular flame.

c) Great difference in the temperature inside the boiler as a result of the irregular flame.
d) Uncompleted combustion that leads to accumulate the uncombusted fuel oil over the pipes surfaces. This leads to reduction of the heat transfer inside the boiler.
e) Creation of direct flame, which raises the water temperature inside the pipe to a higher level. This leads to vibrate the boiler as a result of the keen water boiling.
f) Difficulty in control of air and fuel oil quantities, and that in order to complete combustion operation.
g) Reducing the efficiency of the combustion vents, which are designed to certain properties depending on the fuel oil viscosity.
h) When the atomizing temperature is less than the required temperature, accumulating of ash inside the air heater happens, this increases maintenance periods, and also leads to creation of acids which reduces the time life of the pipes.

Chapter (5)
Solar Collectors

5.1. Solar Energy:

5.1.1. Introduction:

The sun is a large sphere of intensely hot gases which are generated by various kinds of fusion reaction. Its diameter is 1.39 x 10^9 m while that of the earth is 1.27 x 10^7 m. The mean distance between the two is 1.5 x 10^{11} m. Although the sun is large, it subtends an angle of only 32 minutes at the earth's surface. As seen from the earth, the sun rotates on its axis about once every four weeks. However it doesn't rotate as a solid sphere: the equator takes about 27 days and the Polar Regions take about 30 days for each rotation. [4]

Measurements indicate that the energy flux received from the sun outside the earth's atmosphere is essentially constant. The solar constant I_{sc} is the rate at which energy is received from the sun on a unit area perpendicular to the ray of the sun at the mean distance of the earth from the sun. The value of the solar constant has been the subject of extensive investigations and its standard value is 1353 W/m^2. [5]

5.1.2. Variation of Extraterrestrial Radiation:

Two sources of variation in extraterrestrial radiation must be considered. The first is the variation in the radiation emitted by the sun. There are conflicting reports in the literature on periodic variations on intrinsic solar radiation. It has been suggested that there are small variations (less than ±1.5%) with different periodicities and variation related sunspot activities. [5]

Variation of the earth – sun distances, however does lead to variation of extraterrestrial radiation flux in the range of ±3%. The dependence of extraterrestrial radiation on time of year is indicated by equation below:

$$I_{so} = I_{sc} (1+0.033 \cos 360n/365) \qquad (5.1)$$

Where:

I_{so} = is the extraterrestrial radiation measured on the plane normal to the radiation on the nth day of the year. [5]

5.1.3. Total Solar Radiation:

The sum of the beam and diffuse solar radiation on a surface, (the most common measurements of solar radiation are total radiation on horizontal surface, often referred to as global radiation on the surface). Total solar radiation is sometimes used to indicate the quantities of the overall wavelength of the solar spectrum. [5]

5.1.4. Beam Radiation:

It is defined as solar radiation received from the sun without having been scattered by the atmosphere. (Beam radiation is often referred to as direct solar radiation: to avoid confusion between subscripts for direct and diffuse, we use the term beam radiation). [5]

5.1.5. Diffuse Radiation:

It is defined as solar radiation received from the sun after its direction has been changed by scattering by atmosphere. (Diffuse radiation is referred to in some meteorological literature as sky radiation or solar sky radiation; the definition used here will distinguish the diffuse solar radiation from infrared radiation emitted by the atmosphere).

5.1.6. Direction of beam radiation:

The geometric relationships between a plane of any particular orientation relative to the earth at any time (whether that plane is fixed or moving relative to the earth) and the incoming beam solar radiation, that is, the position of the sun relative to that plane, can be described in terms of several angles. Some of the angles are indicate in Fig. (5.1.). [5]

5.1.7. Latitude angleϕ:

The angular location north or south of the equator, north positive south negative ($-90< \phi<90$).

5.1.8 Declination angleδ:

The angular position of the sun at solar noon (i.e. when the sun is on the local meridian) with respect to the plane of the equator, north positive, ($- 23.45 < \delta < 23.45$).

5.1.9. Slope angleβ:

The angle between the plane of the surface in question and the horizontal ($0 < \beta < 180$) (B>90) means that the surface has a downward facing component. [5]

5.1.10. Surface azimuth angleγ:

The deviation of the projection on a horizontal plane of the normal to surface from local meridian, with zero due south, east negative, and west positive – 180 ^Y<180. [5]

5.1.11. Hour angleω:

The angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15 per hour, morning negative and afternoon positive. [5]

5.1.12. Angle of incidenceθ:

The angle between the beam radiation on a surface and the normal to that surface. [5]

Additional angles are defined that describe the position of the sun in the sky:

5.1.13. Zenith angle θ_z:

The angle between the vertical and the line to the sun, i.e. the angle of incidence of beam radiation on a horizontal surface. [5]

5.1.14. Solar altitude angle α_s:

The angle between the horizontal and the line to the sun, i.e. the complement of the zenith angle. [5]

5.1.15. Solar azimuth angle γ_s:

The angular displacement from south of the projection of beam radiation on the horizontal plane shown in Fig. (5.2). Displacements east of south are negative and west of south are positive.

The declination angle δ can be found from equation below:

$$\delta = 23.45 \sin ((360/365) X (284 + n) \qquad (5.2)$$

5.2. Solar Collectors

5.2.1 Introduction:

A solar collector is a device for collecting solar radiation and transfers the energy to a fluid passing in contact with it. Utilization of solar energy requires solar collectors. [4]

In any collection device, the principle usually followed to expose a dark surface to solar radiation so that the radiation is absorbed. Apart of the absorbed radiation is then transferred to fluid like air or water.

The solar energy collector, with its associated absorber, is the essential component of any system for conversion of solar radiation energy into more usable form (e.g. heat or electricity). [4]

A solar collector is a special kind of heat exchanger that transforms solar radiant energy into heat. The latter usually accomplish a fluid to - fluid exchange with high heat transfer rates and radiation as an unimportant factor in the solar collector, energy transfer is from a distant source of radiant energy to a fluid. The flux of incident radiation is, at best, approximately 1100 W/m^2 (without optical concentration), and it is variable. The wavelength range is from 0.3 to 3μm, which is considerably shorter than that of the emitted radiation from most energy absorbing surfaces. Thus, the analysis of solar collectors presents unique problems of low, and variable energy fluxes and the relatively large importance of radiation. [5]

5.2.2. Types of Collectors:

There are two general types of solar collectors:

a) The flat plate collectors or non - concentrating collectors.
b) Concentrating (focusing) collectors. [4]

In the non - concentration type, the collector area (i.e. the area that intercepts the solar radiation) is the same as the absorber area (i.e. the area absorbing the radiation). On the other hand, in concentrating collectors, the area intercepting the solar radiation is greater, some times hundred of times greater than the absorber area. By means of concentrating collectors, much higher temperature can be obtained than with the non - concentrating type. Concentrating collectors may be used to generate medium pressure steam. They use many different arrangements of mirrors and lenses to concentrate the sun's rays on the boiler. This shows better efficiency than the flat plate type. For best efficiency, collectors should be mounted to face the sun as it moves through the sky. [5]

5.2.3. Flat - Plate Collectors:

When no optical concentration is done, the device in which the collection is achieved is called a flat - plate collector. The flat - plate collector is the most important type of solar collectors. Flat - plate collectors can be designed for applications requiring energy delivery moderate temperatures up to perhaps 100°C above ambient temperature. It can be used for a variety of applications in which temperatures ranging from 40C° to about 100C° are required. Flat plate collectors are made in rectangular panels from about 1.7 to 2.9 square meters in area and are relatively simple to construct and erect. Flat plates can collect and absorb both direct and diffuse solar radiation; they are consequently partially effective even on cloudy days when there is no direct radiation. They are mechanically simpler than concentrating collectors. The major applications of these units are in solar water heating, building heating, air conditioning and industrial process heat. [6]

The importance of flat - plate collectors in thermal processes in such that their thermal performance is treated inconsiderable detail. This is done to develop an understanding of how the component functions. In many practical cases of design calculations, the equations for collector performance are reduced to relatively simple from.

5.2.4. Description of a Liquid Flat- Plate Collector:

There are many flat - plate collector designs, but most are based on the principle shown in Fig. (5.2.) & (5.5) It is the plate and tube type collector. It basically consists of a flat surface with high absorptivity for solar radiation called absorbing surface. [4]

The important parts of typical liquid flat - plate collector are:

a) The black solar energy absorbing surface with means for transferring the absorbed energy to a fluid

b) Envelopes transparent to solar radiation over the solar absorber surface that reduce convection and radiation losses to atmosphere

c) Back insulation to reduce condition losses.

The absorbed radiation is partly transferred to a liquid flowing through tubes which are fixed to the absorber plate or are integral with it. This energy transferred is the useful gain. The remaining part of the radiation absorbed in the absorber plate is lost by convection and re-radiation to the surroundings from the top surface, and by conduction through the back side and the edges. The transparent covers help in reducing the losses by convection and re-radiation, while thermal insulation on the back side and the edges helps in reducing the conduction heat loss. The liquid most commonly used is water. A liquid flat - plate collector is usually held tilted in a fixed position on a supporting, facing south if located in the northern hemisphere.

5.2.5. Components of Flat - Plate Collectors:

The majority of the flat- plate collector has five main components as follows:

a) A transparent cover which may be one or more sheets of glass or radiation transmitting plastic film or sheet.

b) Tubes, fins, passage or channels are integral with the collector absorber plate or connected to it, which carry the water, air or other fluid.
c) The absorber plate, normally metallic or with a black surface, although a wide variety of other materials can be used with air heaters.
d) Insulation, which should be provided at the back and sides to minimize the heat losses. Standard insulating materials such as fiber glass or styro-foam are used for this purpose.
e) The casing or container which encloses the other components and protects them from weather. [4]

5.2.5. Materials used in Solar Collectors:

The liquid heated is generally water. However sometimes mixtures of water and ethylene glycol are used if ambient temperatures below zero °C are likely to be countered. Typically metal plates, usually of copper, steel or aluminum material with tubing of copper in thermal contact with the plates are the most commonly used materials. The absorber plate is usually made from metal sheet 1 to 2 mm in thickness, while the tubes which are also of metal, range in diameter from 1 to 1.5 cm. They are soldered, brazed or clamped to the bottom (in some cases to the top) of the absorber plate with the pitch ranging from 5 to 15 cm. In some designs, the tubes are also in line and integral with the absorber plate. For the absorber plate corrugated galvanized sheet is a material widely available throughout the world. However, gradually, steel is being favored more because aluminum collectors require specially treated water in order to avoid corrosion.

Heat is transferred from the absorber plate to a point of use by circulation of fluid (usually water) across the solar heated surface. Thermal insulation of 5 to 10 cm thickness is usually placed behind the absorber plate to prevent the heat losses from the rear surface. Insulation materials are generally mineral wool or glass wool or fiber glass as stated above.

The front covers are generally glass (may be one or more) that is transparent to in-coming solar radiation and opaque to the infra-red re-radiation from the absorber. The glass covers acts as a convection shield reduce the losses from the absorber plate beneath. Glass is generally used for the transparent covers but certain plastic films may be satisfactory. Glass is the most favorable material. Thickness of 3 and 4 mm are commonly used. The usually practice is to have 1 or 2 covers with a specific ranging from 1.5 to 3 cm. [4]

Advantages of second glass which is added above the first one are:

a) Losses due to air convection are further reduced. This is important in windy areas.
b) Radiation losses in the infra-red spectrum are reduced by a further 25%, because half of the 50% which is emitted out wards from the first glass plate is back radiated. It is not worthwhile to use more than two glass plates. This is due to the fact that each plate reflects about 15% of the incoming sunlight. [4]

As we know that main purpose of the transparent cover of the flat - plate collector is to decrease heat loss without significantly reducing the incoming solar radiation. In the first place, the relatively still (or stagnant) air space between the cover and the absorber plate largely prevents loss of heat from the plate by convection.

A certain proportion of the incident solar radiation is lost by absorption in the glass cover plates, but the loss can be kept small by using a clear (water white) glass with allow iron content. A much larger loss occurs as a result of partial reflection. Two glass plates may reflect some 15% of the solar radiation coming from a perpendicular direction. The reflection loss increases as the direction of incidence departs from the perpendicular. The reflection of glass covers may reduced by coating with thin films of certain substances (e.g. magnesium fluoride) or by gentle etching with a solution of hydrofluoric acid. Such antireflective coating adds to the cost of the collectors but make them more efficient. [4]

Transparent plastics have been used in place of glass, but they have some drawbacks. Most plastics are not as opaque as glass to the thermal infra-red radiation and so permit greater loss of heat from the absorber. They also suffer a decrease in transparency and sometimes break up in the course of time due to heating and the action of solar ultraviolet radiation. Efforts are being made to develop better plastic materials that might be used in solar collectors.

For water streams the absorber plate can be any metal, plastic or rubber sheet that incorporates water channels, while for air systems the space above or before the collector plate serves as the conduit. The surface finish of the absorber plate may be a flat black paint with an appropriate primer. The primer coat should preferable be thin since a thick under coat of paint would increase the resistance to heat transfer. Black painted absorbers are preferred because they are considerably cheaper. The coatings applied on absorber plate are called (selective coating) which reduces the amount of energy emitted by thermal infra-red radiation. The header pipes, which lead the water in and out of the collector and distribute it to the tubes, are made of the same metal as the tubes. [4]

5.2.6. Heat Transport System:

The heat generated in the absorber is removed by continous flow of a heat -transport (or heat transfer) medium, either water or air. It is mainly in the design of the heat transfer system that flat - plate collectors differ. When water is used, it is most commonly passed through metal tubes with either circular or rectangular cross-section; the tubes are welded to the absorber plate (or from integral part of it) so as to assure effective heat transfer of heat to the fluid. Some examples are already represented in Fig. (5.3.).The tubes are connected to common headers at each end of the collector. In order to maximize the exposure to solar radiation, collectors are almost invariably sloped. Cooler water then enters at the bottom header, flows upward through the tubes where it is warmed by the absorber, and leaves at the top header. Fig. (5.4). [4]

In one simple type of flat - plate collector, the absorber is a blackened sheet with close corrugations running from top to bottom. The water flows through the grooves formed by the corrugations. A problem with this design is that in cold weather, moisture may condense on the inside of the transmission of solar radiation.

Water is a very effective heat - transport medium, but it suffers from certain drawbacks, one is the possibility of freezing in the collector tubes in cold climates during cold nights. As stated earlier ethylene glycol is added to prevent freezing, but this generally adds to the complexity of the heating system. Further more the antifreeze solution is less effective than water for heat removed from the absorber. In some cases, the water is drained from the collector tubes if freezing is expected, but difficulties have been experienced in refilling all the tubes in the morning.

Another problem arises from corrosion of the metal tubes by the water; this is aggravated if the water is drained at night thus allowing air to enter.. The oxygen in air increases the rate of corrosion of most metals. Corrosion can be minimized by using copper tubing. Aluminum is a less expensive alternative, although periodic chemical treatment of water is desirable. Finally, leaks in a water (or anti freeze) circulation system require immediate attention. [4]

5.2.7. Applications of Solar Flat - Plate Collectors:

The major applications of the flat plate collectors are:

a) Solar water heating.
b) Solar building heating.
c) Air conditioning.
d) Industrial process.

5.2.8. Advantages of Flat - Plate collectors:

a) They have the advantages of using both beam and diffuse solar radiation.

b) They do not require orientation toward the sun.
c) They require little maintenance.
d) They are mechanically simpler than the concentrating reflectors, absorbing surfaces and orientation devices of focusing collectors. [4]

5.2.9. Energy Balance Equation and Collector Efficiency:

The performance of solar collector is described by an energy balance that indicates the distribution of incident solar radiation into the useful energy gain and various losses. The thermal losses can be separated into three components: [4]

a) ***Conductive losses.*** An overall heat transfer coefficient value of less than 0.69 W/m^2K is suggested to minimize back losses.
b) ***Convective losses.*** Sizing the air gap between the collector covers at 1.25 to 2.5 cm reduces internal convective losses to the minimum possible level. Convection losses between glass plates can also be inhibited if a honeycomb type, cellular structure is placed between the absorber and the outer windows plate. Evacuation of the space between the absorber and the outer cover has been proposed to reduce internal convection and conduction, but the cost of added supports and maintenance of a vacuum are excessive.
c) ***Radiative losses.*** Radiative losses from the absorber can be reduced by the use of spectrally selective absorber coatings. Such coatings have a high absorptance of about 0.9 in the solar spectrum and a low emittance, usually of the order of 0.1, in the infra-red spectrum in which the absorber radiates to the

environment. Selective absorber coating, there fore decreases heat losses and increases collector efficiency. [4]

Under steady conditions, the useful heat delivered by solar collectors is equal to the energy absorbed in the metal surface minus the heat losses from the surface directly and indirectly to the surroundings. This principle can be stated in relationship: [4]

$$Q_u = A_c \, [HR \, (\tau.\alpha)_e - U_L \, (t_p - t_a)] \qquad (5.3)$$

Where:

Q_u : The useful energy delivered by collector, watts or kcal/hr.

A_c : The collector area m^2.

HR: The solar energy received on the upper surface of the slopping collector structure W/m^2 or kcal/hr m^2.

H: The rate of incident beam or diffuse radiation on unit area of surface of any orientation.

R: The factor to convert beam or diffuse radiation to that on the plane of collector.

Beam and diffuse radiation are considered separately. $(\tau.\alpha)$ For radiation is determined from the actual angle of incidence; $(\tau.\alpha)$ for diffuse radiation may be taken as that for beam radiation at an incidence angle of 60°.

HR: Used to represent the sum of H_bR_b and H_dR_d.

τ **:** The fraction of incoming solar radiation that reaches the absorbing surface, transmissivity (dimensionless).

α **:** The fraction of solar energy reaching the surface that is absorbed, absorptivity (dimensionless).

$(\tau.\alpha)_e$: Effective transmissivity absorptivity product of cover system for beam and diffuse radiation.

U_L : The overall heat loss coefficient. It is the rate of heat transferred to the surroundings per square meter of exposed collector surface per degree Celsius difference between average collector surface temperature and the surrounding air temperature, W/m^2 C°(kcal / hr m^2 °C).

t_p: The average temperature of the upper surface of the absorber plate °C.

t_a: Atmospheric temperature °C.

A diagrammatic representation of (the terms in this relationship) is shown in Fig. (5.6).

In order that the performance of solar collector be as high as economically practical design and operating factors that increase the value of **HR $(\tau.\alpha)$** in the previous equation and that reduce the value of **U_L $(t_p - t_a)$** are selected .The greater the energy absorption in the metal surface and lower the heat loss from the surface, the higher is useful recovery. [4]

If an unglazed absorber plate is used as the collector, the heat loss coefficient to the atmosphere U_L of 30 to 60 W/m^2 °C (35 to 50 kcal /hr m^2 °C) is so large that an absorber temperature of 15 to 30 °C above atmospheric temperature is the maximum achievable under full solar radiation of 1000 W/m^2 (860 kcal/hr m^2).

Under these conditions, useful heat is delivered from the collector because the heat loss is as large as the solar heat observed. When a fluid is circulated through the collector, useful heat output requires an even lower delivery temperature. Unless a low temperature application is involved, such as swimming pool heating, heat losses must, therefore be reduced. [4]

To reduce the rate of radiation and convection loss as already stated, one or more transparent surfaces, such as glass are placed above the absorber surface. One layer of glass can transmit as much as 92 per cent f solar radiation striking it, while greatly reducing the heat loss coefficient U_L. This reduction is due to suppression of convection loss by interposing a relatively air layer between absorber plate and glass, and by absorption of long wave radiation emitted by the hot metal absorber surface. The combined heat loss coefficient can be reduced to 5 to 10 W/m^2 °C (4.30 to 8.60 kcal/hr m^2 °C) by the use of one glass cover. Similar benefits can be achieved by use of certain transparent plastic materials.

The heat loss coefficient can be reduced further by using a second transparent cover with an air space between the two surfaces. Two convection barriers are then present, as well as two surfaces impeding radiation loss coefficient in the range of 4 W/m^2 °C (4.30 to 8.60 kcal/m^2 °C) are then typically obtained. [4]

Radiation losses can be decreased by other techniques, such as reducing the radiation-emitting characteristics of the absorber. Thermal radiation emitted by the absorber plate may also be reduced reflecting it downward from the lower glass cover by employing an infra-red reflecting coating on the glass. A very thin, optically transparent layer of tin oxide or indium oxide deposited on the glass reflects thermal radiation back to the absorber plate. This coating absorbs some of the solar radiation; however, the reduced thermal loss is largely offset by reducing solar energy input to the absorber plate. The foregoing discussion has been concerned with the method for reducing U_L, the heat loss coefficient. By so doing, the total heat loss is minimized and collector efficiency is increased. It is evident from equation (5.3) that losses also decrease the difference between average plate's temperature and air temperature decreases. The ambient (outside) air temperature is an uncontrollable factor, but the fact that is varies with time and with geographic location means that collector efficiency also depends on these factors. It is clear that a collector is more efficient at lower plate temperatures than at high temperatures. But plate temperature depends on the temperature of the fluid circulateding in contact with the plate, the rate of fluid circulation and the type of fluid. Fluid temperature depends on conditions elsewhere in the heat utilization system; where as the other factors in equation (5.3) depend on collector design, operating conditions, solar energy input, and atmospheric temperature. [4]

The energy balance on the whole collector can be written as:

$$A_C [\{HR (\tau.\alpha)_b + HR (\tau.\alpha)_d\}] = Q_U + Q_L + Q_S \qquad (5.4)$$

Where:

Q_U = rate of useful heat transfer to a working fluid in the solar heat exchanger.

Q_L = rate of energy losses from the collector to the surroundings by re-radiation, convection and by conduction through supports for the absorber plate and so on. The losses due to the reflection from the covers are included in the ($\tau.\alpha$) terms; and

Q_S = rate of energy storage in the collector.

Collector efficiency η_c is the collector performance and is defined as the ratio of the useful gain over any time period to the incident solar energy over the time period.

$$\eta_c = \int Q_u \, d_T / \int HR \, d_T \qquad (5.5)$$

5.2.10. Calculation of the Solar Collector Area A_c:

From the previous equation the area of the solar collector can be calculated as follows:

$$A_c = Qu / [S - U_L (T_p - T_a)] \qquad (5.6)$$

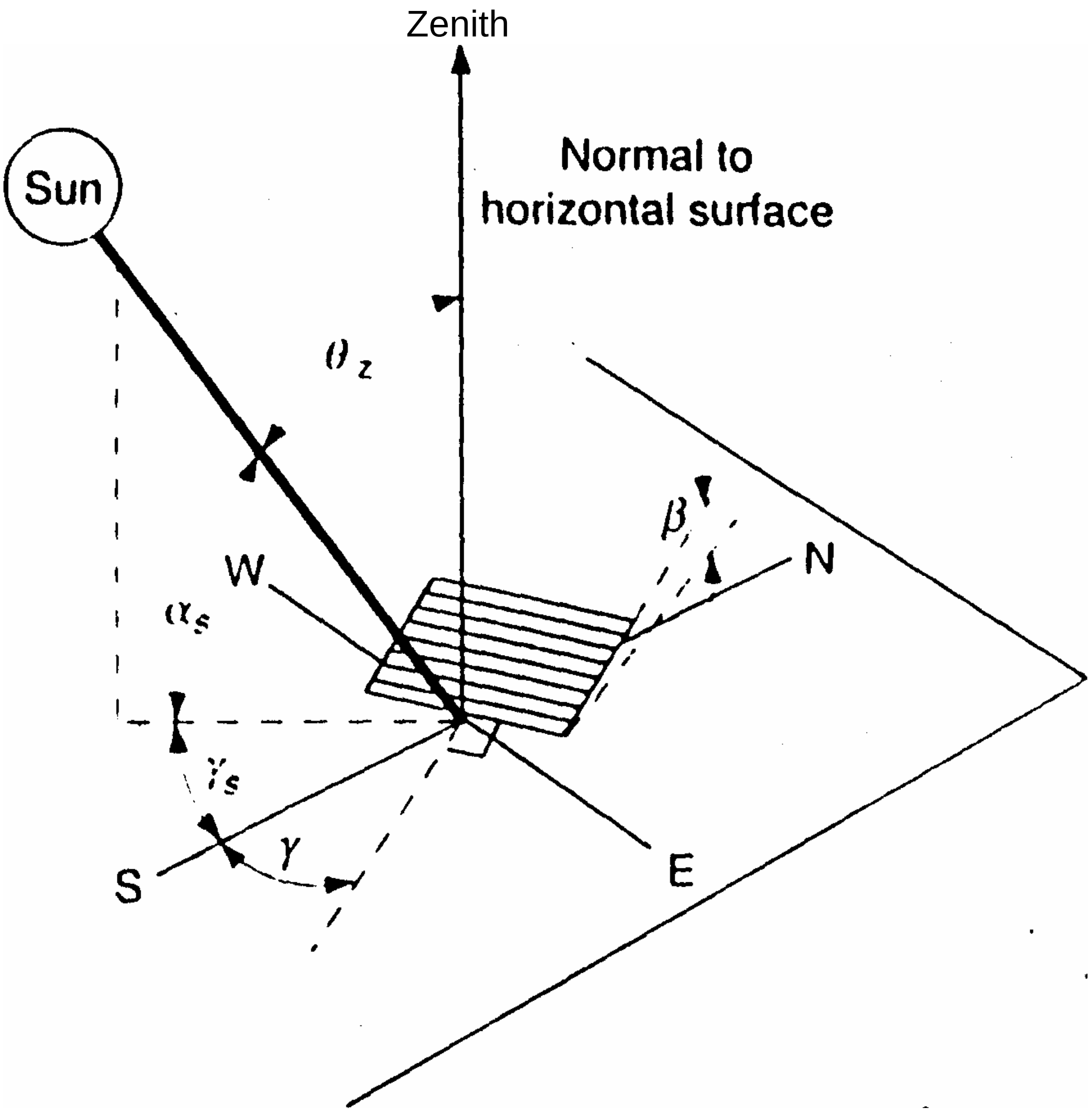


Figure 5.1: Zenith angle, slope, surface azimuth angle, and solar azimuth angle for a tiled surface.

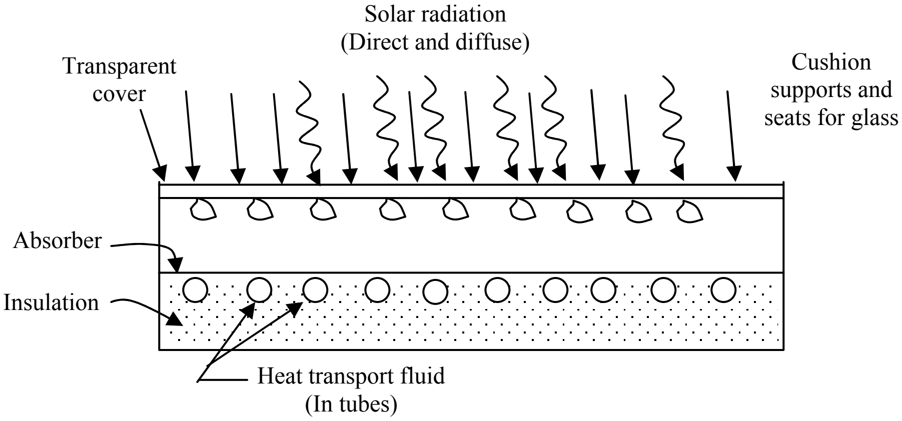


Fig: (5.2) Section through typical flat-plate collector

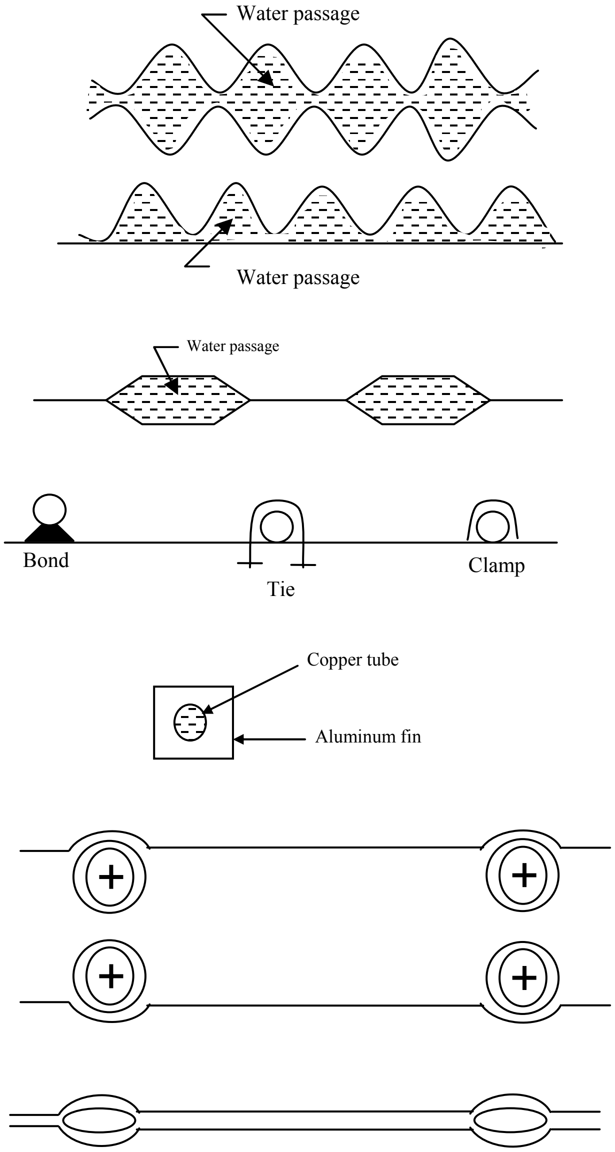


Fig: (5.3) Cross-section through collector plates

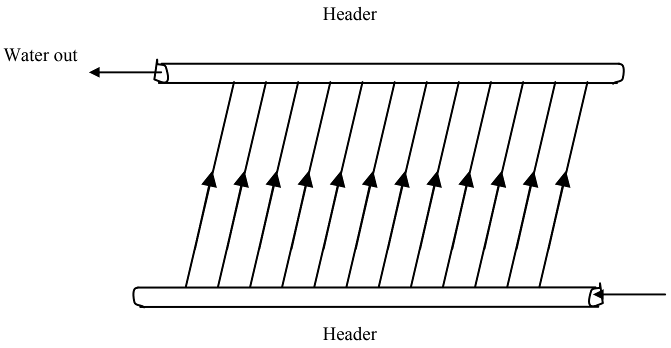


Fig: (5.4) Water flow in flat-plate collector

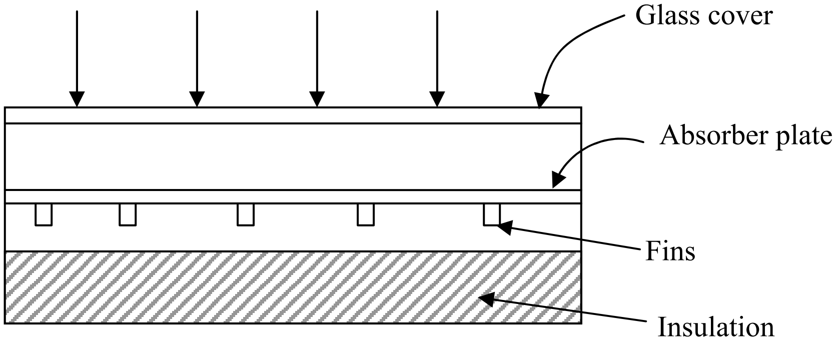


Fig: (5.5) Typical Solar Air Collector

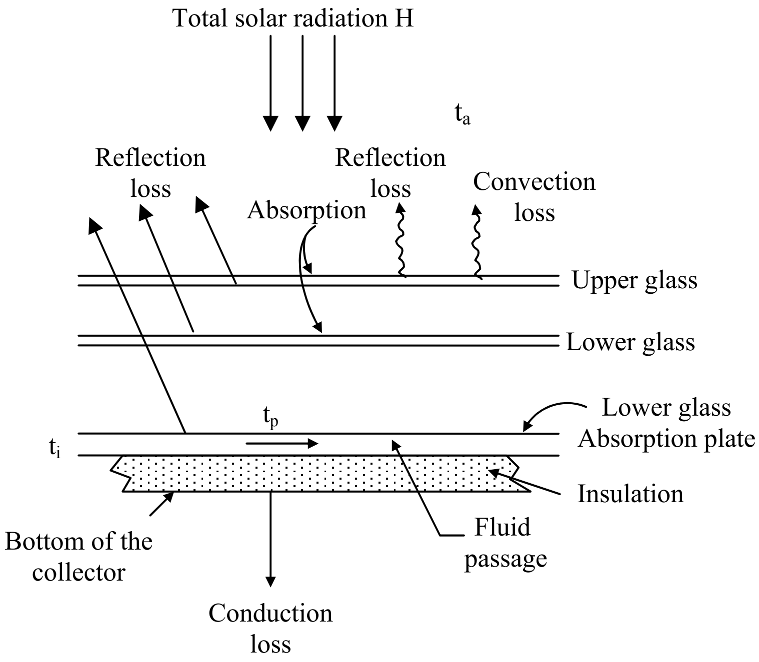


Fig :(5.6) Definition sketch for the previous Equations

Chapter (6)
Calculations & Design of Solar Collector

6.1 Astronomical Relationships:

6.1.1. The Extra-terrestrial Radiation:

The extra-terrestrial radiation, measured on the plane normal to radiation on the nth day of the year is given by:

$$I_0 = I_{SC}\left[1 + 0.033\ \cos\left(360n/365\right)\right] \qquad (6.1)$$

The solar altitude α or angle of incidence on a horizontal surface is:

$$Cos\theta z = sin\alpha = cos\phi\, cos\delta\, cos\omega + sin\phi\, sin\delta \qquad (6.2)$$

For general surface of any orientation and slope,β the angle of incidence, θ, is given by:

$$\text{Cos}\ \theta = \cos(\phi - \beta)\cos\delta\cos\omega + \sin(\phi - \beta)\sin\delta \qquad (6.3)$$

The solar declination is given by:

$$\delta = 23.45\sin\left[360(n + 284)/365\right] \qquad (6.4)$$

Table 6.1 shows the recommended average days for months and values of n by Months.

The hour angle ω is zero at solar noon, negative in the morning and positive in the afternoon, for northern hemisphere. [5]

To express ω in degrees, multiply the hours from solar noon by (360/24):

$$\omega = (LST - 12) \times 15^O \qquad (6.5)$$

LST: is the Local Solar Time used for calculating,ω, given by:

$$LST = standard\ time \pm 4(L_{st} - L_{Loc}) + E \qquad (6.5)$$

(The +ve sign is for western hemisphere and the –ve sign is for eastern hemisphere).

$$\mathbf{E = 9.87\sin 2B - 7.53\cos B - 1.5\sin B} \qquad (6.5.1)$$

$$\mathbf{B = 0.989(n-81)} \qquad (6.5.2)$$

Standard time: is the civil time for a given geographical time zone (covering about 15 degrees of longitude).

1 degree = 4 min., (360 degree = 24 x 60 min., time).

The hour angle at sunrise or sunset (for $\theta z = 90^{o}$ or $\alpha = 0$) is:

$$\omega_s = \pm \frac{24}{360} arc\ \cos(-\tan\phi \tan\delta) \qquad (6.6)$$

The number of daylight (sunshine) hours is $2\omega_s$.

Where:

ω_s: is –ve for sunrise and +ve for sunset.

n: is the number of day in the year.

θ_z: is the zenith angle.

ϕ : is the latitude angle.

β : is the collector inclination (+ve for surfaces sloping towards the south and –ve for surfaces sloping towards the north).

I_{sc}: is the solar constant (= 1353 W/m^2).

E: is the equation of time (minutes).

L_{st}: is the standard meridian for the local time zone (standard time longitude).

L_{Loc}: is the longitude of the location.

Table 6.1 Recommended average days
***For Months and Values of n by Months* [8]**

Month	**n for the ith day of Month**	**For the average day of the month**		
		Date	**Day of Year n**	**Declination δ**
January	i	17	17	-20.9
February	31+i	16	47	-13.0
March	59+i	16	75	-2.4
April	90+i	15	105	9.4
May	120+i	15	135	18.8
Jane	151+i	11	162	23.1
July	181+i	17	198	21.2
August	212+i	16	228	13.5
September	243+i	15	258	2.2
October	273+i	15	288	-9.6
November	304+i	14	318	-18.9
December	334+i	10	344	-23.0

6.1.2. Irradiance on a Tilted Surface:

The global radiation reaching a horizontal surface on the earth is

$$\mathbf{I_g = I_b + I_d} \tag{6.7}$$

Where:

$\mathbf{I_g, I_b, I_d,}$ = the hourly global, beam and diffuse radiation respectively.

The total radiation on a surface of arbitrary orientation,

$$\mathbf{I_T = I_b\, R_b + I_d\, R_d + (I_b + I_d)\, R_r} \tag{6.8}$$

Where,

$\mathbf{R_b}$, $\mathbf{R_d}$ and $\mathbf{R_r}$ are the conversion factors for beam, diffuse and reflected components respectively.

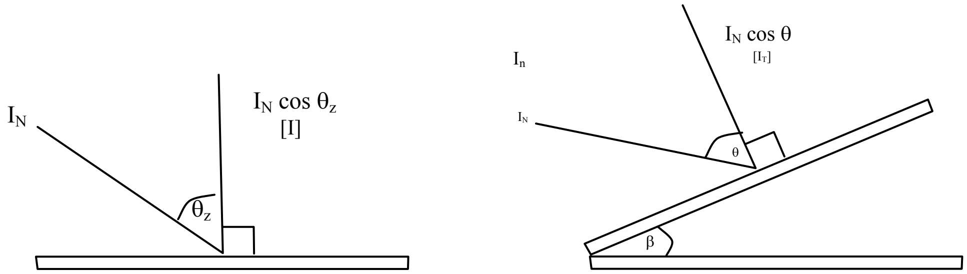


Fig.6.1: The ratio of the flux (beam, diffuse and reflected)

$\mathbf{R_b}$ is the ratio of the flux of beam radiation incident on an inclined surface to that on a horizontal surface,

$$R_b = \frac{I_N \cos\theta}{I_N \cos\theta_Z} = \frac{\cos(\phi - \beta)\cos\delta\cos\omega + \sin(\phi - \beta)\sin\delta}{\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta} \tag{6.9}$$

Where, θ_z and θ are the angles of incidence on the horizontal and inclined surfaces, respectively, and I_N is the intensity of beam radiation.

R_d is the ratio of the flux of diffuse radiation falling on a tilted surface to that on the horizontal surface,

$$R_d = \left(\frac{1 + \cos \beta}{2} \right) \tag{6.10}$$

$$R_r = \left(\frac{1 - \cos \beta}{2} \right) \rho_g \tag{6.11}$$

ρ_g is the reflection coefficient of the ground (= 0.2 and 0.6 for ordinary and snow covered ground respectively). [6]

The hourly extraterrestrial radiation (on a horizontal surface) is:

$$I_0 = \frac{12x3600}{\pi} I_{sc} \left[1 + 0.033\cos\left(\frac{360n}{365} \right) \right] \left[\cos\phi \cos\delta (\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180} \sin\phi \sin\delta \right] \tag{6.12}$$

(ω_2 is the greater).

I_d/I, the fraction of the hourly radiation on a horizontal plane which is diffuse, can be correlated to the hourly clearness index, **($K_T = I/I_o$)**, the ratio of the total radiation to the extraterrestrial radiation for the hour. The equations for the correlation are:

$$\frac{I_d}{I} = \begin{cases} 1 - 0.249K_T & \textit{for } K_T < 0.35 \\ 1.557 - 1.84K_T & \textit{for } 0.35 < K_T < 0.75 \\ 0.177 & \textit{for } K_T > 0.75 \end{cases} \tag{6.13}$$

6.3. Transmissivity of Cover System:

6.3.1. Transmissivity Based on Reflection – Refraction:

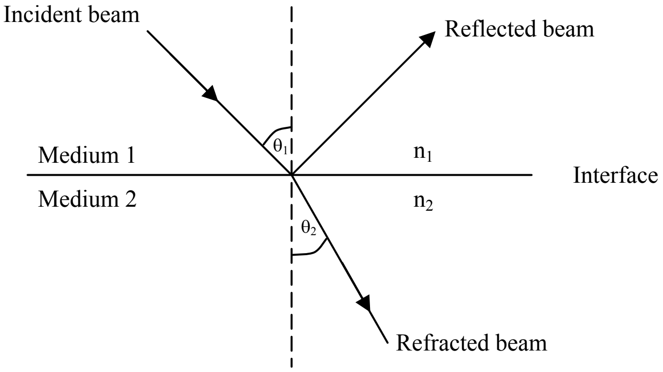


***Fig. 6.2 Angles of incidence (θ_1) and refraction (θ_2) at the Interface of two media with refractive indices n_1 and n_2* [6]**

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{n_1}{n_2} \qquad (6.14)$$

The reflectivity, $\rho = \frac{I_{reflected}}{I_{incident}} = \frac{1}{2}(\rho_\perp + \rho_{||})$ (6.15.1)

$$\rho_\perp = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} \quad , \quad \rho_{||} = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} \qquad (6.15.2)$$

The transmissivity, $\tau_r = \frac{1}{2}(\tau_{r\perp} + \tau_{r||})$ (6.16.1)

$$\tau_{r\perp} = \frac{1 - \rho_\perp}{1 + \rho_\perp} \; , \; \tau_{r||} = (1 - \rho_{||}) / (1 + \rho_{||}) \qquad (6.16.2)$$

6.3.2. Transmissivity Based onAbsorption:

$$\tau_a = \frac{I_{transmitted}}{I_{incident}} = \exp\left(\frac{-KL}{\cos\theta_2}\right) \qquad (6.17)$$

And the transmittance of a single cover becomes:

$$\tau = \tau_a \tau_r \qquad (6.18)$$

Where:

$\rho_\perp$, $\rho_{||}$ are the reflectivities of the perpendicular and parallel components of polarization of incoming radiation.

'r' indicates that only reflection loss has been considered for transmission of radiation.

'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 $32m^{-1}$) for different types of glass (low value is desirable).

L is the total thickness of cover material.

6.3.2. Transmissivity – Absorptivity Product (τα):

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 **(τα)**. [6]

The net fraction absorbed,

$$(\tau\alpha) = \frac{\tau\alpha}{1-(1-\alpha)\rho_d} \tag{6.19}$$

A reasonable approximation for most practical solar collectors is:

$$(\tau\alpha) = 1.01\tau\alpha \tag{6.20}$$

$$(\tau\alpha)_b = \frac{\tau(\theta_b)\alpha}{1-(1-\alpha)\rho_d} \tag{6.21}$$

$$(\tau\alpha)_d = \frac{\tau(\theta_{ed})\alpha}{1-(1-\alpha)\rho_d} \tag{6.22}$$

Where, **$(\tau\alpha)_b$** is the transmissivity-absorptivity product for beam radiation and **$(\tau\alpha)_d$** is the transmissivity – absorptivity product for diffuse radiation (for sky and ground).

ρ_d is the diffuse reflectance of the cover system (at an angle of 60°)
(= 0.15, 0.22, 0.24 for one, two, and three glass cover system). [6]

6.4. Absorbed Solar Radiation:

Incident radiation on a tilted surface at a given hour (from eqn (6.8)) is given by:

$$I_T = I_b R_b + I_d \left(\frac{1+\cos\beta}{2} \right) + \left(I_d + I_b \right) \left(\frac{1-\cos\beta}{2} \right) \rho_g \tag{6.23}$$

In order to determine the absorbed radiation in the absorber plate, each of the terms in the above equation must be multiplied by the term transmissivity – absorptivity product ($\tau\alpha$), so the absorbed radiation, **S**, by a tilted collector at a given hour is given by:

$$S = I_b R_b (\tau\alpha)_b + \left[I_d \left(\frac{1+\cos\beta}{2} \right) + \left(I_d + I_b \right) \left(\frac{1-\cos\beta}{2} \right) \rho_g \right] (\tau\alpha)_d \tag{6.24}$$

6.5. The Overall Heat Transfer Coefficient (U_L):

The heat lost from the collector can be expressed in terms of overall loss coefficient defined by the eqn:

$$Q_L = U_L A_c (T_p - T_a) \tag{6.25}$$

$$U_L = U_t + U_b + U_s \tag{6.26}$$

Where:

A_c = area of absorber plate.
T_p = mean temperature of the absorber plate
T_a = temperature of surrounding air (ambient temperature).
U_L = overall heat transfer coefficient.

U_t, U_b, U_s = top, bottom (or back) and side (or edge) heat loss coefficients respectively.

The top loss coefficient can be calculated from the empirical equation developed by Klein as:

$$U_t = \left[\frac{n}{\frac{C}{T_p}\left(\frac{T_p - T_a}{n+f}\right)^{0.33}} + \frac{1}{h_w} \right]^{-1} + \frac{\sigma\left(T_p + T_a\right)\left(T_p^2 + T_a^2\right)}{\left[\varepsilon_p + 0.05n\left(1-\varepsilon_p\right)\right]^{-1} + \frac{2n+f-1}{\varepsilon_g} - n} \qquad (6.27)$$

Where:

n = number of glass covers (= 1)

f = $(1 - 0.04h_w + 0.0005h_w^2\ \varepsilon_p)\ (1 + 0.091n)$.

C = $365.9(1 - 0.00883\beta + 0.0001298\beta^2)$ for $0^\circ < \beta 70^\circ$ & for $70^\circ < \beta < 90^\circ$ use $\beta = 7^\circ$.

β = collector tilt angle (deg) ($= 15.5^\circ$)

ε_p = emissivity of the absorber plate (0.95)

ε_g = emissivity of the covers (0.88 for glass).

h_w = wind heat transfer coefficient (W/m^2K)

= $2.8 + 3V$

V = velocity of wind ($0 \le V \le 10$) (m/s)

σ = Stefan Boltzmann Constant

= 5.67×10^{-8} (W/m^2K^4)

$U_b = K_i / L_b$ (6.28)

$U_s = 2(L_1 + L_2)\ L_3 K_i / L_1\ L_2\ L_s$

$= (UA)_{edges} / A_c$ (6.29)

Where:

K_i = Thermal conductivity of the insulation (W/mK) = 0.045

L_b = thickness of the back insulation

L_1, L_2 = the dimensions of the absorber plate

L_3 = eight of the collector casing

L_s = thickness of side insulation

$(UA)_{edges}$ = the edges loss coefficient – area product.

6.6. Energy Balance and Collector Efficiency:

The useful energy delivered by or the output of a collector of area **A_c** is the difference between the absorbed solar radiation and the thermal loss and is given by:

$$\mathbf{Q_u = A_c\,[S - U_L\,(T_p - T_a)]} \qquad (6.30)$$

Where,

Q_u is the useful energy delivered by the collector (W) and S is the absorbed solar radiation (W/m^2).

6.6.1. The Collection Efficiency:

The collection efficiency is the ratio of the useful gain over some specified time period to the incident solar energy over the same time period.

$$\eta_c = \frac{\int Q_u\,dt}{A_c \int I_T\,dt} \qquad (6.31.1)$$

Therefore the collector efficiency for any hour from the above eqn is:

$$\eta = \frac{\int Q_u dt}{A_c \int I_T dt} = \frac{Q_u}{A_c I_T} = \frac{q_u}{I_T} \qquad (6.31.2)$$

And the day-long collector efficiency is:

$$\eta_{day} = \frac{\sum q_u}{\sum I_T} \qquad (6.31.3)$$

6.7. Area of the Collector:

In the process of vaporization, interest is drawn to the volume change per unit energy absorbed by the collector.

The energy absorbed by the collector plate per unit area (kW/m^2) = ***S***

The total energy absorbed by the collector plate = $A_c S$ (kW)

$$A_c = Qu /[S - UL\ (T_p - T_a)] \qquad (6.32)$$

6.8. Calculations of the Fuel Oil Tank:

6.8.1. Heat Losses

6.8.1.1. Heat Losses from Fuel Oil Tank:

From Newton's Law of Cooling with assumption of steady heat flow:

$$q = U\ (t_A - t_F) \qquad (6.33)$$

$$1/U = l/h_A + X/K + l/h_F \qquad (6.34)$$

Where:

q = Rate of heat transfer per unit area (kW/m^2).

u = Overall coefficient of heat transfer factor (W/m^2.K).

t_A = Temperature of fluid (air).

t_F = Temperature of fuel oil.

h_A = Heat transfer coefficient of air (W/m^2.K).

h_F = Heat transfer coefficient of fuel oil (W/m^2. K).

x = wall thickness of the tank (m).

k = Thermal conductivity of tank wall material (w/m^2 .k).

$$R_t = X_1/K_1 + X_2/K_2 + 1/h_A \qquad (6.35)$$

$$q = (T_1 - T_2)/R_t \qquad (6.36)$$

R_t = The overall heat flow resistance (it is equal to 1/x of the overall heat transfer)

X_1 = Thickness of the tank wall (5 mm).

X_2 = Thickness of the insulation (100 mm).

K_1 = Thermal conductivity of the tank material (50.5 W/m.K)

K_2 = Thermal conductivity of the insulation.

h_A = Heat transfer coefficient of the outside air (17 W/m^2.K)

T_1 = Fuel oil temperature (70C°).

T_2 = Ambient temperature degree (13C°) [the minimum temperature that the ambient temperature can be reached].

6.8.1.2. Calculation of Losses without Using Insulation:

$$R_t = X/K + 1/h_A \qquad (6.37)$$

$$=0.005/50.5 + 1/17 = \underline{\underline{\mathbf{0.0589}}}\ m^2.\ K/W$$

$$q = (T_1 - T_2)/R_t$$

$$= (70 - 13)/0.0589 = \underline{\underline{\mathbf{0.968}}}\ kW/m^2$$

The heat loss Q_L: **Q_L = qA.**

A = surface area of the fuel oil lank (m^2)

A = 2 x L x w + 4 x L x H

L = length (m)

W = width (w)

H = Height (m)

L=W = 4m H = 5.35m

$= 2 \times L^2 + 4 \times L \times H$

$= 2 \times L^2 + 4 \times 4 \times 5.35 = 2 \times 16 + 85.6 = 32 + 85.6 =$ **117.6** m^2

:. Heat losses $Q_L = q \times A = 0.968 \times 117.6 =$ **113.806** *kW*

6.8.1.3. Calculation of Heat Losses with Insulation:

From equations (6.35.) & (6.36.):

$$Rt = X_1/K_1 + X_2/K_2 + 1/h_A$$

$= (0.005/50.5) + (0.1/0.051) + (1/17) =$ **2.0197** $m^2.K/W$

$$q = (T_1 - T_2)/R_t$$

$(70-13)/2.0197 =$ **28.2219** *W/m*

Heat loss $Q_L = qA = 28.2219 \times 117.6 =$ **3.3189** *kW*

6.8.2. Heat input to the Tank Q_t:

$$Q_t = m\ cp\ (T_1 - T_2) + \text{heat loss}$$

$$Q = mcp\Delta t + qA \qquad (6.38)$$

Where:

Q = the heat energy should be input to the fuel oil tank.

m = mass flow rate of fuel oil (kg/s).

Cp = specific heat of fuel oil (kJ/kg. K)

6.9. Proposals for Heating

There are three proposals for heating the fuel oil in the tank.

6.9.1. First Proposal (Proposal A):

In the first proposal (A) we suggest that we should heat all the quantity that input into the tank (capacity of the tank = 80 metric tons). So the flow rate m will be equal to 0.926 kg/s (80000/ (24x3600).

The heat input to the tank $\mathbf{Q_t}$**:**

$$\mathbf{Q_t = mcp\Delta t + qA}$$

$$\mathbf{0.926x2.0934x\ (60\text{-}33) + 3.3189 = \qquad 47.904\ kW}$$

The useful heat delivered by the solar collector is:

$$\mathbf{Q_u = Ac[S - U_L\ (T_P - Ta)]}$$

But: $\mathbf{Q_u = Q_t}$

$$\mathbf{A_C = Q_t /[S - U_L\ (T_P - T_a)]}$$

$$\mathbf{A_C = 45.536\ m^2}$$

6.9.2. Second Proposal (Proposal B):

In the second proposal we suggest to heat the daily consumption of the fuel oil (the daily consumption of fuel oil is equal to 12 metric tons). So the mass flow rate m will be 0.1389 kg/s (12000 kg/ (24x3600).

The heat input to the tank $\mathbf{Q_t}$:

$$\mathbf{Q_t = mcp\Delta t + qA}$$

$$\mathbf{0.1389x2.0934x\ (60\text{-}33) + 3.3189 = \qquad 10.001\ kW}$$

The useful heat should be delivered by the solar collector is Qu:

$$\mathbf{Q_u = A_C[S - U_L\ (T_P - T_a)]}$$

But: $\mathbf{Q_u = Q_t}$

$$\mathbf{A_C = Q_t /[S - U_L\ (T_P - T_a)]}$$

$$\mathbf{A_C = 9.507\ m^2}$$

6.9.3. Third Proposal (Proposal C):

It is known that the fuel oil is usually be heated when it is unloaded. The third proposal acts to keep the temperature of the fuel oil – during the unloading – constant. That mean we should act to prevent the losses. Then the heat that should delivered by the solar collector $\mathbf{Q_u}$ must be equal to the overall heat that lost from the tank $\mathbf{Q_L}$.

$$\mathbf{Q_u = Q_L = A_C[S - U_L\ (T_P - T_a)]}$$

$$\mathbf{A_C = Q_L/[S - U_L\ (T_P - T_a)]}$$

$$\mathbf{A_C = 3.155\ m^2}$$

6.10. Description of the collector:

***Materia**l*: Aluminium

Net Apsorper Area: 45.536 m^2

Inlet and outlet Connection: 15mm

Casing:

Material
- Bottom … fiber glass reinforced plastic
- Frame …. Stainless steel or plastic coated steel sheet.

Glasing

Material …. Transparent drawn glass

Thickness … 4mm.

Table 6.2: Materials of the Collector

No	Item
1	Wood (yellow pine).
2	Galanized steel sheet.
3	Glass sheet (0.5 inch x 6m).
4	Steel pipe (0.5 inch).
5	Insulator (fiber glass).
6	Elbows (0.5 inch).
7	Nipples (0.5 inch).
8	Non – Return valve (0.5 inch).
9	Gate valve (0.5 inch).
10	Tees (0.5 inch).
11	Steel Angle (90) (0.5 inch).
12	Black paint (blackboard paint).
13	Relief valve.
14	Union (0.5 inch).
15	Galvanised steel nail.
16	Needle nail.
17	Thermocouple wires.
18	Copper tube.
19	Pressure gauge (2 Bar).
20	Steel pipe (0.5 inch x 0.8 m).

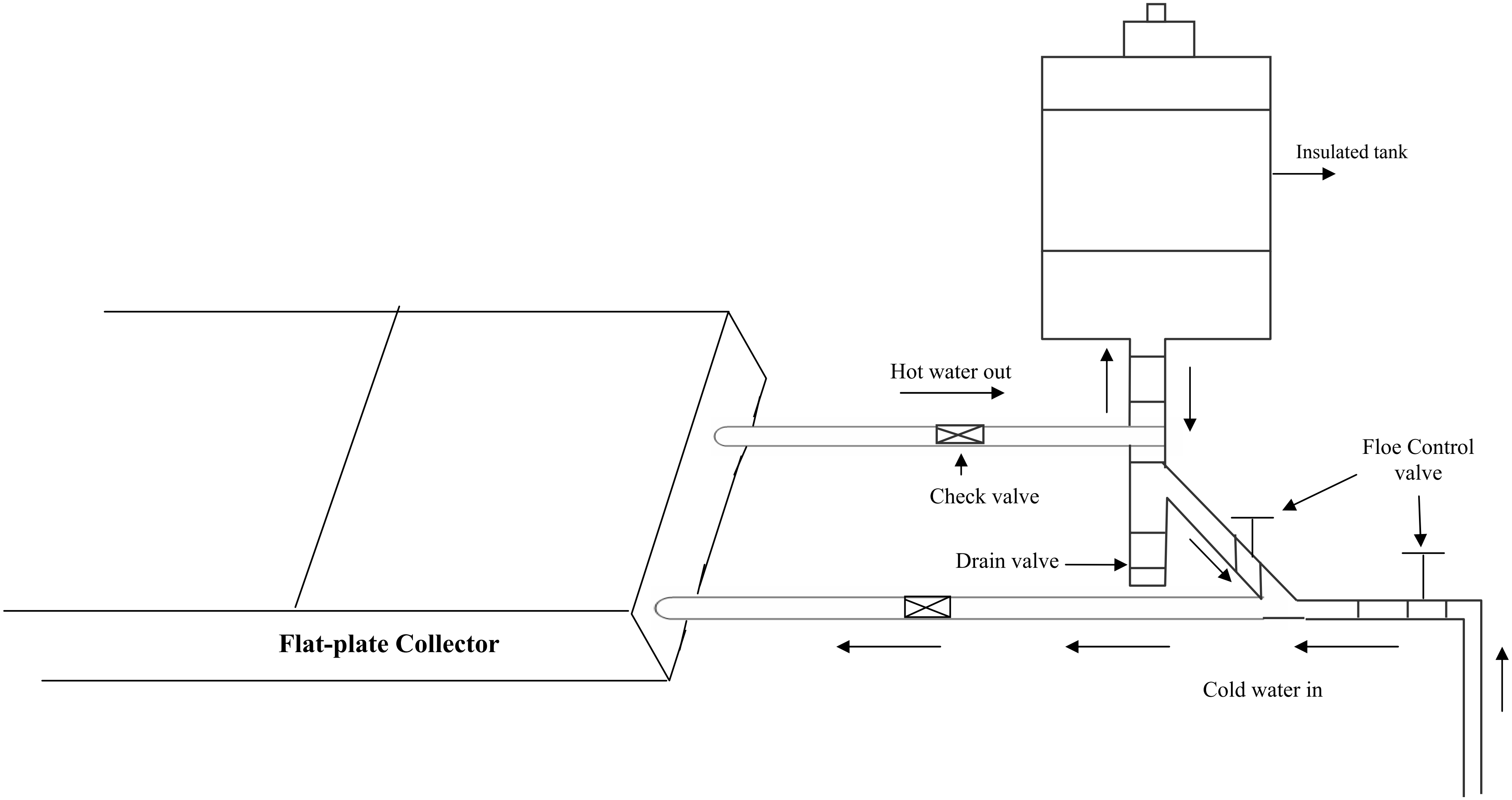


Fig: 6.8. Natural Circulation Water Heating System

Chapter (7)
Economical Analysis

7.1 Calculation of Cost of heating the fuel oil by using Steam from the boiler

7.1.1. General Design Data:-

- The consumption of the fuel oil for the boiler at perfect condition

  = 21 Ton /day

- The real consumption of the fuel oil for the boiler now.

  = 9 ton / day

  - The production of steam at perfect condition =**13.6 ton / day**
  - The actual production of steam now **= 5.72 ton /hr**
  - The total daily production of steam = 5.72× 24

    = 37.28 tons /day

  - The price of the ton of the fuel oil = **62500 SD**
  - The daily cost of steam generation = 9 ×62500 **= 562500 SD**
  - The cost of every ton of steam = 562500/137.28

    = 4097.465 SD

  - The cost of every Kg of steam **= 4.097SD**

7.1.2 The Calculation of Mass Flow Rate of Steam to the Fuel oil tank:-

- The total flow rate of steam from the boiler =**1.589 kg /s**
- The flow rate of steam to the fuel oil tank **= 0.0787 kg/s**

Table 7.1: Distrbution of Steam to the Various Sections in the Factory

Section	Diameter (m)
The Main	0.2032
Pistons.	0.1016
Toilet & Fats.	0.1016
Internal Heating (fuel oil).	0.03175
Refining.	0.1016
External Heating (fuel oil).	0.03175
Glycerine Refining.	0.0762
Refining & Pots.	0.0635
Ambergris & Raw Glycerine.	0.1016
Perfume Pot.	0.03175

- The percent of steam that consumed to heat the fuel oil equal 4.95% of the total quantity of the steam.
- The secondly production of steam = **1.5889 kg/s**
- The secondly consumption of steam for heating the fuel oil
  = 1.5889/0.0495
  = **0.787 kg/s**
- The daily consumption of steam for heating the fuel oil
  = 0.0787 ×3600× 24 **= 6795.835 kg**
- The total daily cost of heating fuel oil by using steam
  6795.835 × 4.097 = **27845.697SD**
- The Total Annual Equivalent cost of heating
  = 27845.697 x 360 = **10024450.9 SD**

7.2. Calculation of Cost of Heating the Fuel Oil by Using Solar Collector:-

We have three proposals (A, B, C). To compare between the three proposals, it is suitable to use the annual equivalent amount AE (i) as a basis for comparison.

The comparison will be done for equal service time for twenty (20) years and for minimum annual rate of return MARR equal to 15% .The salvage value of equipments of every proposal is estimated to be 10 percent of the first cost. [7]

7.2.1. Calculation of Cost of Proposal (A):

a) Cost of the collector;

The area of the collector = **455363 m^2**

Cost of each meter of the collector = **25000 SD**

The total cost of the collector = 45.5363 x 25000 = **1138408 SD**

b) Cost of insulation of the fuel oil tank =117.6 x 1000

= **117600 SD**

P: the present value

P = the total cost = the cost of the collector + the cost of the insulation.

P = 1138408 + 117600 = **1256008 SD**

S.V: the salvage value 10% of the total cost **= 113840.8 SD**

7.2.2. Calculation of Cost of Proposal (B):

a) Cost of the collector;

The area of the collector = **= 9.5067 m^2**

Cost of each meter of the collector = **= 25000 SD**

The total cost of the collector = 9.5067 x 25000 = **237667.5SD**

b) Cost of insulation of the fuel oil tank =117.6 x 1000

= **117600 SD**

P: the present value

P = the total cost = the cost of the collector + the cost of the insulation.

P = 237667.5+ 117600 = **= 355267.5 SD**

S.V: the salvage value 10% of the total cost **=35526.75 SD**

7.2.3. Calculation of Cost of Proposal (C):

a) Cost of the collector;

The area of the collector = **3.154863 m^2**

Cost of each meter of the collector = **25000 SD**

The total cost of the collector = 3.154863 x 25000 = **78871.58 SD**

b) Cost of insulation of the fuel oil tank =117.6 x 1000 =

117600 SD

P: the present value

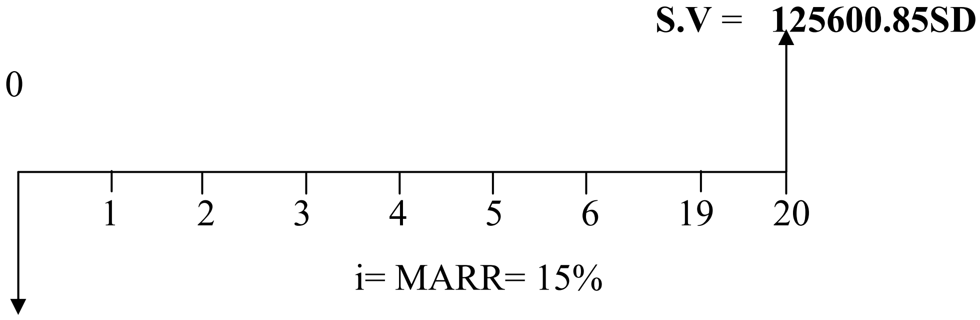
P = the total cost = the cost of the collector + the cost of the insulation.

P = 78871.58+ 117600 = **196471.6 SD**

S.V: the salvage value 10% of the total cost = **19647.16 SD**

Cash flow diagrams of proposals are shown as follows [7]:-

Proposal A:



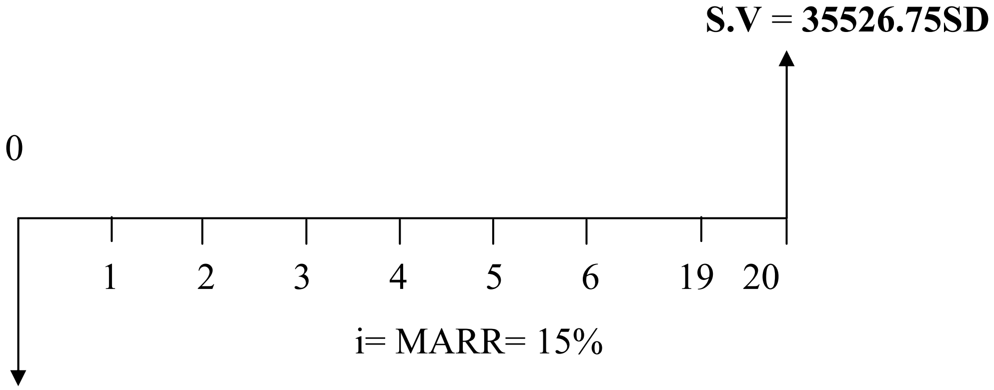
P = 1256008.5 SD n = 20 years

First Cost = 1256008.5 SD

S.V = 125600.85 SD

Figure.7.1: Total Equivalent Annual Cost (Proposal A).

Proposal B:



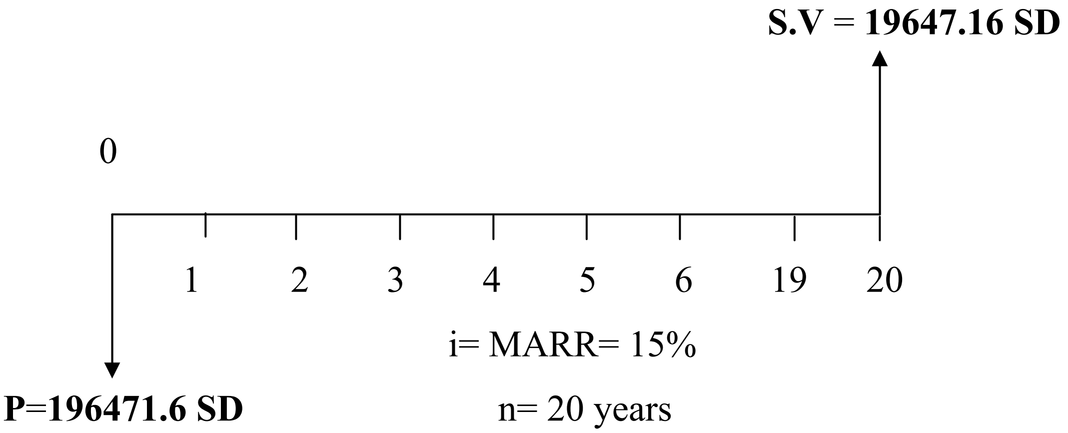
P = 355267.5 SD n= 20 years

First Cost = 355267.5 SD

S.V = 35526.75 SD

Figure.7.2: Total Equivalent Annual Cost (Proposal B).

Proposal C:



First Cost = 196471.6SD

S.V = 19647.16 SD

Figure.7.2: Total Equivalent Annual Cost (Proposal C).

Present Heating:

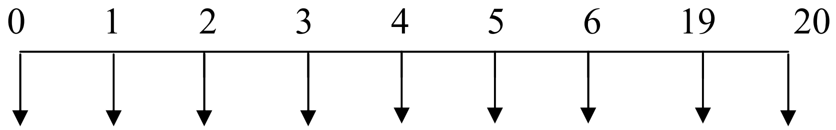


Figure.7.4: Total Equivalent Annual Cost (Present Proposal)

7.2.4. Calculation of Total Equivalent Annual Cost (TEA):

TEA = CRWR +O & M ……………………………... (7.1) [7]

TEA = Total Equivalent Annual Cost

***CRWR*:** Capital recovery with return.

***O & M*:** Operating and maintenance cost.

CRWR is determined by the following relation:-

$$CRWR = P\left(\overset{A/P\ i,\,n}{\qquad\qquad}\right) - SV\left(\overset{A/P\ i,\,n}{\qquad\qquad}\right) \ldots\ldots\ldots\ldots\ldots\ (7.2)\ [7]$$

$\left(^{A/P\ i,\ n} \qquad \right)$: Factor taken from table.

But :$\left(^{A/f\ i,\ n} \qquad \right) = \left(^{A/f\ i,\ n} \qquad \right) - 1$**……………………..…… (7.3) [7]**

Figure.7.5: Total Equivalent Annual Cost (General).

From equation (6-2) & (6-3) it follows that:-

CRWR = (P-S.V) $\left(^{A/P\ i\ n} \qquad \right)$ **+S.V (i)……..……… (7.4) [7]**

Proposal (A):-

$(TEA)_A = (P\text{-}S.V)\ (\qquad\qquad) + S.V\ (i)$

$(TEA)_A = (1256008.5 - 0.125600.85)\ \overset{A/P\ 15,\ 20}{(0.15976)} + ((125600.85))(0.15)$

$=180593.9+18840.1275$ **=199434.1SD**

(TEA)$_A$ **= 199434.1SD**

For Proposal B :

$(TEA)_B = (P\text{-}S.V)\ \left(^{A/P\ i,\ n} \qquad \right) + S.V\ (i)$

$$(TEA)_B = \overset{A/P\ 15,\ 20}{(355267.5-35526.75)}\ \overset{A/P\ 15,\ 20}{(0.15976)} + ((35526.75)\ (0.15)) =$$

51081.78+5329.013 **= 56410.78SD**

$(TEA)_C$ = 56410.78 SD

For Proposal C:

$$(TEA)_A = (P-S.V)\ (\ ^{A/P\ 15,\ 20}\ ) + S.V\ (i)$$

$$(TEA)_C = (196471.6-19647.16)\ \left(\overset{A/P\ 15,\ 20}{0.15976}\right)$$

$+ ((19647.16)\ (0.15)) = 28249.35+2947.062$

$(TEA)_C$ 31196.55 SD

Table7.2. Comparison between the Several Alternatives

Proposal	**Total Equivalent Annual Cost (TEA)**
Proposal (A)	**1,994,34.1 SD**
Proposal (B)	**56,410.78 SD**
Proposal (C)	**31,196.55 SD**
Present heating	**10,024,450.9 SD**

7.3. Comment:

As shown in table (7.1), all alternatives are better than the present heating system. It is seemed that proposal (C) is the best choice because it has the lowest cost. But, the best alternative is proposal (A) because it heats all the fuel oil inside storage tank. Heating of the all fuel oil makes it homogeneous and helps in extracting the water from the fuel oil and facilitate the pumping of the fuel oil. Proposal (A) is the most guaranteed method to melt the fuel oil.

Chapter (8)
Conclusions and Recommendations

8.1. Conclusions

The main idea of this research is to use solar energy for heating the Sudanese fuel oil to be pumpaple.

The heating of the Sudanese fuel oil is achieved by the use of solar flat - plate collector to heat water which is been recycled inside the fuel oil to rise its temperature.

There are three proposals for heating. For the first proposal, the collector is required for heating all the quantity inside the fuel oil tank which equal to 80 (eighty) tons. The advantage of heating all the quantity is homogenizing of fuel oil in the tank which helps in pumping the fuel oil.

For the second proposal, the collector is required for heating only the daily consumption which equals to 12 (twelve) tons.

For the third proposal, the collector is required to supply heat that compensates the lost heat from the fuel oil tank.

1. It is better to choose proposal (A), which acts to heat all the fuel oil inside the storage tank. Heating of all fuel oil makes it homogeneous and helps in extracting the water from the fuel oil and facilitate the pumping of the fuel oil. Proposal (A) is the most guaranteed method to melt the fuel oil.
2. The collector should not be used without any liquid inside it; other wise the high interior temperature generated cause

abnormal expansion of he covers which may become distorted or broken down.

3. The collector must be constructed in such away that damaged or broken components (glass covers) can be replaced easily.
4. Allowance must be made for glass expansion.
5. The insulation materials should be dry (preior to installation).
6. The collector must have vent holes to prevent condensable
7. Clean water must be used.
8. The storage tank of the fuel oil should be close to the collector and at the west side to prevent shading at early morning.
9. The fuel oil storage tank should be insulated to keep the temperature constant.

8.2. Recommendations:

Further research work covering the following is recommended:

1) Study about heating the Sudanese fuel oil in transportaion by utilization of solar energy.
2) Storage of solar energy for heating the fuel oil over night.
3) Use of concentrating collector instead of flat – plate collector to heat the fuel oil.

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Appendix (1) (Tables)

Table 6.3 Hourly mean global solar radiations for Shambat Obs. 1981 in MJ and the mean temperature for the last 30 years.

Time / Month	5-	6-	7-	8-	9-	10-	11-	12-	13-	14-	15-	16-	17-	Total	T_{av}.^{o}C
January		0.07	0.69	1.47	2.05	2.43	2.61	2.58	2.38	1.99	1.41	0.7	0.08	18.45	23.4
February		0.01	0.9	1.69	2.3	2.7	2.8	2.93	2.32	1.76	1.00	1.00	0.24	21.58	25.3
March		0.29	1.06	1.82	2.41	2.77	2.96	3.00	2.8	2.41	1.81	1.07	0.34	22.74	28.7
April	0.02	0.53	1.36	2.09	2.59	2.93	3.06	3.02	2.77	2.38	1.78	1.09	0.37	24.01	31.8
May	0.06	0.58	1.33	1.92	2.42	2.74	2.87	2.78	2.6	2.16	1.56	0.95	0.36	22.35	34.3
June	0.06	0.57	1.24	1.85	2.24	2.51	2.56	2.55	2.36	1.97	1.52	0.44	0.38	20.78	34.3
July	0.01	0.38	1.03	1.66	2.13	2.46	2.69	2.54	2.35	2.01	1.57	1.06	0.45	20.42	31.8
August	0.01	0.4	1.04	1.72	2.17	2.5	2.69	2.44	2.12	1.59	0.95	0.33	0.01	20.72	30.5
September	0.01	0.35	1.06	1.74	2.3	2.69	2.69	2.76	2.66	2.43	2.06	1.5	0.77	20.52	3.2
October	0.00	0.39	1.13	1.81	2.31	2.62	2.66	2.64	2.33	1.84	1.25	0.55	0.03	19.59	32.2
November	0.00	0.34	1.11	1.82	2.34	2.67	2.77	2.68	2.35	1.84	1.25	0.46	0.01	19.63	28.1
December	0.00	0.17	0.91	1.65	2.2	2.54	2.68	2.57	2.32	1.88	1.27	0.50	0.02	18.71	24.4
Total															

Table 6.4: Calculatoins of Solar Flux (January 1)

January								
N	**SST**	**B**	**E (min.)**	**LST**	**ϕ (deg)**	**β (deg)**	**δ (deg)**	**ω (deg)**
17	7	-63.296	-9.968	7.001	15.5	15.5	-20.93	-74.99
17	8	-63.296	-9.968	8.001	15.5	15.5	-20.93	-59.99
17	9	-63.296	-9.968	9.001	15.5	15.5	-20.93	-44.99
17	10	-63.296	-9.968	10.001	15.5	15.5	-20.93	-29.99
17	11	-63.296	-9.968	11.001	15.5	15.5	-20.93	-14.99
17	12	-63.296	-9.968	12.001	15.5	15.5	-20.93	0.01
17	13	-63.296	-9.968	13.001	15.5	15.5	-20.93	15.01
17	14	-63.296	-9.968	14.001	15.5	15.5	-20.93	30.01
17	15	-63.296	-9.968	15.001	15.5	15.5	-20.93	45.01
17	16	-63.296	-9.968	16.001	15.5	15.5	-20.93	60.01
17	17	-63.296	-9.968	17.001	15.5	15.5	-20.93	75.01
17	18	-63.296	-9.968	18.001	15.5	15.5	-20.93	90.01
17	19	-63.296	-9.968	19.001	15.5	15.5	-20.93	105.01

$\cos\theta$	**θ(deg)**	**cos**	**R_b**	**R_d**	**R_r**	**$\omega_{1(deg)}$**	**$\omega_{2(deg)}$**	**$I_{o(MJ/m^2 hr)}$**
0.2419	76.00	0.1376	1.758	0.982	0.004	-74.99	-59.99	1.246
0.4671	62.15	0.3546	1.317	0.982	0.004	-59.99	-44.99	2.265
0.6605	48.66	0.5410	1.221	0.982	0.004	-44.99	-29.99	3.098
0.8089	36.01	0.6840	1.183	0.982	0.004	-29.99	-14.99	3.686
0.9022	25.55	0.7739	1.166	0.982	0.004	-14.99	0.01	3.991
0.9340	20.93	0.8045	1.161	0.982	0.004	0.01	15.01	3.991
0.9021	25.56	0.7738	1.166	0.982	0.004	15.01	30.01	3.686
0.8088	36.02	0.6839	1.183	0.982	0.004	30.01	45.01	3.097
0.6603	48.67	0.5408	1.221	0.982	0.004	45.01	60.01	2.264
0.4669	62.17	0.3544	1.317	0.982	0.004	60.01	75.01	1.244
0.2416	76.02	0.1373	1.759	0.982	0.004	75.01	90.01	0.107
-0.0001	90.01	-0.0956	0.001	0.982	0.004	90.01	105.01	-1.071
-0.2419	104.00	-0.3285	0.736	0.982	0.004	105.01	120.01	-2.208

$I_{g(MJ/m^2 h)}$	K_T	I_d/I	$I_{d\ (MJ/m^2 h)}$	$I_{b\ (MJ/m^2 h)}$	$I_{T(MJ/m^2 h)}$	$\theta_{2(deg)}$	τ_a	$\rho_\perp$
0	0.000	1.000	0.00000	0.00000	0.00000	39.48	0.953	0.435
0.07	0.031	0.992	0.06946	0.00054	0.06916	35.41	0.956	0.206
0.69	0.223	0.945	0.65173	0.03827	0.68911	29.47	0.958	0.113
1.47	0.399	0.823	1.21020	0.25980	1.50078	22.66	0.961	0.073
2.05	0.514	0.612	1.25433	0.79567	2.16655	16.42	0.962	0.056
2.43	0.609	0.437	1.06100	1.36900	2.63981	13.54	0.963	0.052
2.61	0.708	0.254	0.66316	1.94684	2.93019	16.42	0.962	0.056
2.58	0.833	0.177	0.45666	2.12334	2.96885	22.67	0.961	0.073
2.38	1.051	0.177	0.42126	1.95874	2.81377	29.48	0.958	0.113
1.99	1.599	0.177	0.35223	1.63777	2.51051	35.42	0.956	0.206
1.41	13.182	0.177	0.24957	1.16043	2.29157	39.49	0.953	0.435
0.70	-0.654	1.163	0.81397	-0.11397	0.80156	40.94	0.952	1.000
0.08	-0.036	1.009	0.08072	-0.00072	0.07901	39.48	0.953	2.301

$\rho_{\|}$	$\tau_{r\perp}$	$\tau_{r\|}$	τ_r	τ	$(\tau\alpha)_b$	θ_2' (deg)	$\rho_{\perp}'$	$\rho_{\|}'$
0.125	0.394	0.778	0.586	0.559	0.536	34.58	0.185	0.0014
0.004	0.658	0.991	0.825	0.788	0.756	34.58	0.185	0.0014
0.005	0.797	0.989	0.893	0.856	0.821	34.58	0.185	0.0014
0.021	0.864	0.959	0.911	0.876	0.840	34.58	0.185	0.0014
0.032	0.893	0.938	0.916	0.881	0.845	34.58	0.185	0.0014
0.036	0.902	0.931	0.916	0.882	0.846	34.58	0.185	0.0014
0.032	0.893	0.938	0.916	0.881	0.845	34.58	0.185	0.0014
0.021	0.864	0.959	0.911	0.876	0.840	34.58	0.185	0.0014
0.005	0.797	0.989	0.893	0.856	0.821	34.58	0.185	0.0014
0.005	0.658	0.991	0.825	0.788	0.756	34.58	0.185	0.0014
0.125	0.394	0.778	0.586	0.558	0.536	34.58	0.185	0.0014
1.001	0.000	-0.001	0.000	0.000	0.000	34.58	0.185	0.0014
8.025	-0.394	-0.778	-0.586	-0.559	-0.536	34.58	0.185	0.0014

$\tau_{r\perp}'$	$\tau_{r\|}'$	τ_r'	τ_a'	τ'	$(\tau\alpha)_d$	S (MJ/m^2h)	V (m/s)	$h_{w\ (W/m^2 k)}$
0.687	0.997	0.842	0.956	0.805	0.772	0.000	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	0.053	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	0.535	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	1.180	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	1.741	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	2.157	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	2.429	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	2.463	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	2.291	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	1.904	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	1.287	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	0.619	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	0.062	3	11.8

f	C	$T_{p\ (K)}$	$T_{a\ (K)}$	$U_{t(MJ/m^2 hK)}$	$U_{L(MJ/m^2 hK)}$	$Q_L/A_{c(MJ/m^2 h)}$	$Q_u/A_{c(MJ/m^2 h)}$	η_i
0.652	327	333	296.4	0.0212	0.0253	0.925	-0.925	#DIV/0!
0.652	327	333	296.4	0.0212	0.0253	0.925	-0.872	-260.74
0.652	327	333	296.4	0.0212	0.0253	0.925	-0.391	-56.70
0.652	327	333	296.4	0.0212	0.0253	0.925	0.255	16.97
0.652	327	333	296.4	0.0212	0.0253	0.925	0.816	37.66
0.652	327	333	296.4	0.0212	0.0253	0.925	1.231	46.65
0.652	327	333	296.4	0.0212	0.0253	0.925	1.504	51.31
0.652	327	333	296.4	0.0212	0.0253	0.925	1.538	51.80
0.652	327	333	296.4	0.0212	0.0253	0.925	1.365	48.52
0.652	327	333	296.4	0.0212	0.0253	0.925	0.978	38.98
0.652	327	333	296.4	0.0212	0.0253	0.925	0.362	15.78
0.652	327	333	296.4	0.0212	0.0253	0.925	-0.306	-38.18
0.652	327	333	300.2	0.0212	0.0253	0.829	-0.768	-971.44

Table 6.5: Calculatoins of Solar Flux (April)

April								
N	SST	B	E (min.)	LST	ϕ (deg)	β (deg)	δ (deg)	ω (deg)
105	7	23.736	-0.223	7.163	15.5	15.5	9.37	-72.56
105	8	23.736	-0.223	8.163	15.5	15.5	9.37	-57.56
105	9	23.736	-0.223	9.163	15.5	15.5	9.37	-42.56
105	10	23.736	-0.223	10.163	15.5	15.5	9.37	-27.56
105	11	23.736	-0.223	11.163	15.5	15.5	9.37	-12.56
105	12	23.736	-0.223	12.163	15.5	15.5	9.37	2.44
105	13	23.736	-0.223	13.163	15.5	15.5	9.37	17.44
105	14	23.736	-0.223	14.163	15.5	15.5	9.37	32.44
105	15	23.736	-0.223	15.163	15.5	15.5	9.37	47.44
105	16	23.736	-0.223	16.163	15.5	15.5	9.37	62.44
105	17	23.736	-0.223	17.163	15.5	15.5	9.37	77.44
105	18	23.736	-0.223	18.163	15.5	15.5	9.37	92.44
105	19	23.736	-0.223	19.163	15.5	15.5	9.37	107.44

cosθ	θ(deg)	cos	R_b	R_d	R_r	$\omega_{1(deg)}$	$\omega_{2(deg)}$	$I_{o(MJ/m^2 hr)}$
0.2958	72.80	0.3285	0.900	0.982	0.004	-72.56	-57.56	2.144
0.5293	58.04	0.5536	0.956	0.982	0.004	-57.56	-42.56	3.154
0.7268	43.38	0.7439	0.977	0.982	0.004	-42.56	-27.56	3.963
0.8747	28.99	0.8864	0.987	0.982	0.004	-27.56	-12.56	4.516
0.9631	15.62	0.9715	0.991	0.982	0.004	-12.56	2.44	4.776
0.9858	9.68	0.9934	0.992	0.982	0.004	2.44	17.44	4.725
0.9413	19.73	0.9506	0.990	0.982	0.004	17.44	32.44	4.367
0.8327	33.63	0.8459	0.984	0.982	0.004	32.44	47.44	3.725
0.6673	48.14	0.6865	0.972	0.982	0.004	47.44	62.44	2.843
0.4564	62.84	0.4834	0.944	0.982	0.004	62.44	77.44	1.783
0.2145	77.61	0.2502	0.857	0.982	0.004	77.44	92.44	0.615
-0.0421	92.41	0.0030	-14.186	0.982	0.004	92.44	107.44	-0.581
-0.2958	107.20	-0.2415	1.225	0.982	0.004	107.44	122.44	-1.722

$I_{g(MJ/m^2 h)}$	K_T	I_d/I	$I_{d\ (MJ/m^2 h)}$	$I_{b\ (MJ/m^2 h)}$	$I_{T(MJ/m^2 h)}$	$\theta_{2(deg)}$	τ_a	$\rho_\perp$
0.02	0.009	0.998	0.01995	0.00005	0.01971	38.75	0.954	0.362
0.53	0.168	0.958	0.50782	0.02218	0.52172	33.78	0.956	0.169
1.36	0.343	0.915	1.24378	0.11622	1.33966	26.75	0.959	0.093
2.09	0.463	0.706	1.47453	0.61547	2.06266	18.52	0.962	0.061
2.59	0.542	0.559	1.44851	1.14149	2.56311	10.16	0.963	0.048
2.93	0.620	0.416	1.21920	1.71080	2.90529	6.33	0.963	0.045
3.06	0.701	0.268	0.81891	2.24109	3.03436	12.78	0.963	0.051
3.02	0.811	0.177	0.53454	2.48546	2.98239	21.28	0.961	0.068
2.77	0.974	0.177	0.49029	2.27971	2.70725	29.21	0.958	0.111
2.38	1.335	0.177	0.42126	1.95874	2.27193	35.67	0.955	0.213
1.78	2.895	0.177	0.31506	1.46494	1.57165	39.80	0.953	0.477
1.09	-1.877	1.467	1.59956	-0.50956	8.80329	40.90	0.952	1.157
0.37	-0.215	1.054	0.38980	-0.01980	0.35981	38.75	0.954	2.761

$\rho_{\parallel}$	$\tau_{r\perp}$	$\tau_{r\parallel}$	τ_r	τ	$(\tau\alpha)_b$	θ_2' (deg)	$\rho_{\perp}'$	$\rho_{\parallel}'$
0.071	0.468	0.867	0.668	0.637	0.611	34.58	0.185	0.0014
0.000	0.711	1.000	0.855	0.818	0.785	34.58	0.185	0.0014
0.012	0.830	0.977	0.904	0.867	0.832	34.58	0.185	0.0014
0.029	0.885	0.944	0.915	0.880	0.844	34.58	0.185	0.0014
0.039	0.909	0.925	0.917	0.883	0.847	34.58	0.185	0.0014
0.042	0.914	0.920	0.917	0.883	0.848	34.58	0.185	0.0014
0.037	0.904	0.929	0.916	0.882	0.847	34.58	0.185	0.0014
0.024	0.872	0.954	0.913	0.877	0.842	34.58	0.185	0.0014
0.006	0.801	0.988	0.895	0.857	0.823	34.58	0.185	0.0014
0.006	0.648	0.988	0.818	0.782	0.750	34.58	0.185	0.0014
0.162	0.354	0.721	0.538	0.512	0.492	34.58	0.185	0.0014
1.406	-0.073	-0.169	-0.121	-0.115	-0.110	34.58	0.185	0.0014
14.049	-0.468	-0.867	-0.668	-0.637	-0.611	34.58	0.185	0.0014

$\tau_{r\perp}'$	$\tau_{r\parallel}'$	τ_r'	τ_a'	τ'	$(\tau\alpha)_d$	S (MJ/m^2h)	V (m/s)	$h_{w\ (W/m^2 k)}$
0.687	0.997	0.842	0.956	0.805	0.772	0.015	4	14.8
0.687	0.997	0.842	0.956	0.805	0.772	0.403	4	14.8
0.687	0.997	0.842	0.956	0.805	0.772	1.042	4	14.8
0.687	0.997	0.842	0.956	0.805	0.772	1.637	4	14.8
0.687	0.997	0.842	0.956	0.805	0.772	2.064	4	14.8
0.687	0.997	0.842	0.956	0.805	0.772	2.372	4	14.8
0.687	0.997	0.842	0.956	0.805	0.772	2.509	4	14.8
0.687	0.997	0.842	0.956	0.805	0.772	2.474	4	14.8
0.687	0.997	0.842	0.956	0.805	0.772	2.203	4	14.8
0.687	0.997	0.842	0.956	0.805	0.772	1.714	4	14.8
0.687	0.997	0.842	0.956	0.805	0.772	0.861	4	14.8
0.687	0.997	0.842	0.956	0.805	0.772	0.419	4	14.8
0.687	0.997	0.842	0.956	0.805	0.772	0.311	4	14.8

f	C	$T_{p\ (K)}$	$T_{a\ (K)}$	$U_{t(MJ/m^2hK)}$	$U_{L(MJ/m^2hK)}$	$Q_L/A_{c(MJ/m^2h)}$	$Q_u/A_{c(MJ/m^2h)}$	η_i
0.565	327	333	304.8	0.0223	0.0264	0.744	-0.729	-3700.78
0.565	327	333	304.8	0.0223	0.0264	0.744	-0.341	-65.3949
0.565	327	333	304.8	0.0223	0.0264	0.744	0.297	22.18129
0.565	327	333	304.8	0.0223	0.0264	0.744	0.892	43.26806
0.565	327	333	304.8	0.0223	0.0264	0.744	1.320	51.49956
0.565	327	333	304.8	0.0223	0.0264	0.744	1.627	56.01205
0.565	327	333	304.8	0.0223	0.0264	0.744	1.764	58.13696
0.565	327	333	304.8	0.0223	0.0264	0.744	1.729	57.97759
0.565	327	333	304.8	0.0223	0.0264	0.744	1.458	53.86283
0.565	327	333	304.8	0.0223	0.0264	0.744	0.969	42.67065
0.565	327	333	304.8	0.0223	0.0264	0.744	0.117	7.432461
0.565	327	333	304.8	0.0223	0.0264	0.744	-0.326	-3.702
0.565	327	333	304.8	0.0223	0.0264	0.744	-0.433	-120.335

Table 6.6: Calculatoins of Solar Flux (June)

June								
N	SST	B	E (min.)	LST	ϕ (deg)	β (deg)	δ (deg)	ω (deg)
162	7	80.109	0.569	7.176	15.5	15.5	23.08	-72.36
162	8	80.109	0.569	8.176	15.5	15.5	23.08	-57.36
162	9	80.109	0.569	9.176	15.5	15.5	23.08	-42.36
162	10	80.109	0.569	10.176	15.5	15.5	23.08	-27.36
162	11	80.109	0.569	11.176	15.5	15.5	23.08	-12.36
162	12	80.109	0.569	12.176	15.5	15.5	23.08	2.64
162	13	80.109	0.569	13.176	15.5	15.5	23.08	17.64
162	14	80.109	0.569	14.176	15.5	15.5	23.08	32.64
162	15	80.109	0.569	15.176	15.5	15.5	23.08	47.64
162	16	80.109	0.569	16.176	15.5	15.5	23.08	62.64
162	17	80.109	0.569	17.176	15.5	15.5	23.08	77.64
162	18	80.109	0.569	18.176	15.5	15.5	23.08	92.64
162	19	80.109	0.569	19.176	15.5	15.5	23.08	107.64

$\cos\theta$	θ(deg)	$\cos\theta_z$	R_b	R_d	R_r	$\omega_{1(deg)}$	$\omega_{2(deg)}$	$I_{o(MJ/m^2 hr)}$
0.2788	73.81	0.3734	0.747	0.982	0.004	-72.36	-57.36	2.269
0.4962	60.25	0.5829	0.851	0.982	0.004	-57.36	-42.36	3.187
0.6798	47.17	0.7598	0.895	0.982	0.004	-42.36	-27.36	3.921
0.8171	35.21	0.8921	0.916	0.982	0.004	-27.36	-12.36	4.421
0.8987	26.02	0.9707	0.926	0.982	0.004	-12.36	2.64	4.654
0.9190	23.22	0.9903	0.928	0.982	0.004	2.64	17.64	4.604
0.8767	28.75	0.9496	0.923	0.982	0.004	17.64	32.64	4.274
0.7747	39.22	0.8512	0.910	0.982	0.004	32.64	47.64	3.686
0.6198	51.70	0.7020	0.883	0.982	0.004	47.64	62.64	2.881
0.4228	64.99	0.5121	0.825	0.982	0.004	62.64	77.64	1.914
0.1969	78.64	0.2945	0.669	0.982	0.004	77.64	92.64	0.849
-0.0424	92.43	0.0639	-0.664	0.982	0.004	92.64	107.64	-0.239
-0.2788	106.19	-0.1639	1.701	0.982	0.004	107.64	122.64	-1.277

$I_{g(MJ/m^2 h)}$	K_T	I_d/I	$I_{d\ (MJ/m^2 h)}$	$I_{b\ (MJ/m^2 h)}$	$I_{T(MJ/m^2 h)}$	$\theta_{2(deg)}$	τ_a	$\rho_\perp$
0.02	0.009	0.998	0.01996	0.00004	0.01970	39.00	0.954	0.384
0.57	0.179	0.955	0.54461	0.02539	0.55839	34.68	0.956	0.188
1.24	0.316	0.921	1.14235	0.09765	1.21345	28.72	0.959	0.106
1.85	0.418	0.787	1.45611	0.39389	1.79712	22.20	0.961	0.071
2.24	0.481	0.671	1.50411	0.73589	2.16617	16.70	0.962	0.057
2.51	0.545	0.554	1.39033	1.11967	2.41321	14.97	0.962	0.054
2.56	0.599	0.455	1.16453	1.39547	2.44106	18.37	0.962	0.060
2.55	0.692	0.284	0.72468	1.82532	2.38191	24.48	0.960	0.081
2.36	0.819	0.177	0.41772	1.94228	2.13357	30.95	0.958	0.128
1.97	1.029	0.177	0.34869	1.62131	1.68790	36.43	0.955	0.238
1.52	1.790	0.177	0.26904	1.25096	1.10609	39.98	0.953	0.507
0.44	-1.840	1.458	0.64163	-0.20163	0.76544	40.90	0.952	1.159
0.38	-0.297	1.074	0.40815	-0.02815	0.35423	39.00	0.954	2.607

$\rho_{\parallel}$	$\tau_{r\perp}$	$\tau_{r\parallel}$	τ_r	τ	$(\tau\alpha)_b$	θ_2' (deg)	$\rho_{\perp}'$	$\rho_{\parallel}'$
0.086	0.446	0.842	0.644	0.614	0.589	34.58	0.185	0.0014
0.002	0.684	0.997	0.840	0.803	0.771	34.58	0.185	0.0014
0.007	0.808	0.986	0.897	0.860	0.825	34.58	0.185	0.0014
0.022	0.867	0.957	0.912	0.876	0.841	34.58	0.185	0.0014
0.032	0.892	0.939	0.916	0.881	0.845	34.58	0.185	0.0014
0.034	0.898	0.934	0.916	0.882	0.846	34.58	0.185	0.0014
0.029	0.886	0.944	0.915	0.880	0.844	34.58	0.185	0.0014
0.017	0.851	0.967	0.909	0.873	0.837	34.58	0.185	0.0014
0.002	0.774	0.995	0.884	0.847	0.813	34.58	0.185	0.0014
0.012	0.616	0.976	0.796	0.760	0.729	34.58	0.185	0.0014
0.191	0.327	0.680	0.504	0.480	0.460	34.58	0.185	0.0014
1.410	-0.073	-0.170	-0.122	-0.116	-0.111	34.58	0.185	0.0014
11.695	-0.446	-0.842	-0.644	-0.614	-0.589	34.58	0.185	0.0014

$\tau_{r\perp}'$	$\tau_{r\parallel}'$	τ_r'	τ_a'	τ'	$(\tau\alpha)_d$	S (MJ/m^2h)	V (m/s)	$h_{w\ (W/m^2 k)}$
0.687	0.997	0.842	0.956	0.805	0.772	0.015	2.5	10.3
0.687	0.997	0.842	0.956	0.805	0.772	0.431	2.5	10.3
0.687	0.997	0.842	0.956	0.805	0.772	0.942	2.5	10.3
0.687	0.997	0.842	0.956	0.805	0.772	1.413	2.5	10.3
0.687	0.997	0.842	0.956	0.805	0.772	1.723	2.5	10.3
0.687	0.997	0.842	0.956	0.805	0.772	1.941	2.5	10.3
0.687	0.997	0.842	0.956	0.805	0.772	1.978	2.5	10.3
0.687	0.997	0.842	0.956	0.805	0.772	1.948	2.5	10.3
0.687	0.997	0.842	0.956	0.805	0.772	1.717	2.5	10.3
0.687	0.997	0.842	0.956	0.805	0.772	1.246	2.5	10.3
0.687	0.997	0.842	0.956	0.805	0.772	0.593	2.5	10.3
0.687	0.997	0.842	0.956	0.805	0.772	0.473	2.5	10.3
0.687	0.997	0.842	0.956	0.805	0.772	0.339	2.5	10.3

f	C	$T_{p\ (K)}$	$T_{a\ (K)}$	$U_{t(MJ/m^2hK)}$	$U_{L(MJ/m^2hK)}$	$Q_L/A_{c(MJ/m^2h)}$	$Q_u/A_{c(MJ/m^2h)}$	η_i
0.699	327	333	307.3	0.0206	0.0246	0.633	-0.618	-3135.12
0.699	327	333	307.3	0.0206	0.0246	0.633	-0.201	-36.08
0.699	327	333	307.3	0.0206	0.0246	0.633	0.309	25.48
0.699	327	333	307.3	0.0206	0.0246	0.633	0.780	43.41
0.699	327	333	307.3	0.0206	0.0246	0.633	1.090	50.32
0.699	327	333	307.3	0.0206	0.0246	0.633	1.308	54.19
0.699	327	333	307.3	0.0206	0.0246	0.633	1.345	55.12
0.699	327	333	307.3	0.0206	0.0246	0.633	1.315	55.20
0.699	327	333	307.3	0.0206	0.0246	0.633	1.084	50.83
0.699	327	333	307.3	0.0206	0.0246	0.633	0.613	36.34
0.699	327	333	307.3	0.0206	0.0246	0.633	-0.039	-3.56
0.699	327	333	307.3	0.0206	0.0246	0.633	-0.160	-20.88
0.699	327	333	307.3	0.0206	0.0246	0.633	-0.294	-82.98

Table 6.7: Calculatoins of Solar Flux (August)

August								
N	SST	B	E (min.)	LST	ϕ (deg)	β (deg)	δ (deg)	ω (deg)
228	7	145.383	-3.884	7.102	15.5	15.5	13.51	-73.47
228	8	145.383	-3.884	8.102	15.5	15.5	13.51	-58.47
228	9	145.383	-3.884	9.102	15.5	15.5	13.51	-43.47
228	10	145.383	-3.884	10.102	15.5	15.5	13.51	-28.47
228	11	145.383	-3.884	11.102	15.5	15.5	13.51	-13.47
228	12	145.383	-3.884	12.102	15.5	15.5	13.51	1.53
228	13	145.383	-3.884	13.102	15.5	15.5	13.51	16.53
228	14	145.383	-3.884	14.102	15.5	15.5	13.51	31.53
228	15	145.383	-3.884	15.102	15.5	15.5	13.51	46.53
228	16	145.383	-3.884	16.102	15.5	15.5	13.51	61.53
228	17	145.383	-3.884	17.102	15.5	15.5	13.51	76.53
228	18	145.383	-3.884	18.102	15.5	15.5	13.51	91.53
228	19	145.383	-3.884	19.102	15.5	15.5	13.51	106.53

$\cos\theta$	θ(deg)	$\cos\theta_z$	R_b	R_d	R_r	$\omega_{1(deg)}$	$\omega_{2(deg)}$	$I_{o(MJ/m^2 hr)}$
0.2766	73.94	0.3290	0.841	0.982	0.004	-73.47	-58.47	2.108
0.5085	59.44	0.5524	0.920	0.982	0.004	-58.47	-43.47	3.097
0.7057	45.12	0.7424	0.950	0.982	0.004	-43.47	-28.47	3.896
0.8547	31.27	0.8861	0.965	0.982	0.004	-28.47	-13.47	4.449
0.9456	18.99	0.9736	0.971	0.982	0.004	-13.47	1.53	4.719
0.9720	13.59	0.9991	0.973	0.982	0.004	1.53	16.53	4.688
0.9322	21.23	0.9607	0.970	0.982	0.004	16.53	31.53	4.358
0.8288	34.02	0.8611	0.963	0.982	0.004	31.53	46.53	3.751
0.6690	48.01	0.7070	0.946	0.982	0.004	46.53	61.53	2.909
0.4635	62.38	0.5091	0.911	0.982	0.004	61.53	76.53	1.889
0.2265	76.91	0.2807	0.807	0.982	0.004	76.53	91.53	0.760
-0.0259	91.49	0.0374	-0.693	0.982	0.004	91.53	106.53	-0.400
-0.2766	106.06	-0.2042	1.355	0.982	0.004	106.53	121.53	-1.512

$I_{g(MJ/m^2 h)}$	K_T	I_d/I	$I_{d\ (MJ/m^2 h)}$	$I_{b\ (MJ/m^2 h)}$	$I_{T(MJ/m^2 h)}$	$\theta_{2(deg)}$	τ_a	$\rho_\perp$
0.01	0.005	0.999	0.00999	0.00001	0.00985	39.03	0.953	0.386
0.40	0.129	0.968	0.38714	0.01286	0.39339	34.35	0.956	0.181
1.04	0.267	0.934	0.97086	0.06914	1.02271	27.67	0.959	0.099
1.72	0.387	0.846	1.45445	0.26555	1.69042	19.89	0.961	0.064
2.17	0.460	0.711	1.54267	0.62733	2.13178	12.31	0.963	0.050
2.50	0.533	0.576	1.43950	1.06050	2.45419	8.86	0.963	0.047
2.69	0.617	0.421	1.13314	1.55686	2.63297	13.72	0.963	0.052
2.44	0.650	0.360	0.87871	1.56129	2.37438	21.51	0.961	0.069
2.12	0.729	0.216	0.45796	1.66204	2.02985	29.15	0.959	0.110
1.59	0.842	0.177	0.28143	1.30857	1.47356	35.50	0.956	0.208
0.95	1.250	0.177	0.16815	0.78185	0.79949	39.66	0.953	0.458
0.33	-0.825	1.205	0.39781	-0.06781	0.43880	40.93	0.952	1.094
0.01	-0.007	1.002	0.01002	-0.00002	0.010	39.03	0.953	2.588

$\rho_{\parallel}$	$\tau_{r\perp}$	$\tau_{r\parallel}$	τ_r	τ	$(\tau\alpha)_b$	θ_2' (deg)	$\rho_{\perp}'$	$\rho_{\parallel}'$
0.088	0.443	0.839	0.641	0.611	0.586	34.58	0.185	0.0014
0.001	0.694	0.998	0.846	0.809	0.776	34.58	0.185	0.0014
0.009	0.821	0.981	0.901	0.864	0.829	34.58	0.185	0.0014
0.026	0.879	0.949	0.914	0.879	0.843	34.58	0.185	0.0014
0.037	0.905	0.929	0.917	0.882	0.847	34.58	0.185	0.0014
0.040	0.911	0.923	0.917	0.883	0.847	34.58	0.185	0.0014
0.035	0.901	0.931	0.916	0.882	0.846	34.58	0.185	0.0014
0.023	0.871	0.955	0.913	0.877	0.842	34.58	0.185	0.0014
0.006	0.802	0.988	0.895	0.858	0.823	34.58	0.185	0.0014
0.005	0.655	0.990	0.823	0.786	0.754	34.58	0.185	0.0014
0.145	0.372	0.747	0.560	0.533	0.512	34.58	0.185	0.0014
1.233	-0.045	-0.105	-0.075	-0.071	-0.068	34.58	0.185	0.0014
11.428	-0.443	-0.839	-0.641	-0.611	-0.586	34.58	0.185	0.0014

$\tau_{r\perp}'$	$\tau_{r\parallel}'$	τ_r'	τ_a'	τ'	$(\tau\alpha)_d$	S (MJ/m^2h)	V (m/s)	$h_{w\ (W/m^2\ k)}$
0.687	0.997	0.842	0.956	0.805	0.772	0.008	3.5	13.3
0.687	0.997	0.842	0.956	0.805	0.772	0.304	3.5	13.3
0.687	0.997	0.842	0.956	0.805	0.772	0.794	3.5	13.3
0.687	0.997	0.842	0.956	0.805	0.772	1.324	3.5	13.3
0.687	0.997	0.842	0.956	0.805	0.772	1.692	3.5	13.3
0.687	0.997	0.842	0.956	0.805	0.772	1.973	3.5	13.3
0.687	0.997	0.842	0.956	0.805	0.772	2.146	3.5	13.3
0.687	0.997	0.842	0.956	0.805	0.772	1.938	3.5	13.3
0.687	0.997	0.842	0.956	0.805	0.772	1.648	3.5	13.3
0.687	0.997	0.842	0.956	0.805	0.772	1.117	3.5	13.3
0.687	0.997	0.842	0.956	0.805	0.772	0.453	3.5	13.3
0.687	0.997	0.842	0.956	0.805	0.772	0.299	3.5	13.3
0.687	0.997	0.842	0.956	0.805	0.772	0.008	3.5	13.3

f	C	$T_{p\ (K)}$	$T_{a\ (K)}$	$U_{t(MJ/m^2\ hK)}$	$U_{L(MJ/m^2\ hK)}$	$Q_L/A_{c(MJ/m^2\ h)}$	$Q_u/A_{c(MJ/m^2\ h)}$	η_i
0.607	327	333	303.5	0.0218	0.0259	0.763	-0.755	-7663.53
0.607	327	333	303.5	0.0218	0.0259	0.763	-0.459	-116.61
0.607	327	333	303.5	0.0218	0.0259	0.763	0.031	3.04
0.607	327	333	303.5	0.0218	0.0259	0.763	0.561	33.20
0.607	327	333	303.5	0.0218	0.0259	0.763	0.929	43.59
0.607	327	333	303.5	0.0218	0.0259	0.763	1.210	49.32
0.607	327	333	303.5	0.0218	0.0259	0.763	1.383	52.52
0.607	327	333	303.5	0.0218	0.0259	0.763	1.175	49.50
0.607	327	333	303.5	0.0218	0.0259	0.763	0.885	43.59
0.607	327	333	303.5	0.0218	0.0259	0.763	0.354	24.01
0.607	327	333	303.5	0.0218	0.0259	0.763	-0.310	-38.73
0.607	327	333	303.5	0.0218	0.0259	0.763	-0.463	-105.57
0.607	327	333	303.5	0.0218	0.0259	0.763	-0.755	-666.73

Table 6.8: Calculatoins of Solar Flux (January 2)

January								
N	SST	B	E (min.)	LST	ϕ (deg)	β (deg)	δ (deg)	ω (deg)
17	9	-63.296	-9.968	9.001	15.5	15.5	-20.93	-44.99
17	10	-63.296	-9.968	10.001	15.5	15.5	-20.93	-29.99
17	11	-63.296	-9.968	11.001	15.5	15.5	-20.93	-14.99
17	12	-63.296	-9.968	12.001	15.5	15.5	-20.93	0.01
17	13	-63.296	-9.968	13.001	15.5	15.5	-20.93	15.01
17	14	-63.296	-9.968	14.001	15.5	15.5	-20.93	30.01
17	15	-63.296	-9.968	15.001	15.5	15.5	-20.93	45.01
17	16	-63.296	-9.968	16.001	15.5	15.5	-20.93	60.01
17	17	-63.296	-9.968	17.001	15.5	15.5	-20.93	75.01

$\cos\theta$	θ(deg)	cos	R_b	R_d	R_r	$\omega_{1(deg)}$	$\omega_{2(deg)}$	$I_{o(MJ/m^2 hr)}$
0.6605	48.66	0.5410	1.221	0.982	0.004	-44.99	-29.99	3.10
0.8089	36.01	0.6840	1.183	0.982	0.004	-29.99	-14.99	3.69
0.9022	25.55	0.7739	1.166	0.982	0.004	-14.99	0.01	3.99
0.9340	20.93	0.8045	1.161	0.982	0.004	0.01	15.01	3.99
0.9021	25.56	0.7738	1.166	0.982	0.004	15.01	30.01	3.69
0.8088	36.02	0.6839	1.183	0.982	0.004	30.01	45.01	3.10
0.6603	48.67	0.5408	1.221	0.982	0.004	45.01	60.01	2.26
0.4669	62.17	0.3544	1.317	0.982	0.004	60.01	75.01	1.24
0.2416	76.02	0.1373	1.759	0.982	0.004	75.01	90.01	0.11

$I_{g(MJ/m^2 h)}$	K_T	I_d/I	$I_{d\ (MJ/m^2 h)}$	$I_{b\ (MJ/m^2 h)}$	$I_{T(MJ/m^2 h)}$	$\theta_{2(deg)}$	τ_a	$\rho_\perp$
0.69	0.223	0.945	0.652	0.038	0.689	29.47	0.958	0.113
1.47	0.399	0.823	1.210	0.260	1.501	22.66	0.961	0.073
2.05	0.514	0.612	1.254	0.796	2.167	16.42	0.962	0.056
2.43	0.609	0.437	1.061	1.369	2.640	13.54	0.963	0.052
2.61	0.708	0.254	0.663	1.947	2.930	16.42	0.962	0.056
2.58	0.833	0.177	0.457	2.123	2.969	22.67	0.961	0.073
2.38	1.051	0.177	0.421	1.959	2.814	29.48	0.958	0.113
1.99	1.599	0.177	0.352	1.638	2.511	35.42	0.956	0.206
1.41	13.182	0.177	0.250	1.160	2.292	39.49	0.953	0.435

$\rho_{\|}$	$\tau_{r\perp}$	$\tau_{r\|}$	τ_r	τ	$(\tau\alpha)_b$	θ_2' (deg)	$\rho_\perp'$	$\rho_{\|}'$
0.005	0.797	0.989	0.893	0.856	0.821	34.58	0.185	0.0014
0.021	0.864	0.959	0.911	0.876	0.840	34.58	0.185	0.0014
0.032	0.893	0.938	0.916	0.881	0.845	34.58	0.185	0.0014
0.036	0.902	0.931	0.916	0.882	0.846	34.58	0.185	0.0014
0.032	0.893	0.938	0.916	0.881	0.845	34.58	0.185	0.0014
0.021	0.864	0.959	0.911	0.876	0.840	34.58	0.185	0.0014
0.005	0.797	0.989	0.893	0.856	0.821	34.58	0.185	0.0014
0.005	0.658	0.991	0.825	0.788	0.756	34.58	0.185	0.0014
0.125	0.394	0.778	0.586	0.558	0.536	34.58	0.185	0.0014

$\tau_{r\perp}'$	$\tau_{r\parallel}'$	τ_r'	τ_a'	τ'	$(\tau\alpha)_d$	S (MJ/m^{2}h)	V (m/s)	$h_{w\ (W/m^2\ k)}$
0.687	0.997	0.842	0.956	0.805	0.772	0.535	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	1.180	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	1.741	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	2.157	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	2.429	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	2.463	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	2.291	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	1.904	3	11.8
0.687	0.997	0.842	0.956	0.805	0.772	1.287	3	11.8

f	C	$T_{p\ (K)}$	$T_{a\ (K)}$	$U_{t(MJ/m^2\ hK)}$	$U_{L(MJ/m^2\ hK)}$	$Q_L/A_{c(MJ/m^2\ h)}$	$Q_u/A_{c(MJ/m^2\ h)}$	η_i
0.652	327	333	296.4	0.0212	0.0253	0.925	-0.391	-56.70
0.652	327	333	296.4	0.0212	0.0253	0.925	0.255	16.97
0.652	327	333	296.4	0.0212	0.0253	0.925	0.816	37.66
0.652	327	333	296.4	0.0212	0.0253	0.925	1.231	46.65
0.652	327	333	296.4	0.0212	0.0253	0.925	1.504	51.31
0.652	327	333	296.4	0.0212	0.0253	0.925	1.538	51.80
0.652	327	333	296.4	0.0212	0.0253	0.925	1.365	48.52
0.652	327	333	296.4	0.0212	0.0253	0.925	0.978	38.98
0.652	327	333	296.4	0.0212	0.0253	0.925	0.362	15.78

Appendix (2) (Figures)

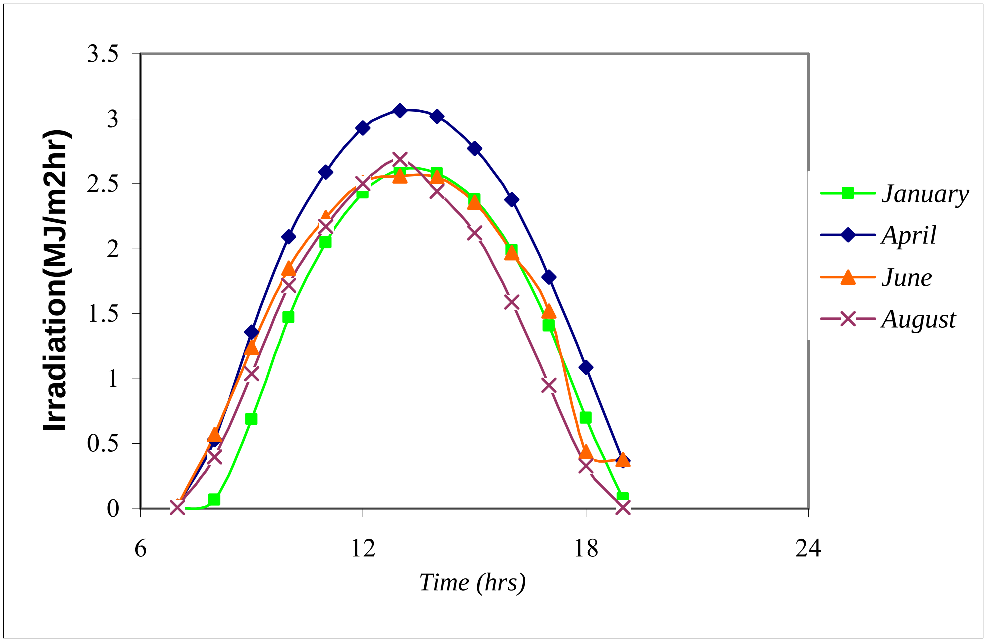

Fig: 6.3. (Irradiation (MJ/m^{2}hr) vs. Time (hrs)

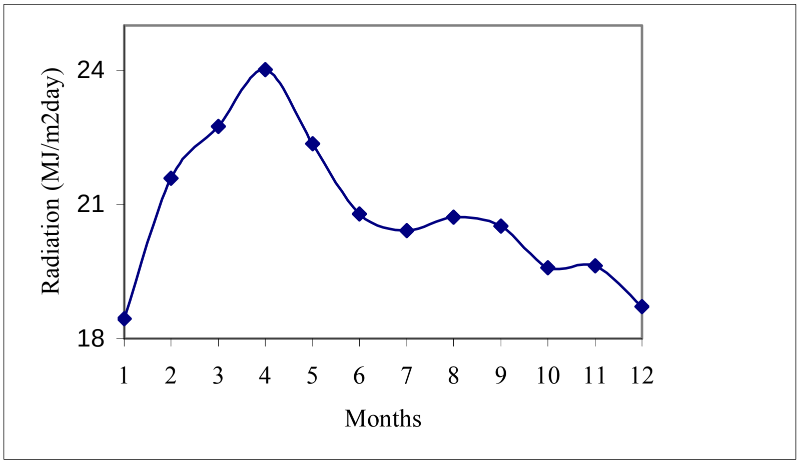

Fig: 6.4. Radiation (MJ/m^{2}day) vs. Months

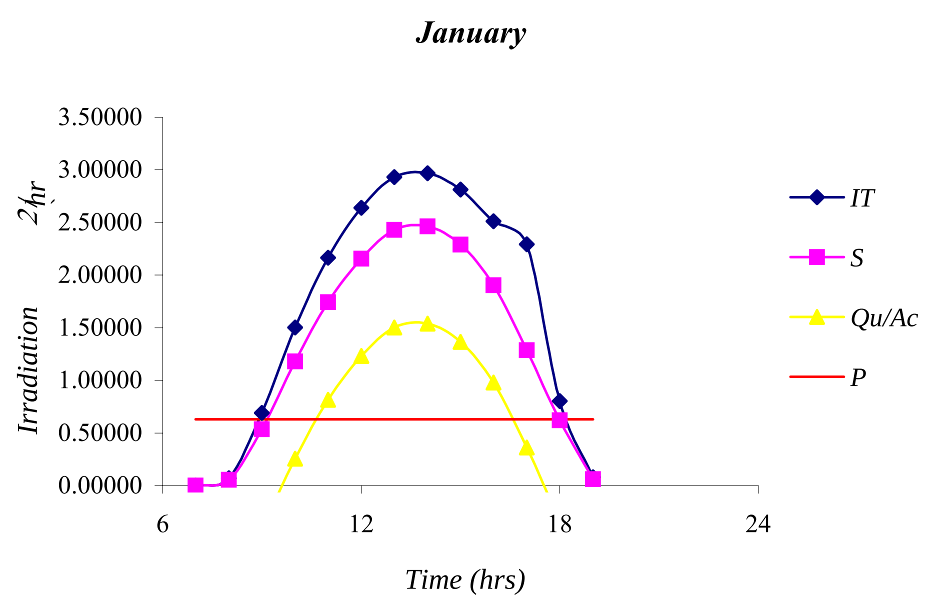

Fig: 6.5. (Irradiation (MJ/m^2hr) vs. Time (hrs). (January)

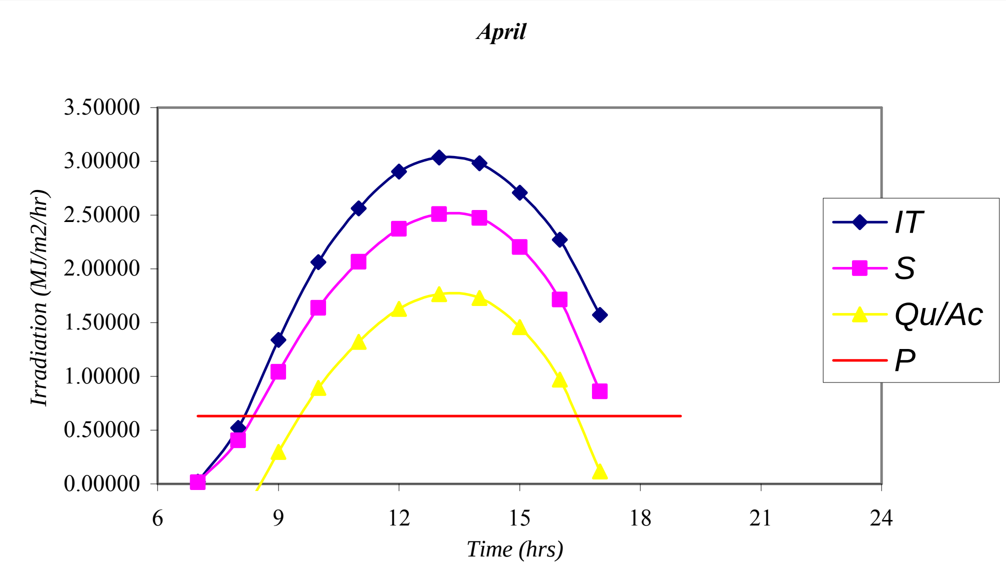

Fig: 6.6. Radiation (MJ/m^2day) vs. Time (hrs). (January)

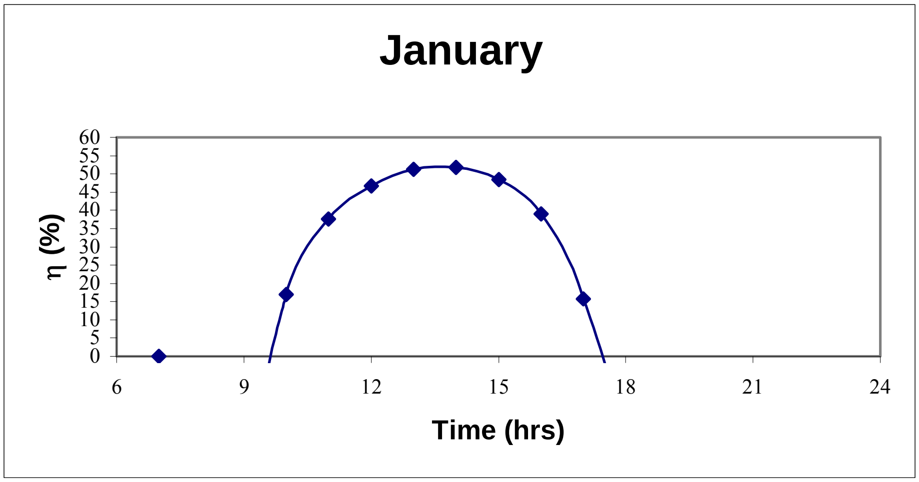

Fig: 6.7. Efficiency (%) vs. Time (hrs). (January)

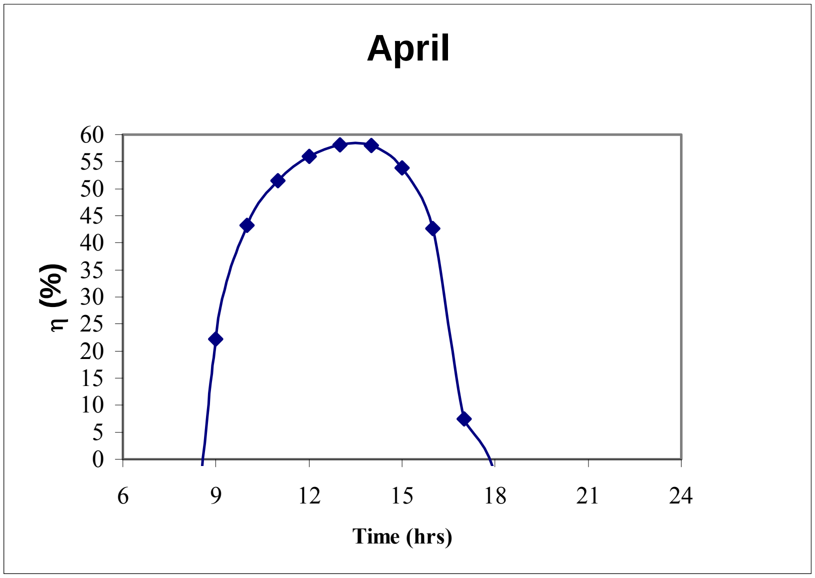

Fig: 6.8. Efficiency (%) vs. Time (hrs). (April)

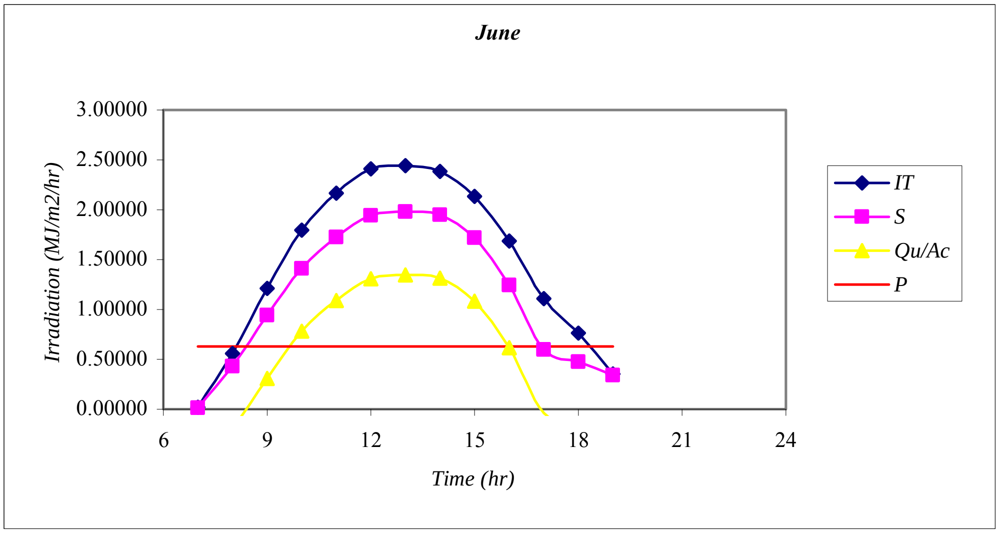

Fig: 6.9. Irradiation (MJ/m^2day) vs. Time (hrs). (June)

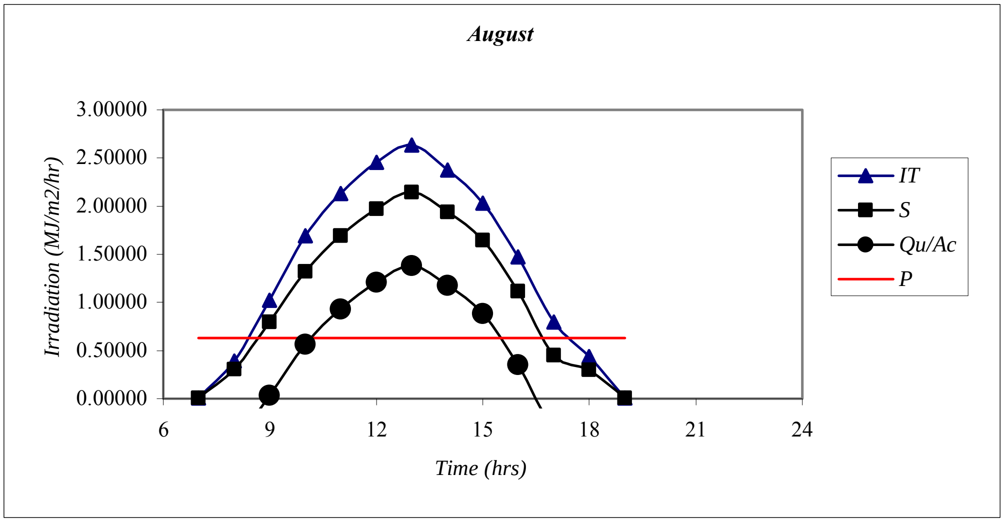

Fig: 6.10. Irradiation (MJ/m^2day) vs. Time (hrs). (August)

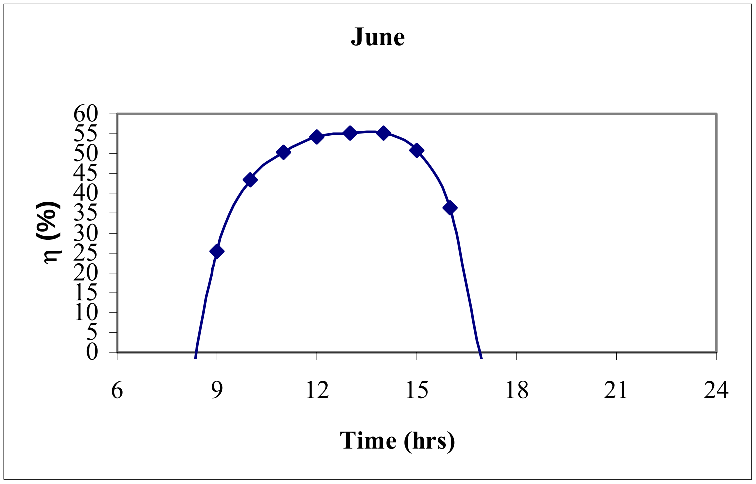

Fig: 6.11. Efficiency (%) vs. Time (hrs). (June)

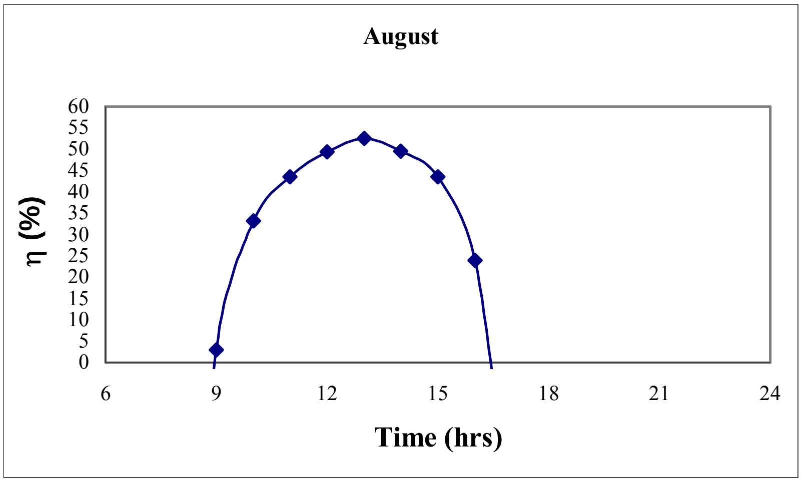

Fig: 6.12. Efficiency (%) vs. Time (hrs). (August)

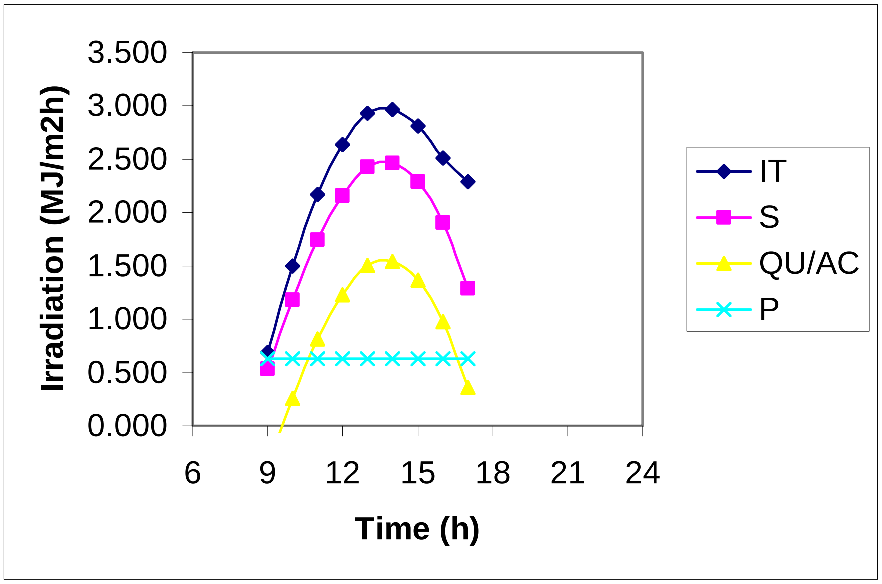

Fig: 6.14. Irradiation (MJ/m^2day) vs. Time (hrs).

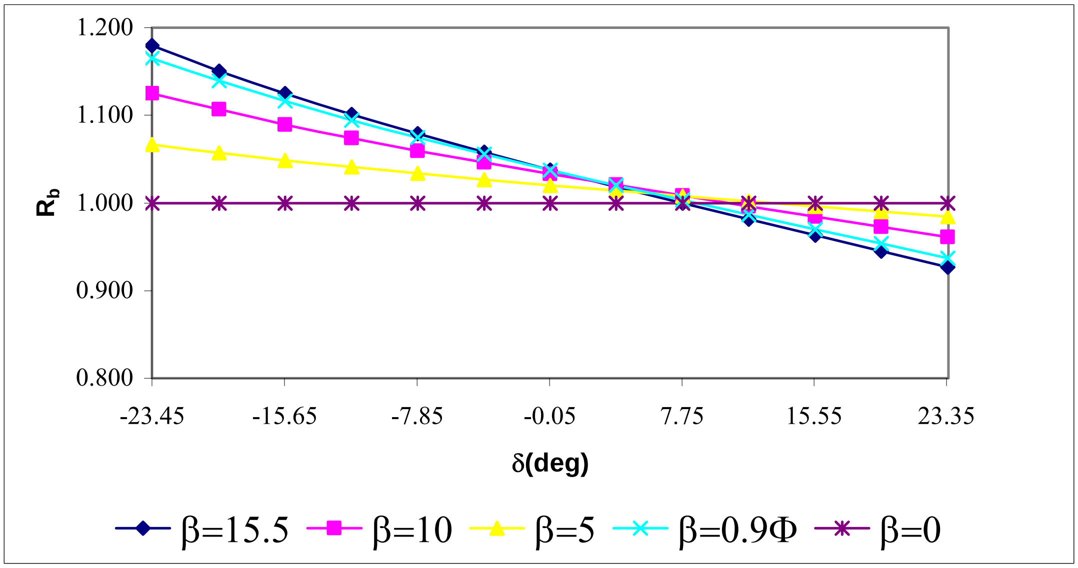

Fig: 6.14. Rb vs. Declination angle (degree).