Study to Find Out the Optimum Number of Transparent Covers and Refractive Index for the Best Performance of Sunearth Solar Water Heater Using Matlab Software

by

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ABSTRACT

Research was conducted to observe the effect of Number of Transparent Covers and Refractive Index on performance of a domestic Solar Water heating system. The enhancement of efficiency for solar thermal system is an emerging challenge. The knowledge gained from this research will enable to optimize the number of transparent covers and refractive index prior to develop a solar water heater with improved optical efficiency and thermal efficiency for the collector. Numerical simulation is conducted on the performance of the liquid flat plate collector for July 21st and October 21st from 8 am to 4 pm with different refractive index values 1.1, 1.4, 1.7 and different numbers of transparent covers (0-3). In order to accomplish the proposed method the formulation and solutions are executed using simple software MATLAB. The result demonstrates efficiency of flat plate collector increases with the increase of number of covers. The performance of collector decreases when refractive index is higher. The improved useful heat gain is obtained when number of cover used is 3 and refractive index is 1.1.

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TABLE OF CONTENTS

Page

LIST OF TABLES…....................................………………………v

LIST OF FIGURES vi

CHAPTER

1 INTRODUCTION 1

1.1 Problem Statement 6

1.2 Objective ....……… …... .. 6

2 BACKGROUND LITERATURE 7

3 METHODOLOGY 9

3.1 Description of Sunearth Flat Plate Collector 11

3.2 Flat Plate Collector Efficiency 17

3.2.1 Optical Efficiency...18

3.2.2 Thermal Efficiency...22

3.2.3 Convective Heat Transfer Coefficient into Fluid 25

3.2.4 Convective Heat Transfer Coefficient of Ambient Air 26

4 DATA ANALYSIS AND RESULT 28

4.1 Case 1 29

4.2 Case 2 36

5 CONCLUSION AND FUTURE WORK...52

REFERENCES 55

Page

APPENDIX..58

A DOWFROST^{TM} HD HEAT TRASFER FLUID PROPERTY. 58

B ASHRAE MODEL 60

C AIR PROPERTY 62

LIST OF TABLES

Table		Page
3.1	Sunearth Solar Collector Specifications	15
3.2	Specification of Sunearth Flat Plate Collector	16
4.1	Sunearth Collector Performances for July 21st & Oct 21st	44
4.2	Collector Performance with No Cover for July 21st	48
4.3	Collector Performance with 1 Cover for July 21st	48
4.4	Collector Performance with 2 Covers for July 21st	49
4.5	Collector Performance with 3 Covers for July 21st	49
4.6	Collector Performance with No Cover for Oct 21st	50
4.7	Collector Performance with 1 Cover for Oct 21st	50
4.8	Collector Performance with 2 Covers for Oct 21st	51
4.9	Collector Performance with 3 Covers for Oct 21st	51

LIST OF FIGURES

Figure Page

1.1 Direct Systems with Passive Circulation 3

1.2 Typical Active Solar Energy Collection 3

1.3 Bath Collector 4

1.4 Basic Components in Flat Plate Collector 5

3.1 Heat Losses at Flat Collector 11

3.2 Sunearth Single Tank Schematic 12

3.3 Diagram of the Sunearth Flat Collector 13

3.4 Sunearth Flat Plate Collector 14

4.1 Efficiency Versus Watch Time with No Cover, July 21st....................31

4.2 One Cover, 1.1 Refractive Index, July21st 32

4.3 One Cover, 1.4 Refractive Index, July 21st 32

4.4 One Cover, 1.7 Refractive Index, July 21st 33

4.5 Two Covers, 1.1 Refractive Index, July 21st....................33

4.6 Two Covers, 1.4 Refractive Index, July 21st....................34

4.7 Two Covers, 1.7 Refractive Index, July 21st....................34

4.8 Three Covers, 1.1 Refractive Index, July 21st....................35

4.9 Three Covers, 1.4 Refractive Index, July 21st....................35

4.10 Three Covers, 1.7 Refractive Index, July 21st....................36

4.11 Efficiency versus Watch Time with No Cover, Oct 21st....................37

4.12 One Cover, 1.1 Refractive Index, Oct 21st 38

Figure Page

4.13 One Cover, 1.4 Refractive Index, Oct 21st..38

4.14 One Cover, 1.7 Refractive Index, Oct 21st..39

4.15 Two Covers, 1.1 Refractive Index, Oct 21st...39

4.16 Two Covers, 1.4 Refractive Index, Oct 21st..40

4.17 Two Covers, 1.7 Refractive Index, Oct 21st..40

4.18 Three Covers, 1.1 Refractive Index, Oct 21st......................................41

4.19 Three Covers, 1.4 Refractive Index, Oct 21st......................................42

4.20 Three Covers, 1.7 Refractive Index, Oct 21st......................................42

4.21 Efficiency Versus Number of Covers, 1.1 Refractive Index, July 21st44

4.22 Efficiency Versus Number of Covers, 1.1 Refractive Index, Oct 21st.45

4.23 Overall Heat Loss Coefficient vs Watch Time………………………49

4.24 Overall Heat Loss Coefficient vs Watch time……………………….49

CHAPTER 1

INTRODUCTION

The United States currently relies immensely on natural gas, oil, and coal to produce energy but since fossil fuels are non-renewable, very expensive and harmful for the environment renewable energy sources are gaining popularity due to technological advancements. Increasing energy demand and environmental concerns drive the development of policy and market investments of renewable energy technologies. Federal governments, state governments and utilities offer tax rebates, credits, and other incentives to help companies and consumers make investments in renewable energy to facilitate and promote renewable energy goals. The federal tax credit for residential energy property initially applied to solar water heating systems, fuel cells and solar-electric systems [16]. In the United States, especially in Arizona with ideal combination of land area and resource has a great potentiality for solar power because the state has the second highest solar photovoltaic capacity [19]. In order to reduce energy cost with tax rebate testing and modeling solar water heating system to determine their effectiveness are becoming very significant. Therefore solar water heating systems can be deployed to decentralize energy supply to decrease the need for extension of the grid capacity and save capital.

Renewable energy comes from replenished resource such as sunlight, wind, rain, tides, waves and geothermal heat. Solar energy is one of the renewable energy which provides a compelling solution to meet needs and abundant sources of energy in future. Solar water heating system is one of the simplest and most direct applications of convergence of solar radiation into heat. Function wise, solar water heaters have two different technologies: circulation types and collector types.

There are two types of Circulation systems: the direct system and the indirect system. In the direct system, portable water directly flows through the collector while in the indirect system a non-freezing heat transfer fluid runs through the collector. In the indirect system The heat transfer fluid (HTF) passes on its heat to the water through a heat exchanger and the most common fluid used in this system is a mixture of water and propylene glycol to avoid freezing. In the direct system the water sent directly to the solar water collector is at risk of freezing in cold climates but it works well in warm climates. Two types of water heating systems are in the direct systems: active which have circulating pumps to force water through the collectors and passive which don't have pumps but the hot water rising through natural convection will move the water from the collector to storage tank when it heats up [20].

A direct passive circulated system is depicted below in figure 1.1

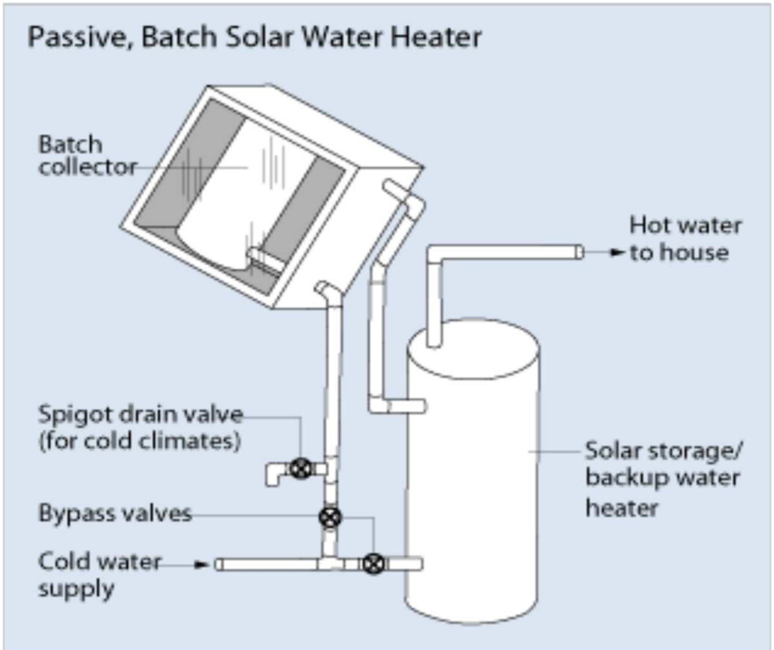

Figure 1.1 Direct systems with passive circulation [20]

An active system is shown below

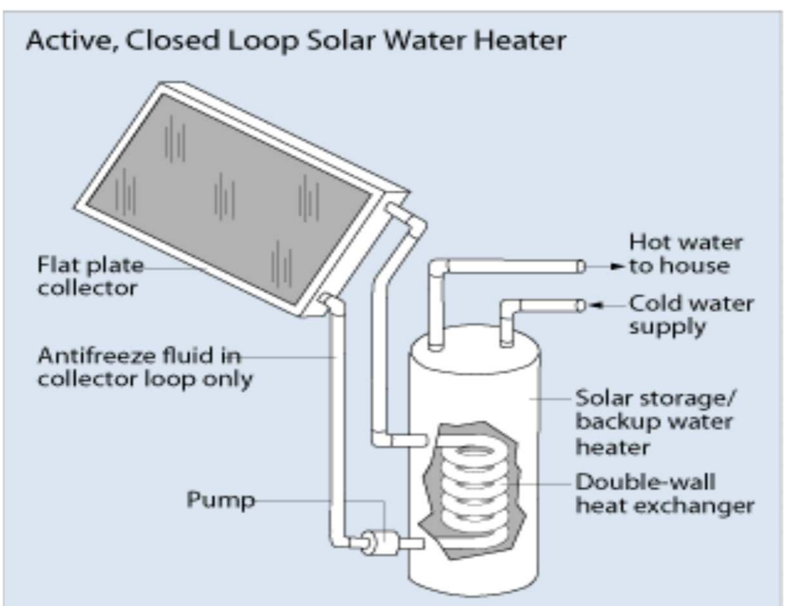

Figure 1.2: Typical active solar energy collection [20]

There are four types of collector used in residential applications. These are batch collectors, glazed an insulated flat-plate collectors evacuated tube collectors and unglazed and non-insulated flat-plate collectors. A batch collector is used in direct systems to pump the portable water directly through the collector. The bath collector system cannot be used in cold climates where freezing temperatures occur. In these systems heat water in either tube placed in an insulated box or dark tanks. The batch collector is shown in figure 1.3

Figure 1.3 batch collectors [21]

Flat-plate collector (FPC) is widely used in space heating/drying and domestic hot-water. Three main components of flat-plate collectors are absorber plate, top covers and heating pipes. The absorber has selective coated to achieve high absorptivity and it receives heat by solar radiation and by conduction. Heat is then transmitted to the flowing fluid where fluid flows through collector pipes are by natural or by forced circulation. The water runs through the pipes inside the insulated box in a direct system while the HTF runs through the collector in an indirect system. The insulations prevent heat loss due to convection and conduction. Basic flat plate collector consist of six components: Glazing cover, glazing frame, tubing or fluids pipe, absorber plate, insulator and casing [5]. Glazing cover is transparent cover to put on top of flat plate collector which transmit the shorter wavelength solar radiation and block the longer wavelength from the absorber plate to reduce heat loss by convection from the top of the absorber. The function of glazing frame is to hold the glazing material. Fluid pipes facilitate the flow of working fluid, absorber plate absorb incident solar radiation to gain heat, insulator reduce heat loss from bottom and sides of the casing and casing is a water-proof box to keep the components free from dust and moisture[5].. Basic flat plate collector shown in figure 1.4 below.

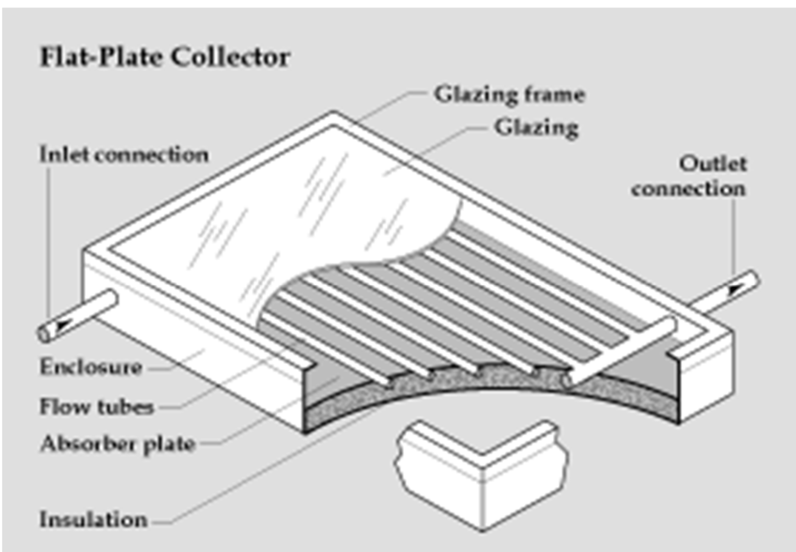

Figure 1.4 Basic components in flat plate collector [5]

1.1 Problem Statement

Although federal and state governments and local utilities provide financial incentives, utilities and consumers are often uncertain of the cost savings and payback periods of these investments. Beneficiaries for investment support or production support are selected not only on the basis of costs, but also on the basis of their technical quality, socio-economic impact, geographic and environmental concerns. As a result, research, development and demonstration is widely used to simulate the development of renewable energy sources to decrease investments and production costs. In this research an attempt has been made to optimize the number of transparent cover and refractive index to improve optical efficiency and thermal efficiency of Sunearth Solar water heater.

1.2 Objectives

The main objectives focuses of this research are:

Develop a mathematical model for the Sunearth flat-plate solar collector with different number of glass covers (0-3) and different refractive index; propose a solution method to derived model has the capability to compute optical efficiency and thermal efficiency at any location and any time and generate a code which can numerically apply the proposed solution method by utilizing MATLAB software.

CHAPTER 2

BACKGROUND LITERATURE

An extensive research has been done to predict the performance of different types solar collector due to it high demand. Saussure [2], a Swiss scientist, invented the solar liquid flat plate collector for water heating during 1767, as reported by Ackermann in the year 1915. Owing to the many parameters affecting the solar collector performance researchers and scientist from all over the world have contributed this field by developing detailed analyses of different types of liquid flat plate collectors. Lampert [3] analyzed the optical properties of materials and coating to increase the performance of the solar collector. He emphasized that a low emittance coating material for glazing reduces the radiative heat loss between the top surface of the flat plate collector and the atmosphere. Gmbert et al. [4] investigated the ways to increase the performance by increasing the transmittance of glass cover. Maatouk study shows the effect of the thickness of glass cover at low and high temperature. He also reported the effect of radiative and conductive heat transfer for one or two glasses. He found that the heat flux through the glass decreases at high temperature when the thickness is increased. Khoukhi and Maruyama found from their work that a rigorous radiative model should be applied for the glass cover and its properties to increase the performance of solar collector[27]. The effect of wind speed in the performance of solar flat plate collector with single glass cover was studied by Bhatt et al and he found that the increase of wind speed decreases the performance due to radiative and convective heat loss. The performance of solar flat plate collector was investigated by Madhukeshwara and Prakash with different selective coating [27]. It was found that the thermal efficiency for black chrome coating is higher among the three different selective coatings. Augustus and Kumar build mathematical to predict the thermal performance of an unglazed transpired collector and found that the solar absorptivity, airflow, and collector pitch have the strongest effect on the performance of collector [15].

CHAPTER 3

METHODOLOGY

The optical efficiency of the flat plate collector is determined by the quantity of the sun energy absorb by absorber plate and the thermal efficiency is the total useful heat take by the collector plate in heating the fluid. Absorbed radiation is a function of plate and cover characteristics and it is convenient to use a transmittance absorptance product ($\tau\alpha$) for the calculation of the amount of radiation that is transmitted to the absorber plate. The transmittance absorptance product ($\tau\alpha$) shows how much energy passes through the cover is reflected by the absorber plate and reflected back by the cover. The value of transmittance absorptance product ($\tau\alpha$) decrease with the increase in the number of covers .The flux absorbed by the absorber plate decreases with increase in the number of covers and thus heat loss reduces from the absorber plate. Similarly the refractive index of the transparent cover is a property of the glass cover which affects the collector performance. To obtain maximum efficiency the glass cover material should have a very high transmissivity and low emittance and lower the refractive index higher the transmissivity of the glass cover. Thus the thermal efficiency also increases with lower refractive index. In a flat plate collector that transfers heat to a liquid, the performance is affected by the selection of number of transparent covers and refractive index of transparent cover. To achieve higher efficiency irrespective of solar insulation and location, finding an optimum number of cover and an effective refractive index is very important.

When the solar flat plate collector is exposed to solar radiation, some of its radiation absorbs and the balance is reflected back to the surroundings. Heat losses occur in the form of conduction, convection, and radiation, shown in Fig 1.1. Glazing can be used to minimize heat losses since glazing has a property of being largely transparent to solar radiation and largely opaque to infrared radiation resulting in the increase of inner temperature and working fluid as well. Optical efficiency and thermal efficiency of solar water heater are greatly affected by the refractive index of the transparent cover since the refractive index is a property of transparent cover. Similarly the number of transparent covers also influences the performance of solar water heater.

The flat plate collector is a heat exchanger where the energy of solar radiation is converted to heat with the use of solar panel. Solar collectors gather the sun's energy, transform its radiation into heat, and then transfer that heat to a fluid.

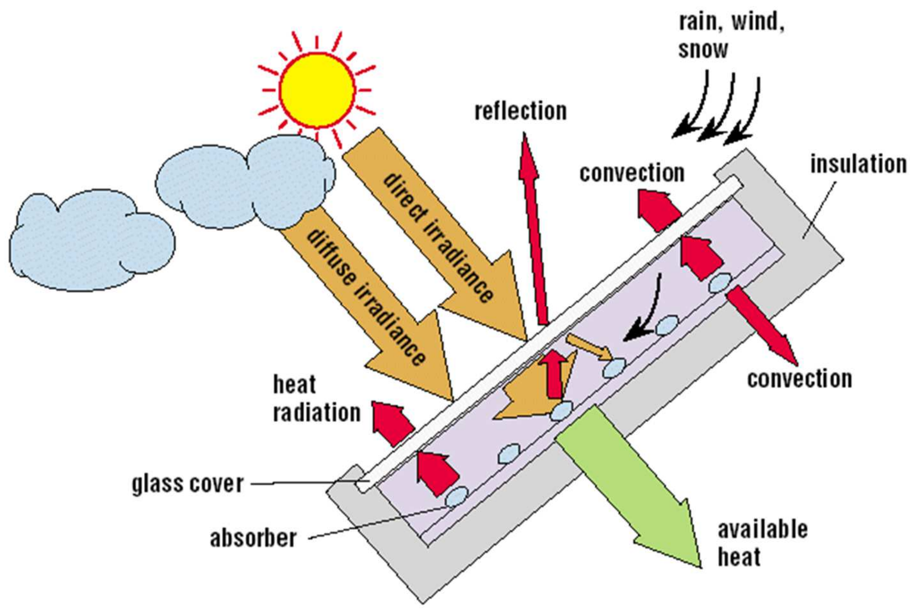

Fig 3.1: Heat losses at flat plate collector [22]

Optical and thermal efficiency is calculated for zero cover, 1 cover, 2 covers and 3 covers and for each cover the efficiency is calculated with different refractive index 1.1, 1.4 and 1.7. Almost 22 different cases are calculated for two days July21st and October 21st from 8 am to 4 pm, at an interval of every 1 hour.

3.1 Description of Sunearth flat-plate collector

Most solar water heating for buildings has two main components: a solar collector and a storage tank. The flat plate collector that is used in this research is Sunearth SolaRay unit with a glazed flat-plate collector which was installed at the facilities of the engineering department at the Polytechnic campus of Arizona-State University. The water heating unit is installed in the Tuff Shed, and the solar collector for the solar water heater is installed on the roof of the shed.

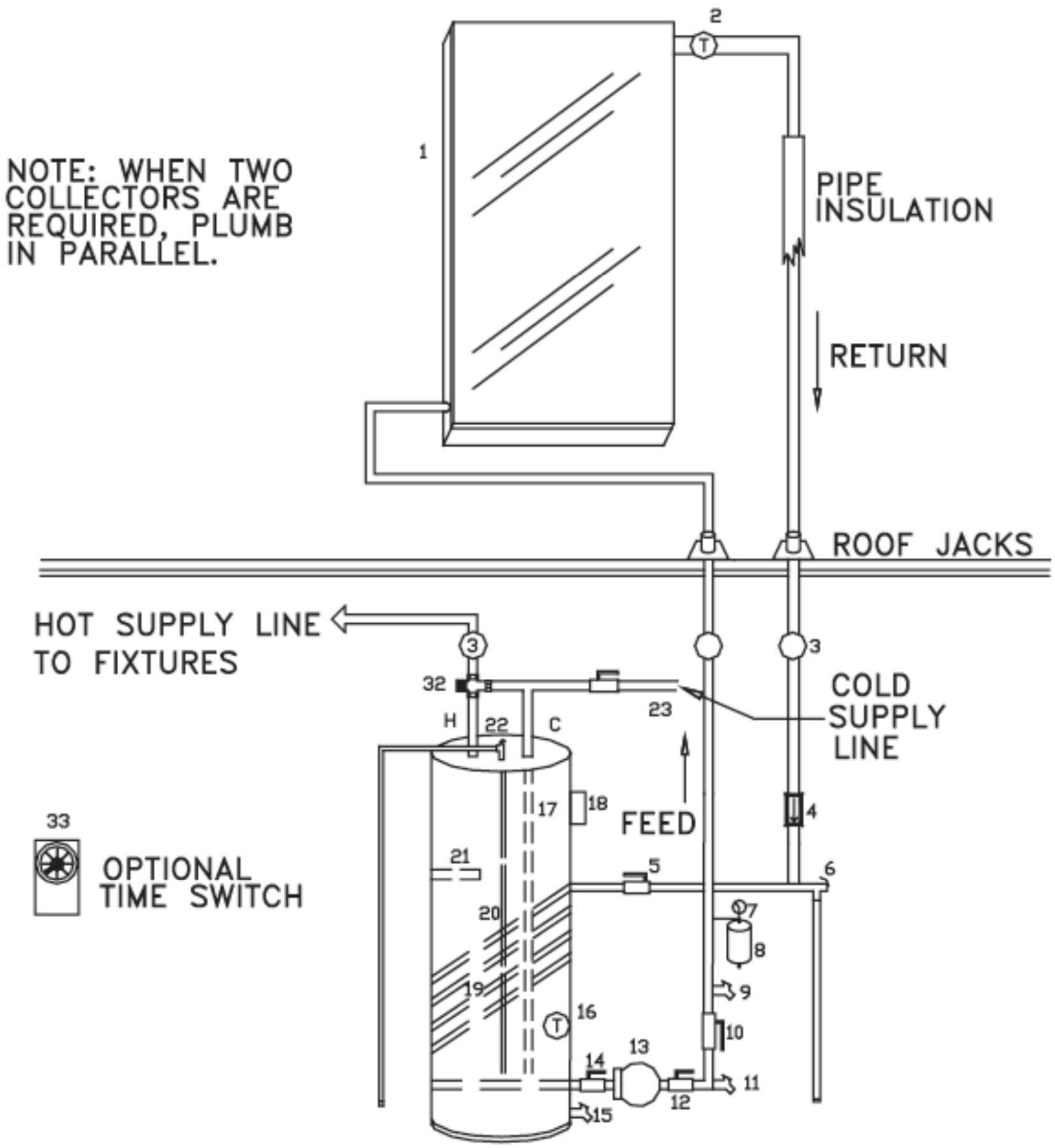

Figure 3.2 Sunearth Single Tank Schematic

A single pump is used in this unit to cycle actively the heat transfer fluid through the solar collector. The HTF (Heat Transfer Fluid) consists of 30% DowFrost^{TM} HD propylene glycol and 70% water. A diagram of the Sunearth collector can be seen in Figure 3.3.

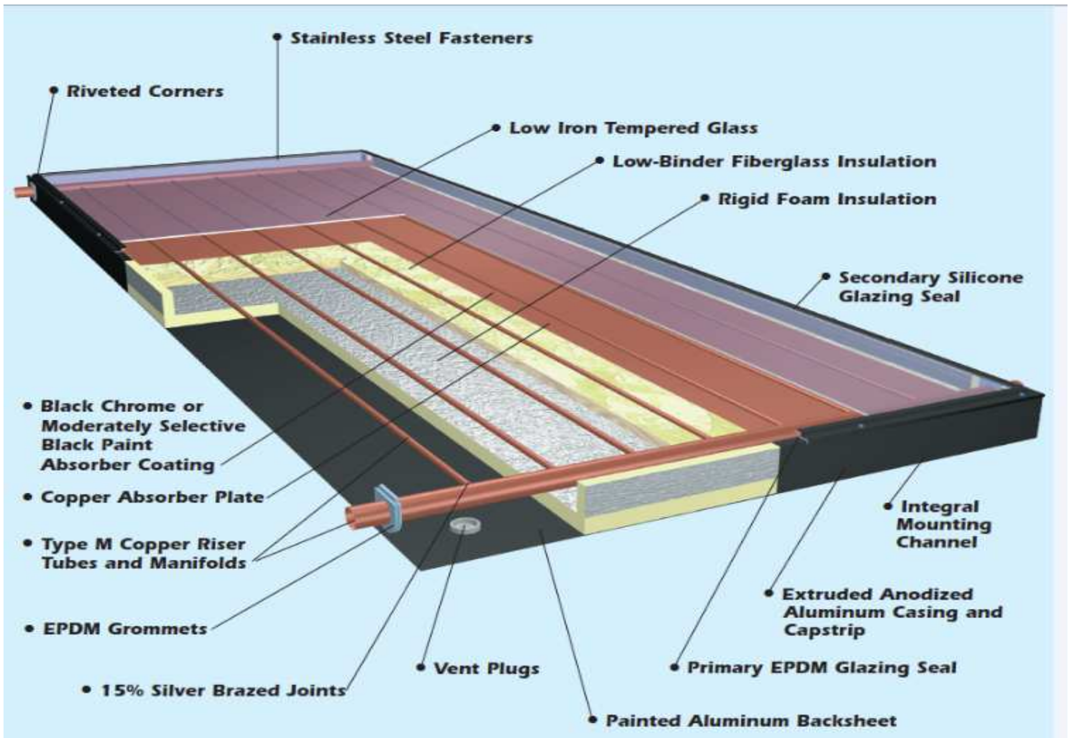

Figure 3.3: Diagram of the Sunearth Flat-Plate Collector [1]

Sunearth Flat plate collectors typically consist of enclosure, glazing, insulation, absorber, flow tubes. Enclosure is a box or frame o hold all components together, glazing is a transparent cover over the enclosure to allow the solar radiation pass through to the absorber. In Sunearth Solar collector glazing is one sheet of low iron tempered glass the insulation is foil-faced polyisocyanurate foam sheathing board underneath the absorber to reduce conduction heat loss from the collector. The absorber consists of a roll-formed copper plate which can absorb and transfer high levels of solar energy. Type M copper tubes across the absorber through which fluid flows and transfer heat from the absorber to the fluid. The Sunearth collector was installed facing directly south, parallel to the roof, with a 4/12 pitch [24]. A photo of the Sunearth collector mounted on the roof can be seen in figure 3.4

Figure 3.4: Sunearth Flat-plate collector

Table 3.1 below shows the summary statics of the Sunearth solar collector, taken from manufacturer spec sheets [23].

Table 3.1 Sunearth Solar Collector specifications

	Sunearth
Collector Panel	Empire EP-40
Solar Collector SRCC OG-100 Certification	2007032A
Collector Type	Flat-plate with copper tube and plate glazed glass cover
Insulation	Polyisocyanurate and fiberglass
Gross Area (ft^2)	40.9
Net Aperture(ft^2)	37.1
Fluid capacity(gal)	1.3
Fluid Type	30% DowFrost™ HD Propylene Glycol/70% Water
Installed Angle	18.43 degrees

3.1 Flat Plate Collector Specifications

Table 3.1 shows the specifications of Sunearth Flat Plate Collector for this project.

Table 3.1: Specification of Sunearth Flat Plate Collector

Description	Specification
Collector dimension(Length X Width)	122.25inch X 48inch
Absorber dimension(Length X Width)	117.13inch X 46inch
Collector type	Flat plate
Plate to cover Spacing	0.98inch
Spacing between covers	0.98inch
Thermal conductivity of plate	401w/mk
Cover extinction coefficient	4/m
Cover thickness	0.08inch
Plate absorptivity	.94
Outer diameter of lateral tube	0.5 inch
Inner diameter of lateral tube	0.45inch
Tube center to center distance	4.56 inch
Glass cover absorptivity/emissivity	0.84
Bottom loss coefficient	0.08w/m^{2} ^{0}C
Bond thermal conductivity	63 w/mk
DowFrost^{TM} HD heat transfer fluid flow rate	0.11kg/sec
Inlet water temperature	60^{0}C
Ambient temperature	25^{0}C
Wind speed	3 m/sec
Side loss coefficient	Negligible
Collector tilt	11.5
Date	July 21st, October 21st
Location of flat plate collector	Arizona State University(33.27^{0}N, 112.04^{0}W)

3.2 Flat Pate Collector efficiency

3.2.1 Optical efficiency

The first step of numerical calculation is to find solar time using the formula below.

Solar time = watch time – $4(L_{st} - L_{lo})$+EOT (3.1)

EOT = 9.87 sin2B -7.53cosB – 1.5sinB (3.2)

Where:

B is B = 360(n-81)/364, as noted above

n is the day of the year

L_{st} is the standard time for the local time zone

L_{lo} is the longitude of the location

EOT is the equation of time

The next step is to find hour angle ω, the zenith angle θ_z, the incident angle θ:

$$\omega = (\text{solar time} - 720)/4 \quad (3.3)$$

$$\theta_z = \cos^{-1}(\sin\Phi.\ \text{Sin}\delta+\cos\Phi.\ \cos\delta.\cos\omega) \quad (3.4)$$

$$\theta = \cos^{-1}(\sin(\Phi-\beta).\ \text{Sin}\delta +\cos(\Phi-\beta).\ \cos\delta.\cos\omega) \quad (3.5)$$

Beam, Diffuse and Reflected radiation tilt factors, r_b, r_d and r_r respectively, are given by:

$$r_b = \frac{\cos\theta}{\cos\theta z} \quad (3.6)$$

$$r_d = \frac{1+\cos\beta}{2} \quad (3.7)$$

$$r_r = \rho_g\{\frac{1-\cos\beta}{2}\} \quad (3.8)$$

Where:

r_b is the beam radiation tilt factor

r_d is the diffused radiation tilt factor

r_r is the reflected radiation tilt factor

To calculate direct solar radiation the ASHRAE model is used in this analysis.

The beam, diffuse radiation is given by:

$$I_{bn} = A * \exp(-\frac{B'}{\cos\theta z}) \quad (3.9)$$

$$I_b = I_{bn} * \cos\theta z \quad (3.10)$$

$$I_d = C * I_{bn} \quad (3.11)$$

Where:

I_{bn} is the hourly beam radiation in the direction of rays

A is the apparent direct normal solar flux at the outr edge of the earth's atmosphere

B' is the apparent atmospheric extinction coefficient

I_d is the hourly diffuse radiation on the horizontal surface

I_b is the hourly beam radiation received on the horizontal surface

Where A, B', C are constant whose values changes every month.

The total incident radiation on top surface of the cover can be determined

$$I_T = I_b * r_b + I_d * r_d + (I_b + I_d) * r_r \quad (3.12)$$

The collector performance is determined by the transmission, reflection, and absorption of solar radiation by the collector. These parameters are determined from the collector component geometry, such as the thickness of the glass, material properties, such as transmittance, absorptance and reflectance and refractive index, as well as orientation of the collector. For example, the Sunearth solar water heater has low tempered iron glass for cover and the material properties for this substance are well known. In my calculation I investigated collector performance with different refractive indexes of the same material cover.

Since a portion of the radiation passing through the cover system and incident on the plate is reflected back to the cover system it is necessary to find the transmissittance-absorptance product ($\tau\alpha$), which is calculated by using solar incidence angle as the angle of incidence(θ_1) and in Snell's law,

$$\mathrm{Sin}\theta 1/\sin\theta 2 = n_2/n_1 \tag{3.13}$$

Where:

θ_1 is the zenith angle θ_z

n_2/n_1 is the refractive index ratio.

From this equation 3.13 θ_2 can be determined. Neglecting absorption in the cover material the perpendicular and parallel component of polarization is

$$\rho_I = \sin^2(\theta_2 - \theta_1)/ \sin^2(\theta_2 + \theta_1) \tag{3.14}$$

$$\rho_{II} = \tan^2(\theta_2 - \theta_1)/ \tan^2(\theta_2 + \theta_1) \tag{3.15}$$

where :

ρ_I is the reflectivities of perpendicular component of polarization

ρ_{II} is the reflectivities of parallel component of polarization

θ_1 is the angle of incidence

θ_2 is the angle of refraction

For a system of M covers the transmittance is,

$$\tau_r = \frac{1}{2}\left(\frac{1-\rho I}{1+(2M-1)\rho I} + \frac{1-\rho II}{1+(2M-1)\rho II}\right) \tag{3.16}$$

Where:

M is the number of covers

Using Bouguer's law the transmittance based on absorption is,

$$\tau_a = \exp\left(-\frac{K\delta c}{cos\theta 2}\right) \tag{3.17}$$

where K is the extinction coefficient and δc is the thickness of the cover. The transmittance of single cover is,

$$\tau = \tau_a * \tau_r \tag{3.18}$$

τ_a transmittance when absorption is considered

τ_r transmittance account for reflection

The transmissivity-absorptivity product ($\tau\alpha$) for beam radiation,

$$(\tau\alpha)_b = \frac{\tau\alpha}{1-(1-\alpha)\rho_b} \tag{3.19}$$

The transmissivity-absorptivity product($\tau\alpha$) for diffused radiation is calculated in the same way assuming the diffuse radiation is equivalent to beam radiation coming at an angle of incidence of 60^0.

Now we can calculate the solar radiation absorbed by the collector using the formula,

$$S = I_b * r_b * (\tau\alpha)_b + \{I_d * r_d + (I_b + I_d) * r_r\} * (\tau\alpha)_d \quad (3.20)$$

Now with the solar flux at the top surface of the glass cover and the solar radiation absorbed by the plate we can calculate

Optical efficiency = S/I_T.

3.2.2 Thermal Efficiency

The collector efficiency factor is:

$$F' = \frac{1}{WU_l[\frac{1}{U_l(Do+(W-D0)F)}+\frac{1}{Cb}+\frac{1}{\pi D_i h_{fi}}]} \quad (3.21)$$

Where :

F is the standard fin efficiency for straight fin

W is the distance between the tubes

D_0 is the tube outer diameter

D_i is the tube inner diameter

U_l is the overall heat loss coefficient

C_b is the bond conductance[$\frac{k_b b}{\gamma}$]

k_b is the bond thermal conductivity

b is the bond width

γ is average bond thickness

h_{fi} is the convective heat transfer coefficient of fluid

Fin efficiency is obtained using the following formula:

$$F = \frac{\tanh[m(W-D_0)/2}{m(W-D_0)/2} \tag{3.22}$$

Where:

m is $[\sqrt{\frac{U_l}{k\delta'}}]$

k is the thermal conductivity of plate

δ' is the plate thickness

The collector heat removal factor can be expressed as

$$F_R = \frac{\dot{m}c_p}{A_c U_l}[1 - \exp(-\frac{F' A_c U_l}{\dot{m}\, C_p})] \tag{3.23}$$

Where:

$\dot{m}$ is the mass flow rate of DowFrost™ HD heat transfer fluid

C_p is the specific heat

A_c is the collector area

In equation 3.23 both F_R and U_l are unknown and independent of each other. An iterative process is followed to find collector heat removal factor by assuming overall heat loss coefficient. The useful energy gain q_u in heating the fluid can be expressed as

$$q_u = F_R [S - U_l (T_i - T_a)] \tag{3.24}$$

Now the heat loss can be calculated by absorber plate mean temperature

$$q_l = U_l A_p (T_{pm} - T_a) \tag{3.25}$$

Heat loss can also be calculated as

$q_l = (SX\ A_p) - q_u$ (3.26)

Combining equation 3.25 and 3.26 we get:

$U_l\ A_p(\ T_{pm} - T_a) = (SX\ A_p) - q_u$ (3.27)

Using the above formula the plate mean temperature (T_{pm}) is found. Convective and radiative heat transfer coefficients between parallel plates are calculated and since the energy exchange between plates must be equal to the overall heat loss, a new cover temperature is calculated. Starting at the absorber plate, a new temperature is calculated for the cover 1. Then with this new first cover temperature the next cover temperature is found and so on. For any two adjacent covers or plate, the new temperature of plate can be determined in terms of the temperature of plate or cover which is shown below

$T_j = T_i - \frac{U_t(T_p - T_a)}{h_{c,i-j} + h_{r,i-j}}$ (3.27)

The process is continued until the same cover temperature is found between successive iterations.

When all cover temperatures are found the top loss coefficient is calculated. Now the bottom loss is calculated and side loss is assumed zero [25]. Now we can find the overall heat loss coefficient using the following formula

$U_l = U_t + U_b + U_e$ (3.28)

Where:

U_t is the top loss coefficient

U_b is the Bottom loss coefficient

U_e is the Edge loss coefficient

Then iterative procedure is repeated until the overall heat loss coefficients do not change significantly between successive iterations [25].

Finally when we get the overall heat loss coefficient we can calculate total useful heat gain q_u and thermal efficiency as well. The thermal efficiency is expressed as:

$$\text{Collector thermal efficiency} = \frac{q_u}{I_T} \tag{3.29}$$

3.2.3 Convective Heat Transfer coefficient into the Heat Transfer Fluid (h_c):

To estimate the convective heat transfer coefficient it is necessary to determine the Reynolds and Prandtl numbers of the fluid:

$$Re_D = \frac{4\dot{m}}{\pi D_i \mu} \tag{3.30}$$

Where:

$\dot{m}$ is the mass flow rate of DowFrost™ HD heat transfer fluid

D_i is the Inner diameter of copper tube

μ is the dynamic viscosity

$$Pr = \frac{C_p \mu}{K} \tag{3.31}$$

Where C_p is the specific heat and K is the thermal conductivity of the DowFrost™ HD heat transfer fluid. The Convective correlations are:

For laminar flow (Re_D <= 2300):

$$Nu_d = 0.040\ Re_D^{0.75}\ Pr^{1/3} \tag{3.32}$$

$$hc = \frac{Nu_d K}{D_i} \tag{3.33}$$

For turbulent flow

$$Nu_d = 0.023\ Re_D^{0.8}\ Pr^{1/3} \tag{3.34}$$

$$hc = \frac{Nu_d K}{D_i} \tag{3.35}$$

Where:

Nu_d is the nusselt number

Pr is the prandtl number

k is the thermal conductivity

These coefficients are then used in the overall energy balance, which ultimately finds the overall heat transfer coefficient [26].

3.2.4 Convective heat transfer coefficient of ambient air (h_w)

In this case, since the air flows over the outside of the surfaces, it is convenient to define the Reynolds number with different velocity and length scales than those that were previously used:

$$Re_L = \frac{V_w L}{v} \tag{3.36}$$

Where V_w = wind speed, L = Length of collector surface and ν = kinematic viscosity. A Colburn factor, j, is also defined:

$$j = \frac{0.86}{\sqrt{Re_L}} \tag{3.37}$$

The convective heat transfer coefficient is estimated as:

$$h_w = j\rho c_p V_w \tag{3.38}$$

Where ρ is the density and c_p is the specific heat of air.

The solar water heater numerical simulation is summarized in the following flowchart:

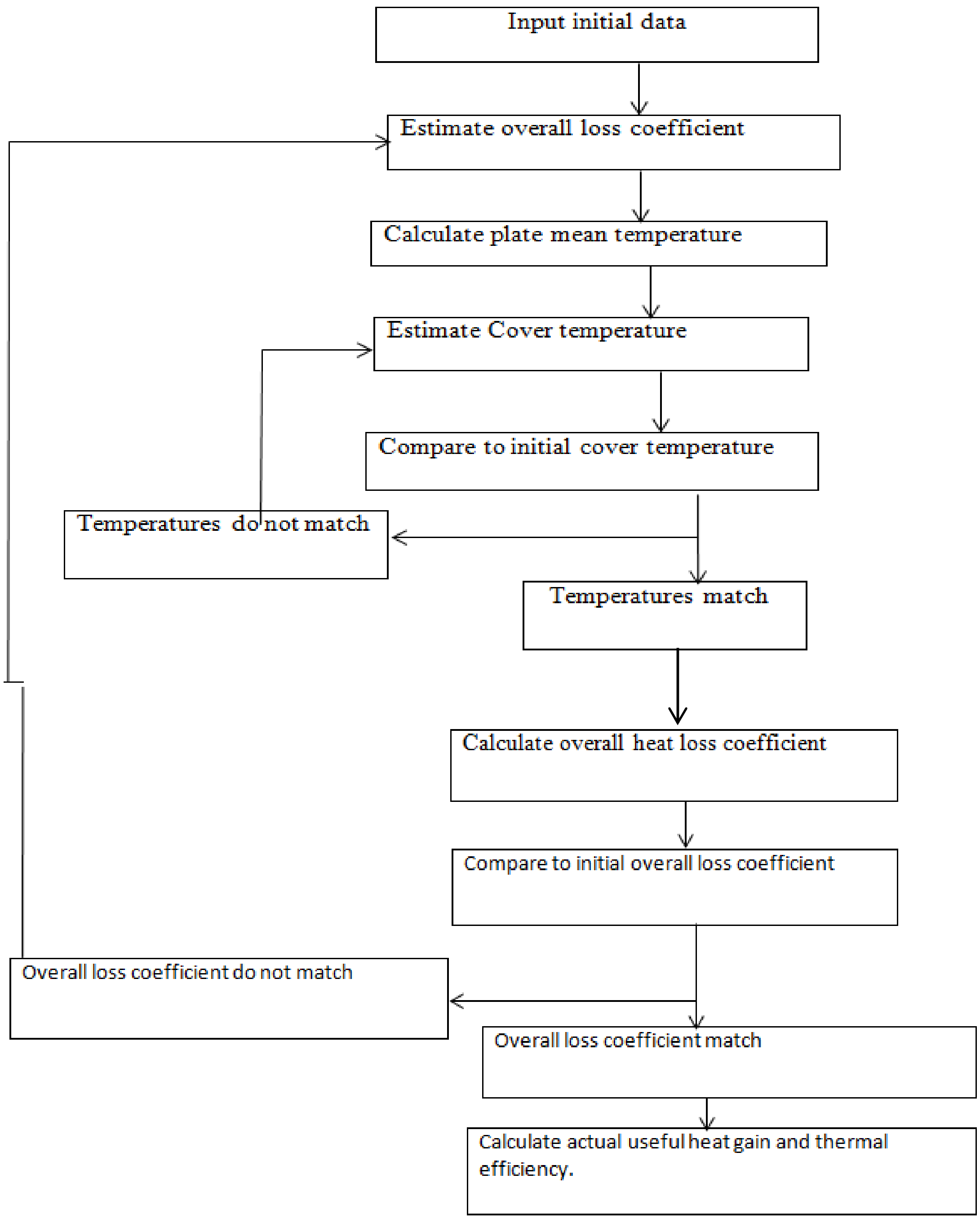

Figure 3.1 Flowchart of solar collector simulation for thermal efficiency

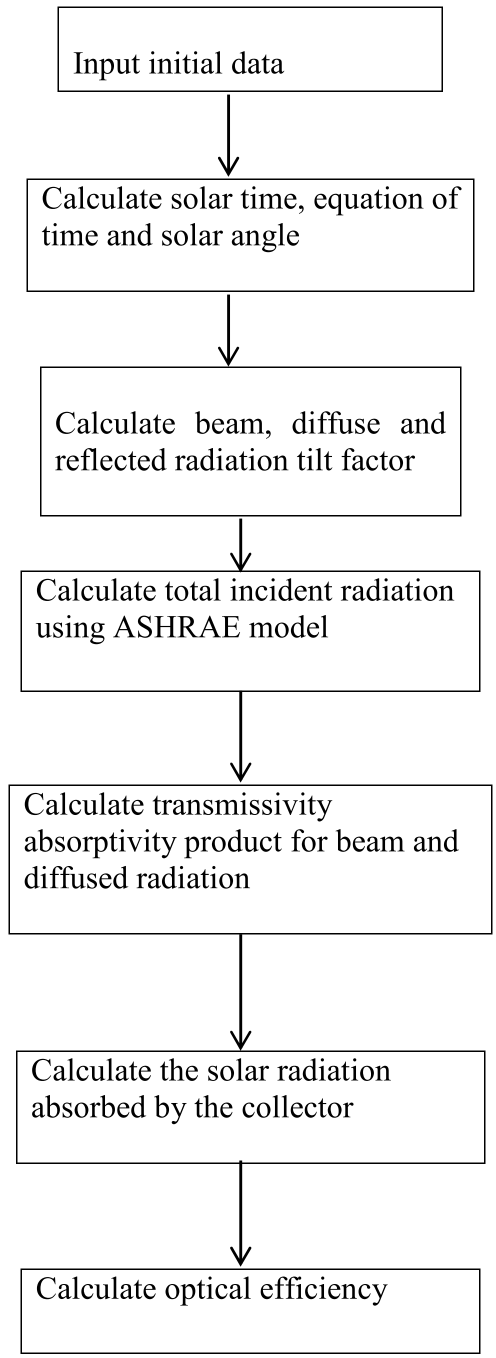

Figure 3.2 Flowchart of solar collector simulation for optical efficiency

CHAPTER 4

DATA ANALYSIS AND RESULT

The purpose of the cover to collect as much solar radiation as possible and reduce heat loss from the top surface. The glass cover material (low tempered iron glass) used in the Sunearth has a very high transmissivity with a small low absorption coefficient. Ani-reflection coating can make significant improvement in transmission. The performance of collector is affected by the number of covers, and the covers performance is greatly influenced by its refractive index. The Refractive index is the ratio of speed of light in the vacuum to speed of light in the substance,

$$n= c/v$$

The speed of light in the medium depends on frequency and wavelength,

$$c = f\,\lambda, \text{ so}$$

$$n=\frac{c}{f\lambda}$$

It is clear from above equation that when wavelength of the rays decreases, the refractive index increases. Therefore, the rays change from visible range to infrared range to which the glass acts as opaque resulting in low solar radiation transmission [13].

Heat gain is an important factor for thermal performance analysis of the Sunearth Collector. In this analysis useful energy gain is calculated as a function of inlet temperature for convenience. The analysis has been conducted on Sunearth flat plate collector with a tilt angle of 11.5^0.

So it is important to find out how the property of refractive index of the glass cover, n, and the number of glass panels affects the optical efficiency and thermal efficiency of solar collecting system. Consequently, the next goal is to find out the number of glass cover and an effective refractive index for which the solar collector system shows the best performance.

For this analysis two different months were selected from summer and fall. For summer the month of July and for fall the month of October represent two different weather conditions. The performance of the Sunearth Solar water heater was calculated from morning 8 am to afternoon 4 pm, at an interval of every 1 hour. In both cases, the performance was calculated for no cover, cover 1, cover 2, and cover 3 with different refractive index 1.1, 1.4, and 1.7.

4.1 Case 1

The first case was selected on July 21st which is convenient to calculate Optical efficiency and Thermal efficiency using ASHRAE MODEL. The month of July has the most amount of sunshine. Figure 4.1, through 4.10 shows the efficiency versus time curve for SunEarth flat plate collector with no cover, 1 cover, 2 covers and 3 covers. The optical efficiency of the solar flat plate with no cover is 94%[figure 4.1]. This low efficiency is due to the transmission of outgoing radiation caused by unwanted reflection. Figure 4.1, 4.2, 4.5 and 4.5 below shows that at 8 am the optical efficiency with refractive index 1.1 for 1 cover 89%, 2 covers 87%, 3 covers 86%. The optical efficiency decreases with the increase of number of covers. This is because the incoming radiation(r) of the incident beams, (1-r) of the incident beam reaches the second surface. Of this $(1\text{-r})^2$ pass through the interface and r (1-r) reflected back to the first cover. The same process is reversed when the beam leaves the cover. this absorption, reflection, and transmissivity of solar radiation through the transparent cover reduces the transmissivity-absorptivity($\tau\alpha$) product[13]. As a result the solar radiation absorbed by the absorber decreases and optical efficiency becomes low when number of cover increases.[Figure 4.2] In this case the thermal efficiency increases with the increase of number of covers with refractive index 1.1. This is due to glass cover has high transmittance for solar radiation and also serves as an insulator.

Figure 4.2, 4.3, 4.4 below with 1 cover at 8am the optical efficiency is 89% for refractive index 1.1, 80% for refractive index 1.4, 75% for refractive index 1.7 and the thermal efficiency 44% for refractive index 1.1, 36% for refractive index 1.4 and 31% for refractive index 1.7. The result shows the optical and thermal efficiency decreases with the increase of refractive index. When refractive index is high the wavelength of solar radiation decreases to which the glass cover act as an opaque. As a result the reflectance increase and the transmittance decrease relative to the transmittance with lower refractive index. Thus the performance of flat-plate collector degrades.

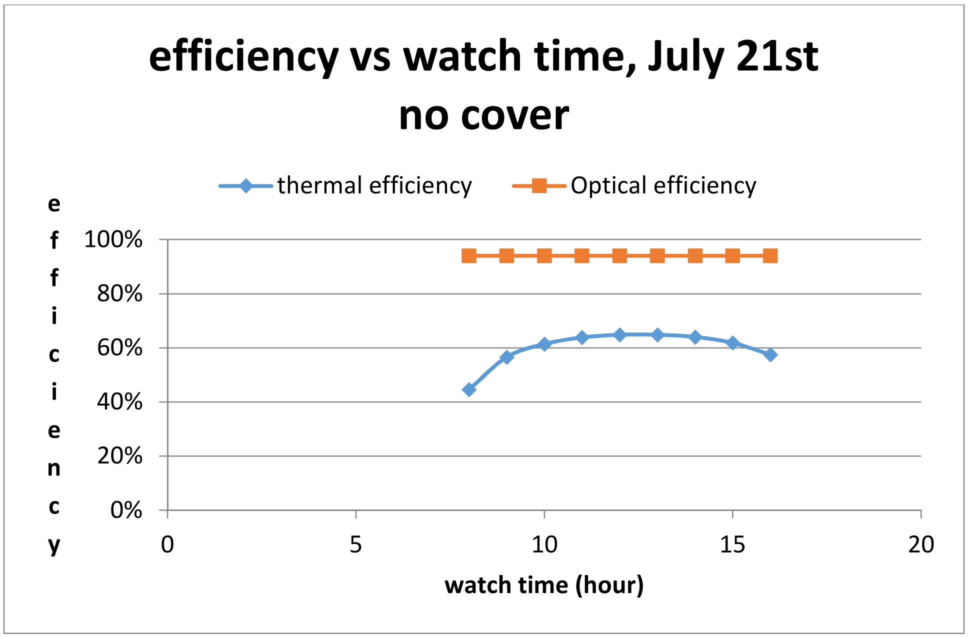

Fig 4.1: efficiency versus watch time with no cover, July 21st

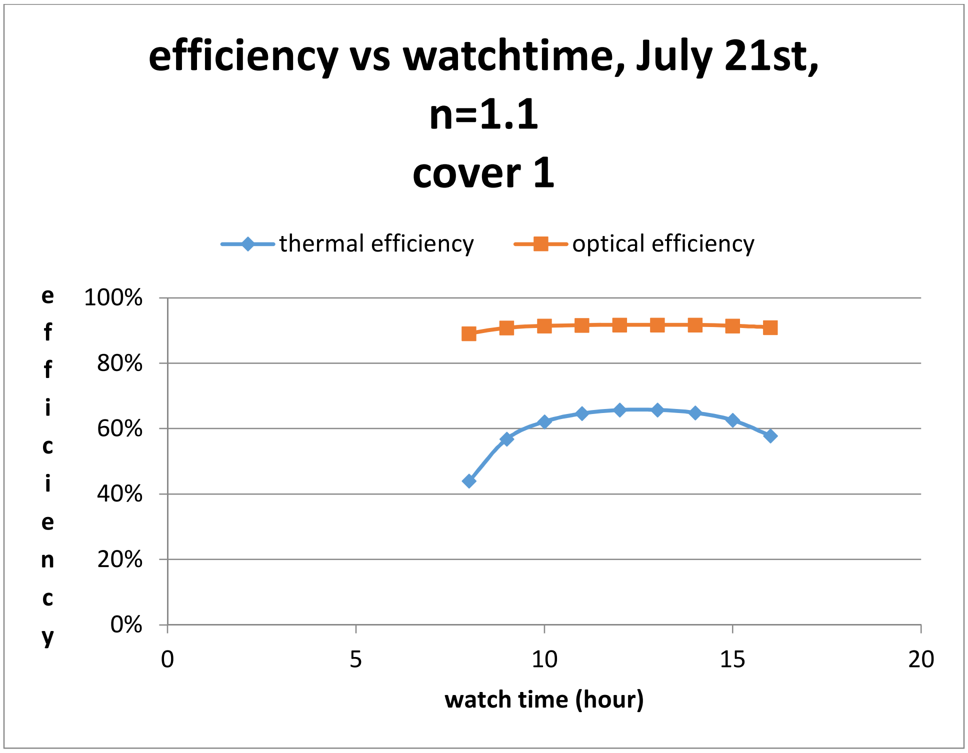

Fig 4.2: one cover, 1.1 refractive index, July21st

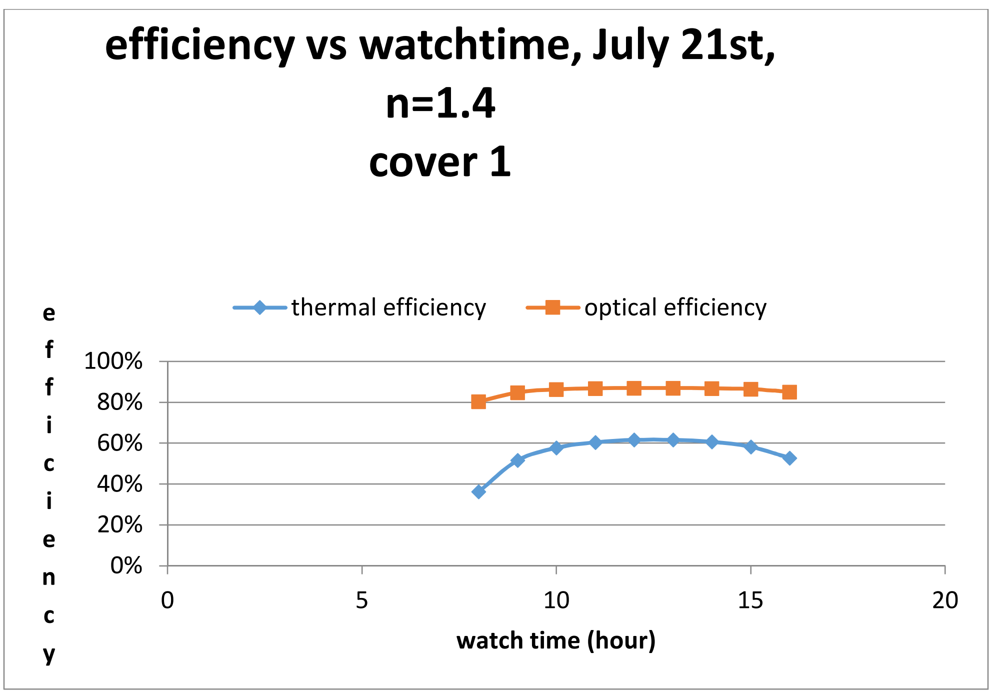

Fig 4.3: one cover, 1.4 refractive index, July 21st

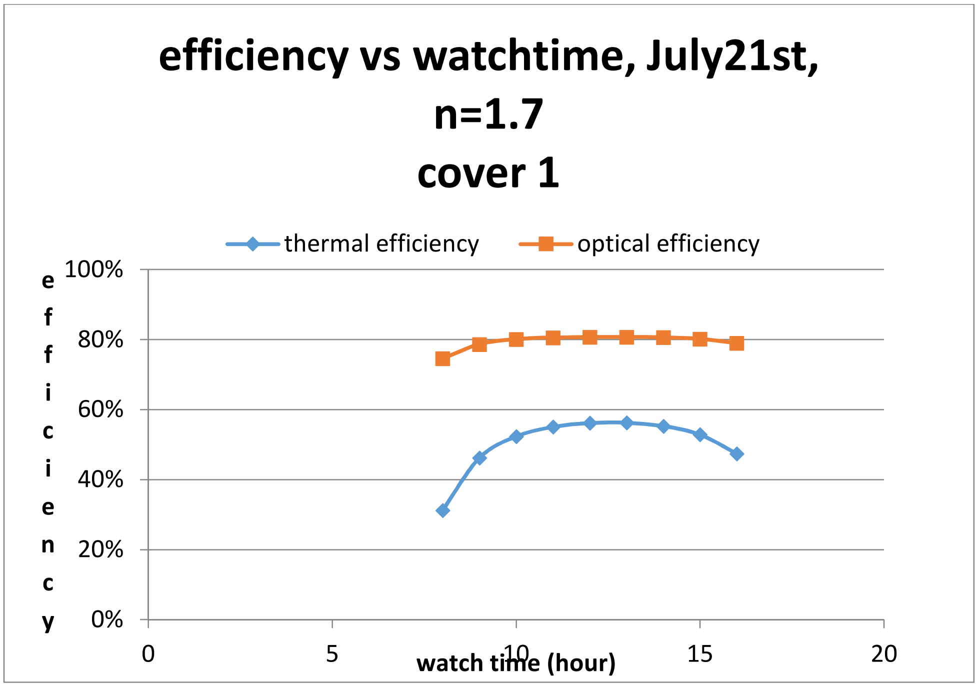

Fig 4.4 : one cover, 1.7 refractive index, July 21st

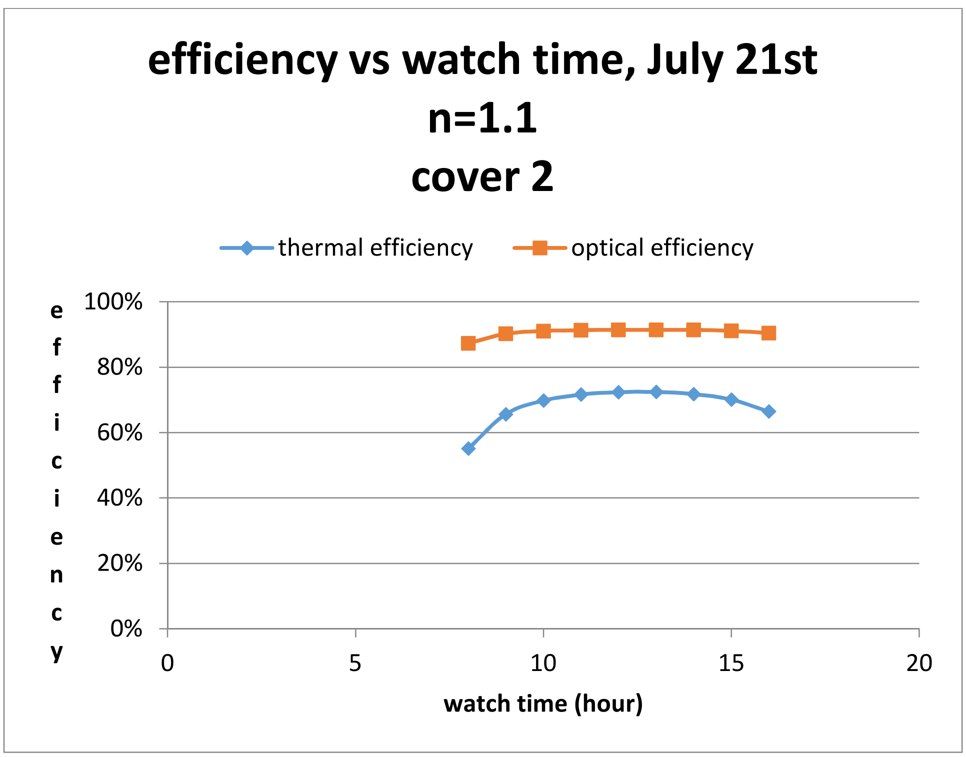

Fig 4.5 : two covers, 1.1 refractive index, July 21st

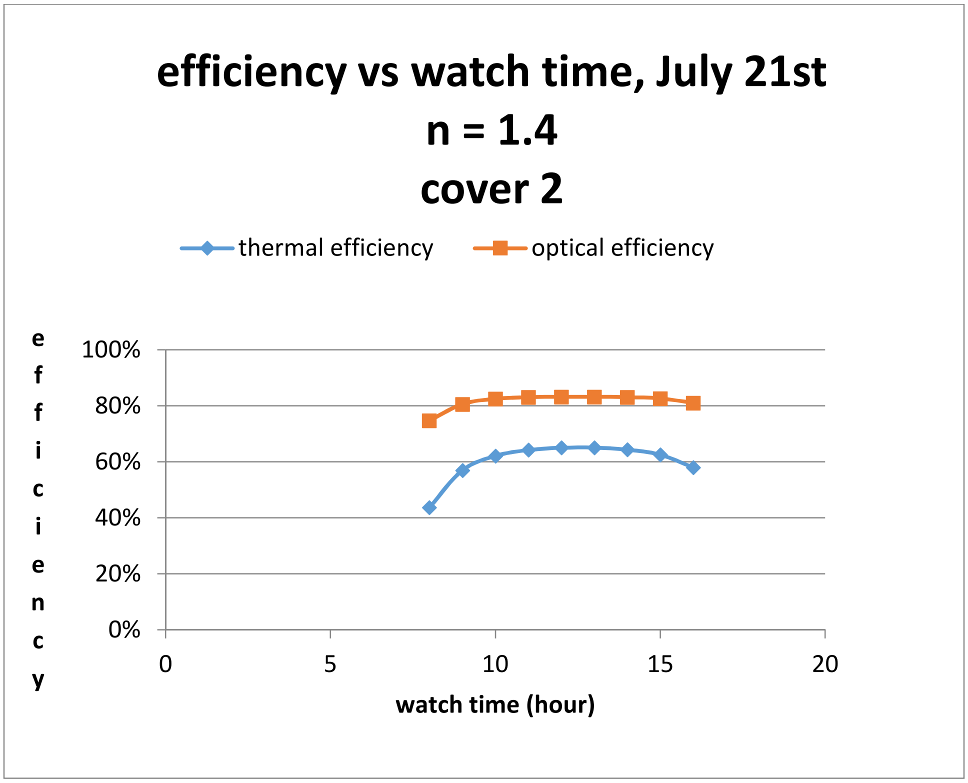

Fig 4.6 : two covers, 1.4 refractive index, July 21st

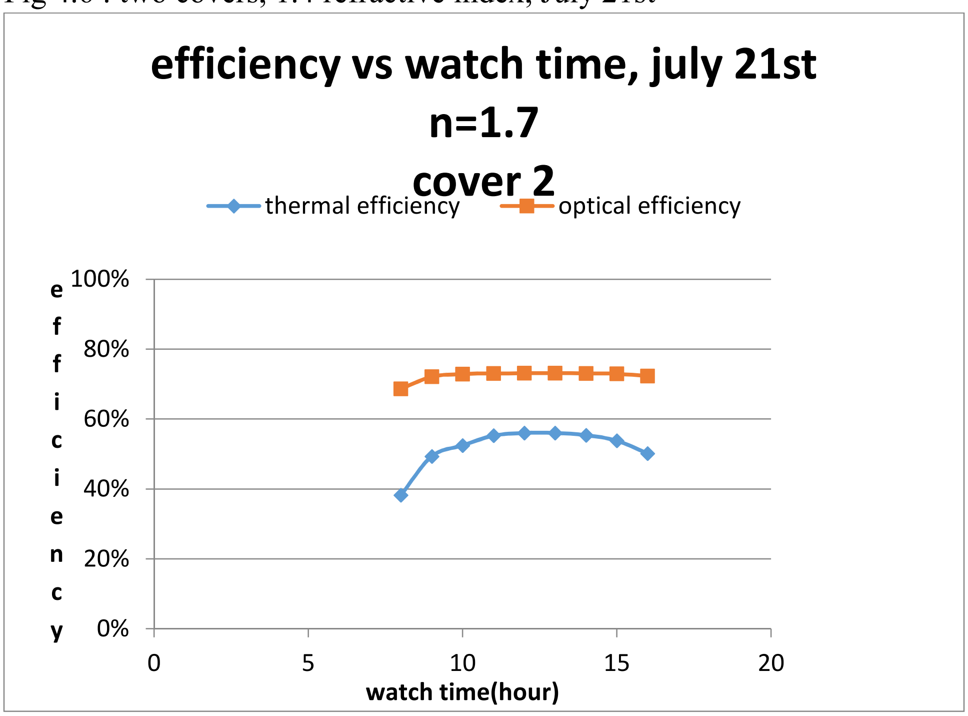

Fig 4.7: two covers, 1.7 refractive index, July 21st

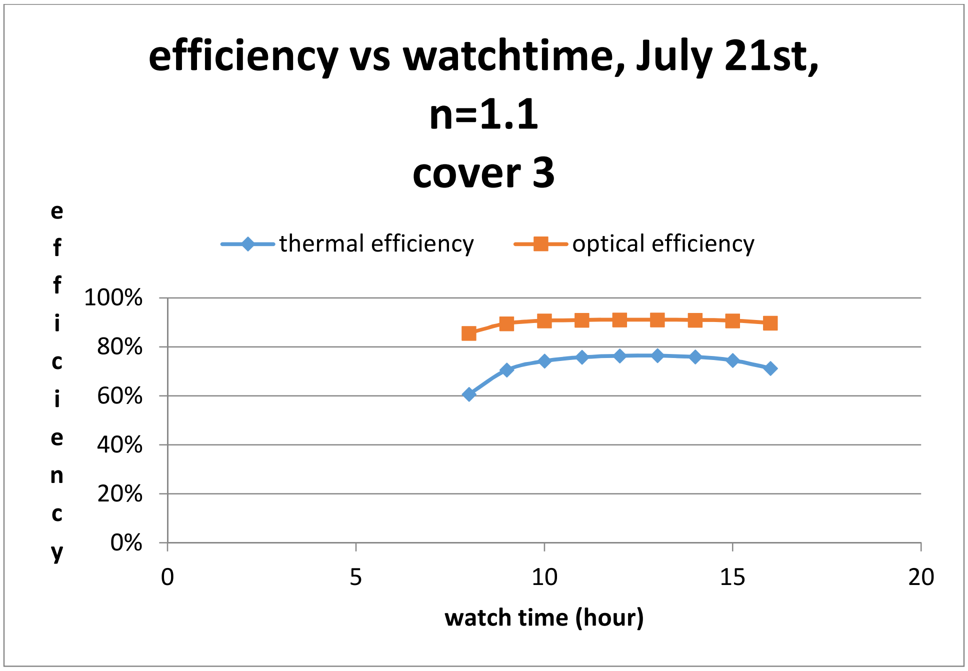

Fig 4.8: three covers, 1.1 refractive index, July 21st

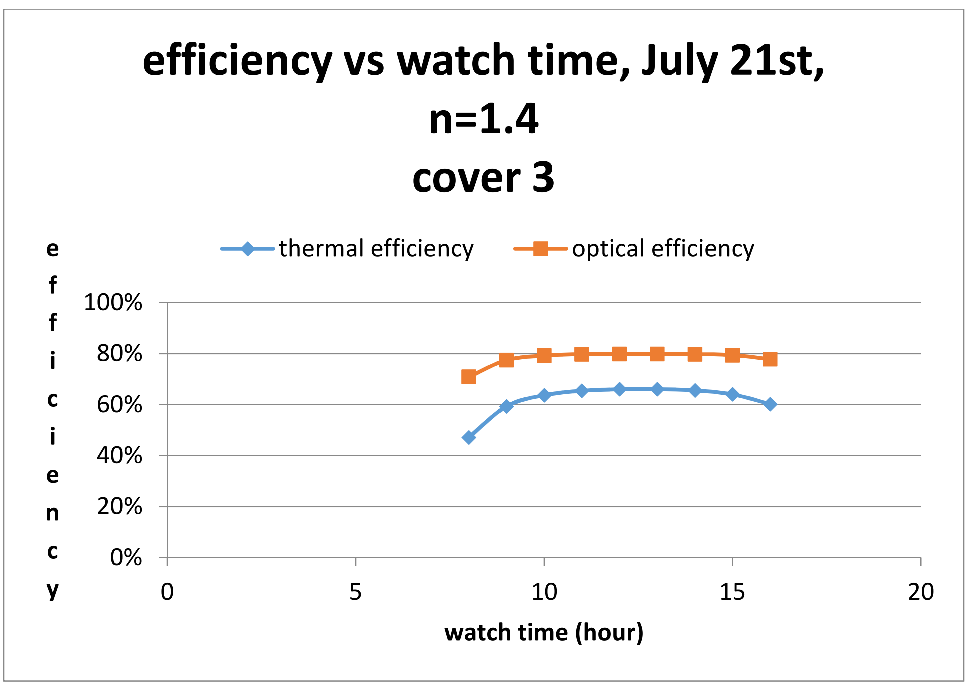

Fig 4.9: three covers, 1.4 refractive index, July 21st

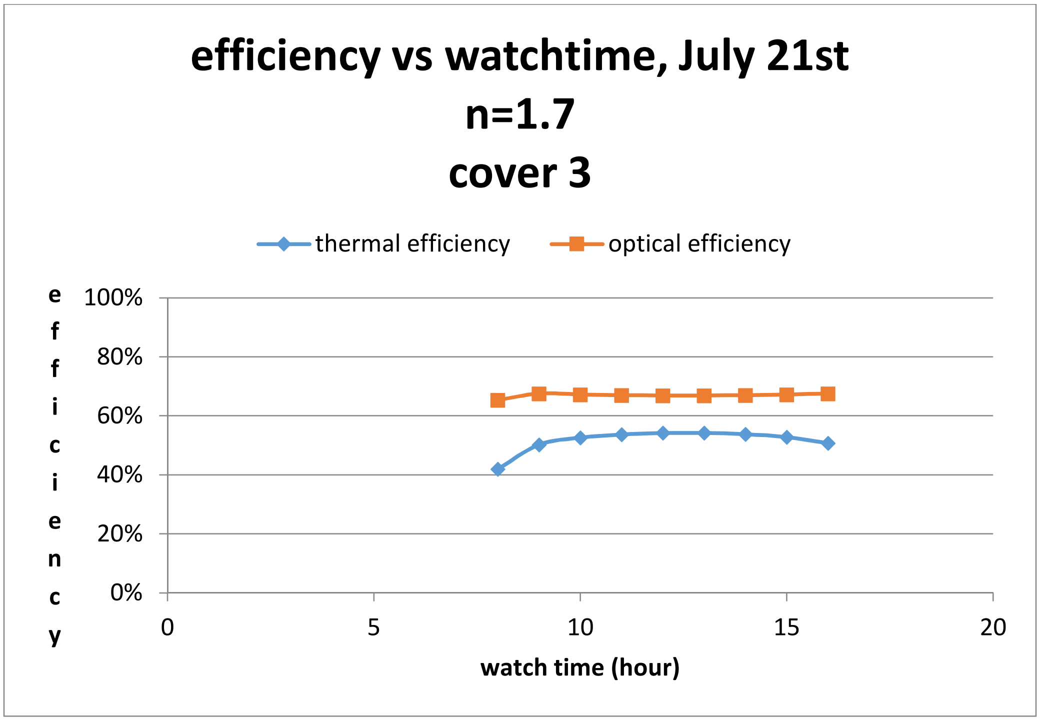

Fig 4.10: three covers, 1.7 refractive index, July 21st

4.2 Case 2

The second selected case was on October 21st which is convenient to calculate Optical efficiency and Thermal efficiency using ASHRAE MODEL. The month of October has the moderate amount of sunshine. Figure 4.11, through 4.20 shows the efficiency versus time curve for Sunearth flat plate collector with no cover, 1 cover, 2 covers and 3 covers for refractive indexes of 1.1, 1.4 and 1.7. The optical efficiency of the solar flat plate with no cover is 94% due to the unwanted transmission of reflected radiation. The refractive index does not have any influence on this performance when no cover is used.

From figure 4.12, 4.15 and 4.18 at 8 am with same refractive index 1.1 and different number of covers the optical efficiency for 1 cover 79%, for 2covers 71% , 3 covers 64%.

This showing the same result like case 1 keeping same refractive index the optical efficiency decreases when the number of cover is increased. Also from figure 4.12, 4.13, 4.14 at 9 am with cover 1 and different refractive index the optical efficiency 88% and thermal efficiency 49% for refractive index 1.1, optical efficiency is 78% and thermal efficiency 40%for refractive index 1.4, optical efficiency 73% and thermal efficiency 35% for refractive index 1.7. In this case same result found with same cover the increase of refractive index degrades the performance of the collector.

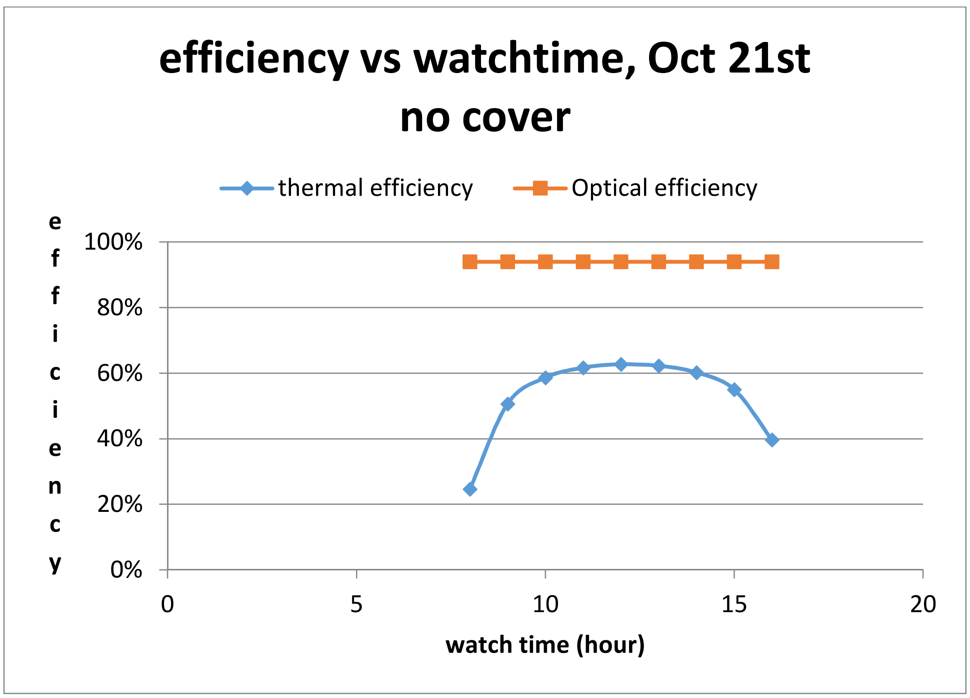

Fig 4.11 : efficiency versus watch time with no cover, Oct 21st

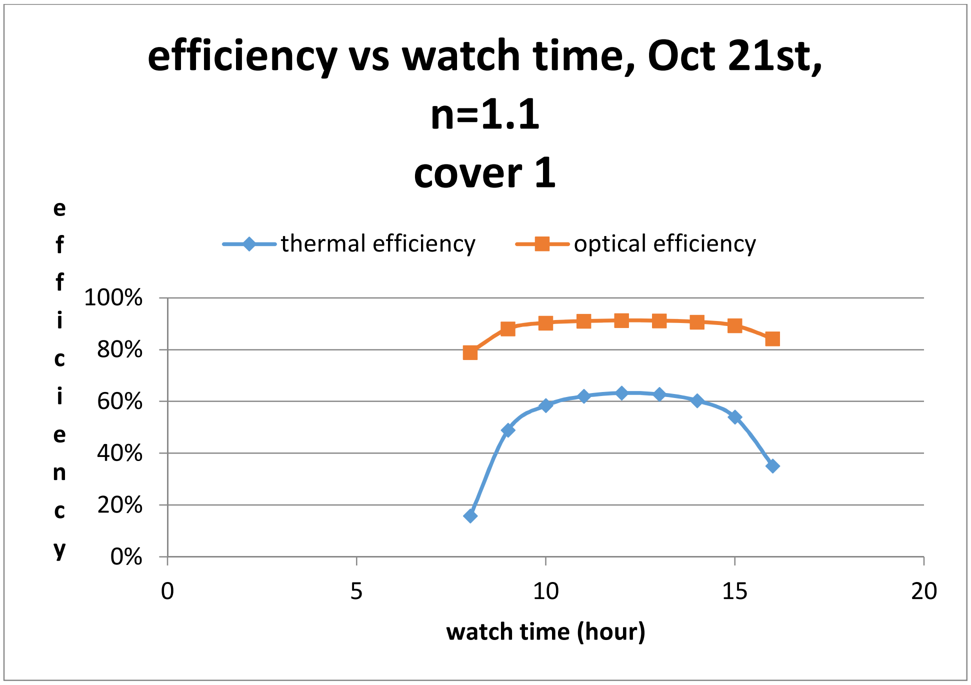

Fig 4.12 : one cover, 1.1 refractive index, Oct 21st

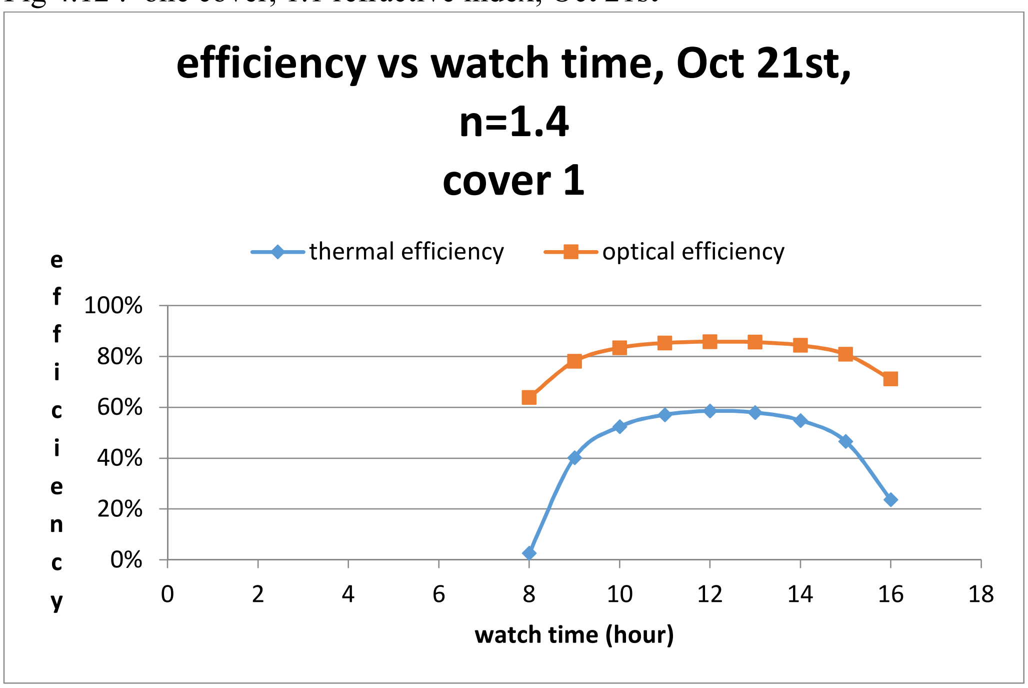

Fig 4.13 : one cover, 1.4 refractive index, Oct 21st

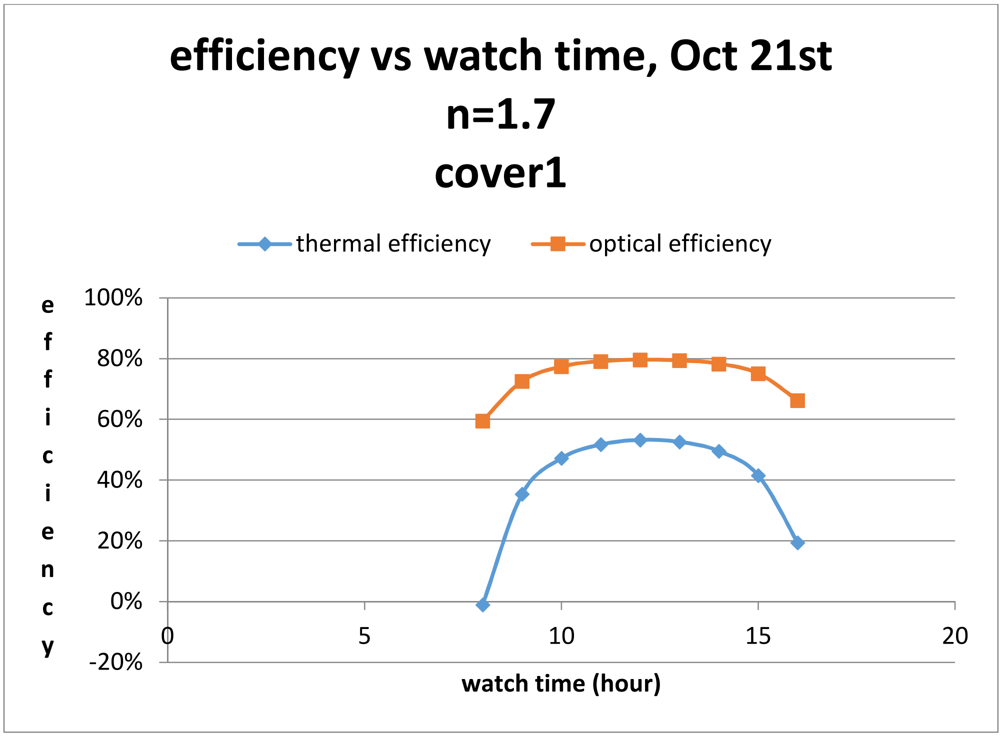

Fig 4.14: one cover, 1.7 refractive index, Oct 21st

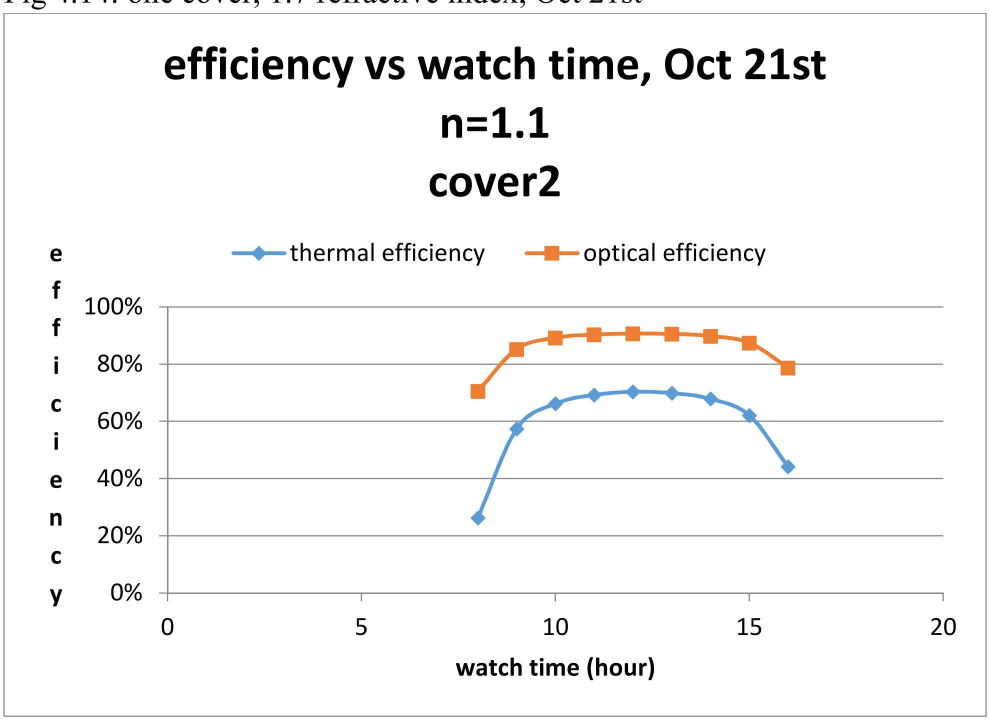

Fig 4.15: two covers, 1.1 refractive index, Oct 21^{st}

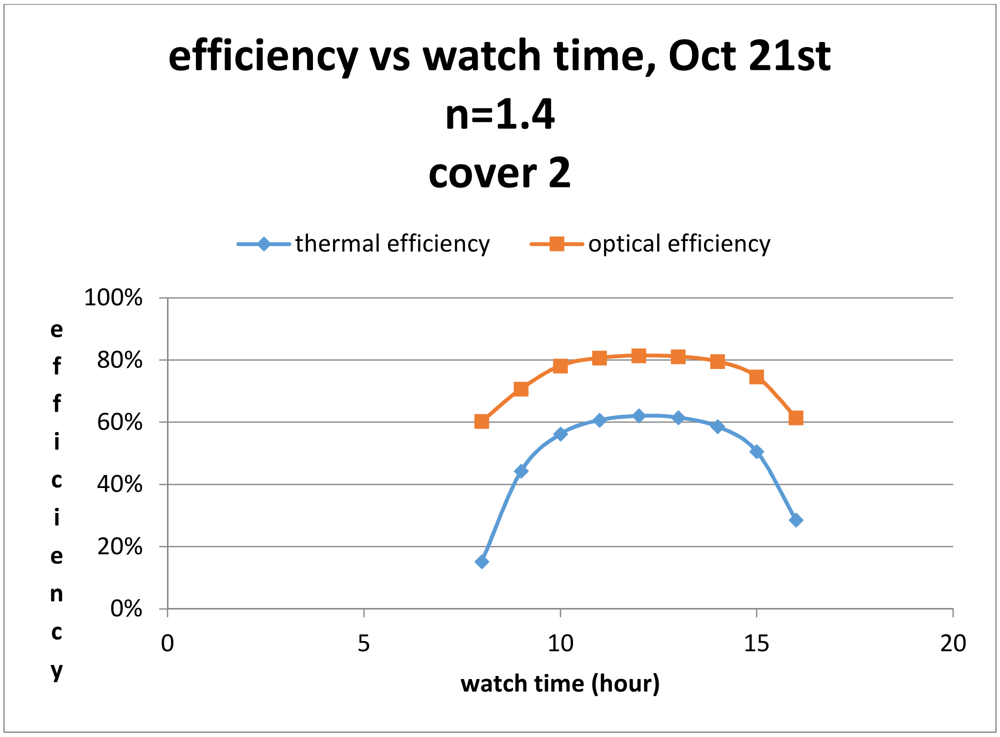

Fig 4.16: two covers, 1.4 refractive index, Oct 21st

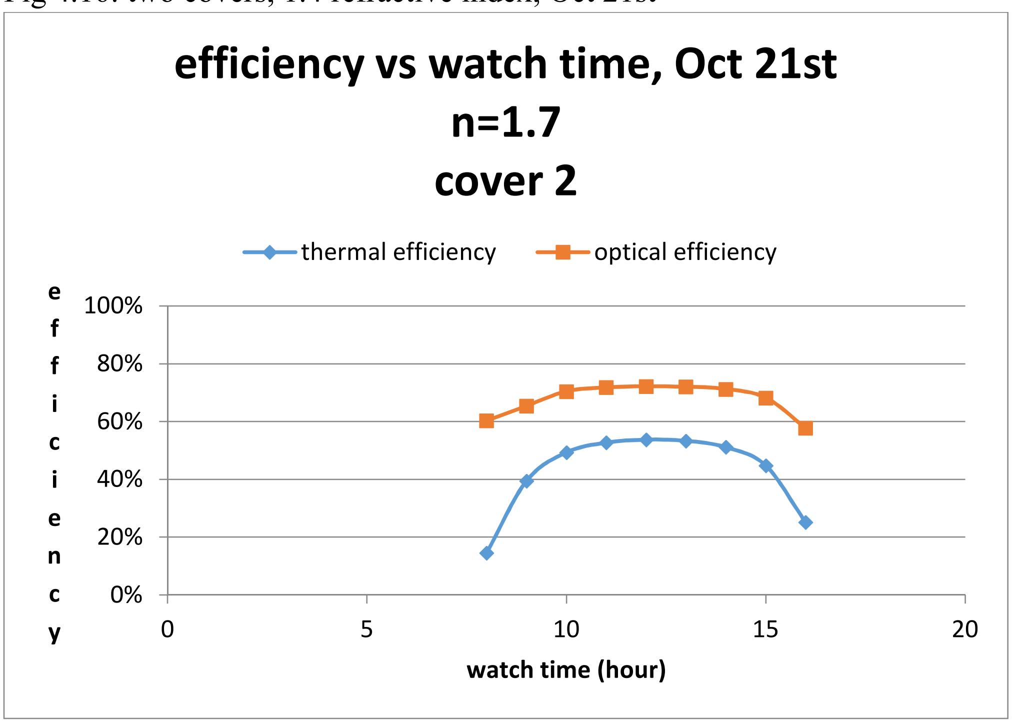

Fig 4.17: two covers, 1.7 refractive index, Oct 21st

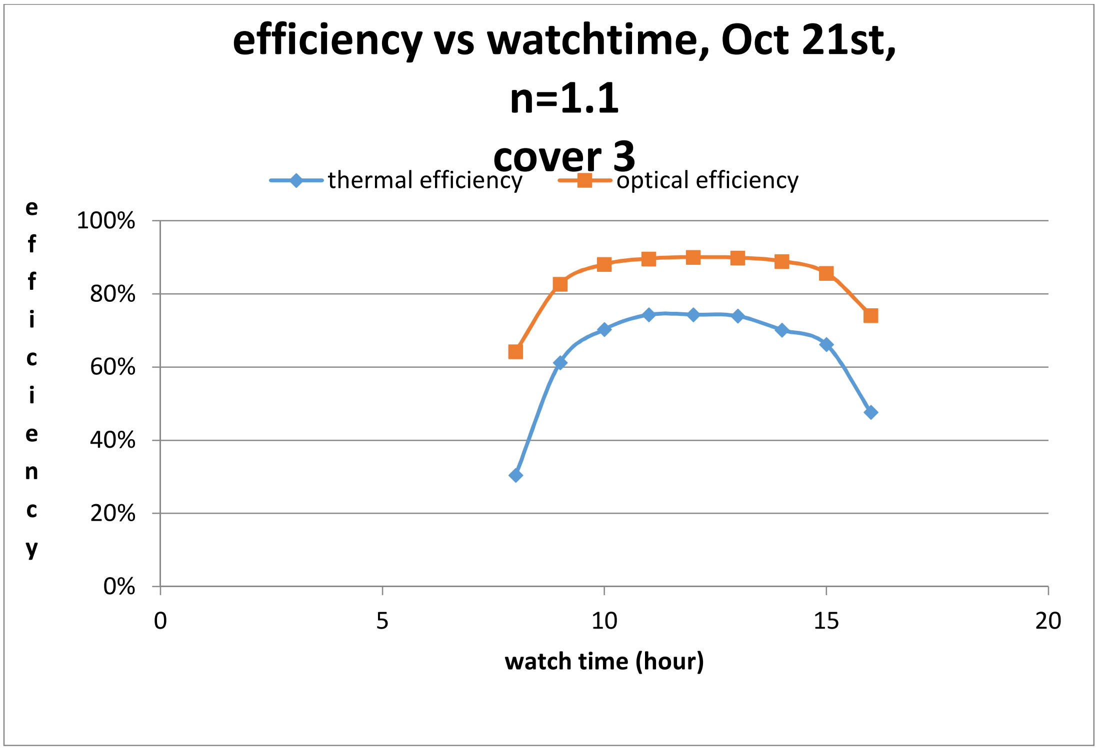

Fig 4.18: three covers, 1.1 refractive index, Oct 21st

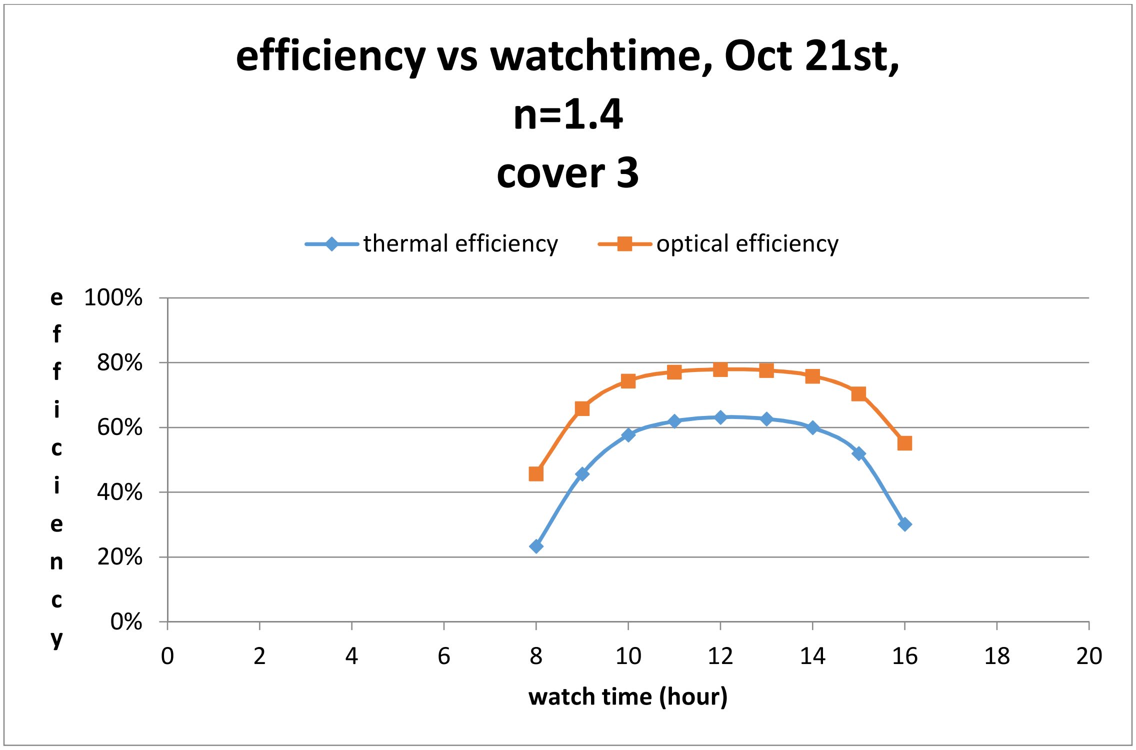

Fig 4.19 : three covers, 1.4 refractive index, Oct 21st

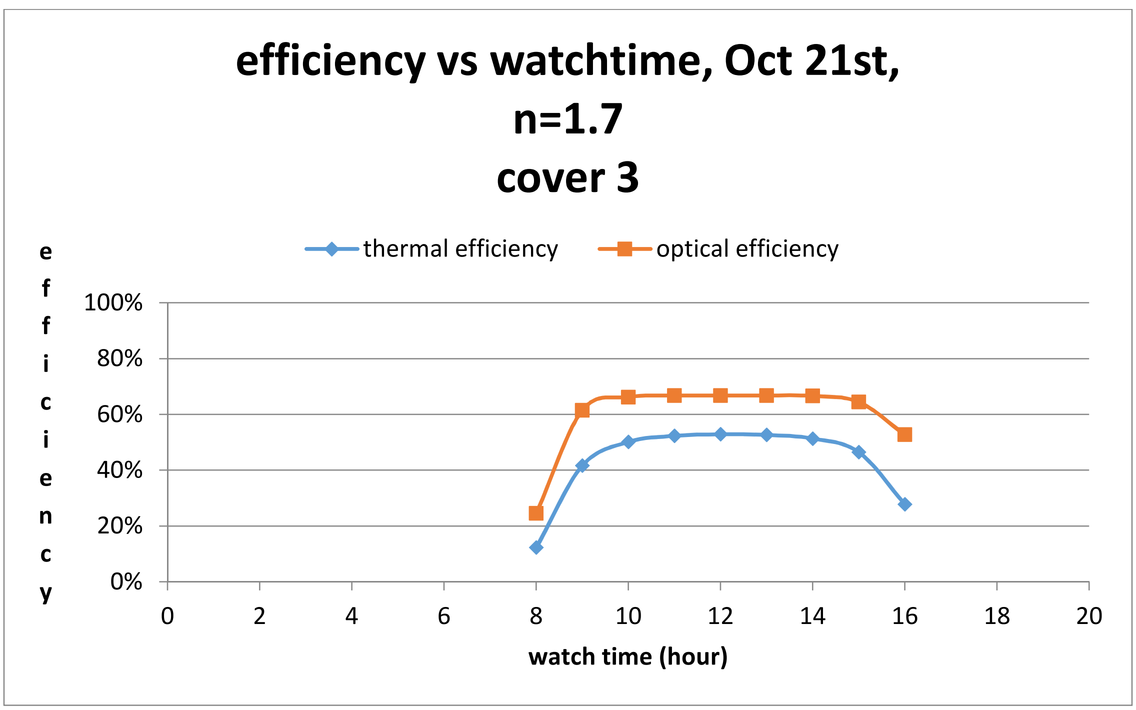

Fig 4.20: three covers, 1.7 refractive index, Oct 21st

A number of general observations can be made from the results of simulation for case 1 and case 2. Figure 4.1 and 4.11 shows the expected result that when no cover is used the refractive index does not have any influence on the performance of the collector. Although in most systems the inlet temperatures will vary throughout the day, the estimated performance is very convenient to compare the performance of solar water heating system with different covers' refractive index.

In this research it is observed from figure 4.2 to 4.10 and figure 4.12 to 4.20 that for the same watch time with same number of covers, and different refractive index the collector shows higher thermal efficiency and optical efficiency when refractive index is 1.1..

From the table 4.1 and figure 4.21, 4.22 below shows the performance of collector with refractive index 1.1 and different covers, 1, 2, 3. The result shows highest thermal efficiency found with 3 covers which is 76% for July 21st and 74% for October 21st. The thermal efficiency is higher in July than in October. This is because the most solar radiation received in the month of July and then decreases in the rest of the year. So the month of October receives less radiation than the month of July and the collector performance is less in October.

With the lowest refractive index 1.1 and different covers, 1, 2, 3 for July 21st and October 21st the performance of the Sunearth solar water heater shown below:

Table 4.1 Sunearth collector performance for July21st and October 21st

with refractive index 1.1

July 21st			
no. of cover	1	2	3
thermal efficiency	66%	72%	76%
optical efficiency	92%	91%	91%
Oct 21st			
no. of cover	1	2	3
thermal efficiency	63%	70%	74%
optical efficiency	91%	91%	90%

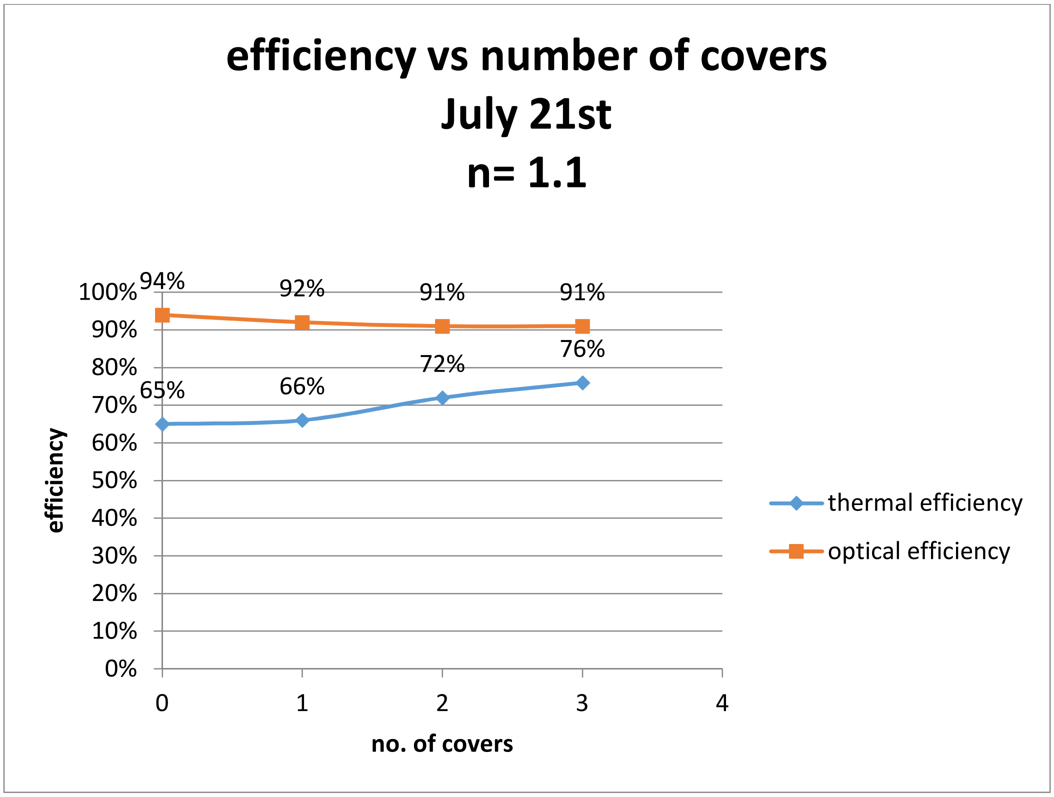

Fig 4.21: efficiency versus number of covers, 1.1 refractive index, July 21st

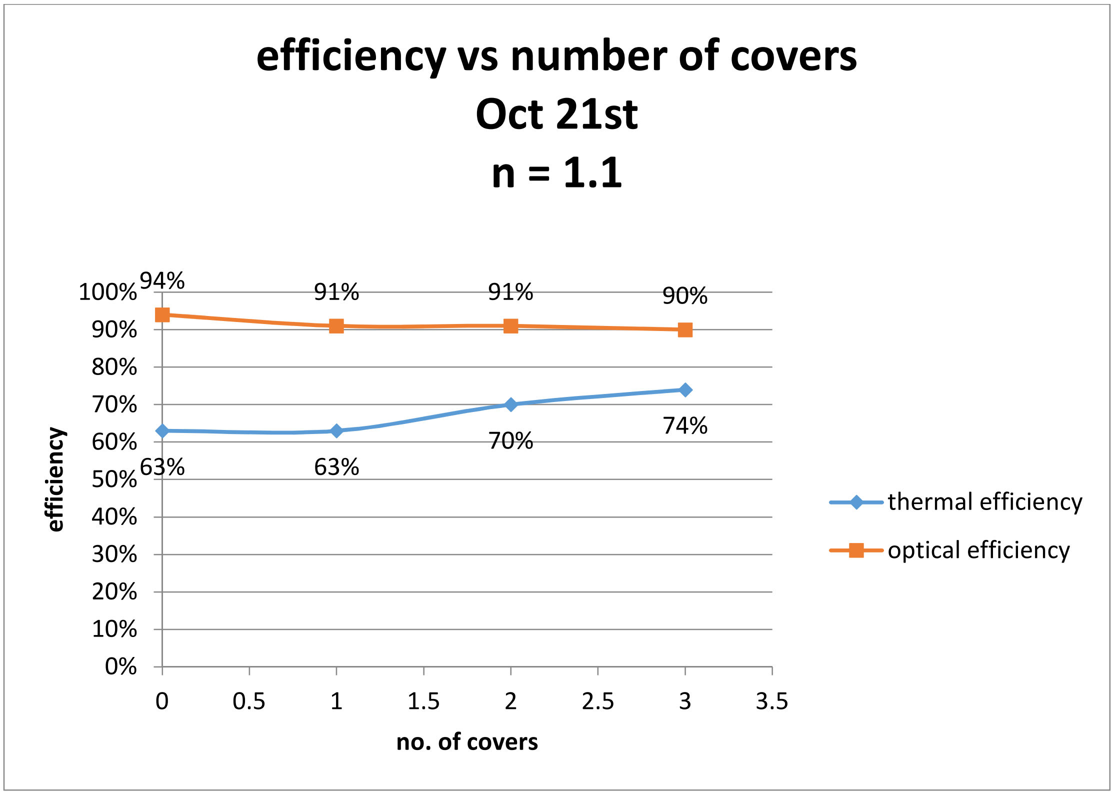

Fig 4.22: efficiency versus number of cover, 1.1 refractive index, Oct 21st

It is noted that in this analysis that factors affecting the performance of the collector are number of covers, refractive index, weather condition and the period while the collector is operating. It is observed from figure 4.1 through 4.20 that the performance of the collector decreases during the early morning and late afternoon. From figure 4.18 the optical efficiency for 3 covers with refractive index at 8 am 30%, 12 noon 74%, and 16:00 PM 48% and from figure 4.8 the thermal efficiency at 8 am 61%, 12 noon 76% and 16:00 PM 63%. The angle of sun is dependent on the time of day. During the day from sunrise until noon the sun's angle to any location decreases and then increases until sunset. Solar radiation has to pass through more of the atmosphere at greater angles and reduces its irradiance. It is seen from figure 4.1 through 4.20 that the efficiency is low in the morning and then increases to maximum efficiency at noon and 13:00 PM, after 13:00 PM it gradually decreases as irradiation decreases. So the collector shows its best performance at noon 12:00 and at 13:00 PM due to higher irradiance.

The low efficiency of the collector is also due to thermal losses and optical losses. The thermal losses are conduction, convective and radiative heat losses. This is because the temperature always flows from hot surface to cold surface in order to maintain equilibrium condition. The top surface of the collector plate or cover experiences convective heat loss and radiative heat loss. The radiation is not sufficient during the early morning and late afternoon to overcome the thermal and optical losses and the performance decreases. When the radiant flux increases at a given fluid inlet temperature the heat loss from the collector remains about same, and the collector efficiency increases.

Having determined the overall heat loss coefficient U_L, from figure 4.23 and figure 4.24 the effect of the number of covers on collector performance becomes apparent. On July 21st at 8 am the overall heat loss coefficient with same refractive index 1.1 for 1 cover is 4.94 w/m^2 ^{0}c, for 2 covers 3.46 w/m^2 ^{0}c and for 3 covers 2.65 w/m^2 ^{0}c. The result shows that glass cover reduces convective and radiative heat transfer between absorber of the system and the ambient media.

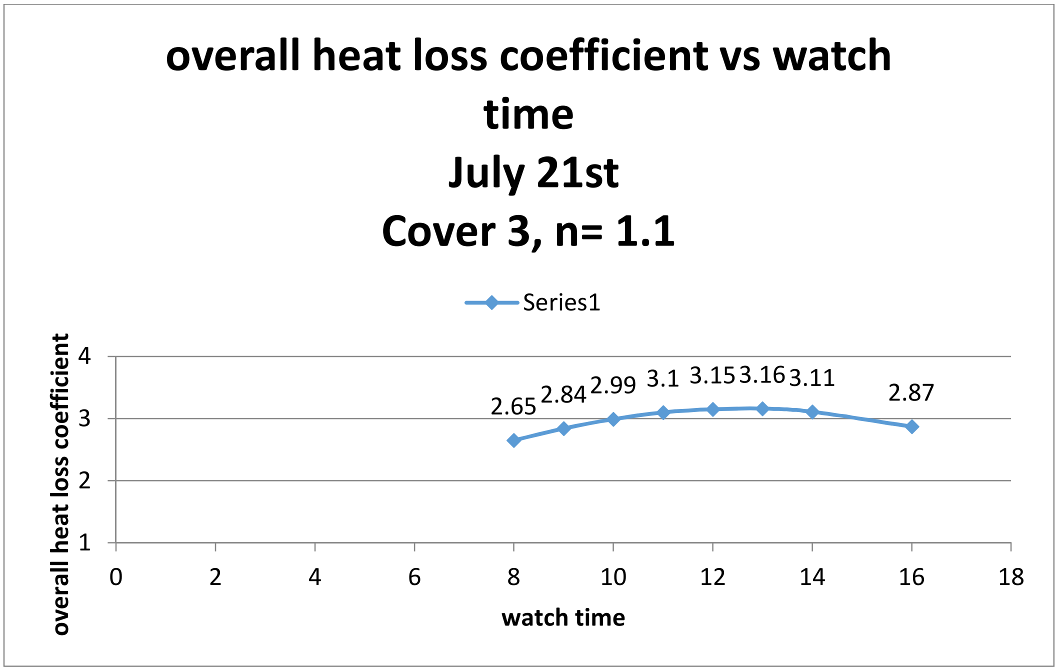

Fig 4.23 Overall Heat Loss Coefficient vs Watch Time

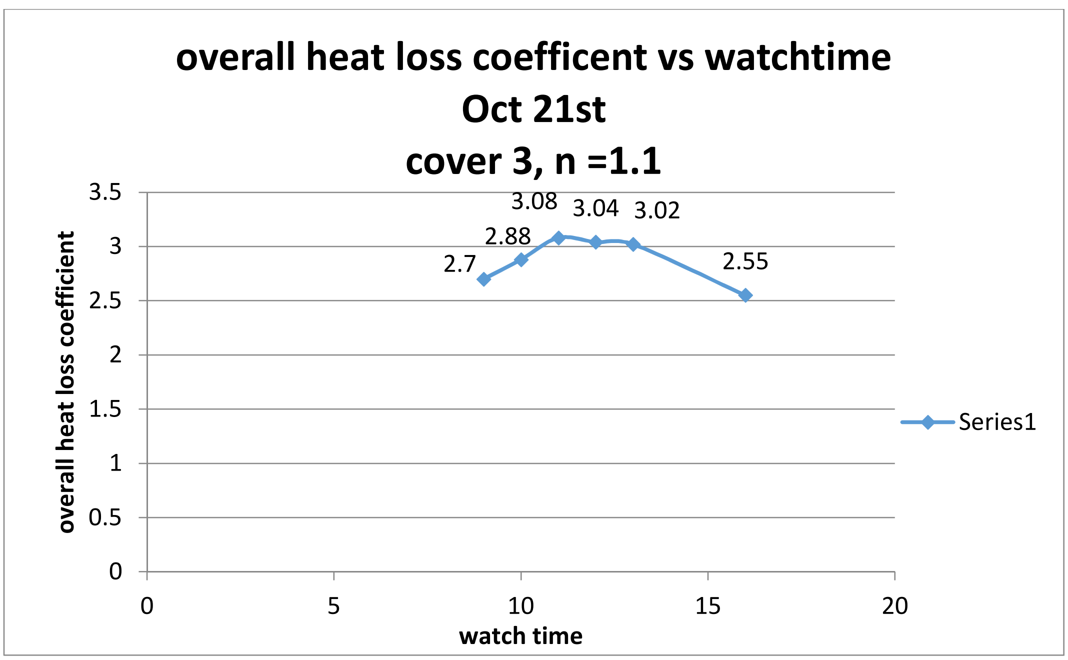

Fig 4.24 Overall Heat Loss Coefficient vs Watch Time

Therefore, heat loss through the single cover is higher than that through two covers and three covers and the performance of the collectors with a single cover decreases more rapidly than the performance of the collector with two or three covers. Same result found for October 21st that the collector overall heat loss coefficient is lower when cove 3 is used. It is also noted with fixed fluid temperature the overall heat loss coefficient increases when radiation flux increases from sunrise to noon, then decreases again until sunset.

Variation of instantaneous efficiency with time of Sunearth solar plate collector is shown below in table 4.1 through 4.8 for July 21st and October 21st. The result shows that as irradiation increases with time, the efficiency also increases and efficiency decreases when irradiation deceases. . It is shown in table 4.2 for July 21st that thermal efficiency with cover 1 and refractive index 1.4 at 8:00 AM 36% and then increases to maximum efficiency 62% from 12 noon to 13:00 PM. After 13:00 PM the efficiency gradually decreases as irradiation decreases and at 16:00 PM the efficiency reduces to 53%. In the month of October 21st from table 4.6 the lowest efficiency found at 8 AM 3%, and the highest efficiency is found at noon 12 only which is 59%. After noon the efficiency decreases to 24 % at 16:00 PM. It is noted from the result that weather condition also affects the performance of the collector. In the month July has the most amount of sunshine and so that the maximum efficiency remains same for a longer period of time which is found at noon 12 and 13:00 PM but since the month of October has moderate sunshine the maximum efficiency is found only at noon. It is also observed that with 3 covers and refractive index 1.1 from table 4.4 in July 21st the maximum efficiency is found at 12 noon, 13:00 PM, 14:00 PM and from table 4.8 in October 21st the maximum efficiency is found at 11:00 PM, 12:00 PM and 13:00 PM. In this analysis also the collector performs best for a longer period of time when number of cover is 3 and refractive index is 1.1.

Table 4.2 collector performance with no cover for July 21st

July 21st	no cover	
watch time	thermal efficiency	Optical efficiency
8	45%	94%
9	57%	94%
10	61%	94%
11	64%	94%
12	65%	94%
13	65%	94%
14	64%	94%
15	62%	94%
16	57%	94%

Table 4.3 Collector performance with 1 cover and refractive index 1.1 for July 21st

	cover 1, n =1.4	
	July 21st	
watch time	thermal efficiency	optical efficiency
8	36%	80%
9	52%	85%
10	58%	86%
11	60%	87%
12	62%	87%
13	62%	87%
14	61%	87%
15	58%	86%
16	53%	85%

Table 4.4 Collector performance with 2 covers and refractive index 1.7 for July 21st

	cover 2, n =1.7	
	July 21st	
watch time	thermal efficiency	optical efficiency
8	38%	69%
9	49%	72%
10	52%	73%
11	55%	73%
12	56%	73%
13	56%	73%
14	55%	73%
15	54%	73%
16	50%	72%

Table 4.5 Collector performance with 3 covers and refractive index 1.1 for July 21st

July 21st	cover 3,n =1.1	
watch time	thermal efficiency	optical efficiency
8	61%	86%
9	71%	90%
10	74%	91%
11	76%	91%
12	76%	91%
13	76%	91%
14	76%	91%
15	74%	91%
16	71%	90%

Table 4.6 collector performance with no cover for October 21st

october21st	no cover	
watch time	thermal efficiency	Optical efficiency
8	25%	94%
9	51%	94%
10	59%	94%
11	62%	94%
12	63%	94%
13	62%	94%
14	60%	94%
15	55%	94%
16	40%	94%

Table 4.7 Collector performance with 1 cover and refractive index 1.4 for October 21st

october21st	cover 1, n =1.4	
watch time	thermal efficiency	optical efficiency
8	3%	64%
9	40%	78%
10	52%	83%
11	57%	85%
12	59%	86%
13	58%	86%
14	55%	84%
15	47%	81%
16	24%	71%

Table 4.8 Collector performance with 2 covers and refractive index 1.7 for October 21st

october21st	cover 2, n =1.7	
watch time	thermal efficiency	optical efficiency
8	15%	60%
9	39%	65%
10	49%	70%
11	53%	72%
12	54%	72%
13	53%	72%
14	51%	71%
15	45%	68%
16	25%	58%

Table 4.9 Collector performance with 3 covers and refractive index 1.1 for October 21st

october21st	cover 3, n =1.1	
watch time	thermal efficiency	optical efficiency
8	30%	64%
9	61%	83%
10	70%	88%
11	74%	90%
12	74%	90%
13	74%	90%
14	70%	89%
15	66%	86%
16	48%	74%

CHAPTER 5

CONCLUSION AND FUTURE WORK

In this work theoretical analysis is performed on Sunearth flat plate collector to investigate the effect of number of transparent cover and the refractive index of transparent cover using MTALAB software. . The parameters that affects absorber plate and cover characteristics are transmittance absorptance product (τα) and refractive index and the collector performance is observed with different number of covers depending on these parameters. It is observed that when the value of transmittance absorptance product (τα) decreases when number of cover increases and therefore, optical efficiency decreases with the increase of number of covers. Since the glass cover acts as an insulator and high in transmittance and low in reflectance, the thermal efficiency increases with the increase of number of covers. When the refractive index is low the transmissivity of glass cover becomes high and thus the thermal efficiency increases with lower refractive index.

It is also observed that lower the overall heat loss coefficient higher the collector performance. The glass cover reduces convective and radiative heat transfer between absorber of the system and ambient media to 46% when 3 covers are used. The weather condition is also examined to observe the collector performance. In the month of July the collector shows better performance than in October due to higher irradiance in July. The collector performance is also affected by the period when it is running. In early morning and late afternoon the performance is low and the performance is high at noon 12 and 13:00 PM in July and in October performance is high at noon 12.

It can be concluded that the optical efficiency decreases with the increase of number of covers and the thermal efficiency increases with the increase of number of covers with lower refractive index. Efficiency of Sunearth Solar Water Heater is best to cover the amount of three layers with refractive index 1.1 compared to other combination of number of transparent cover glass and refractive index.

The design of collector array requires an optimization which provides the lowest heat price. Though the efficiency of collectors is high if the number of covers is increase, it is often not optimal for overall efficiency since there is a maximum limit for the number of covers due to weight, size and cost. But there is huge scope to change geometric shape of Sunearth flat plate collector to get better performance.

Recommendations for Future work

Experimental investigations are needed to confirm the efficiency of the collector by testing the code for different cases. Additional research also includes inspecting collector performance for a full year and the effect of dust, shading, and weather change on the performance of collector which would help in further validating the code.

In the MATLAB simulation the inlet fluid temperature is kept constant. Since inlet temperature has a strong effect on the collector performance and it varies throughout the day, investigation of the collector performance with varying inlet fluid temperature will provide more accurate result

The effect of number of covers on the performance collector one may want to explore increasing the number of covers to see impact of both thermal and optical efficiency of the collector. These simulations will give more accurate predictions of the optimum number of covers and will help to determine correct number of covers to be used for collector array design.

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APPENDIX A

DOWFROST^{TM} HD HEAT TRANSFER FLUID PROPERTY

Temp(^{0}C)	Viscosity (mPa sec)	Thermal Conductivity(w/mk)	Specific Heat (kJ/Kg K)
0	7.07	0.409	3.728
5	5.61	0.415	3.742
10	4.52	0.421	3.757
15	3.69	0.426	3.771
20	3.06	0.431	3.785
25	2.57	0.436	3.8
30	2.19	0.441	3.814
35	1.88	0.445	3.828
40	1.63	0.45	3.842
45	1.43	0.453	3.857
50	1.26	0.457	3.871
55	1.13	0.46	3.885
60	1.01	0.463	3.9
65	0.92	0.466	3.914
70	0.83	0.469	3.928
75	0.76	0.471	3.943
80	0.7	0.473	3.957
85	0.65	0.474	3.971
90	0.6	0.476	3.985
95	0.56	0.477	4
100	0.53	0.478	4.014
105	0.5	0.479	4.028
110	0.47	0.48	4.043
115	0.45	0.48	4.057
120	0.42	0.48	4.071
125	0.41	0.48	4.086
130	0.39	0.48	4.1
135	0.37	0.48	4.114
140	0.36	0.479	4.128
145	0.34	0.478	4.143
150	0.33	0.478	4.157

APPENDIX B

ASHRAE MODEL

Table B.1: Values of A, B, C for the calculation of solar irradiance according to the ASHRAE handbook:

Date	A(w/m^2)	B(w/m2)	C(w/m2)
21-Jan	1230	0.142	0.058
21-Feb	1215	0.144	0.060
21-Mar	1186	0.156	0.071
21-Apr	1136	0.180	0.097
21-May	1104	0.196	0.121
21-Jun	1088	0.205	0.134
21-Jul	1085	0.207	0.136
21-Aug	1107	0.201	0.122
21-Sep	1152	0.177	0.092
21-Oct	1193	0.160	0.073
21-Nov	1221	0.149	0.063
21-Dec	1234	0.142	0.057

APPENDIX C

AIR PROPERTY

Temperature - *t* - (°C)	**Density** - *ρ* - (kg/m³)	**Specific Heat** - c_p - (kJ/(kg K))	**Thermal Conductivity** - *k* - (W/(m K))	**Kinematic Viscosity** - *ν* - x 10^{-6} (m²/s)	**Expansion Coefficient** - *b* - x 10^{-3} (1/K)	**Prandtl's Number** - P_r -
-150	2.793	1.026	0.0116	3.08	8.21	0.76
-100	1.980	1.009	0.0160	5.95	5.82	0.74
-50	1.534	1.005	0.0204	9.55	4.51	0.725
0	1.293	1.005	0.0243	13.30	3.67	0.715
20	1.205	1.005	0.0257	15.11	3.43	0.713
40	1.127	1.005	0.0271	16.97	3.20	0.711
60	1.067	1.009	0.0285	18.90	3.00	0.709
80	1.000	1.009	0.0299	20.94	2.83	0.708
100	0.946	1.009	0.0314	23.06	2.68	0.703
120	0.898	1.013	0.0328	25.23	2.55	0.70
140	0.854	1.013	0.0343	27.55	2.43	0.695
160	0.815	1.017	0.0358	29.85	2.32	0.69
180	0.779	1.022	0.0372	32.29	2.21	0.69
200	0.746	1.026	0.0386	34.63	2.11	0.685

Temperature - t - (^oC)	Density - ρ - (kg/m^3)	Specific Heat - c_p - ($kJ/(kg\ K)$)	Thermal Conductivity - k - ($W/(m\ K)$)	Kinematic Viscosity - v - $x\ 10^{-6}$ (m^2/s)	Expansion Coefficient - b - $x\ 10^{-3}$ ($1/K$)	Prandtl's Number - P_r -
250	0.675	1.034	0.0421	41.17	1.91	0.68
300	0.616	1.047	0.0454	47.85	1.75	0.68
350	0.566	1.055	0.0485	55.05	1.61	0.68
400	0.524	1.068	0.0515	62.53	1.49	0.68