Performance Analysis of Active Solar Water Heating System

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Abstract- The objective of this thesis is to investigate the temperature distribution in a flat-plate solar collector tube by experimentally and numerically. Experimental study is performed on a small scale flat-plate solar collector in December at Mandalay 21.98˚latitude and 96.1˚longitude. The cover and absorber plate are made of glass (0.9144m length×0.6096m width) and steel (0.762m length×0.5558m width). The riser tubes are made of steel with 0.014m diameter and 0.762m length respectively. The back cover is insulated with foam of 0.0254m thickness. The absorber plate transfers heat energy to water flowing in the tubes. The flow can takes place due to thermosyphon effect. However, certain energy absorbed by temperature of the plate which in turn is dependent on the nature of flow of water inside the tube, solar insolation, collector inclination angle, number of riser tube, ambient temperature and material. According to the experimental results, the highest water outlet temperature is 50˚C at 31th December with collector efficiency 35% while the ambient temperature is 29˚C. Then, the water outlet temperature from experiment is compared with numerical analysis. From this research, useful factors can be provided to apply for industrial water heating.

Indexed Terms- Flat plate collector, industrial water heating, solar insolation, collector inclination angle, ambient temperature

I. INTRODUCTION

The sun is the world's largest resource, and solar energy is a form of renewable energy which is abundant in our environment. The sun was supplying all the energy needs of man either directly or indirectly and that man was using only renewable source of energy. Today, every country draws its energy needs from a variety of sources such as coal, oil and natural gas. It has been become obvious that fossil fuel resources are fast depleting and that the fossil fuel era is gradually coming to an end. So, the energy problems are currently faced by developing countries.

The reality is that resources like coal, oil and natural gas will not be around forever. The use of solar energy can reduce the use of fossil fuels as well as reducing harmful environmental emission resulting from the burning of fossil fuels. In addition, it appears to be no significant polluting affects from its use. Besides, solar energy is renewable and will not deplete within the next several billion years.

Solar energy systems are very practical now for many applications in the building industry such as water and space heating. There are a variety of technologies that have been developed to take advantage of solar energy. The technologies are classified as passive or active depending on the way they capture, convert and distribute sunlight. An active solar technology uses photovoltaic panels and fans to convert sunlight into useful outputs. A passive solar technology uses sunlight for energy without active mechanical systems. Such technologies convert sunlight into useable heat (water, air, and thermal mass), cause air-movement for ventilating, or store heat for future use, without the assistance of other energy sources. While costs associated with operating these products may be limited or nil, maintenance costs are very low.

When considering renewable energy sources one should pay attention to the best possible match between available energy type and desired end use energy type. The conversion efficiency from solar energy to electricity around 10% - 20 % is also much lower than the efficiency of solar heat collection. These facts suggest that one should use solar thermal collectors when heat is desired end use energy form.

II. OVERVIEW OF SOLAR ENERGY

The sun is just one of the more than 100 billion stars. It is no more than average in size, not especially hot compared to other stars, and is therefore not a very bright star. Form a vantage point in some far-off constellation, astronomers would probably catalog our sun as an “insignificant” star. For life on earth, however, the sun is all important. Its mass contributes directly to the force of mutual attraction that holds the earth and the other eight planets in the orbital geometry that we call solar system. The sun is a gigantic sphere of high-temperature gases, about 865,000 miles (1,392,000) km in diameter. Its mass is on the order of 2.2×1027 tons (2.0×1030 kg), or some 330,000 times that of the earth. As a gaseous sphere, its average density is not great – about 1.4 time that of water, or 87 lb/ft3, or 1.4 kg/L. However, the sun’s size and mass are so great that the resultant gravitational force (the gravity force on the surface of the sun is about 28 times that at the earth’s surface) causes the density to increase steadily from the surface to the center, where it may be on the order of 160 kg/L (that is, 160 times as dense as water) at pressure on about 70×109 (earth) atm.

The total energy streaming out into space from the sun’s surface is estimated to be about 3.8×1020MW, radiating outward in all directions. This represents an energy release of about 63 MW/m2 (8000 hp/ft2) at the sun’s (photosphere) surface. Only a small of this amount of this immense total is captured by the earth, since the solid angle in space subtended by the earth at its 93-million-mile distance from the sun is small indeed. At a point just outside the earth’s atmosphere, the solar power is estimated to be about1.35 kW/m2 (429 Btu/hr-ft2 or 0.17 hp/ft2). In summary, the sun is a fantastic nuclear furnace producing energy at temperatures in the millions of degrees. The high-frequency gamma radiation produced by nuclear fusion in the interior of the sun is tempered by its passage to the surface, and the energy that we call solar radiation emanates from the photosphere mostly as visible light and infrared waves characteristic, of a radiating surface at a temperature of about 5800˚C (6000 K or 10,000˚F).

A. The Trajectory of the Sun and Myanmar

The country ‘Myanmar’ is situated between northern latitude of 9˚ 58', 28˚ 31' and the eastern longitude of 92˚ 10', 101˚ 11'. The path of the sun is on equator on twenty-first March. On June twenty-second the track of the sun is on “Tropic of Capricorn”; then on March twenty-first the sun is on equator again, making one complete cycle. In this rhythmic-nature the cyclic order in Myanmar, the weather is summer from first March to fifteenth of May. The rainy season starts from fifteenth May to end of October and winter is from November to end of February, thus creating three seasons in Myanmar.

The “Standard Time of Myanmar” in reference is positioned on the east longitude of 97˚ 30'. Total area or total square miles of Myanmar is 261228. The radiated heat energy from the sun on to the earth converted to horse power is 469×1011. Therefore total approximate horse power in total area of Myanmar is calculated to be 123×1010 that is the sun’s radiated heat power.

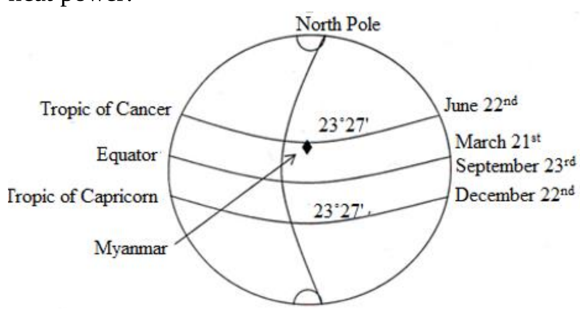

Figure 1. The Trajectory of the Sun and Myanmar [Department of Meteorology (Mandalay)]

B. Sun-earth Geometry

The earth rotates around the sun. This causes the sun to “rise” and “set”. The angle of the sun and its intensity on earth is affected by location of the place on the surface of the earth. The length of the atmosphere that the solar radiation has to pass through determines the amount of radiation that reaches the earth’s surface.

On March twenty-first and again on September twenty-first, the sun appears to be directly over the equator, and both hemispheres are receiving the same amount of solar radiation. On these days, the duration of daylight is equal to the duration of darkness (equinox means “equal night”).

The sun rises earliest and sets latest on this day, and the sun's path is higher on this day than on any other day of the year. By December twenty-first, the sun's path is as far south as it will go, it is winter in the northern hemisphere, the sun is low in the sky all day, and the sun rises late and sets early, resulting in short days and long nights. This is an acceptable approximation for solar energy calculations because the eccentricity of the earth's orbit is very small. The distance between sun and earth changes by ± 17% between apogee and perihelion.

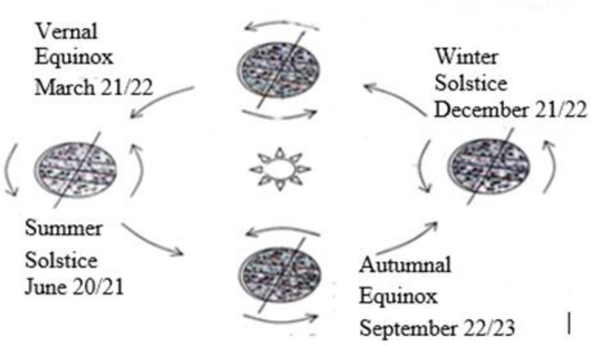

Figure 2. Sun-earth Geometry [78Kre]

i) Collector's Tilt Angle (β)

The angle between the horizontal surface and the inclined plane. It can also be defined as an angle between the collector's normal direction and the vertical plane.

ii) Solar Declination (δ)

It is an angle between the sun's rays and a plane passing through the equator. This is illustrated in Figure 3. The declination is positive when the sun is directly overhead north of the equator (December 21 through June 21 and it is negative when the sun is directly overhead south of the equator (June 21 through December 21). The declination, δ, can be calculated from the equation:

$$\delta = 23.45 \sin\left[\frac{360}{365}(284+n)\right] \qquad (1)$$

Where n is the day of year (i.e., n=1 for January 1, n=32 for February 1, etc.).

The solar declination has a maximum value of + 23.45˚ on June 21 and a minimum value of -23.45˚ on December 21.

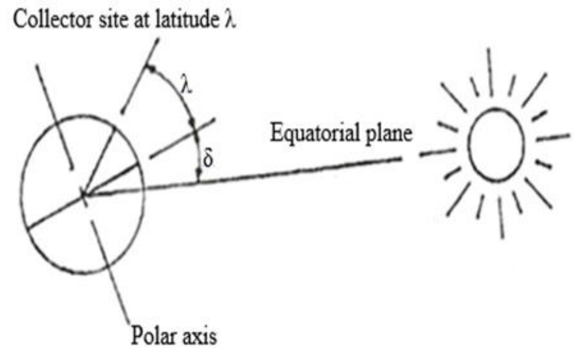

Figure 3. Schematic of Solar Declination [77Fro]

1) Hour Angle (ω)

The solar hour angle is the angular displacement of the sun from noon. It is also measured in degree and illustrated in Figure 3.4. It can be expressed by

$$\omega = \frac{360^\circ}{\tau_{day}} t$$

Where, τ day = length of day

= 24 hr

= 1440 min

t = 12- LSoT (am) or (h or min)

= LSoT-12 (pm) (h or min)

2) Solar Altitude Angle (α)

It is an angle between the sun's rays and a horizontal plane. When the sun is just rising or setting, the altitude angle is zero. When the sun is directly overhead, the altitude angle is 90˚. The solar altitude angle, α, can be calculated for any location and time from the latitude λ, solar declination, δ, and solar hour angle, ω, using the following equation:

$$\alpha = \sin^{-1}[\sin\lambda \sin\delta + \cos\lambda \cos\delta \cos\omega] \qquad (3)$$

3) Local Solar Time (LSoT)

It is the time of day measured from solar noon. Solar time coincides with real time only at certain time of the year which earth is at the perigee or apogee of its orbits. At other times, real and solar time may differ by as much as ± 15 minutes. The solar time is defined as following.

LSoT = ST + 4 (Lst – Lloc) + e (4)

The equation-of-time correction can be determined from the equation.

$$e = 9.87 \sin(2B) - 7.53 \cos B - 1.5 \sin B \qquad (5)$$

Then, B = 360 ((n-81))/364 where, n = the day of the year after 1 January

4) Solar Zenith Angle (θz)

It is the angle between the vertical axis of the collector and the sun's ray's direction.

$$\theta_z = \cos^{-1}[\sin\lambda \sin\delta + \cos\lambda \cos\delta \cos\omega] \qquad (6)$$

5) Solar Azimuth Angle (φ_s)

It is an angle between the horizontal components of the sun's rays and the horizontal axis extending due south.

$$\phi_s = \sin^{-1}\left[\frac{\cos\delta \sin\omega}{\sin\theta_z}\right] \qquad (7)$$

6) Solar Incidence Angle (θ)

The area of solar collector presents to the direct solar radiation is determined by the angle between the solar rays and the collector normal direction. It is illustrated in Figure 4.

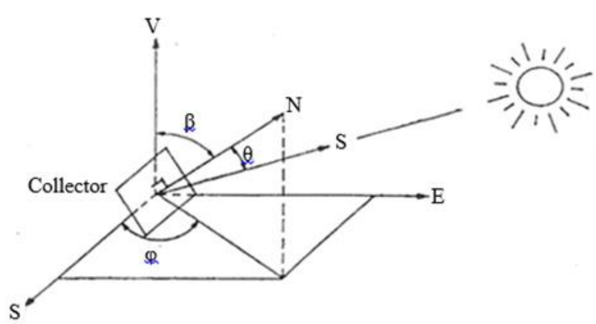

Figure 4. Orientation of a Sloped Collector in Local Coordinates [91Joh]

C. Solar Radiation

Solar radiation is a vital rule after passing through the atmosphere, same parts of radiation are scattered by the atmospherical substances such as gases, dust and clouds. So, solar radiation can be distinguished in three types, namely;

1) Direct radiation
2) Diffuse radiation
3) Reflected radiation

- Clear Sky Radiation

Hottel [1976] has presented a convenient method for estimating beam radiation under clear sky conditions. In terms of zenith angle θ_z and effective solar constant $I_{0,eff}$, the beam irradiance Ib at the earth's surface is indicated by,

$$I_b = I_{0,e}\left[a_0 + a_1 \exp\left(\frac{-k}{\cos\theta_z}\right)\right] \qquad (8)$$

Where, Ib = beam irradiance

Io,eff = effective solar constant

θz = solar zenith angle

The clear sky diffuse irradiance, Id (on the horizontal) can be estimated from a relation due to Liu and Jordan [1960].

$$I_d = [0.2710\, I_{0,eff} - 0.2939\, I_b] \cos\theta_z$$

- Effective Solar Constant

It varies with the time of year according to the formula

$$I_{0,eff} = I_0\left[1 + 0.033 \cos\left(\frac{360\,n}{365.25}\right)\right] \qquad (9)$$

D. Types of Insolation

The atmosphere cause not only absorption but scattering. Thus, it is necessary to distinguish between beam insolation (coming directly from the solar disk, diffuse insolation, and hemispherical insolation (the sum of the beam and diffuse, also called total or global).The magnitude of the solar flux received by a surface depends on its orientation. This necessitates a fairly elaborate notation to differentiate between various insolation types.

The following conventions are

(1) The subscript b designates beam insolation; the surface orientation is normal to the sun unless otherwise specified by a father subscript,

(2) The subscript d designates diffuse insolation; the surface orientation is horizontal unless otherwise specified by a father subscript and

(3) The subscript h designates hemispherical insolation; the surface orientation is horizontal unless otherwise specified by father subscript.

1) Seasonal Variation of Insolation

In addition to the total annual solar radiation, one may want to know something about its seasonal variation. This is particularly important if the load varies with time of year. The seasonal variation of insolation is due to the following factor;

(1) The seasonal variation in the elevation of the sun above the horizon and in the length of the day,

(2) Seasonal changes in the average transparency of the atmosphere and

(3) The ±3% variation of the effective solar constant for the seasonal variation.

III. OVERVIEW OF SOLAR

WATER HEATING SYSTEM: Solar water heating is a technology that is simple to adopt for both urban and rural applications. It basically consists of the solar collector, the flow pipe network and the water storage tank. The storage tank is placed to top of the collector to prevent the reverse circulation during off-sunshine hours (Garg, 1987). As the sun heats the collector, the hot water inside rises by natural convection and the colder storage tank water leaving from its bottom flow into the collector by gravity. Thus the circulation loop is automatically established whenever there is sufficient insolation and circulation automatically stops during insufficient insolation when the upward buoyancy force is unable to overcome the friction losses inside the pipes.

A. Types of Solar Water Heating Systems

Solar water heating system types are classified by the following types:

1) Active - Requires electric power to activate pumps and controls.
2) Passive - Relies on buoyancy (natural convection) rather than electric power to circulate the heated water. Thermosyphon systems locate a storage tank above the solar collector, while integrated-collector-storage collectors place the storage inside the collector.
3) Direct - Heats potable water directly in the collector.
4) Indirect - Heats propylene glycol or other heat transfer fluid in the collector and transfers heat to potable water via a heat exchanger.

B. Types of Solar Collector

Solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium. The major component of any solar system is the solar collector. This is a device which absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a water flowing through the collector. Generally three types of solar collectors are used for residential applications that are described below.

- Flat-plate collector

Flat-plate collectors are the most common for residential water heating. A typical flat-plate collector consists of an absorber plate, transparent cover sheets and an insulated box. The absorber plate is usually a sheet of high-thermal-conductivity metal with tubes or ducts either integral or attached. Its surface is painted or coated to maximize radiant energy absorption and in some cases to minimize radiant emission. The insulated box provides structure and sealing and reduces heat loss from the back and sides of the collector. The cover sheets, called glazing allow sunlight to pass through to the absorber plate but insulate the space above the absorber plate to prevent cool air from flowing into this space. However, the glass also reflects a small part of the sunlight, which does not reach the absorber plate.

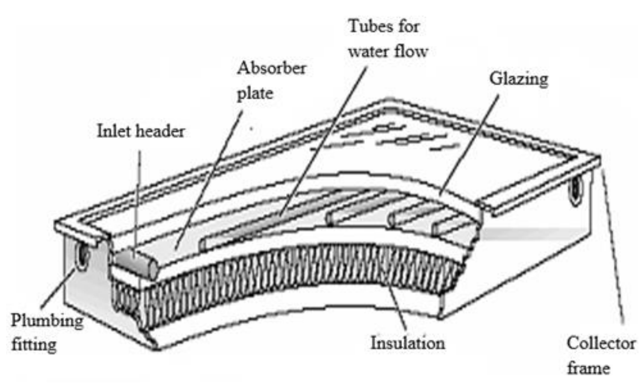

Figure 5. Flat-plate Water Collector [79Tre]

C. Heat transfer in Flat-Plate Collectors

Heat transfer is the thermal energy exchange between bodies when there is a temperature differences them.

Thermal energy is transferred from the higher temperature, to the lower temperature. Heat transfer processes are classified into three modes: conduction, convection and radiation. The heat losses from any solar water heating system take the three mode of heat transfer: radiation, convection and conduction. The conduction heat losses occur from sides and back of the collector plate. The convection heat losses take place from the absorber plate to the glass cover and can be reduced by evacuating the space between the absorber plate and the glass cover and by optimizing the gap between them. The radiation losses occur from the absorber plate due to the plate temperature.

- Conduction

Conduction occurs when there is a temperature gradient across a body. It is an energy transfer across a system due to random molecular movement. Higher temperatures are related with higher molecular energies, hence when they collide with molecules of lower energy and conduction occurs.

The energy loss through the bottom of the collector is represented by the following equation.

$$U_b = \frac{k}{L} \qquad (10)$$

Where, k = thermal conductivity of the insulation
L = the insulation thickness

- Convection

Convection is the transmission of heat within a liquid or gas due to the bulk motion of the fluid.

$$N_u = \frac{hL}{k} \qquad (11)$$

$$P_r = \frac{\nu}{\alpha} \qquad (12)$$

Where, h = natural convection heat transfer coefficient
L = plate spacing
k = thermal conductivity

- Radiation Heat Transfer Coefficient

In a flat-plate collector, radiation heat transfer is occurred at the top, between the absorber plate and the glass cover. Radiation heat transfer coefficient from the glass cover to the ambient air is following.

$$h_{r,c\text{-}a} = \varepsilon_c \sigma (T_c^2+T_a^2)(T_c+T_a) \qquad (13)$$

Where, σ = Stefan-Boltzmann constant
T_c = cover temperature
T_a = ambient temperature

D. Collector Overall Heat Loss Coefficient

It is useful to develop the concept of an overall loss coefficient for a solar collector to simplify the mathematics

$$U_L = U_t + U_b + U_e \qquad (14)$$

1) Collector Top Heat Loss Coefficient (Ut)

The energy loss through the top is the result of convection and radiation between the parallel plates. The loss per unit area through the top is equal to the heat transfer from the absorber plate to the glass cover.

$$U_t = \left[\frac{1}{h_w + h_{r,c-a}} + \frac{1}{h_{c,p-c} + h_{r,p-c}}\right]^{-1} \qquad (15)$$

Where, hw = wind heat transfer coefficient
hr,c-a = radiation heat transfer coefficient at the top cover
hr,p-c = radiation heat transfer coefficient between cover and absorber plate
hc,p-c = convection heat transfer coefficient between cover and absorber plate

Heat is transferred by wind convection and radiation from the absorber plate to the ambient air.

$$h_w = 5.7 + 3.8V \qquad (16)$$

2) Efficiency of Glazed Flat-plate Collector

Solar collector efficiency is defined as the ratio of the useful energy output of collector to the incident solar energy and can be expressed as:

$$\eta_c = \frac{Q_u}{A_c I} \qquad (17)$$

Where, Qu = actual useful gain
Ac = collector area
I = total incident solar energy input to the collector

The factor coming out from substitution of T_i for T_p is called the collector heat removal overall efficiency factor, F_R. The complete equation is

$$\eta = F_R [\tau\alpha - U_L (T_p-T_a) \qquad (18)$$

Then, $$\eta = F_R [\tau\alpha - U_L (T_i-T_a)/I] \qquad (19)$$

IV. DESIGN CALCULATION OF DIRECT SOLAR WATER HEATING SYSTEM

A. Known Data of Calculation for Solar Radiation

To calculate the solar radiation, the following specifications must be known. Weather is clear sky and no wind.

Clearness adjustment factor is 1.00.

Design location, Mandalay.

Climate type, tropical

North latitude, λ = 21.98º N

East longitude, Lloc = 96.1º E

The elevation above sea level, H = 74.676 m

The solar constant, I0 = 1373 W/m2

The local standard time of meridian, Lst = 97.5º E

No: of day, n = 365 (for 31st December)

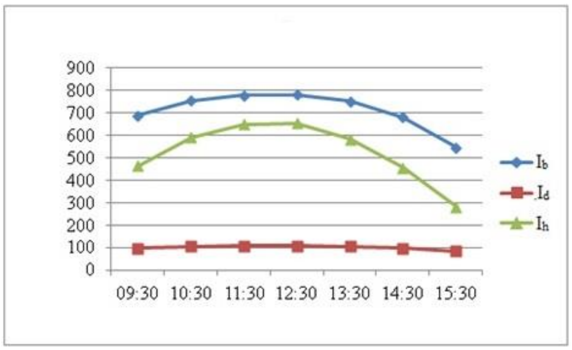

Figure 6. Beam, Diffuse and Hemispherical Irradiance Varies with Time

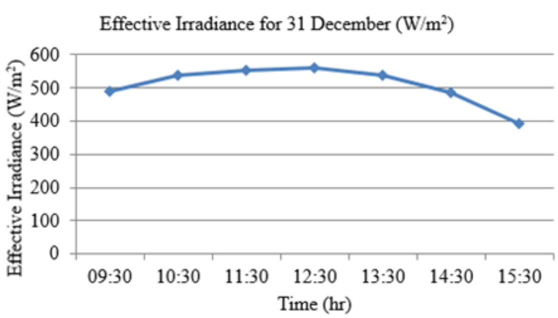

Figure 7. Effective Irradiance Varies with Time

B. Specification of Constructed Flat-Plate Solar Collector

Collector length	=	91.44 cm
Collector width	=	60.96 cm
Collector thickness	=	7.62 cm
Type of insulation	=	Foam insulation
Back insulation thickness	=	2.54 cm
Material of absorber plate	=	Steel
No; of plate	=	1
Material of tube	=	Steel
No; of straight tubes	=	5 lines
Header pipe diameter	=	32 mm
Inside diameter of tube	=	14 mm
Outside diameter of tube	=	16 mm
Center distance of straight tubes	=	9.906 cm
Space between cover and plate	=	3.81 cm
Glazing cover	=	Glass

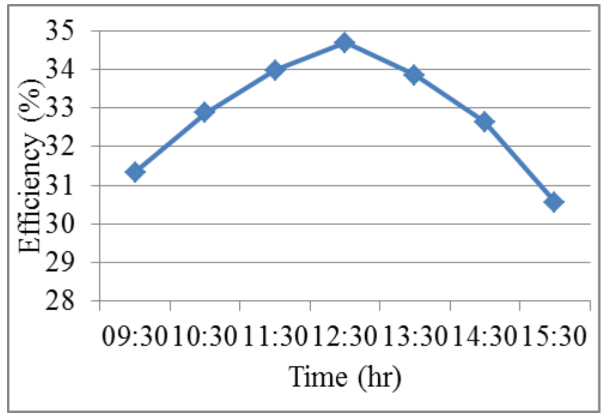

Figure 8. Collector Efficiency for December

Figure 9. Collector Efficiency versus Months

Table I
Result Data of Radiation and Efficiency

Month	Effective irradiance, I (12:30 pm) W/m2	Collector efficiency, ηc
December	558.808	34.69%
January	562.486	35.58%
February	598.327	36.43%
March	606.256	37.13%

April	610.077	38.42%
May	602.758	36.99%
June	601.519	35.97%
July	601.049	35.01%

C. Experimental Analysis
All the experimental work that was done to verify the taken place in the Mechanical Engineering Department of Mandalay Technological University, using the flat-plate solar collector.

The flat-plate collector is oriented in such a way that it receives maximum solar radiation during the desired season of use. The best stationery orientation in the south is the northern hemisphere. In this position, the inclination of the collector to the horizontal planes for the best all year round performance. This approach is used in this work and a tilt angle of 40˚ is used for location at Mandalay (longitude 96.1˚E, latitude 21.98˚N). The absorbing surfaces were painted in black. The absorbing plate and the absorbing surface of the pipes absorb solar radiation and the absorbed heat is then transmitted to the water in the pipes. Under the mode of natural convection the water rises through the pipes by the thermodynamic force.

To read out and record the temperatures during the experiments, the thermometer was used. The data recorded during the experiments was the inlet, outlet, cover and ambient temperatures were recorded every one hour interval.

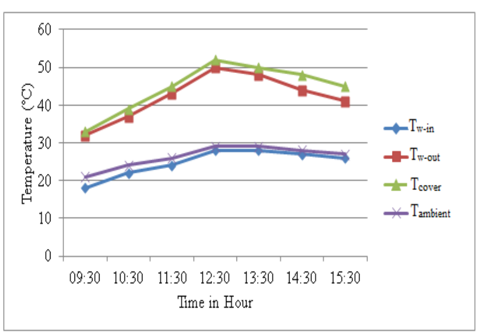

Figure 10. Temperature from Experiment Result (December)

Table II
Experimental Test Results Conducted on 31th December, 2013

Time	Water Inlet Temp, $T_{w\text{-}in}$	Water Outlet Temp, $T_{w\text{-}out}$	Cover Temp, T_c	Ambient Temp, T_a	V_{wind}
9:30	18	32	33	21	0.2
10:30	22	37	39	24	0.3
11:30	24	43	45	26	0.6
12:30	28	50	52	29	1.1
13:30	28	48	50	29	0.8
14:30	27	44	48	28	0.7
15:30	26	41	45	27	0.6

IV. CONCLUSION

The flow system of a natural circulation solar water heater was designed and the system was constructed and tested at Mandalay on latitude 21.98˚N. The results obtained shows that the water temperature in the system is a function of solar insolation and the ambient air. A typical analysis of the system shows that collector efficiency is high especially around mid-day when the solar collector receives the highest energy. Experimental results show that the performance of the solar water heater depends very much on the flow rate through the collector. The collector efficiency increases as the flow rate and the incident solar radiation. During the test, the results showed that the system exhibited optimum flow rate of 0.0011 kg/sec at a maximum collector efficiency of 35%. The maximum water temperature is obtained 50˚C, while the maximum ambient temperature is 29˚C. The water outlet temperature from experimental result is compared with simulation result.

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