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Design Calculation and Heat Transfer Analysis of Heat Pipe Evacuated Tube Solar Collector for Water Heating

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Abstract: The objective of this research is to investigate the heat transfer analysis of Heat Pipe Evacuated Tube solar collector is made of Borosilicate glass with length 1.8m and 0.058m and 0.049m diameter of outside and inside tubes respectively. The inner surface is covered with black coating to enhance the absorption rate of solar radiation. Heat Pipe is made of copper with length 1.8m and 0.015m and 0.012m diameter of outside and inside tubes respectively. Working fluid, ethylene glycol (0.1L) is used within the Heat Pipe 30 numbers of tubes are used to generate 300L of hot water. Manifold casing is 2.19m length, 0.13m height and 0.14m width with aluminum. The design location [Mandalay] is situated 21.98°N and 96.1°E. Heat transfer between the inner and outer glass tubes, heat transfer through the Heat Pipe wall of Heat Pipe ETC are analyzed by COMSOL Multiphysics. The maximum hot water temperature is 43ºC at ambient temperature 21ºC and collector efficiency is 72% for December. The result shows that higher solar radiation is required to obtain maximum hot water temperature, and Heat Pipe ETC is more efficient than ETC without Heat Pipe & Flat Plate collector. Thus, from this study, useful information are provided for constructing Heat Pipe ETC for water heating.

Keywords: Evacuated Tube, Heat Pipe, Water Heating, Solar Radiation, Collector Efficiency.

I. INTRODUCTION

Solar energy is one of the alternative energy sources. Solar energy can be converted into a more useful form by either an electrical, chemical or thermal process. Water heating systems are provided by solar energy using solar collectors that convert solar energy (sunlight) directly to thermal energy. In this research, the utilization of solar energy through solar water heating systems plays a big role in the quantity of conventional energy required. Solar water heaters therefore have significant potential to reduce environmental pollution arising from the use of fossil fuels.

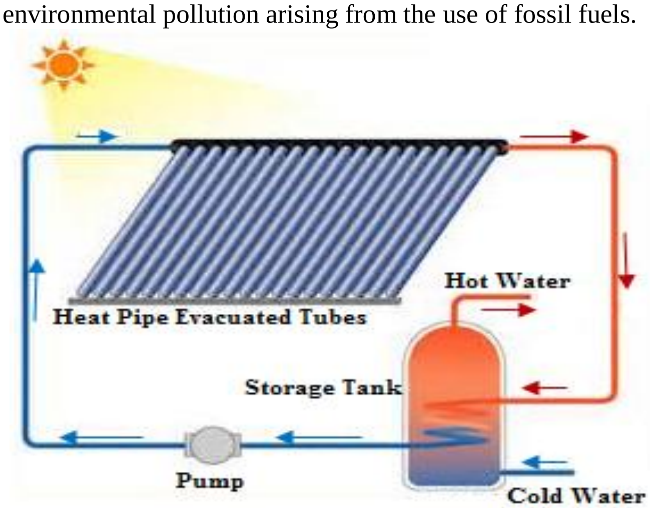

Figure1. Heat Pipe ETC for Water Heating System.

Water heating is one of the simplest application of solar heat and one of the least expensive. Evacuated tube solar collectors exhibit better performance than flat-plate solar collectors, in particular for high temperature operation. Therefore, the glass evacuated tube is gradually becoming the key component in solar thermal utilization such as the solar water heating system. At present, heat extraction manifold designs of evacuated tubes include fluid-in-metal designs, such as Heat Pipes, fluid-in-glass and U-tube inserted into the tube. Among them, heat pipe ETC is large amount of heat energy output and high performance efficiency. They are attracting increasing attention to Heat Pipe evacuated tube solar collectors because of their anti-freezing systems, rapid start-up, and easy installation. In Figure 1, water heating system is described by using Heat Pipe evacuated tube solar collectors.

II. HEAT PIPE EVACUATED TUBE SOLAR COLLECTOR

Inside the glass evacuated tube described above a copper heat pipe is installed. The heat pipe is a device of very high thermal conductance; that is, it will transport thermal energy without an appreciable drop in temperature. The heat pipe is suitable for a wide range of applications including solar collector. In a heat pipe, the process is evaporation-condensation-convection. The copper heat pipe transmits heat to its tip which is plugged into the collector's heat transfer manifold. As water runs through the manifold heat is transferred from the copper heat pipe to the water as shown in diagram below. The heat transfer manifold gets housed in a highly insulated aluminum housing (see fig 2).

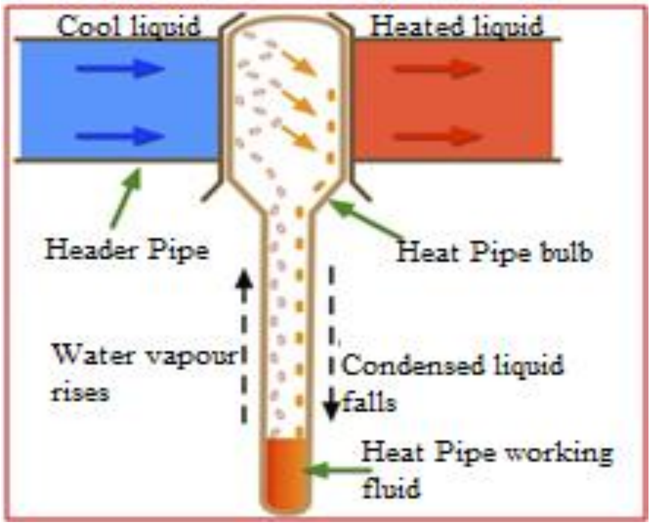

Figure2. Heat transfer in Heat Pipe ETC.

The Heat Pipe is a very efficient means of transferring heat from within the evacuated tube to the water. The Heat Pipe is simply inserted into the glass tube, held in place with high quality silicon based cap. The Heat Pipe transfers the heat to the manifold by a very simple method. The copper Heat Pipe is hollow and contains a small amount of working fluid. The hollow centre of the Heat Pipe is a vacuum, so that even at temperatures of around 30º C the fluid will vaporize (boil). The vapor rises to the tip (condenser) of the heat pipe where the heat is transferred to the water flowing through the manifold. This heat transfer causes the vapor to condense and flow back down the heat pipe where the process is once again repeated. Heat Pipe evacuated tubes are separated from the heating circuit by means of “dry connection”. This means that individual tubes can be easily replaced at any time whenever necessary without interrupting the operation of the solar system and without a water leakage problem as well.

A. Energy Transfer Solar Fluid

As the solar collector heats up, the fluid in the collector increases in temperature. This fluid is then moved out of the collector so the heat can be extracted for some useful purpose. Ethylene Glycol based water solutions are common in heat-transfer applications where the temperature in the heat transfer fluid can be below 32^oF (0^oC). Characteristics of ethylene glycol are high heat transfer capacity, moderate cost, low toxicity, low flammability and low corrosiveness. Ethylene Glycol is the most common antifreeze fluid for standard heating and cooling applications. Water is nontoxic and inexpensive. With a high specific heat, and a very low viscosity, it’s easy to pump.

III. METHODOLOGY

The design location is considered at Mandalay and the design month is December (2013).

North Latitude is 21.98º N
East Longitude is 96.1ºE
I_o, solar constant is $1373 W/m^2$
Elevation above sea level is 74.676×10^{-3} km
Climate type is tropical
Local standard time of meridian for Mandalay is 97.5ºE

A. Essential Solar Angles for Solar Radiation

Solar declination angle,

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

Solar zenith angle,

$$\theta_z = \cos^{-1}[\sin\lambda\sin\delta + \cos\lambda\cos\delta\cos\omega] \tag{2}$$

Solar hour angle,

$$\omega = \frac{360}{\tau_{day}}\ t \tag{3}$$

B. Monthly Beam, Diffuse, Hemispherical, Effective and Total Solar Insolation

Beam radiation,

$$I_b = I_{0,eff}\left[a_0 + a_1\exp\left(-\frac{k}{\cos\theta_z}\right)\right] \tag{4}$$

Diffuse radiation,

$$I_d = [0.2710\, I_{0,eff} - 0.2939\, I_b]\cos\theta_z \tag{5}$$

Hemispherical radiation,

$$I_h = I_b\cos\theta_z + I_d \tag{6}$$

Effective solar radiation,

$$I_{0,eff} = I_0[1+0.033\cos(\frac{360n}{365.25})] \tag{7}$$

Total solar insolation,

$$I = I_b\cos\theta + I_d(1+\cos\beta)/2 + I_h\,\rho_{ground}(1-\cos\beta)/2 \tag{8}$$

IV. SPECIFICATION OF HEAT PIPE EVACUATED TUBE SOLAR COLLECTOR

A. Optical Efficiency for Heat Pipe ETC

$$\eta_{opt} = \tau_t\alpha_t f_{ref} \tag{9}$$

Multiple Reflection Factor,

$$f_{ref} = \frac{1}{1-\rho_o\rho_i\frac{A_i}{A_o}} \tag{10}$$

TABLE I: SPECIFICATIONS

Sr	Design Parameters	Symbol	Value	Unit
1	Glass Tube Length	L_t	1.8	m
2	Outer Tube Diameter	D_o	0.058	m
3	Inner Tube Outside Diameter	$D_{i,o}$	0.049	m
4	Inner Tube Inside Diameter	$D_{i,i}$	0.047	m
5	Glass Thickness	G_t	0.016	m
6	Number of Tube	N_t	30	–
7	Heat Pipe Outer Diameter	$D_{o,HP}$	0.015	m
8	Heat Pipe Inner Diameter	$D_{i,HP}$	0.014	m
9	Heat Transfer Liquid (ethylene glycol)	–	0.0001	m^3

B. Thermal Losses for Heat Pipe ETC

The overall heat losses for a heat pipe ETC used in the system. Some portion of the collected solar thermal energy at the Solar Selective Absorber area (SSA) is dissipated into ambient or the sky through radiation heat transfer between the Solar Selective Absorber (SSA) and outer tube, forced convection heat transfer by wind and radiation heat transfer between the outer tube and ambient. The thermal losses from the SSA through the outer tube to ambient and/or the sky can be decomposed into the following three main heat transfer mechanisms:

1. Radiation heat transfer coefficient between the inner and outer tube in this case is given by

$$h_{o,i} = \frac{\sigma\left(T_{t,o}^2 + T_{t,i}^2\right)\left(T_{t,o} + T_{t,i}\right)}{\frac{1}{\varepsilon_{t,i}} + \frac{A_i}{A_0}\left(\frac{1}{\varepsilon_{t,o}} - 1\right)} \quad (11)$$

2. Forced convection heat transfer coefficient on the outer tube of the Heat Pipe ETC by the wind is given by

$$h_{t,wind} = 5.7 + 3.8v \quad (12)$$

where v is the wind velocity in m/s.

3. Radiation heat transfer coefficient between the outer tube and the sky is given by

$$h_{t,sky} = \sigma\varepsilon_{t,o}\left(T_{t,o}^2 + T_{sky}^2\right)\left(T_{t,o} + T_{sky}\right) \quad (13)$$

Overall Heat Loss Coefficient,

$$U_t = \frac{1}{A_i}\left(\frac{1}{h_{o,i} \times A_i} + \frac{1}{(h_{t,wind} + h_{t,sky})A_o}\right)^{-1} \quad (14)$$

C. Thermal Resistances for Heat Pipe ETC

As shown in fig 3, the thermal resistance between the solar selective absorber area (SSA) of a Heat Pipe ETC and heat transfer liquid (ethylene glycol) can be written as:

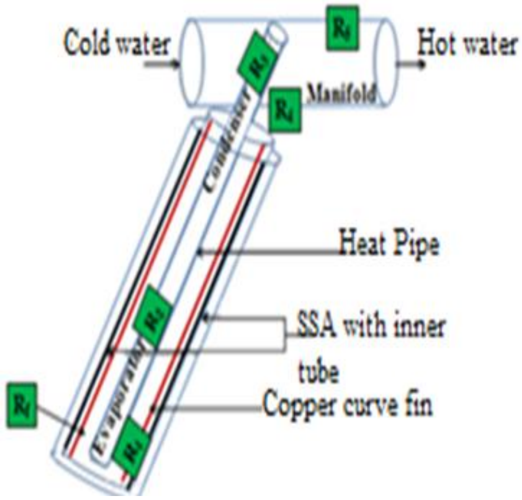

Figure3. Thermal resistances of Heat Pipe ETC

Thermal resistance of the outer wall of the evaporation segment of the Heat Pipe ETC

$$R_1 = \frac{\sigma_m}{\pi k_{HP} d_m L_e} \quad (16)$$

Thermal resistance between the liquid and vapor of the evaporation segment of the Heat Pipe ETC

$$R_2 = \frac{R T_s^2 \sqrt{2\pi R T_s}}{P_v h_{fg}^2 \pi d_e L_e} \quad (17)$$

Thermal resistance between the vapor and liquid of the Heat Pipe ETC

$$R_3 = \frac{R T_s^2 \sqrt{2\pi R T_s}}{P_v h_{fg}^2 \pi d_c L_c} \quad (18)$$

Thermal resistance of the outer wall of the condensation segment of the Heat Pipe ETC

$$R_4 = \frac{\sigma_m}{\pi k_{HP} d_m L_c} \quad (19)$$

Thermal resistance between the outer wall of the condensation segment of the Heat Pipe ETC and the cold water within the manifold casing.

$$R_5 = \frac{1}{h\pi d_c L_c} \quad (20)$$

D. Useful Thermal Power Received by a Heat Pipe ETC

$$Q_{thermal} = \eta_{opt} I A_{SSA} - \left(U_t A_i + \frac{1}{R_t}\right)\left(T_{t,i} - T_a\right) \quad (21)$$

Solar Selective Absorber Area of Heat Pipe ETC

$$A_{SSA} = \pi D_{i,o} L_t \quad (22)$$

E. Heat Pipe Evacuated Tube Collector Efficiency

$$\eta_{collector} = \frac{Q_{thermal} \times N_t}{I(A_{SSA} \times N_t)} \quad (23)$$

F. Hot Water Outlet Temperature of Heat Pipe ETC

$$Q_{thermal} = \overset{\circ}{m}_w C_{p_w} \left(T_{w,o} - T_{w,i}\right) \quad (24)$$

V. RESULTS AND DISCUSSIONS

The following figure 4 shows the Total Monthly Solar Insolation for Mandalay (12:00 noon, December 21th)

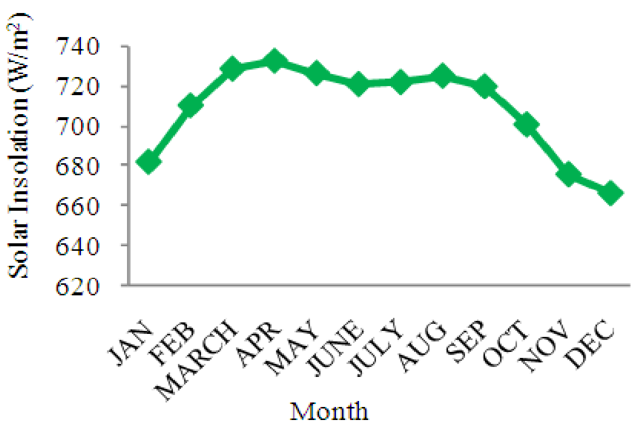

Figure4. Total Monthly Solar Insolation for Mandalay (12:00 noon, December 21th)

1. Collector Efficiency

Figure 5 shows the monthly results of collector efficiency of Heat Pipe ETC. From this Figure, collector efficiency of December is higher than other months due to the decrease solar insolation.

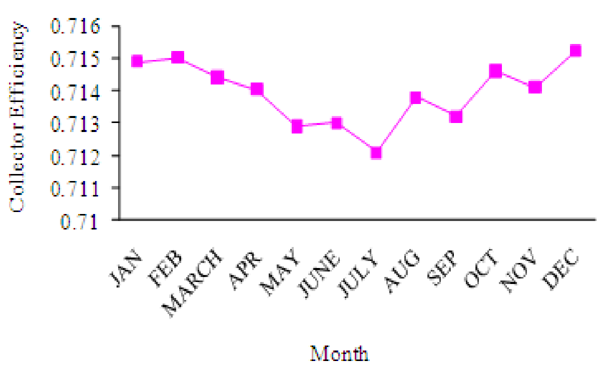

Figure 5. Collector Efficiency for Heat Pipe ETC.

2. Water Outlet Temperature

Figure6 shows the monthly results of water outlet temperature with Heat Pipe ETC. In the results of water outlet temperature for Heat Pipe ETC, water outlet temperature of April is higher than other months due to the increase useful thermal power and ambient temperature.

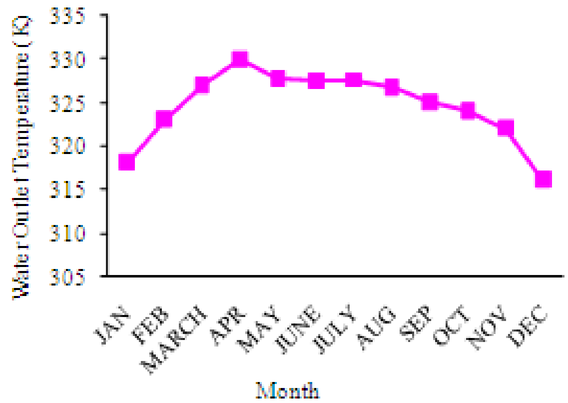

Figure6. Water Outlet Temperature for Heat Pipe ETC.

A. Numerical Results

1. Heat Transfer Analysis of Evacuated Glass Tube

By using Fourier law, the outer and inner surface temperatures of Heat Pipe ETC obtained. The evacuated glass tube material for the analysis is borosilicate glass with thermal conductivity 1.13W/mK. The boundary conditions for the heat flux through the wall of a cross section hollow cylinder (evacuated glass tube) operating with one steady state heat conduction surface temperature T_1= 295.72K on the inner surface r_1= 0.0235m, and T_2= 297K on the outer surface r_2= 0.0245m.

2. Heat Transfer Analysis of Heat Pipe

According to Fourier law, the inner and outer surface temperatures of Heat Pipe attained. When there are many pipes in the Heat Pipe ETC, the temperature of one pipe is affected by all the pipes in the tube. To estimate the heat conduction and total heat flux of evacuated gass tube, commercial finite element package, COMSOL Multiphysics has been used. The heat pipe material for the analysis is copper with thermal conductivity 401W/mK. The boundary conditions for the heat flux through the wall of a cross section hollow cylinder (heat pipe) operating with one steady state heat conduction surface temperature T_1= 312.572K on the inner surface r_1= 0.006m, and T_2= 312.577K on the outer surface r_2= 0.0075m.

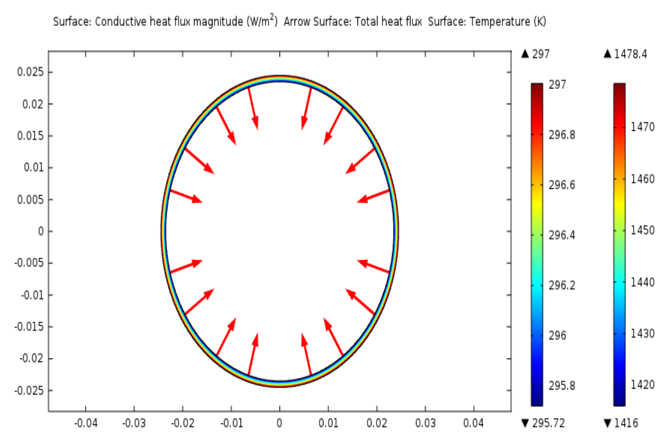

Figure 7. Surface Conductive Heat Flux, Total Heat Flux and Temperature Distribution of Evacuated Glass Tube.

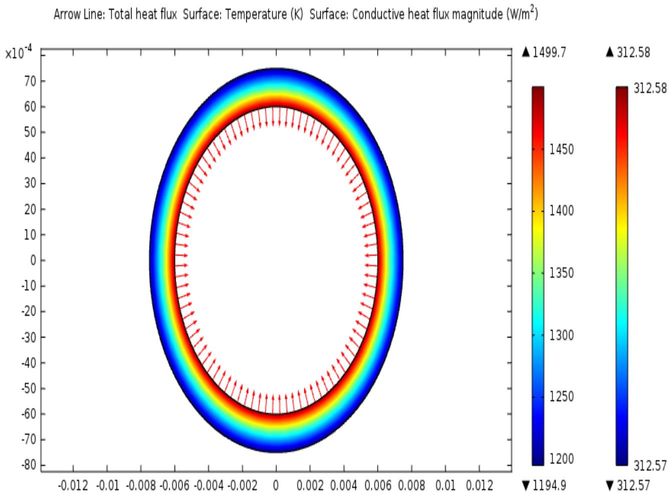

Figure 8. Surface Conductive Heat Flux, Total Heat Flux and Temperature Distribution through the Heat Pipe Wall.

Figure 7 and 8 show the surface conductive heat flux, total heat flux and temperature distribution through the evacuated glass tube and heat pipe wall. As shown in these Figures, the temperature distribution through the evacuated glass tube and heat pipe wall slightly increase on the outer surface than inner surface due to the little heat loss. By using Fourier's law (steady state one dimensional heat conduction), the surface heat flux value due to the heat conduction is 1417.606W/m^2 and the values of surface heat flux evacuated glass tube and heat pipe are 1478.4W/m^2 and 1499.7W/m^2 by utilizing COMSOL Multiphysics. Therefore, these values are not so much difference. According to these results, this Heat Pipe Evacuated Glass Tube design is suitable to get the required heat conduction within the glass tube and Heat Pipe wall.

VI. CONCLUSIONS

The main advantage for Heat Pipe Evacuated Tube Solar collector is low heat loss at high temperatures relative to ambient temperature. The design of this collector is simple and easy without the need for sophisticated facilities. The collector efficiency is obtained 72% vary to daily heat required. If the number of collector is less, the amount of collecting heat will be less. Heat Pipe Evacuated Tube Solar collector is used for water heating application of domestic and industrial used. So, the numbers of collector are important for the several applications. From this research, it can be obtained hot water outlet temperature is 43ºC for December, lowest solar radiation than other months. So, design month based on December to save for other months. Therefore, this system can be used throughout a whole year. Hot water outlet temperatures depend on the number of Heat Pipe ETC, amount of solar radiation and environment conditions. Heat Pipe ETC can absorb heat easily due to the cylindrical shape. So, Heat Pipe ETC can be applied not only summer but also winter. Thus, this research can be provided for commercial usage concerning with Heat Pipe Evacuated Tube Solar collector.

VII. ACKNOWLEDGMENT

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VIII. APPENDIX

TABLE II: ENVIRONMENTAL PARAMETERS USED IN CALCULATING THE THERMAL LOSSES OF A SINGLE HEAT PIPE ETC

Sr	Environmental Parameters	Symbol	Value	Unit
1	Ambient Temperature	T_a	294	K
2	Wind Velocity	v	0.8	m/s

TABLE III: PHYSICAL PROPERTIES OF ETHYLENE GLYCOL WITHIN THE HEAT PIPE

Sr	Environmental Parameters	Symbol	Value	Unit
1	Ambient Temperature	T_a	294	K
2	Wind Velocity	v	0.8	m/s

TABLE IV: GEOMETRICAL PARAMETERS OF AN EVACUATED GLASS TUBE

Sr	Physical Parameters	Symbol	Value
1	Transmission Coefficient	τ_t	0.78
2	Absorption Coefficient	α_t	0.93
3	Outer Tube Emission Coefficient	$\varepsilon_{t,o}$	0.9
4	Inner Tube Emission Coefficient	$\varepsilon_{t,i}$	0.9
5	Outer Tube Reflection Coefficient	ρ_o	0.14
6	Inner Tube Reflection Coefficient	ρ_i	0.08

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