

Simulation Modelling For the Performance of Evacuated Tube Solar Collector

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ABSTRACT: Most of energy that we are using is non-renewable resources which increase the pollution and amount of CO₂ in environment so it required using renewable and clean energy. In present scenario we are dependent on conventional energy sources for producing energy to sustain our lives. Since these sources are depleting at faster rate and cost of energy is increasing simultaneously, so conversion of renewable form of energy is much desired now. In this work for converting solar energy in to some other kind of useful energy e.g. for the purpose of water heating the theoretical performance of evacuated tube collector is introduced. A simulation model is developed to determine the theoretical efficiency of the evacuated tube collector and the effect of atmospheric conditions on the performance is presented in this work.

KEYWORDS: Solar collectors; simulation ; water heating ; evacuated tube collector

I. INTRODUCTION

Conventional solar collectors were developed for use in sunny and warm climates. Their benefits however are greatly reduced when conditions become unfavourable during cold, cloudy and windy days. Further more, weathering influences such as condensation and moisture will cause early deterioration of internal materials resulting in reduced performance and system failure. Evacuated tube solar collectors (tubes) operate differently than the other collectors available on the market. ETC have demonstrated that the combination of a selective surface and an effective convection suppressor can result in good performance at high temperatures. The vacuum envelope reduces convection and conduction losses, so the collectors can operate at higher temperatures. However, their efficiency is higher at low incidence angles. ETC use liquid-vapour phase change materials to transfer heat at high efficiency. Evacuated tube collectors are composed of multiple evacuated glass tubes [1]. The vacuum inside of the evacuated tube collectors have been proven to last more than 25 years, the reflective coating for the design is encapsulated in the vacuum inside of the tube, which will not degrade until the vacuum is lost. The vacuum that surrounds the outside of the tube greatly reduces convection and conduction heat loss, therefore achieving greater efficiency in colder conditions. This advantage is largely lost in warmer climates, except in those cases where very hot water is desirable. In this paper work has involved a simulation modelling of performance of evacuated tube collector. A simulation model in MATLAB is developed via mathematical modelling to compare the experimental data with theoretical result.

II. METHODOLOGY

A complete design and fabricated experimental setup of a evacuated tube solar collector is presented in this paper fig 1. In this research work this solar collector is be used for heating water, for different applications. This system consists of storage tank, setup of evacuated tube solar collector, measuring devices etc. Water in atmospheric conditions is stored in a storage tank which is placed at some height.

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 6, Issue 4, April 2017

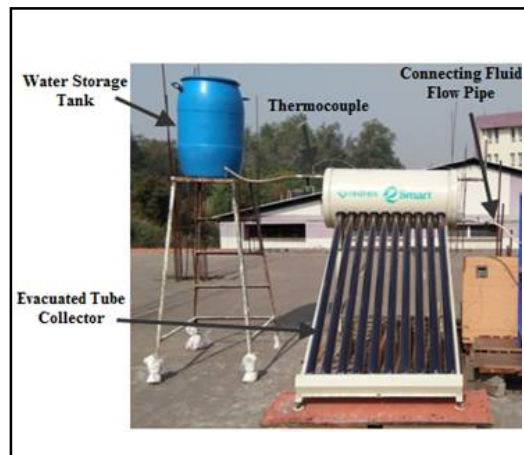


Fig 1 : Experimental Setup Evacuated Tube Collector

The outlet of this storage tank is connected with the inlet of the evacuated tube collector with the help of a connecting pipe. A control valve is connected between inlet of evacuated tube collector and outlet of storage tank to control the flow of liquid. The temperature of water entering the evacuated tube through pipes are measured by a thermocouple connected in between them [4]. The temperature of the water which is flowing through the evacuated tube collector is increased due to the effect of solar energy and can be measured by another thermocouple places at the outlet of the collector .

Technical Specification of Evacuated Tube Collector : Evacuated tube consists of two glass tubes made from extremely strong borosilicate glass. The outer tube is transparent to allowing light rays to pass through with minimal reflection and the inner tube is coated with a special selective coating (Al-Nickel/Al) which features excellent solar radiation absorption and minimum reflective characteristics. This vacuum plays an important role in the performance of the direct flow evacuated tubes.

Properties of Borosilicate Glass Tube

Thermal Conductivity k	:	1.125 W/mK
Solar Transmittance τ_g	:	0.9
Solar Absorptance α_g	:	0.05 (Thickness 2 mm)
Solar Reflectance ρ_g	:	0.05 (Normal Incidence)
Thermal Emittance ϵ_g	:	0.85

Dimensions of Evacuated Tube Collector

Number of Tubes	:	10
Length of Tube	:	1.5 m
Outer diameter of Glass Cover	:	42 mm
Outer diameter of Absorber tube	:	35 mm
Inner diameter of Absorber tube	:	31 mm
Thickness of Tube	:	2 mm
Distance between tubes	:	11.2 mm
Total Heat Collecting Area	:	2.11 m ²
Total Area of Absorber tube	:	1.64 m ²

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 6, Issue 4, April 2017

The ambient temperature and outer glass temperature were measured by calibrated mercury thermometer, wind speed were measured by anemometer. The solar intensity was measured with the help of a lux meter.

III. ANALYSIS OF EVACUATED TUBE COLLECTOR

Calculation of Experimental (Actual) Efficiency of the System : Under steady-state conditions, the useful heat delivered by a solar collector is equal to the energy absorbed by the heat transfer fluid minus the direct or indirect heat losses from the surface to the surroundings [2].

$$Q_{u,\text{exp}} = mc_p (T_{f,o} - T_{f,i})$$

The Experimental thermal efficiency of a collector can be obtained by dividing $Q_{u,\text{exp}}$ by $I_b A_c$ from the following given formula:

$$\eta_{\text{exp}} = \frac{Q_{u,\text{exp}}}{I_b A_c}$$

IV. MODELING AND SIMULATION

Two valuable tools of the systems engineering trade or discipline are modelling and simulation. Systems engineers are use modelling and simulation to determine system requirements, predict system performance, calculate process inputs, outputs, support trade studies, estimate cost and schedules and optimize processes.

Development of a Simulation Model via Mathematical Modelling

Considering the assumptions, a one dimensional transient model based on the heat transfer, energy balance by different heat transfer coefficients and other performance parameters of evacuated tube collector is developed [6]. In this work simulation model of ETC has been developed partying to satisfy the mathematical modelling of the system in MATLAB version 2012b.

Model Equations

To calculate performance parameters of ETC the model equations are expressed in the following steps.

Step 1 : To develop a mathematical model of the overall heat transfer coefficient.

$$U_L = \left\{ \frac{1}{h_{c,p-c} + h_{r,p-c}} + \frac{1}{h_w + h_{r,c-a}} \right\}^{-1}$$

Step 2 : To develop a mathematical model of Radiation Coefficient from the Plate to the Cover.

$$h_{r,p-c} = \frac{\sigma(T_p^2 + T_c^2)(T_p - T_c)}{\frac{1}{\epsilon_p} + \frac{1}{\epsilon_c} - 1}$$

T_p is the absorber tube temperature and has been taken as the average of inlet fluid and outlet fluid temperature

$$T_p = T_m = \frac{T_{fi} + T_{fo}}{2}$$

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Vol. 6, Issue 4, April 2017

Step 3 : To develop a mathematical model of Radiation Coefficient for the Cover to Air

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

Step 4 : To develop a mathematical model Convection Coefficient between Plate and the Cover

$$T_c = T_p - \left\{ \frac{U_L (T_p - T_a)}{h_{c,p-c} + h_{r,p-c}} \right\}$$

Step 5 : To develop a mathematical model of Convective Heat Transfer Coefficient on the Glass Tube Surface (h_w)

$$\text{Nusselt Number } N_u = \frac{h_w D_g}{k}$$

$$\text{Reynolds Number } R_e = \frac{D_g W}{\nu}$$

If $1 < R_e < 4$ then Nusselt Number is $N_u = 0.891 R_e^{0.330}$

If $4 < R_e < 40$ then Nusselt Number is $N_u = 0.821 R_e^{0.385}$

If $40 < R_e < 4000$ then Nusselt Number is $N_u = 0.615 R_e^{0.466}$

Step 6 : To develop a mathematical model of Convection heat transfer coefficient inside the absorber tube (h_{fi})

$$\text{Nusselt Number } N_u = \frac{h_{fi} D_{o,absorber}}{k_w}$$

$$\text{Reynolds Number } R_e = \frac{D_{i,absorber} V_w}{\nu}$$

$$\text{If } L/D_i < 0.0048 R_e \text{ then } Nu = \log \left[1 / \left\{ 1 - \frac{1}{\left\{ \sqrt{\frac{Re Pr D_i}{L}} \right\} \cdot Pr^{0.167}} \right\} \right]$$

Step 7 : To develop a mathematical model of Standard Fin Efficiency

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Vol. 6, Issue 4, April 2017

$$F = \frac{\tanh \left\{ \sqrt{\frac{U_L}{k\delta}} (W - D) / 2 \right\}}{\sqrt{\frac{U_L}{k\delta}} (W - D) / 2}$$

Step 8 : To develop a mathematical model Collector Efficiency Factor

$$F' = \frac{1/U_L}{W \left[\frac{1}{U_L \{D + (W - D)\} F} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}} \right]}$$

Step 9 : To develop a mathematical model Heat Removal Factor

$$F_R = \frac{mc_p}{A_c U_L} \left[1 - \exp \left\{ \frac{-A_c U_L F'}{mc_p} \right\} \right]$$

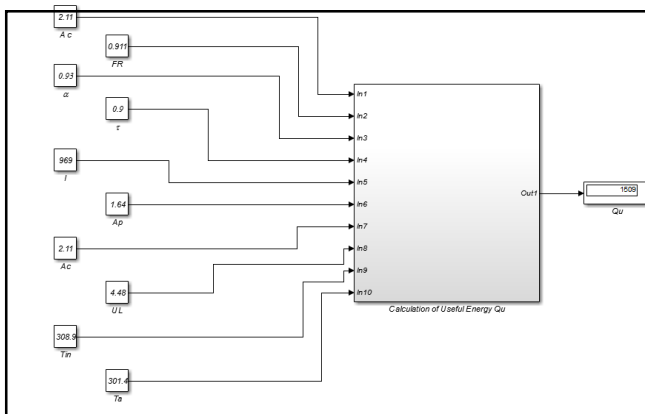
Step 10 : Complete mathematical model including all the models to develop a model for Useful Energy of the collector

$$Q_{u,th} = A_c F_R \left[(\alpha\tau) I - \left\{ \frac{A_p}{A_c} \right\} U_L (T_{fi} - T_a) \right]$$

Once the complete model for useful energy is developed, a modelling for the theoretical efficiency may be calculated by

$$\eta_{exp} = \frac{Q_{u,th}}{I_b A_a}$$

Subsystem developed for the generation of useful energy is shown in figure 2 and Logical Implementation blocks in figure 3



Subsystem developed for the generation of Q_{Uth}

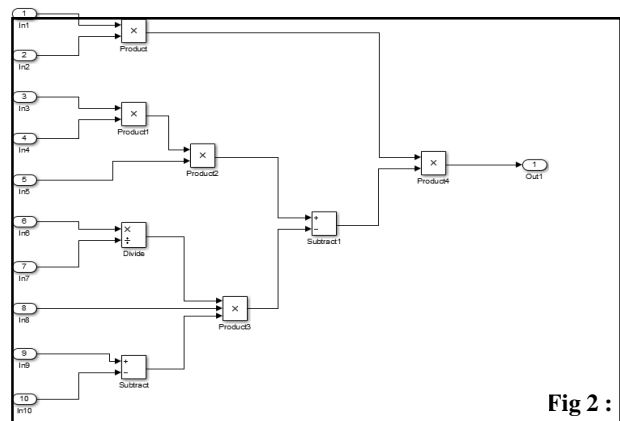


Fig 2 :

Fig 3 : Logical Implementation blocks of Q_{Uth}

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Vol. 6, Issue 4, April 2017

Determination of Theoretical Performance Parameters of ETC from time Period of Jan to May

By using simulation model, performance parameters are calculated and theoretical mean values are tabulated

Table 1 : Average values of performance parameters of Evacuated Tube Solar Collector

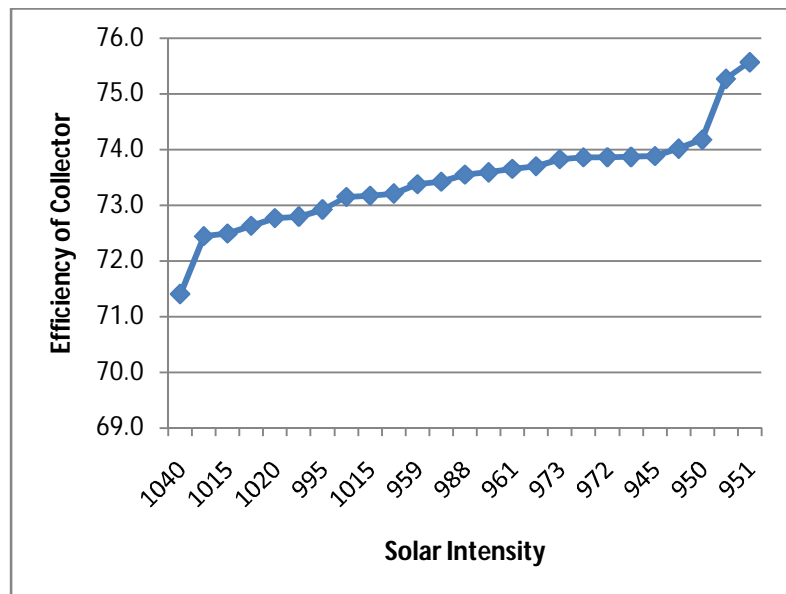
Days	ν	T_s	I	T_{in}	T_{out}	U_L	F'	F_R	$Q_{(a)th}$	Q_i	η
Day 1	0.72	28.9	972	36.5	45.6	4.44	0.926	0.910	1514.9	2050.9	73.9
Day 2	0.75	29.1	973	36.6	45.8	4.45	0.926	0.912	1515.7	2053.0	73.8
Day 3	0.85	25.5	951	36.9	46.1	4.49	0.925	0.910	1516.4	2006.6	75.6
Day 4	1.1	28.3	968	35.8	45.0	4.50	0.925	0.910	1505.4	2042.5	73.7
Day 5	1.4	27.1	961	34.6	43.6	4.54	0.925	0.910	1493.5	2027.7	73.7
Day 6	0.7	30.3	981	37.9	47.2	4.36	0.928	0.913	1532.1	2069.9	74.0
Day 7	0.87	26.8	959	35.8	44.9	4.43	0.927	0.912	1484.8	2023.5	73.4
Day 8	0.86	26.8	959	34.3	41.7	4.45	0.926	0.912	1494.5	2023.5	73.9
Day 9	1.5	24.5	945	31.9	39.2	4.43	0.926	0.912	1473.2	1994.0	73.9
Day 10	0.77	25.37	950	32.7	40.1	4.28	0.929	0.914	1486.9	2004.5	74.2
Day 11	0.94	31.4	988	38.5	46.1	4.46	0.926	0.921	1533.3	2084.7	73.6
Day 12	0.85	30.8	984	35.8	43.4	4.49	0.926	0.911	1508.0	2076.2	72.6
Day 13	1.05	28.3	968	39.1	46.8	4.52	0.926	0.911	1537.4	2042.5	75.3
Day 14	0.92	30.3	981	37.9	45.6	4.48	0.927	0.912	1529.0	2069.9	73.9
Day 15	2.2	31.8	990	39.5	47.2	4.86	0.921	0.906	1528.0	2088.9	73.1
Day 16	2.9	35.2	1013	43.1	51.0	5.05	0.919	0.903	1556.0	2137.4	72.8
Day 17	1.6	35.1	1012	43.0	50.8	4.84	0.922	0.907	1563.3	2135.3	73.2
Day 18	1.8	35.7	1015	43.5	51.4	4.88	0.922	0.906	1567.1	2141.7	73.2
Day 19	2.3	36.3	1020	44.2	52.1	5.06	0.919	0.903	1566.2	2152.2	72.8
Day 20	2.4	32.5	995	40.2	47.9	4.92	0.920	0.904	1531.0	2099.5	72.9
Day 21	3.8	39.3	1040	44.8	52.8	5.21	0.917	0.900	1566.9	2194.4	71.4
Day 22	2.5	32.4	994	40.1	47.8	4.68	0.923	0.908	1539.9	2097.3	73.4
Day 23	1.2	37.3	1027	45.3	53.2	4.66	0.925	0.910	1594.7	2167.0	73.6
Day 24	3.5	38.2	1033	46.2	54.2	5.25	0.917	0.900	1579.0	2179.6	72.4
Day 25	3.8	35.5	1015	43.4	51.3	5.18	0.917	0.900	1552.5	2141.7	72.5

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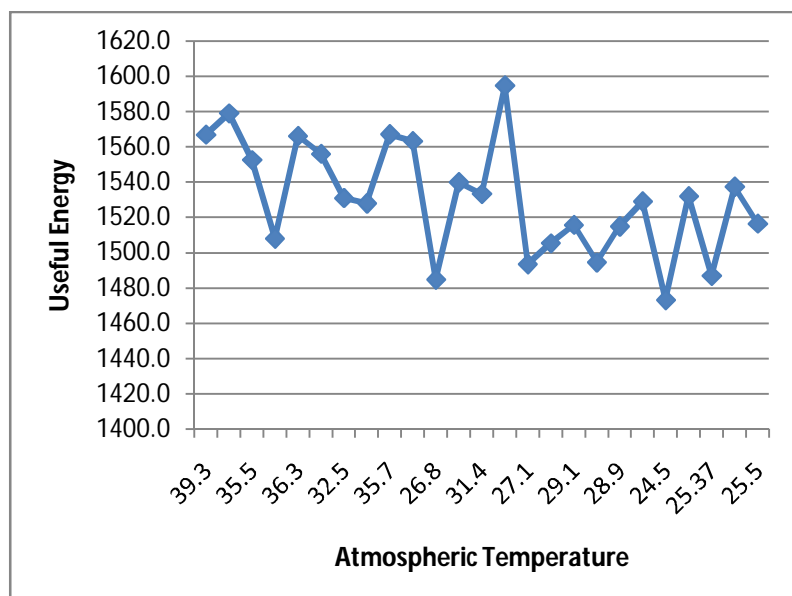
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Vol. 6, Issue 4, April 2017



Graph 1 : Variation in Efficiency with Solar Intensity



Graph 2 : Variation in Useful Energy with Atmospheric Temperature

Day wise average values are tabulated in the table from the period of January to May 2015. To observe the effect of wind on the performance of collector the velocity of wind is also taken in to account. Observed data is taken as the input parameter for determining the theoretical values of performance parameters of the collector which is tabulated in the table 1. Graph shows the variation in performance parameters with atmospheric conditions.

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Vol. 6, Issue 4, April 2017

V. RESULTS AND DISCUSSION

The present study of evacuated tube solar water heating system report that the trend of using power efficient device will be rapidly growing in coming decades. The numerical solution of the mathematical model used was carried out by considering the thermo physical properties as listed above. Day wise average value of overall convective heat transfer coefficients U_L and useful energy Q_{th} were determined and reported in table 1. It is seen that the average efficiency of the collector is determines in the range of 71.4 % to 75.6% which is in the allowable range of maximum and minimum efficiency of the physical setup of collector model. The variation in the efficiency and useful energy gained is shown in graph 1 and graph 2.

VI. CONCLUSIONS

The evacuated tube solar water heating device is one of the efficient way for house hold purpose not because of it is efficient as compare to other mean of water heating devices but also it is eco-friendly and non-polluting device. In this paper, we have presented a simple mathematical model enabling the evaluation of the thermal efficiencies of the Evacuated tube collector. We showed that the performance of ETC depends upon the atmospheric conditions. Collector performance was found to be highly dependent on the incident thermal radiation on the collector. The use of a highly reflective thermal coating on the inner surface of the cover substantially increase the performance of a collector with a receiver of high emittance.

Nomenclature

A_a = Aperture area [m^2]
 A_o = External surface area of cover [m^2]
 A_i = internal surface area of absorber [m^2]
 c_p = Specific heat of water [$J/kg \cdot ^\circ C$]
 C = Concentration ratio [dimensionless]
 D_o = External diameter of cover [m]
 D_i = Internal diameter of cover [m]
 W = Collector width [m]
 L = Collector length [m]
 F = Efficiency factor of collector [dimensionless]
 F_R = Heat removal factor of collector [dimensionless]
 $h_{c,i}$ = Convective heat transfer coefficient between receiver and fluid [$W/m^2 \cdot ^\circ C$]

$h_{r,r-a}$ = Radiation heat transfer coefficient between receiver and ambient [$W/m^2 \cdot ^\circ C$]
 h_w = Convective heat transfer coefficient between receiver and ambient [$W/m^2 \cdot ^\circ C$]
 U_l = Overall heat loss coefficient [$W/m^2 \cdot ^\circ C$]
 I_b = Beam solar radiation [W/m^2]
 $Q_{u,exp}$ = Experimental useful energy [W]
 $Q_{u,th}$ = Theoretical useful energy [W]
 T_a = Ambient temperature [$^\circ C$]
 T_r = Receiver temperature [$^\circ C$]
 $T_{f,i}$ = Inlet fluid temperature [$^\circ C$]
 $T_{f,m}$ = Mean fluid temperature [$^\circ C$]
 $T_{f,o}$ = Outlet fluid temperature [$^\circ C$]

Non Dimensional Numbers

N_{ua} = Nusselt number of air [dimensionless]
 Re_a = Reynolds number of air [dimensionless]
 Re_w = Reynolds number of water [dimensionless]

Properties of Fluid

k_a = Conductivity of air [$W/m \cdot ^\circ C$]
 k_r = Conductivity of receiver [$W/m \cdot ^\circ C$]
 k_w = conductivity of water [$W/m \cdot ^\circ C$]
 m = Mass flow rate [Kg/hr]
 u_w = Water velocity [m/s]
 v = Wind velocity [m/s]

Greek symbols

α = Absorptance [dimensionless]
 ν_a = Kinematic viscosity of air [m^2/s]
 ν_w = Kinematic viscosity of water [m^2/s]
 ρ = Reflectivity [dimensionless]
 σ = Stefan-Boltzman constant [$5.6697 \times 10^8 W/(m^2 K^4)$]

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 6, Issue 4, April 2017

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