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# Exergetic Efficiency of Passive Solar Air Heater with Phase Change Energy Storage Material

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***ABSTRACT:*** *Energy and exergy analysis of solar air heater with phase change material energy storage is considered in this research work. Energy and exergy models for component systems like flat plate solar collector and phase change material in one-dimensional heat conduction in a cylindrical pipe, for storing periods were obtained. Exergy analysis, which is based on the second law of thermodynamics, and energy analysis, under first law, was applied to improve system efficiency. Measured data, for five days, hourly insolation, collector temperature, PCM temperature, environmental temperature and air flow rate were used as an input on the energy and exergy models to determine system performance. The Software, Engineering Equation Solver (EES) was used to solve the generated equation models. The results of the analysis revealed that the average energy and exergy efficiencies were 48% and 35% respectively.*

***Keywords**: Exergy, Energy, absorber plate, hot air and paraffin, efficiency.*

## I. INTRODUCTION

Storage of solar energy is an important issue as solar radiation isa time- dependent energy source. Thermal energy can be stored as sensible heat (water and rock), latent heat (water, ice and salt hydrates), heat of reaction, etc. Parameters such as storage period required, economic viability or operating conditions are important in the selection of these methods.

Latent heat storage system through phase change material (Paraffin wax) is selected in this study. The reason for this selection is the fact that, theuse of PCMs for the thermal energy storage in solar heating systems has received considerable attention in the literature. Major advantages of the system are that, PCMs can store large amounts of heat, changing the phase from solid to liquid.The most important PCMs include Glauber's salt, calcium chloride hex-hydrate, sodium thiosulphate, sodium carbonate decahydrate, fatty acid, and paraffin wax. PCMs are used in application to heat up buildings, dry food stuff for storage etc.

The analysis of quality and quantity of energy in a thermodynamic system is important for energy saving and obtaining efficiency of the system. In this context, the second law of thermodynamics assesses the quality of energy, but the first law focuses on the quantity of energy. Exergy by definition is the maximum work obtained in a reversible system interacting with the environment to attain, equilibrium, considering the environmental parameters (such as temperature and pressure) at the reference state.

There is an increasing interest in the combined utilization of the first and second laws of thermodynamics, using such concepts as exergy (availability, available useful quality energy), entropy generation and irreversibility (exergy destruction) to evaluate the efficiency with the available energy being consumed. Energy analysis allows a thermodynamic evaluation of energy conservation. It provides the necessary tool for a clear distinction between energy losses to the environment and internal irreversibility in the process. Exergy analysis acknowledges the fact that, energy cannot be created nor destroyed, it can be degraded in quality eventually reaching a state in which it is in complete equilibrium with the surroundings and hence of no further use for performing useful task.

Furthermore, a comprehensive exergy analysis assessing the magnitude of exergy destruction identifies the location, the magnitude and the source of thermodynamic inefficiencies in a thermal system. This knowledge is useful in directing the attention of process design researchers and practicing engineers to those components of the system being analyzed, that offer the maximum opportunities for improvement.

In addition, exergy analyses are a method that uses the conservation of mass and energy principles together with the second law of thermodynamics for the design and analysis of energy system. It can reveal whether or not, it is possible to design more efficient energy system by reducing inefficiencies in the system. The exergy method gives information on the quality of the energy transferred in latent heat energy storage systems such as PCMs and finally obtain the energetic and exergetic performance efficiency of PCMs [8]and

[1].They defined exergy as the maximum work potential derived from a reversible engine interacting with the environment to reach a dead state, taking temperature and pressure as the reference state. They employed second law of thermodynamic which emphasizes on irreversibility or entropy generation minimization to improve the performance of machine. They showed thatexergy analysis can indicate the possibilities of thermodynamic improvement of any system. Their results recorded more meaningful efficiencies than those obtained using energy analysis alone.

[10]experimentally evaluated the energy efficiency, friction factor and dimensionless exergy loss, of a solar air heater, having five solar sub-collections of same length and width arranged in series in a common case, for various values of Reynolds number.

[11] presented the determination of the optimal operation mode of a flat solar collector by exergetic analysis and numerical simulation. This paper proposes an exergy analysis of a flat plate –solar collector based on the assumption that $T_{fi}$=$T_e$ = constant ($T_e$ - environmental temperature). The method has proven valuable in the design of solar collectors for the specific climatic insolation conditions of a certain region. And the exergy efficiency of a flat – plate solar collector, $\eta_{ex}$ = f (m, $A_c$) presents points of local maxima and a point of global maximum.

[6]discussed the performance evaluation of solar air heater for various artificial roughness geometries based on energy, and exergy efficiencies. It is found that artificial roughness on absorber surface effectively increases the efficiencies in comparison with smooth surface. The energy efficiency in general increases in the following sequence: smooth surface, circular ribs, v shaped ribs, wedge shaped rib, expanded metal mesh, rib-grooved, and chamfered rib –groove. The effective energy efficiency based criteria also follow same trend of variation among various considered geometries, and trend is reversed at very high Re. It is found that for the higher range of Re, circular ribs and V shape ribs give appreciable exergy efficiency up to high Reynolds number :while for low Re. chamfered rib -groove gives more exergy efficiency.

[6]considered the exergetic performance evaluation and parametric studies of solar air heater. It was observed that the exergy output depends on heat gain and entropy created term. If the inlet temperature of air is low, then maximum exergy output is achieved.

[8]reported energy and exergy analysis of a latent heat storage system with phase change material for a solar collector. The exergy analysis, which is based on the second law of thermodynamics, and energy analysis, which is based on the first law, were applied for evaluation of the system efficiency for charging period. It was observed that the average net energy and exergy efficiencies are 45% and 2.2% respectively.

[4]considered the performance of a natural circulation solar air heating system with phase change material energy storage. He tested the system experimentally under daytime no- load conditions at Nsukka, Nigeria over the ambient temperature range of 19 -41$^0$C. The results show that the system can be operated successfully for crop drying applications, with suitable values to control the working chamber temperature. It can also operate as a poultry egg incubator.

[5] studied the transient thermal analysis of a natural convections solar air heater. It includes a single-glazed flat –plate solar collector integrated with a paraffin- type PCM energy storage subsystem as an application. [2]studied the energy and exergy efficiencies of different types of solar system like photovoltaic, active and passive solar collectors.

[9]did thermal analysis of flat plate solar collector and derived fin efficiency and useful energy of the collector. [3]did an extensive detailed work on collector design to obtain fin efficiency of the collector, flow factor and heat removal factor. They also worked on the phase change material energy storage to calculate the quantity of energy stored per hour, from solid to liquid phase. [16]did analysis of heat influx on three-dimensional heat conduction coordinate axes, using Fourier law equation.

[12] considered the Performance simulation of a natural circulation solar air heating system with phase change material energy storage for low temperature application.predicted temperatures of the system is compared with the experimental data under daytime no-load condition over the ambient temperature range of 18.5-36.0$^0$C and daily global irradiation of 4.9-20.1 MJ/$m^2$-day. The predicted temperatures agree closely with experimental data to within acceptable limits.

[17] studied the energy and exergy efficiencies of close systems for thermal energy storage. [13] studied Transient Multidimensional Second Law analysis of solar collector subjected to time-varying insolation with diffuse components. The instantaneous optimum flow rates were found to follow the insolation pattern. It was also found that the daily optimum exergetic efficiencies and optimum flow rates were 30% and 10% respectively.

[14]analyzed the Second law optimization of integral type natural circulation solar energy crop dryers. It is shown that operating the dryer at conditions of minimum entropy generation yields a useful criterion for choosing dryer dimensions and is compatible with the desire to maintain allowable limits on crop temperature.

[18]considered the entropy generation in a closed system at a steady flows. They analyzed the entropy flows of different systems, both open and closed ones. Adrian Bejan (1996) studied the entropy generation

minimization. He used second law of thermodynamic mainly on different systems to analyze entropy generation of that system. Rai (2006) looked into how to convert solar energy in different systems from one form to another and other sources of energy conversion. The objective of this research work is to examine the exergetic efficiency of passive solar air heater with phase change energy storage material.

## II. MATERIALS AND METHODS

The data used to test the exergy equation model generated in this work was obtained from Obi (2008). This was used on exergy and Energy analyses, in order to calculate daily energy storage of the system.

**Descriptions:**
Section 1**,** isthe air flow channel to the solar panel, then the exit of the passage B leads to the paraffin cylinder (storage cylinder). The paraffin melts during the sunny-day and gets charged. It discharges when in used, either to heat up house in humid period or to dry agricultural seeds for preservation. The storage chemical gets solidify after discharging.

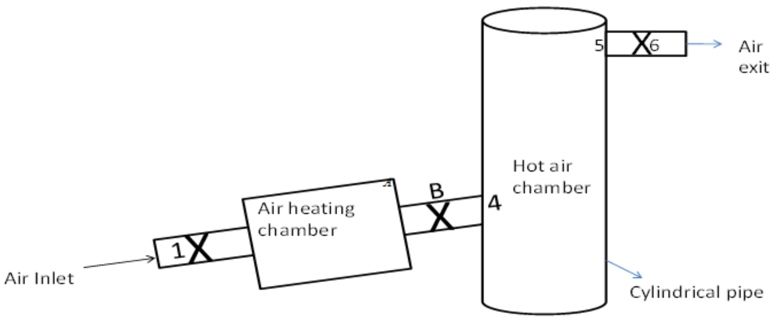


**Fig1** Schematic view of a natural circulation air heater:

**2.1 Design Calculations:**
Solar air heater panel: this is a panel that absorbed insolation from the sun. It has in-built hollow passage, to allow hot air mass, to flow across.

**2.1.3 Energy Analysis of the Absorber Plate (Panel)**

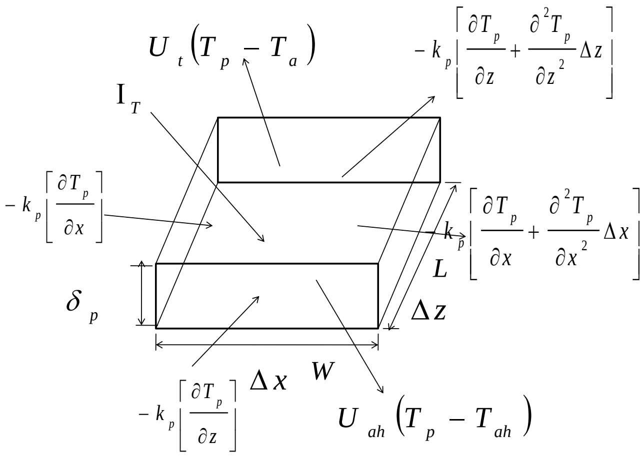


**Fig 2.1:** Energy fluxes on a differential element of the absorber plate [5]

Energy balance equation of the solar collector is given as**;**

$$\rho_p C_p \delta_p \frac{\partial T_P}{\partial t} = K_p \delta_p \left[\frac{\partial^2 Tp}{\partial x^2} + \frac{\partial^2 Tp}{\partial z^2}\right] + q_u \quad (1)$$

Where

$$q_u = I_T \alpha\tau - U_t(T_p - T_a) - U_{ah}(T_p - T_{ah}) \quad (2)$$

The useful heat gain ofthe absorber plate is given as;

$$Q_u = A_c \alpha\tau\, I_T - A_c U_t (T_p - T_{env}) - A_c U_{ah} (T_p - T_{ah}) \quad (3)$$

The useful heat gain of the collector, as a function of the fluid inlet temperature is given as;

$$Q_u = F_R A_c [\alpha\tau\, I_T - U_t (T_{fi} - T_{env}) - U_{ah} (T_{ahc} - T_{fi})] \quad (4)$$

Energy loss on top of the absorber plate is given as;

$$Q_o = A_c U_t (T_{fi} - T_{env}) \quad (5)$$

Heat flowing immediately under the absorber plate is given as;

$$Q_{ah} = A_c U_{ah} (T_{ahc} - T_{fi}) \quad (6)$$

Heat input from the sun is given as;

$$Q_{(sun)i} = A_c \alpha\tau\, I_T \quad (7)$$

$F_R = heat \ \ removal \ \ factor$

Collector energy efficiency

$$\eta_{enc} = \frac{Q_u}{Q_{(sun)i}} = \frac{Heat \ \ gain}{Heat \ \ from \ \ the \ \ sun} \quad (8)$$

Exergy Equation of the Solar Collector is given as;

$$\left(1 - \frac{T_{env}}{T_{su}}\right) A_c \alpha\tau\, I_T + E_{(air)ic} = E_{(air)oc} + \left(1 - \frac{T_{env}}{T_{fi}}\right) A_c U_t (T_{fi} - T_{env}) +$$

$$\left(1 - \frac{T_{env}}{T_{ah}}\right) A_c U_{ah} (T_{ah} - T_{fi}) + E_{(irr)c} \quad (9)$$

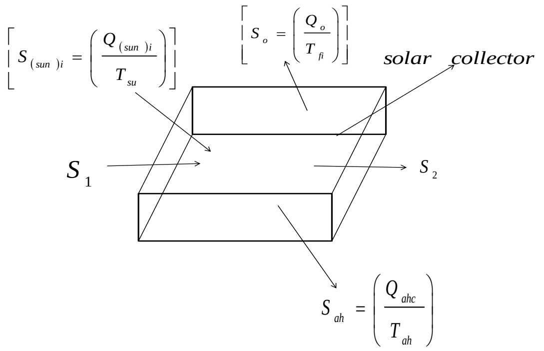


**Fig (2.2):** Entropy Generation in the solar collector (Sgc)

The Entropy equation is given as;

$$(S_2 - S_1) = \dot{m}\, Cp_{air}\, In \frac{T_{fo}}{T_{fi}} \quad (10)$$

The rate of entropy generation in the collector then becomes;

$$S_{gc} = \left[\dot{m}\, Cp_{air}\, In \frac{T_{fo}}{T_{fi}}\right] - \left[\frac{Q_{(sun)i}}{T_{su}} - \frac{Q_o}{T_{fi}} - \frac{Q_{ahc}}{T_{ah}}\right] \quad (11)$$

Irreversibility $E_{(irr)c}$ in the collector can also be;

$$E_{(irr)c} = T_{env} . S_{gc} \quad (12)$$

$$E_{(irr)c} = T_{env}\left[\dot{m}\,Cp_{air}\,In\frac{T_{fo}}{T_{fi}}\right] - T_{env}\left[\frac{Q_{(sun)i}}{T_{su}} - \frac{Q_{o}}{T_{fi}} - \frac{Q_{ahc}}{T_{ah}}\right] \tag{13}$$

The exergy of incoming solar radiation is given by;

$$E_{(sun)i} = \tau\alpha\, I_T A_c\left(1 - \frac{T_{env}}{T_{su}}\right) \tag{14}$$

The exergy of the inlet air is given by;

$$E_{(air)ic} = \dot{m}\,Cp_{air}\left(T_{fi} - T_{env}\right) - \dot{m}\,T_{env}\left(Cp_{air}\,In\frac{T_{fi}}{T_{env}}\right) \tag{15}$$

while the exergy of the outlet air is given by;

$$E_{(air)oc} = \dot{m}\,Cp_{air}\left(T_{fo} - T_{env}\right) - \dot{m}\,T_{env}\left(Cp_{air}\,In\frac{T_{fo}}{T_{env}}\right) \tag{16}$$

Thus, the useful exergy of the collector becomes,

$$E_{uc} = E_{(air)oc} - E_{(air)ic} \tag{17}$$

Exergy efficiency of the collector is then obtained by dividing
the useful exergy by the exergy of the incoming solar radiation, namely;

$$\eta_{exc} = \frac{E_{uc}}{E_{(sun)i}} \tag{18}$$

**3.2 Phase Change Material**

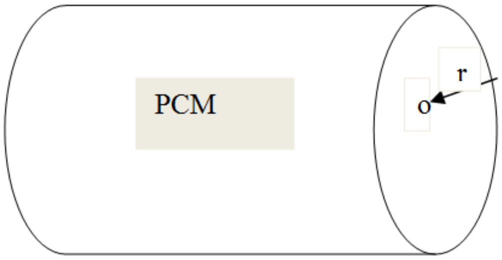


**Fig. 2.3** Cylinder Containing PCM

The energy balance equation of the PCM is as fellows**;**
The useful energy of the PCM is;

$$\therefore\ Q_{us} = -kA_{so}\frac{\partial T_s}{\partial r} = h_{so}A_{so}\left(T_{ahs} - T_s\right) \tag{19}$$

As given by Rajput (2009).
The energy storage of PCM is given as;

$$IF\ \left(T_o < T_L\right)\ then$$

$$Q_{stpcm} = V_s C_s \rho_s \left(T_o - T_s\right)$$

$$If\ \left(T_o = T_L\right)\ then$$

$$Q_{stpcm} = V_s\left[C_s\rho_s\left(T_L - T_s\right) + x_1\rho_{li}X_L\right] \tag{20}$$

$$if\ \left(T_o > T_L\right)\ then$$

$$Q_{stpcm} = V_s\left[C_s\rho_s\left(T_L - T_s\right) + \rho_{li}X_L + C_{li}\rho_{li}\left(T_o - T_L\right)\right]$$

The heat loss to the environment becomes;

$$Q_L = V_{so}\left[Cp_{li}\,\rho_{li}\,(T_o - T_{env})\right] \tag{21}$$

The resulting energy balance of PCM becomes;

$$Q_{us} = Q_{stpcm} + Q_{loss} \tag{22}$$

The energy efficiency of the PCM is given by Rosen (1992) as follows;

$$\eta_{enst} = 1 - \frac{energy\ loss\ during\ storing}{energy\ accumulation\ during\ charging} = 1 - \frac{Q_L}{Q_{stpcm}} \tag{23}$$

Exergy equation for storing periods.

$$k\left[\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r}\frac{\partial T_s}{\partial r}\right]\left(1 - \frac{T_{env}}{T_s}\right) - E_{(irr)s} = \left(1 - \frac{T_{env}}{T_s}\right)\rho_s c_s \frac{\partial T_s}{\partial t} + \left(1 - \frac{T_{env}}{T_o}\right) q_{Loss} \tag{25}$$

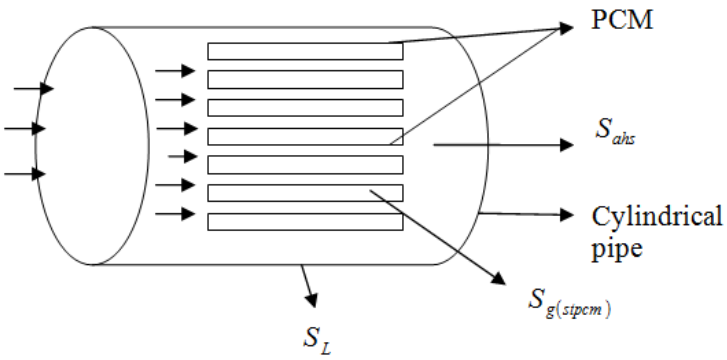


**Fig. 2.4** Entropy Generation in the PCM (Sgs)

The entropy generation in the paraffin wax becomes;

$$S_{g(stpcm)} = (S_2 - S_1)_{stpcm} - S_{stpcm} \tag{26}$$

The entropy change at constant pressure between the initial state of paraffin wax and the final state is given as;

$$(S_2 - S_1)_{stpcm} = V_s Cp_s \rho_s \ln\left(\frac{T_o}{T_s}\right)_{at\ (T_o < T_L)}$$

$$(S_2 - S_1)_{stpcm} = V_s\left[Cp_s \rho_s \ln\left(\frac{T_L}{T_s}\right) + \left(\frac{x_1 \rho_{li} X_L}{T_L}\right)\right]_{at\ (T_o = T_L)} \tag{27}$$

$$(S_2 - S_1)_{stpcm} = V_s\left[Cp_s \rho_s \ln\left(\frac{T_L}{T_s}\right) + \frac{\rho_{li} X_L}{T_L} + Cp_{li}\rho_{li}\ln\left(\frac{T_o}{T_L}\right)\right]_{at\ (T_o > T_L)}$$

*the entropy due to heat transfer to the paraffin wax is given as;*

$$S_{stpcm} = \frac{Q_{stpcm}}{T_o},\ at\ (T_o < T_L)$$

$$S_{stpcm} = \frac{Q_{stpcm}}{T_L},\ at\ (T_o = T_L)$$

$$S_{stpcm} = \frac{Q_{stpcm}}{T_o},\ at\ (T_o > T_L) \tag{28}$$

*The entropy due to heat loss from the cylinder*

$$S_L = \left(\frac{1}{T_o}\right) V_s \rho_{li} Cp_{li} (T_o - T_{env}) \tag{29}$$

The entropy resulting from useful energy of the system.

$$S_{ahs} = \left(\frac{Q_{us}}{T_{ahs}}\right) \tag{30}$$

The entropy generation in the cylindrical pipe is given as follows;
When the flows is reversible and adiabatic in the cylindrical pipe,
then the entropy remains constant, $S_e = S_i$,

$$\therefore (S_e - S_i) = 0$$

$$S_{gs} = 0 - [S_{ahs} - S_{g(stpcm)} - S_L] \tag{31}$$

$E_{(irr)s} = S_{gs} T_{env}$ = irreversibility of the system

The useful exergy in the cylindrical pipe is;

$$E_{us} = \left(1 - \frac{T_{env}}{T_s}\right) kA_{so} \frac{\partial T_s}{\partial r} = \left(1 - \frac{T_{env}}{T_{ahs}}\right) A_{so} h_s (T_{ahs} - T_s) \tag{32}$$

The exergy storage of the phase change material is;

$IF\ (T_o < T_L)\ then$

$$E_{stpcm} = \left(1 - \frac{T_{env}}{T_0}\right) V_s C_s \rho_s (T_o - T_s)$$

$If\ (T_o = T_L)\ then$

$$E_{stpcm} = \left(1 - \frac{T_{env}}{T_L}\right) V_s [C_s \rho_s (T_L - T_s) + x_1 \rho_{li} X_L] \tag{33}$$

$if\ (T_o > T_L)\ then$

$$E_{stpcm} = \left(1 - \frac{T_{env}}{T_o}\right) V_s [C_s \rho_s (T_L - T_s) + \rho_{li} X_L + C_{li} \rho_{li} (T_o - T_L)]$$

The exergy loss to the environment is given as;

$$E_L = \left(1 - \frac{T_{env}}{T_0}\right) (V_{so} \rho_{li} Cp_{li} (T_o - T_{env})) \tag{34}$$

The exergy balance equation in the cylinder becomes;

$$E_{us} = E_{stpcm} + E_{Loss} + E_{(irr)s} \tag{35}$$

The exergy efficiency of the PCM is givenbyRosen (1992) as;

$$\eta_{\exp cm} = 1 - \frac{E_L + E_{(irr)s}}{E_{stpcm}} \tag{36}$$

## III. RESULT AND DISCUSION

### 3.1 Results

The results of this research work are shown in Table 4.1 to 4.5as obtained after running computer program of energy and exergy models.

**Table 1** Results of June10, 2006.

| eta_enpcm | eta_expcm | E_irrC | E_ah | E_o | E_irrpcm | E_Loss | E_stpcm | E_sunI | E_uc |
|---|---|---|---|---|---|---|---|---|---|
| | | [w] | [w] | [w] | [w] | [w] | [w] | [w] | [w] |
| 0.3204 | 0.1957 | 0.003615 | 4.4E-05 | 0.001533 | 2.069 | 0.5227 | 3.222 | 0.006861 | 0.00167 |
| 0.5096 | 0.3989 | 0.004527 | 7.33E-05 | 0.001817 | 1.347 | 0.8614 | 3.674 | 0.01047 | 0.004049 |
| 0.4846 | 0.372 | 0.000759 | 0.000103 | 0.001854 | 1.839 | 1.392 | 5.144 | 0.01222 | 0.009507 |
| 0.2497 | 0.1197 | 0.003096 | 0.000367 | 0.001892 | 3.983 | 1.59 | 6.331 | 0.01603 | 0.01068 |
| 0.3082 | 0.1826 | 0.002892 | 0.000293 | 0.002195 | 4.044 | 1.87 | 7.235 | 0.01956 | 0.01418 |
| 0.5114 | 0.3208 | 0.004314 | 0.000513 | 0.002403 | 4.494 | 1.944 | 9.48 | 0.02274 | 0.01551 |
| 0.5437 | 0.4355 | 0.000256 | 0.000455 | 0.001381 | 3.166 | 1.428 | 8.14 | 0.009028 | 0.006936 |
| 0.428 | 0.3112 | 0.000339 | 0.00044 | 0.001079 | 1.338 | 0.9203 | 3.278 | 0.005381 | 0.003523 |

| E_us | I | Q_ah | Q_loss | Q_i | Q_o | Q_stpcm | Q_u | Q_us | T_D |
|---|---|---|---|---|---|---|---|---|---|
| [w] | [w/m^2] | [w] | | [w] | [w] | [w] | [w] | [w] | [K] |
| 5.813 | 255.8 | 0.00088 | 50.05 | 0.09802 | 0.03065 | 73.64 | 0.05252 | 123.7 | 6 |
| 5.883 | 390.2 | 0.001466 | 41.18 | 0.1495 | 0.03633 | 83.98 | 0.08826 | 125.2 | 10.9 |
| 8.374 | 455.7 | 0.002053 | 60.6 | 0.1746 | 0.03709 | 117.6 | 0.107 | 178.2 | 19.9 |
| 11.9 | 597.7 | 0.007332 | 108.6 | 0.229 | 0.03784 | 144.7 | 0.1452 | 253.3 | 21.5 |
| 13.15 | 729.2 | 0.005866 | 114.4 | 0.2794 | 0.0439 | 165.4 | 0.1814 | 279.8 | 25 |
| 15.92 | 847.9 | 0.01027 | 111.2 | 0.3249 | 0.04806 | 227.5 | 0.2106 | 338.7 | 26 |
| 12.73 | 336.6 | 0.009092 | 84.89 | 0.129 | 0.02763 | 186 | 0.07288 | 270.9 | 17.8 |
| 5.537 | 200.6 | 0.008799 | 42.86 | 0.07686 | 0.02157 | 74.94 | 0.03673 | 117.8 | 12 |

| T_env | T_ah | T_fi | T_fo | T_h | T_ahs | T_o | T_s | T_Ds |
|---|---|---|---|---|---|---|---|---|
| [K] | [K] | [K] | [K] | [hrs] | | [K] | [K] | |
| 298.9 | 307.3 | 307 | 313 | 9 | 308.7 | 306 | 300.3 | 5.7 |
| 299.4 | 309.5 | 309 | 319.9 | 10 | 313.1 | 311.1 | 304.6 | 6.5 |
| 300.2 | 310.7 | 310 | 329.9 | 11 | 322.1 | 319.1 | 310 | 9.1 |
| 302.5 | 315 | 312.5 | 334 | 12 | 330.1 | 324.1 | 312.9 | 11.2 |
| 304.4 | 318 | 316 | 341 | 13 | 336 | 329.8 | 317 | 12.8 |
| 307.3 | 323.5 | 320 | 346 | 14 | 340.7 | 333.7 | 317.7 | 16 |
| 305.6 | 316 | 312.9 | 330.7 | 15 | 329 | 325 | 310.6 | 14.4 |
| 297.3 | 306 | 303 | 315 | 16 | 312 | 309.8 | 304 | 5.8 |

**Table 2** Results of June11, 2006.

| eta_enpcm | eta_expcm | E_irrC | E_o | E_irrpcm | E_Loss | E_stpcm | E_uc | E_ah | E_sunI |
|---|---|---|---|---|---|---|---|---|---|
| | | [w] | [w] | [w] | [w] | [w] | [w] | | [w] |
| 0.2398 | 0.1995 | 0.003255 | 0.001453 | 2.999 | 0.07804 | 3.844 | 0.002037 | 0.000469 | 0.007215 |
| 0.424 | 0.3879 | 0.002738 | 0.001726 | 2.795 | 0.09571 | 4.722 | 0.002682 | 0.000528 | 0.007674 |
| 0.309 | 0.2702 | 0.01258 | 0.001741 | 5.692 | 0.1185 | 7.962 | 0.005203 | 0.000563 | 0.02009 |
| 0.4986 | 0.4641 | 0.007429 | 0.002044 | 5.207 | 0.1782 | 10.05 | 0.01012 | 0.000657 | 0.02025 |
| 0.5713 | 0.5385 | 0.008338 | 0.001847 | 4.565 | 0.1988 | 10.32 | 0.01205 | 0.000446 | 0.02268 |
| 0.5625 | 0.5296 | 0.002404 | 0.001817 | 3.872 | 0.1583 | 8.566 | 0.008932 | 0.000364 | 0.01352 |
| 0.5026 | 0.4683 | 0.001549 | 0.001801 | 4.087 | 0.1171 | 7.907 | 0.004338 | 0.000364 | 0.008052 |
| 0.3704 | 0.333 | 0.001604 | 0.00168 | 3.309 | 0.09645 | 5.107 | 0.003203 | 0.000235 | 0.006722 |

| E_us | I | m_s | Q_i | Q_ah | Q_loss | Q_o | Q_stpcm | Q_u | Q_us |
|---|---|---|---|---|---|---|---|---|---|
| [w] | [w/m^2] | [kg] | [w] | [w] | [w] | [w] | [w] | [w] | [w] |
| 6.921 | 269 | 64.6 | 0.1031 | 0.01173 | 63.59 | 0.03633 | 83.66 | 0.04346 | 147.3 |
| 7.613 | 286.1 | 64.6 | 0.1096 | 0.0132 | 59.2 | 0.04314 | 102.8 | 0.0421 | 162 |
| 13.77 | 749 | 64.6 | 0.287 | 0.01408 | 119.7 | 0.04352 | 173.3 | 0.1812 | 293 |
| 15.43 | 755 | 64.6 | 0.2893 | 0.01642 | 109.7 | 0.05109 | 218.7 | 0.1752 | 328.4 |
| 15.09 | 845.6 | 64.6 | 0.324 | 0.01115 | 96.33 | 0.04617 | 224.7 | 0.2107 | 321 |
| 12.6 | 503.9 | 64.6 | 0.1931 | 0.009092 | 81.56 | 0.04541 | 186.4 | 0.1095 | 268 |
| 12.11 | 300.2 | 64.6 | 0.115 | 0.009092 | 85.59 | 0.04503 | 172.1 | 0.04811 | 257.7 |
| 8.513 | 250.6 | 64.6 | 0.09602 | 0.005866 | 69.97 | 0.04201 | 111.1 | 0.03804 | 181.1 |

| T_D | T_env | T_fi | T_fo | T_ah | T_h | T_o | T_ahs | T_s | T_Ds |
|---|---|---|---|---|---|---|---|---|---|
| [K] | [K] | [K] | [K] | [K] | [hr] | [K] | [K] | [K] | |
| 6 | 296.4 | 306 | 312 | 310 | 9 | 307 | 310 | 300 | 7 |
| 6.8 | 297.6 | 309 | 315.8 | 313.5 | 10 | 310.6 | 313 | 302 | 8.6 |
| 11.6 | 303.5 | 315 | 326.6 | 319.8 | 11 | 319.6 | 325 | 305.1 | 14.5 |
| 17.8 | 304.8 | 318.3 | 336.1 | 323.9 | 12 | 329 | 333 | 310.7 | 18.3 |
| 20.8 | 301 | 313.2 | 334 | 317 | 13 | 328 | 331 | 309.2 | 18.8 |
| 16.9 | 300.9 | 312.9 | 329.8 | 316 | 14 | 322.4 | 325 | 306.8 | 15.6 |
| 9.8 | 299 | 310.9 | 320.7 | 314 | 15 | 314.9 | 318 | 300.5 | 14.4 |
| 8 | 298.9 | 310 | 318 | 312 | 16 | 312 | 315 | 302.7 | 9.3 |

**Table 3** Results of June 12, 2006.

| eta_enpcm | eta_expcm | E_irrC | E_ah | E_o | E_irrpcm | E_Loss | E_stpcm | E_sunI | E_uc |
|---|---|---|---|---|---|---|---|---|---|
| | | [w] | [w] | [w] | [w] | [w] | [w] | [w] | [w] |
| 0.3204 | 0.1957 | 0.003615 | 4.4E-05 | 0.001533 | 2.069 | 0.5227 | 3.222 | 0.006861 | 0.00167 |
| 0.5096 | 0.3989 | 0.004527 | 7.33E-05 | 0.001817 | 1.347 | 0.8614 | 3.674 | 0.01047 | 0.004049 |
| 0.4846 | 0.372 | 0.000759 | 0.000103 | 0.001854 | 1.839 | 1.392 | 5.144 | 0.01222 | 0.009507 |
| 0.2497 | 0.1197 | 0.003096 | 0.000367 | 0.001892 | 3.983 | 1.59 | 6.331 | 0.01603 | 0.01068 |
| 0.3082 | 0.1826 | 0.002892 | 0.000293 | 0.002195 | 4.044 | 1.87 | 7.235 | 0.01956 | 0.01418 |
| 0.5114 | 0.3208 | 0.004314 | 0.000513 | 0.002403 | 4.494 | 1.944 | 9.48 | 0.02274 | 0.01551 |
| 0.5437 | 0.4355 | 0.000256 | 0.000455 | 0.001381 | 3.166 | 1.428 | 8.14 | 0.009028 | 0.006936 |
| 0.428 | 0.3112 | 0.000339 | 0.00044 | 0.001079 | 1.338 | 0.9203 | 3.278 | 0.005381 | 0.003523 |

| E_us | I | Q_ah | Q_loss | Q_i | Q_o | Q_stpcm | Q_u | Q_us | T_D |
|---|---|---|---|---|---|---|---|---|---|
| [w] | [w/m^2] | [w] | | [w] | [w] | [w] | [w] | [w] | [K] |
| 5.813 | 255.8 | 0.00088 | 50.05 | 0.09802 | 0.03065 | 73.64 | 0.05252 | 123.7 | 6 |
| 5.883 | 390.2 | 0.001466 | 41.18 | 0.1495 | 0.03633 | 83.98 | 0.08826 | 125.2 | 10.9 |
| 8.374 | 455.7 | 0.002053 | 60.6 | 0.1746 | 0.03709 | 117.6 | 0.107 | 178.2 | 19.9 |
| 11.9 | 597.7 | 0.007332 | 108.6 | 0.229 | 0.03784 | 144.7 | 0.1452 | 253.3 | 21.5 |
| 13.15 | 729.2 | 0.005866 | 114.4 | 0.2794 | 0.0439 | 165.4 | 0.1814 | 279.8 | 25 |
| 15.92 | 847.9 | 0.01027 | 111.2 | 0.3249 | 0.04806 | 227.5 | 0.2106 | 338.7 | 26 |
| 12.73 | 336.6 | 0.009092 | 84.89 | 0.129 | 0.02763 | 186 | 0.07288 | 270.9 | 17.8 |
| 5.537 | 200.6 | 0.008799 | 42.86 | 0.07686 | 0.02157 | 74.94 | 0.03673 | 117.8 | 12 |

| T_env | T_ah | T_fi | T_fo | T_h | T_ahs | T_o | T_s | T_Ds |
|---|---|---|---|---|---|---|---|---|
| [K] | [K] | [K] | [K] | [hrs] | | [K] | [K] | |
| 298.9 | 307.3 | 307 | 313 | 9 | 308.7 | 306 | 300.3 | 5.7 |
| 299.4 | 309.5 | 309 | 319.9 | 10 | 313.1 | 311.1 | 304.6 | 6.5 |
| 300.2 | 310.7 | 310 | 329.9 | 11 | 322.1 | 319.1 | 310 | 9.1 |
| 302.5 | 315 | 312.5 | 334 | 12 | 330.1 | 324.1 | 312.9 | 11.2 |
| 304.4 | 318 | 316 | 341 | 13 | 336 | 329.8 | 317 | 12.8 |
| 307.3 | 323.5 | 320 | 346 | 14 | 340.7 | 333.7 | 317.7 | 16 |
| 305.6 | 316 | 312.9 | 330.7 | 15 | 329 | 325 | 310.6 | 14.4 |
| 297.3 | 306 | 303 | 315 | 16 | 312 | 309.8 | 304 | 5.8 |

**Table 4** Results of June 13, 2006.

| eta_enpcm | eta_expcm | E_irrC | E_irrpcm | E_Loss | E_o | E_ah | E_stpcm | E_sunI | E_uc |
|---|---|---|---|---|---|---|---|---|---|
| | | [w] | [w] | [w] | [w] | [K] | [w] | [w] | [w] |
| 0.298 | 0.2355 | 0.003663 | 2.038 | 0.06111 | 0.000435 | 0.000587 | 2.746 | 0.006672 | 0.001987 |
| 0.2122 | 0.1465 | 0.003529 | 3.093 | 0.09424 | 0.000568 | 0.000616 | 3.734 | 0.00893 | 0.004217 |
| 0.3745 | 0.3148 | 0.00742 | 3.224 | 0.1252 | 0.000757 | 0.00066 | 4.887 | 0.01561 | 0.006772 |
| 0.595 | 0.5434 | 0.002787 | 4 | 0.187 | 0.000946 | 0.000748 | 9.17 | 0.0171 | 0.01262 |
| 0.4903 | 0.4348 | 0.004704 | 4.606 | 0.1421 | 0.000378 | 0.000411 | 8.401 | 0.01467 | 0.009179 |
| 0.5412 | 0.4875 | 0.004895 | 3.804 | 0.1355 | 0.00036 | 0.000249 | 7.687 | 0.01238 | 0.006881 |
| 0.5152 | 0.4606 | 0.005215 | 3.754 | 0.1259 | 0.000341 | 0.000176 | 7.193 | 0.01234 | 0.006612 |
| 0.4804 | 0.4245 | 0.005005 | 3.689 | 0.1031 | 0.000189 | 0.000147 | 6.589 | 0.01114 | 0.005803 |

| E_us | I | Q_ah | Q_i | Q_loss | Q_o | Q_stpcm | Q_u | Q_us | T_D |
|---|---|---|---|---|---|---|---|---|---|
| [w] | [w/m^2] | [w] | [w] | [w] | [w] | [w] | [w] | [w] | [K] |
| 4.845 | 290.2 | 0.01173 | 0.1112 | 42.51 | 0.008704 | 60.56 | 0.0717 | 103.1 | 10 |
| 6.921 | 388.4 | 0.01232 | 0.1488 | 64.88 | 0.01135 | 82.37 | 0.09887 | 147.3 | 15 |
| 8.236 | 678.9 | 0.0132 | 0.2601 | 67.43 | 0.01514 | 107.8 | 0.1831 | 175.2 | 19 |
| 13.36 | 744 | 0.01496 | 0.2851 | 81.91 | 0.01892 | 202.3 | 0.1984 | 284.2 | 26.7 |
| 13.15 | 638.2 | 0.008212 | 0.2445 | 94.45 | 0.007569 | 185.3 | 0.1807 | 279.8 | 24.7 |
| 11.63 | 538.7 | 0.004986 | 0.2064 | 77.81 | 0.00719 | 169.6 | 0.1534 | 247.4 | 21.1 |
| 11.07 | 536.9 | 0.00352 | 0.2057 | 76.93 | 0.006812 | 158.7 | 0.1544 | 235.6 | 20.7 |
| 10.38 | 484.7 | 0.002933 | 0.1857 | 75.52 | 0.003784 | 145.4 | 0.1414 | 220.9 | 20 |

| T_env | T_ah | T_fi | T_fo | T_h | T_ahs | T_o | T_s | T_Ds |
|---|---|---|---|---|---|---|---|---|
| [K] | [K] | [K] | [K] | [hr] | [K] | [K] | [K] | |
| 297.7 | 304 | 300 | 310 | 9 | 308 | 306 | 301 | 5 |
| 299 | 306.2 | 302 | 317 | 10 | 315 | 311.8 | 305 | 6.8 |
| 300 | 308.5 | 304 | 323 | 11 | 320 | 317 | 308.1 | 8.9 |
| 302 | 312.1 | 307 | 333.7 | 12 | 330 | 327.4 | 310.7 | 16.7 |
| 304 | 308.8 | 306 | 330.7 | 13 | 327 | 323.3 | 308 | 15.3 |
| 302.8 | 306.4 | 304.7 | 325.8 | 14 | 324 | 321.2 | 307.2 | 14 |
| 302 | 305 | 303.8 | 324.5 | 15 | 322 | 319.1 | 306 | 13.1 |
| 302 | 304 | 303 | 323 | 16 | 319 | 316 | 304 | 12 |

**Table 5** Results of June 14, 2006.

| eta_enpcm | eta_expcm | E_ah | E_irrC | E_irrpcm | E_Loss | E_o | E_stpcm | E_sunI | E_uc |
|---|---|---|---|---|---|---|---|---|---|
| | | [w] | [w] | [w] | [w] | [w] | [w] | [w] | [w] |
| 0.3497 | 0.1164 | 0.000675 | 0.00547 | 1.887 | 0.06111 | 0.000454 | 2.204 | 0.007942 | 0.001343 |
| 0.3435 | 0.1092 | 0.001203 | 0.005089 | 3.887 | 0.09129 | 0.0007 | 4.465 | 0.009991 | 0.003 |
| 0.4032 | 0.1774 | 0.001217 | 0.005854 | 3.962 | 0.1296 | 0.000719 | 4.974 | 0.01262 | 0.004832 |
| 0.4548 | 0.1258 | 0.003329 | 0.004827 | 10.33 | 0.1973 | 0.000795 | 12.04 | 0.02165 | 0.0127 |
| 0.7828 | 0.6107 | 0.002933 | 0.00784 | 4.073 | 0.1745 | 0.000568 | 10.91 | 0.01835 | 0.007009 |
| 0.7524 | 0.576 | 0.002581 | 0.005993 | 4.253 | 0.1568 | 0.000454 | 10.4 | 0.01549 | 0.006461 |
| 0.7623 | 0.5873 | 0.002082 | 0.000939 | 4.094 | 0.1524 | 0.000435 | 10.29 | 0.00971 | 0.006253 |
| 0.6159 | 0.4202 | 0.002053 | 0.000267 | 4.94 | 0.1399 | 0.000378 | 8.761 | 0.007695 | 0.004996 |

| E_us | Q_ah | Q_i | Q_loss | Q_o | Q_stpcm | Q_u | Q_us | T_h | I |
|---|---|---|---|---|---|---|---|---|---|
| [w] | [w] | [w] | [w] | [w] | [w] | [w] | [w] | [hr] | [w/m^2] |
| 4.152 | 0.01349 | 0.1135 | 34.81 | 0.009083 | 53.54 | 0.0718 | 88.35 | 9 | 296.1 |
| 8.443 | 0.02405 | 0.1427 | 71.2 | 0.014 | 108.4 | 0.0827 | 179.6 | 10 | 372.5 |
| 9.066 | 0.02434 | 0.1803 | 72.1 | 0.01438 | 120.8 | 0.1119 | 192.9 | 11 | 470.6 |
| 22.56 | 0.06658 | 0.3092 | 169.4 | 0.01589 | 310.7 | 0.1791 | 480 | 12 | 807 |
| 15.16 | 0.05866 | 0.2621 | 57.54 | 0.01135 | 264.9 | 0.1518 | 322.5 | 13 | 684.1 |
| 14.81 | 0.05162 | 0.2213 | 62.53 | 0.009083 | 252.6 | 0.1269 | 315.1 | 14 | 577.5 |
| 14.53 | 0.04165 | 0.1387 | 59.38 | 0.008704 | 249.8 | 0.0698 | 309.2 | 15 | 362 |
| 13.84 | 0.04106 | 0.1099 | 81.72 | 0.007569 | 212.8 | 0.04843 | 294.5 | 16 | 286.9 |

| T_D | T_env | T_ah | T_fi | T_fo | T_ahs | T_o | T_s | T_Ds |
|---|---|---|---|---|---|---|---|---|
| [K] | [K] | [K] | [K] | [K] | [K] | [K] | [K] | [K] |
| 10 | 297.6 | 304.6 | 300 | 310 | 308 | 305.9 | 302 | 3.9 |
| 15 | 298.3 | 310.2 | 302 | 317 | 315 | 310.7 | 302.8 | 7.9 |
| 20 | 301.2 | 313.3 | 305 | 325 | 323.1 | 318.8 | 310 | 8.8 |
| 35 | 306.2 | 333.1 | 310.4 | 345.4 | 344 | 333 | 311.4 | 21.6 |
| 25.8 | 305.9 | 328.9 | 308.9 | 334.7 | 332.2 | 329.6 | 310.3 | 19.3 |
| 25.1 | 304.3 | 324.3 | 306.7 | 331.8 | 328.6 | 325.6 | 307.2 | 18.4 |
| 24.7 | 303.5 | 320 | 305.8 | 330.5 | 327 | 324.2 | 306 | 18.2 |
| 22 | 302 | 318 | 304 | 326 | 325.5 | 321 | 305.5 | 15.5 |

**Table 6** Average energy and exergy efficiency.

| AVERAGE ENERGY EFFICIENCY | AVERAGE EXERGY EFFICIENCY | $T_h$ (hrs) |
|---|---|---|
| 0.42 | 0.29 | 9 |
| 0.44 | 0.39 | 10 |
| 0.58 | 0.42 | 11 |
| 0.43 | 0.38 | 12 |
| 0.54 | 0.34 | 13 |
| 0.44 | 0.4 | 14 |
| 0.52 | 0.3 | 15 |
| 0.46 | 0.27 | 16 |
| 48% | 35% | |

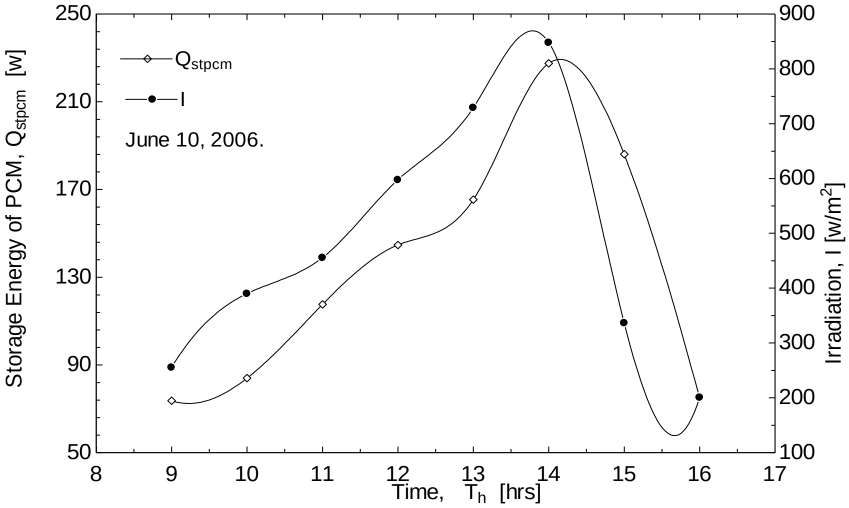


**Fig1.**variation of energy storage and irradiation with time of the day

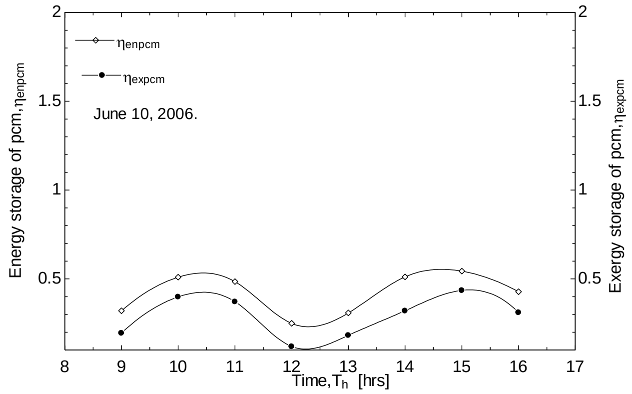


**Fig. 2:** variation of energy efficiency and exergy efficiency with time of the day.

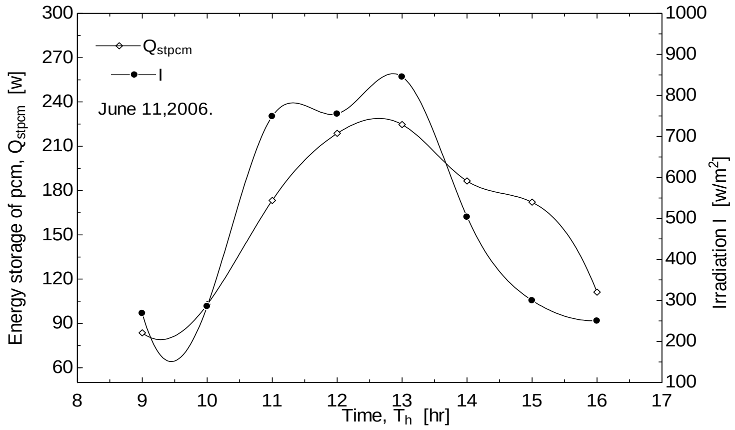


**Fig 3.**variation of energy storage with irradiation on time of the day

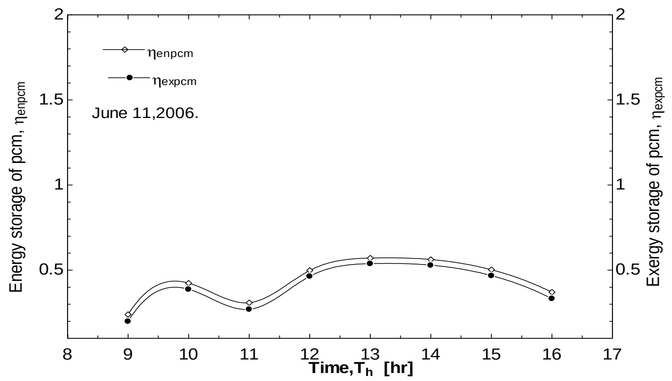


**Fig. 4.**Variation of energy efficiency and exergy efficiency on time of the day.

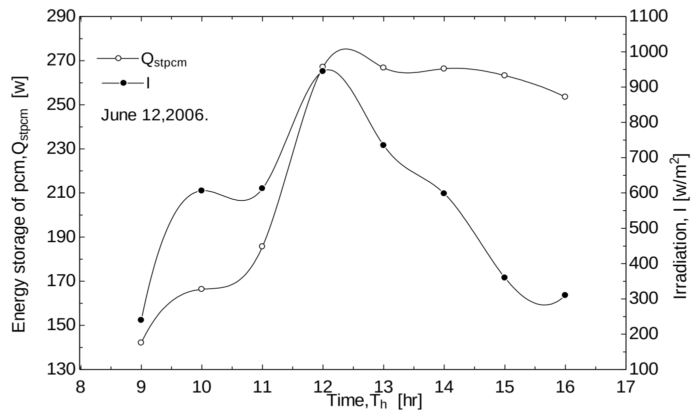


**Fig.5.**variation of energy storage and irradiation with time of the day

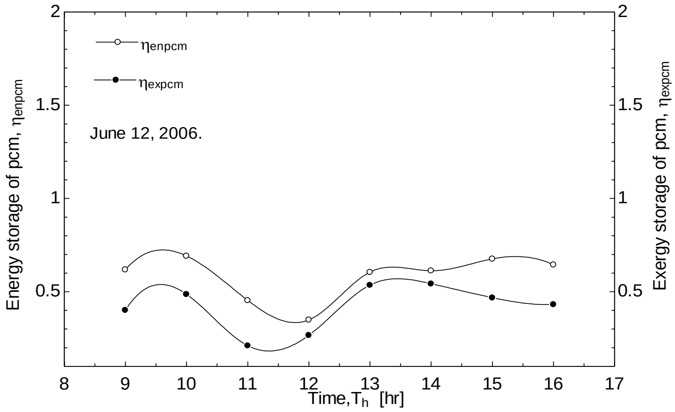


**Fig. 6:** variation of energy efficiency and exergy efficiency with time of the day.

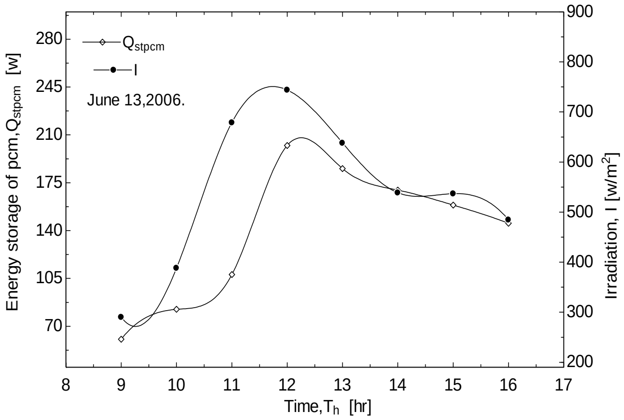


**Fig 7.**variation of energy storage with irradiation on time of the day

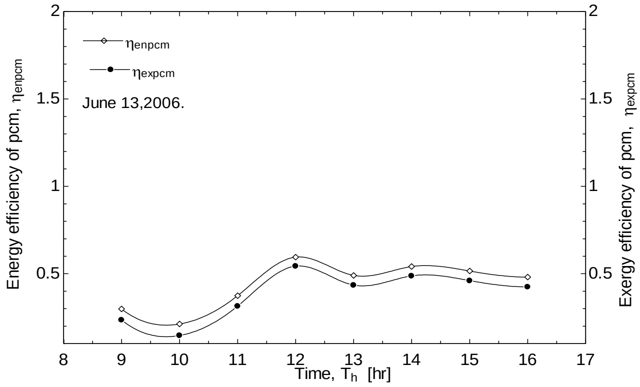


**Fig 8:** variation of energy efficiency and exergy efficiency with time of the day.

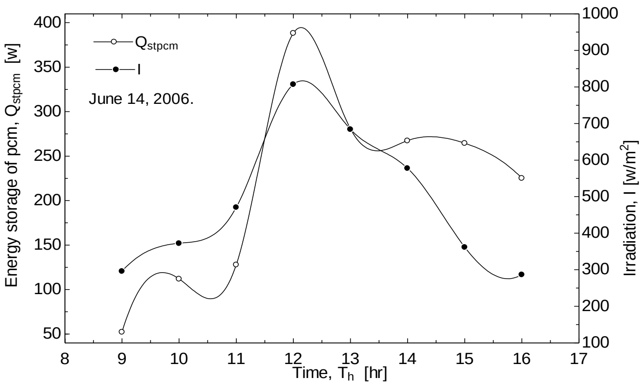


**Fig.9.**variation of energy storage with irradiation on time of the day

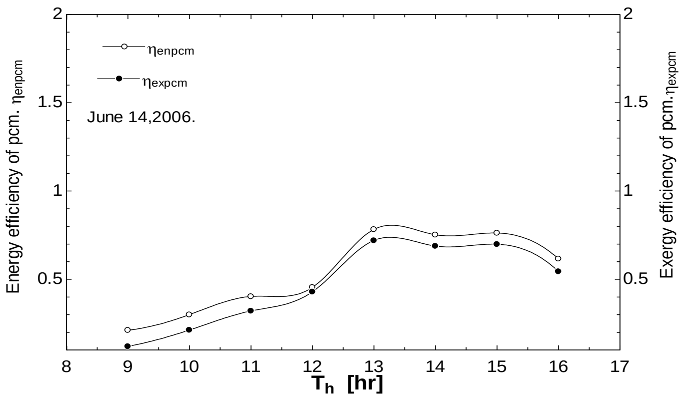


**Fig. 10:** variation of energy efficiency and exergy efficiency on time of the day.

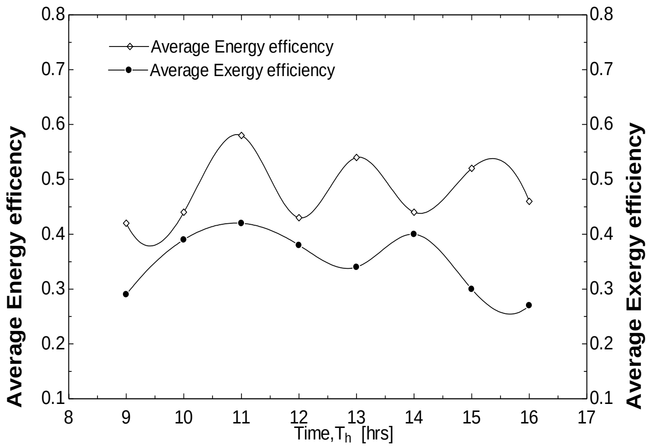


**Fig. 11.**variation of Average energy efficiency and Average exergy efficiency with time of the day.

### 3.2 Discussion

Energy and exergy analyses were performed for a solar collector with thermal energy system (TES) unit using paraffin wax as a PCM. From the literature, the exergy analysis is a better method to improve system performance efficiency. Analysis of exergy takes into account, the loss of availability of heat in TES. Thus, it reflects the thermodynamic, energy and economic value of the system.

In this study, the experimental data, reported in [12] were used as an input to the energy and exergy model equations. The graphs were plotted, from the results in the tables 1 to 11, which were obtained after running the computer program of the equation model using Engineering equation Solver (software). The graphs and their descriptions are highlighted below:

For June 10, 2006, the energy storage of PCM, and the measured solar radiation are plotted with time of the day as shown in fig. 1. Both variables increase rapidly in the morning and fall after 14 hours.

Fig. 2 shows the graph of energy and exergy efficiency with time of the day. The graph took a parabolic shape. The energy efficiency remained higher than exergy efficiency as predicted. The maximum irradiation was 847.9 (w/m$^2$) and the temperature was 60.7 ($^0$C). They fall within the predicted results.

In June 11, 2006's results, the graph of fig. 3 shows the energy storage and irradiation with time of the day. Both increased rapidly in the morning and fall immediately after midday as the insolation dropped.

In fig. 4, The energy efficiency maintained higher values than the exergy efficiency as predicted. The system recorded 56$^0$C as the maximum melting temperature of the day. The maximum temperature was observed to be closed to the predicted temperature. The maximum insolation obtained was 845.6 (w/m$^2$)

From the results obtained in June 12, 2006, Fig .5 shows the graph of energy storage and irradiation with time of the day. The graph increases in the morning as temperature increases and falls after midday due to fall in isolation.

Fig. 6 shows the graph of both efficiencies. They have a parabolic shape. The energy efficiency still maintained higher values than the exergy efficiency. The maximum insolation of the system was 945.6w/m$^2$, while that of temperature was 70.8$^0$C. This figure lies within the expected result from the system.

According to results obtained in June 13, 2006, Fig.7 shows the graph of energy storage and irradiation with time of the day. The graph increases rapidly in the morning and falls slowly after midday due to fall in insolation.

Fig. 8 shows the graph of energy and exergy efficiency with time of the day. Both graphs moves slowly in the morning and rapidly but took a little parabolic shape after 12 hours. The energy efficiency value remained higher than exergy values as predicted. The maximum temperature is $54.4^0$C, which is below the melting point. So the maximum temperature is closed to the prediction temperature. The maximum insolation for the day is 744($w/m^2$).

From the results of June 14 2006, Fig.9 shows the graph of energy storage and irradiation with time of the day. The graph took a dome-bell shape. It increases in the morning and started falling gradually after 12 hours, as the insolation fall.

Fig. 10, increased in the morning till 12 hours, but fall slowly after 13 hours. The energy efficiency remained higher than exergy efficiency as required. The maximum insolation was 807($w/m^2$), while that of temperature was $60^0$C. These values are within the predicted values.

In summary of the efficiencies of the system, using Fig.11 the graphs of Average energy with Average exergy efficiency took a parabolic shape. The energy is higher than exergy because of irreversibility that occurred in the system.

From the analysis, the results revealed that the average energy and exergy efficiency were 48% and 35% respectively.

## IV. CONCLUSION/RECOMMENDATIONS

A complete analysis of the flat-plate solar collector with phase change material energy storage subjected to time varying insolation was carried out. The analysis of the system which is based on the first and second law of thermodynamics was carried out, such as, the energy of the collector, the exergy of the collector, the entropy generation of the collector, energy of the PCM, the exergy of the PCM and the entropy generation of the PCM. Input parameters reported by Obi (2008) were applied on the equation model, to generate results using computer program. Graphs were plotted for each day, between 9 hours to 16 hours, which reveals the daily amount of energy and exergy storage by the system for ten days.

The energy and exergy efficiencies of PCM are considered with one- dimensional heat conduction in cylindrical pipe for storing periods. Exergy analysis was employed in order to improve system performance efficiency by reducing system irreversibility or internal loss or loss of availability which leads to maximization of energy system performance efficiency. Energy efficiency of the system was improved by minimizing energy losses to the environment. The analysis reveals that solar radiation and temperature are the most effective parameters and the average energy and exergy efficiencies were 48% and 35% respectively.

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