

# Numerical Analysis of Thermal Performance in Solar Thermal Collector System with Artificial Roughness

<sup>1</sup>Arbind Kumar Amar, <sup>2</sup>Dr Mani Kant Paswan, <sup>3</sup>Dr. Ajay Giri

<sup>1</sup>Associate professor in Mechanical Engineering Department, B.P. Mandal College of Engineering, Madhepura, India,

<sup>2</sup>Director , SLIET Longowal , Punjab

<sup>3</sup>Assistant professor in Mechanical Engineering Department, B.P. Mandal College of Engineering, Madhepura, India,

Corresponding Author – Arbind Kumar Amar

EMail- akamarak73@gmail.com

---

## Article History:

*Received:* 23-09-2024

*Revised:* 25-11-2024

*Accepted:* 04-12-2024

## Abstract:

In this paper investigation of exergetic analysis of artificial roughness in solar thermal collector is done (STC) done. Here an investigation is done through Thermal model for artificial roughness incorporate in thermal collector is developed. Experimental trial and observations are performed in India under (25° N, 86° E) climatic nature. It is observed that on the performance account approximate 9.95 percent of deviation is seen at out let temperature of STC between theoretical and of Experimental values. Proposed STC reflects improved exergy efficiency about 2.65 %. This result predicts that improvement found in proposed STC which incorporates artificial roughness.

**Keywords:** Solar collector; Fin efficiency; Total loss; Exergy destructions.

---

## I. INTRODUCTION

The growth of any nation is equally related to use of its available energy resources or resources through their capability to do. In current scenario India's performed well in different era such as transportation, manufacturing, agriculture & Clean energy. Fossil fuels plays very key role in India to accomplished utilization and consumption of energy. The pace & rate of use of these natural resources are very speedy and it will not be continued for coming long duration. [1, 2, and 3]. Thus, an alternative source, such as clean energy becomes etc, is equally useful. Solar energy is available for all at no cost and also release energy, at the rate of  $38 \times 10^{22}$  kW, in that, just around about  $18 \times 10^{13}$  kW is falls and or intercept on earth [4]. The simple, & the upmost proficient technic to utilize this clean energy, by transforming free energy for heating application's through STC. STC, because of their simplicity & ease, it is very cheap & most widely can be used [5]. The thermal nature or behavior of STCs's is depends on or upon the material, its shape, Size & design of collector's. Improvement or upgrading, in the excellence on the Performance, achieved by varying the above different parameters. Improvement on STC in order to increase the rate of heat transfer can be possible.

This includes, use of absorber - (corrugated absorber or and matrix-based absorber), and with (packed bed or else baffles or & fins). Thermal investigation or analysis is given effective impact , to obtain most accurate and an important idea to predict or know energy efficiency , & different losses because of the irreversibility in and actual real state [6]. First law is mostly widely , used in actual practice & also is depends on the impact , on heat balance technique etc i.e. universally used as, in the performance investigation any case. Second law involves , the reversibility and , or irreversibility of process. It is very fundamental aspects, and of exergy & energy of STC investigation's [7]. Exergy data's, are very practical , and are realistic , & in compare to respective energy values; Exergy

analysis can , provides a more realistic prediction of processes, & also sometimes different, in comparison with standard energy analysis values [8-9].

## II. EXPERIMENTAL SETUP

Proposed STC with finned as artificial roughness with the single pass nature is Made or fabricated. A galvanized sheet which is black coated of low or small thicknesses are used. Artificial roughness i.e. Fin's are fixed, at back side of absorber plate, (In perpendicular position in provision that to maintained the minor linear gap from the base plate) to enhance thermal performance i.e availability in proposed STC. It works or function under forced convection, & the window fan is fitted at the place of inlet of the experimental set up. In order improve performance proposed STC is fully glass insulated with the help of this heat losses is minimized. The rate of flow of mass as air is considered 0.0361Kg/sec, 0.0392Kg/sec & 0.0421Kg/sec is throughout constant maintained through regulator over the study. Solar intensity and the wind velocity, is also noted all over study by solary meter & anemometer.

K-type thermocouple, is used here in order to measure temperature at the different point of STC. 2-D Figure of artificial roughness on STC as finned absorber plate on STC shown in Fig1. Table 1. Table 1 reflects all dimension and standard parameter

Total fins = 19

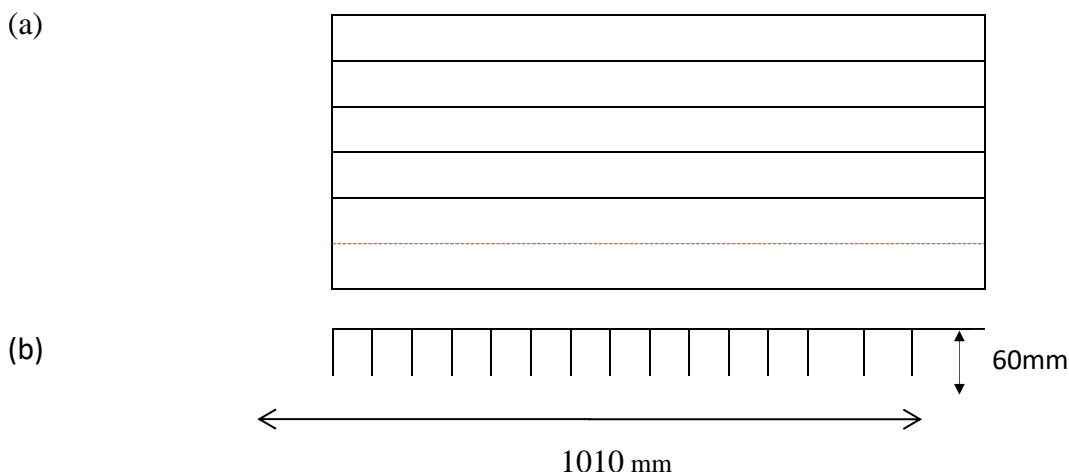


Figure1 View of Artificial roughness as finned STC.

The experiments on Proposed STC is done in the Solar Energy laboratory, In Mechanical Engineering Department, B.P. Mandal College of Engineering, Madhepura, India. The experiments and readings, are recorded October, in light winter climatic & observations are noted from 8 am to 5:00 pm.

## III. MATHEMETICAL MODEL

### (a) ENERGY ANALYSIS

The 2-D Presentation of STC with artificial roughness considered as finned on absorber plate, in STC under performance investigation depict in Fig.1. In the analysis for solar input energy balance empirical formulas are predicted for rate of heat and mass flow through out STC along with heat losses. Flow of heat on collector is depicted in fig 2. Energy input to system through the solar radiation impinges on

absorber surface. Different loss and total loss because of radiation and convection through black absorber plate is elaborated in [10, 11].

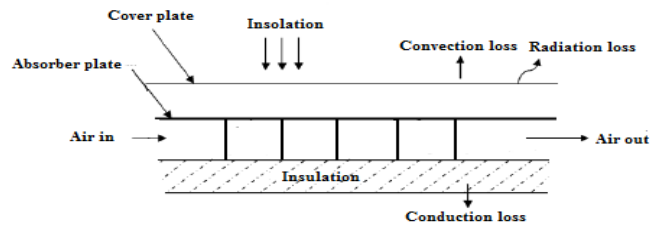


Fig. 2 Energy impact on absorber plate

The energy investigation on STC is elaborated by sukhatme (1993). usable heat gain:

$$Q_u = \dot{m} C_p \Delta T \tag{1}$$

Hottel - Whiller empirical technique for usable heat gain obtained from STC:

$$Q_u = A_c F_R \varpi \tag{2}$$

Exit air temperature of STC:

$$T_o = T_i + \frac{1}{u_L} \varpi \tag{3}$$

Thermal Efficiency estimated in solar collector:

$$\eta_c = \frac{Q_u}{I_T A_p} \tag{4}$$

**ARTIFICIAL ROUGHNESS AS FIN ON STC:** A proposed fin on STC depicted in Fig 2. Gap in between fins  $W_1$  & the length of fin is  $W_2$ . All fins as artificial roughness is fixed on back or reverse portion on plate along with minor gap to each other and with bottom plate.

Efficiency factor,  $F'$  on STC collector: [12].

$$F' = F'_o \left[ 1 + \frac{1 - F'_o}{\frac{F'_o}{F_p} + \frac{W_1 h_1}{2W_2 h_2 F_f}} \right] \tag{5}$$

**(b) EXERGY ANALYSIS:**

Through use of exergy equilibrium in STC shown in Fig.1, Balance of Exergy STC is elaborated by Chamoli (2013):[13]

$$\Psi_{in} - \Psi_{out} - \Psi_{loss} - \Psi_{change} - \Psi_{des} = 0 \tag{6}$$

Exergy efficiency determined with use of in & outlet exergy:

$$\eta_{\Psi} = \frac{\dot{m}}{I_T A_p \eta_p} \left[ C_p \left( T_o - T_i - T_a \ln \frac{T_o}{T_i} \right) \right] \tag{7}$$

**DESTRUCTION ON EXERGY:** Exergy destruction is happened due to irreversibility's occurred in system. Exergy destroyed has three terms:

One, Difference of temperature in between STC absorber plate surface & sun:

$$\Psi_{des,abs} = \eta_o I_T A_p T_a \left( \frac{1}{T_p} - \frac{1}{T_s} \right) \tag{8}$$

Second, due to duct's pressure drop:

$$\Psi_{des,\Delta p} = \frac{\dot{m}}{\rho} \times \frac{\Delta_p T_a \ln\left(\frac{T_o}{T_a}\right)}{(T_o - T_{in})} \tag{9}$$

Third, temperature difference in between STC absorber plate surface & fluid:

$$\Psi_{des,conv} = \dot{m} C_p T_a \left( \ln\left(\frac{T_o}{T_{in}}\right) - \frac{(T_o - T_{in})}{T_p} \right) \tag{10}$$

Hence, exergy destruction:

$$\Psi_{des} = \frac{\Psi_{des,abs} + \Psi_{des,\Delta p} + \Psi_{des,conv}}{\Psi_{in,r}} \tag{11}$$

As considered that drop in duct pressure is negligible, hence exergy destruction:

$$\Psi_{des} = \frac{\Psi_{des,abs} + \Psi_{des,conv}}{\Psi_{in,r}} \tag{12}$$

**EXERGY IN:** In view of Petela's, exact exergy on Collector surface  $A_p$  becomes:

$$\Psi_{in,r} = I_T A_p \eta_p \tag{13}$$

**(c) PARAMETER RANGE:**

Table 1: different parameters considered for investigation

S.No	Used Parameters	Ranges	S.No	Used Parameters	Ranges
1	Glazing of glass	Single glass	8	Transmittance-absoptance	0.85
2	Fluid medium	Air	9	Thickness of plate $\delta$	0.003m
3	Finn counts	18	10	Absorber plate emittance, $\epsilon_p$	0.93
4	plate length	L=1.25m	11	Glass cover emittance, $\epsilon_g$	0.88
5	plate width	W=0.98m	12	Stefan-Boltzman constant	5.67x10 <sup>-8</sup> W/m <sup>2</sup> K <sup>4</sup>
6	Channel Depth	s=0.07m	13	Space in between fins W1	0.0659m
7	Temperature of Sun	5760K	14	Fin Length W2	.06m

**HEAT TRANSFER COEFFICIENTS:** Heat transfer, convective or radiative can be predicted is elaborated in : [14] , radiative heat transfer:

$$h_{r,p-g} = \frac{\sigma(T_p^2 + T_g^2)}{\left(\frac{1}{\epsilon_p}\right) + \left(\frac{1}{\epsilon_g}\right) - 1} \tag{14}$$

Sherwin have proposed in types of laminar flow, for proposed STC modeled has suggested relations to estimate coefficient of heat transfer.

For  $R_{eL} \leq 5 \times 10^5$  and  $(P_r \geq 0.5)$ ,  $N_u = 0.664 P_r^{\frac{1}{3}} R_{eL}^{\frac{1}{2}}$

Niles et al. has given following empirical relation in case of turbulent flow:

For  $5 \times 10^5 < R_{eL} < 10^8$  and  $0.6 < P_r < 60$ ,  $N_u = 0.333 R_e^{0.8} P_r^{0.33}$

Convective heat loss:

$$h_c = \left(\frac{k}{L}\right) \times 0.664 \times (P_r)^{\frac{1}{3}} \times (R_e)^{\frac{1}{2}} \tag{15}$$

**LOSS COEFFICIENTS:** Top loss coefficient, in single glass cover design [15, 16] :

$$U_t = \left( \frac{1}{h_{cp-c} + h_{pp-c}} + \frac{1}{h_w + h_{rc-a}} \right)^{-1} \tag{16}$$

Total loss:  $U_L = U_t + U_b + U_e$  (17)

#### IV. RESULT AND DISCUSSION

In order to obtain out let or exit temperature, different empirical relations and energy balance equations are incorporated and discussed. STC performance efficiency is made subjected to input parameters as mentioned above, the process of recording data at different points is done till sun set. At the stage of initialization plate of STC absorber is black and ambient temperature is considered as air temperature.

Experimental work and readings were taken in winter season in real Indian climate & in the premises of B.P. Mandal College of Engineering, Madhepura, India. Test readings are taken throughout month and out of which moderate and good value of any particular day is considered. Fig.3 reflects, Plot of solar Intensity with time, Solar intensities are observed here closed at different flow of mass and have the same pattern .

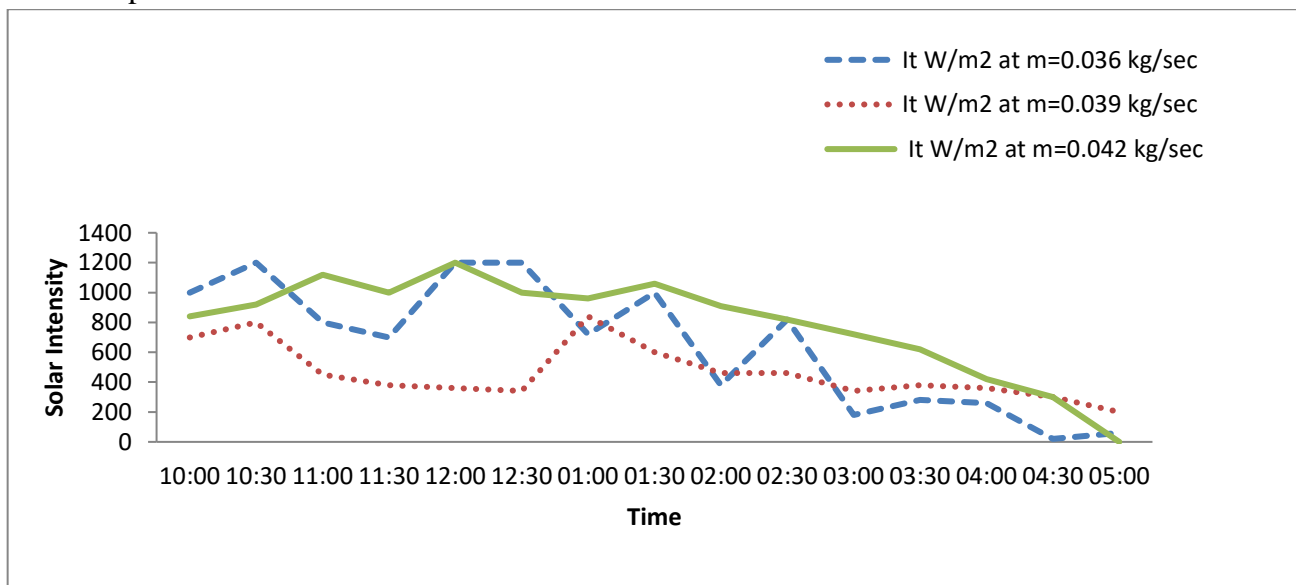


Figure 3 Plot of solar intensity, mass flow rate V/s span of day

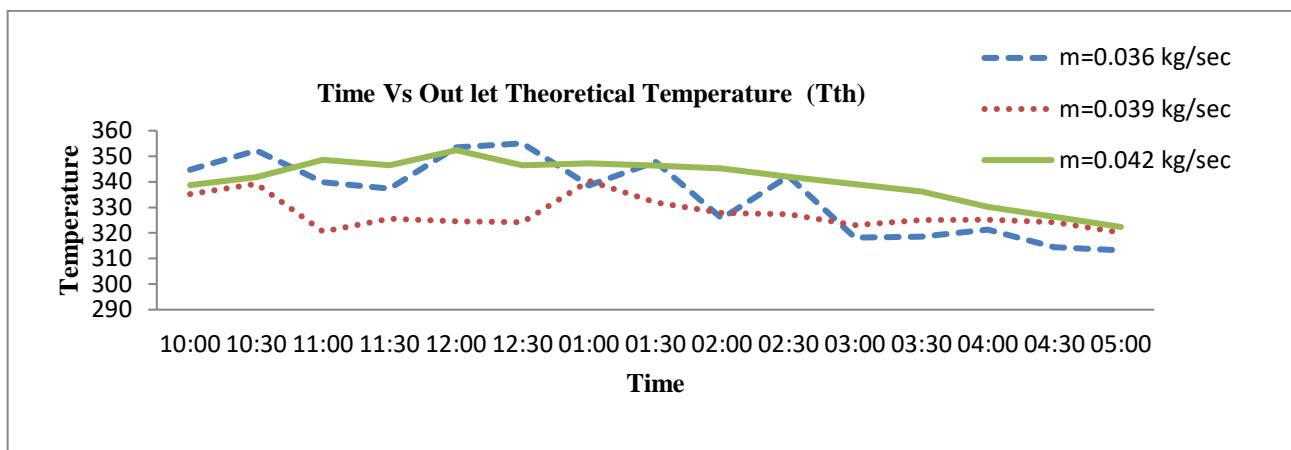


Figure 4 Plot of exit theoretical temperatures V/s different mass flow rate & Span of day

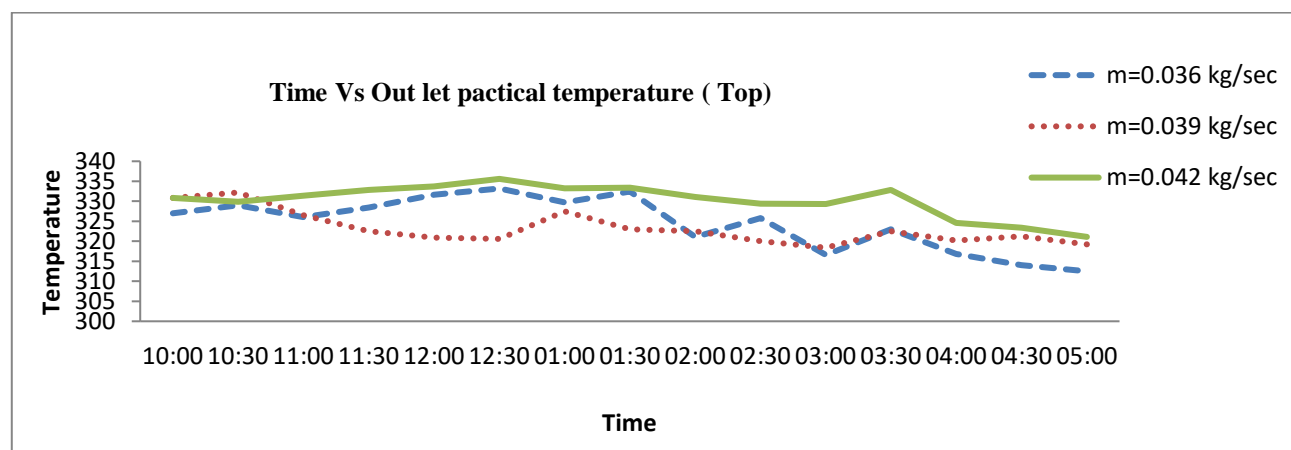


Figure 5 plot of Exit practical temperature V/s different mass flow rate at span of day

Fig. 4 and Fig. 5 depicts plot of out let temperatures with different mass flow rates, (0.036 kg/s, 0.039 Kg/sec & 0.042 kg/s) theoretical & practical. Out let also improves accordingly as solar Intensity in same fashion. It is found that experimental values enhanced with a limit of 10 percent then that of Theoretical values.

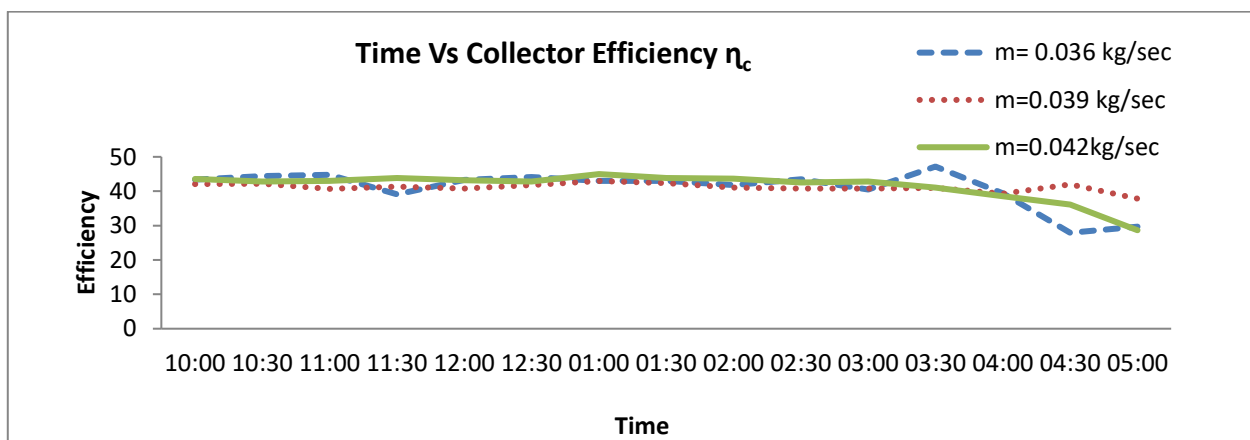


Figure.6 Plot of Collector efficiencies V/s day time with different mass flow rate

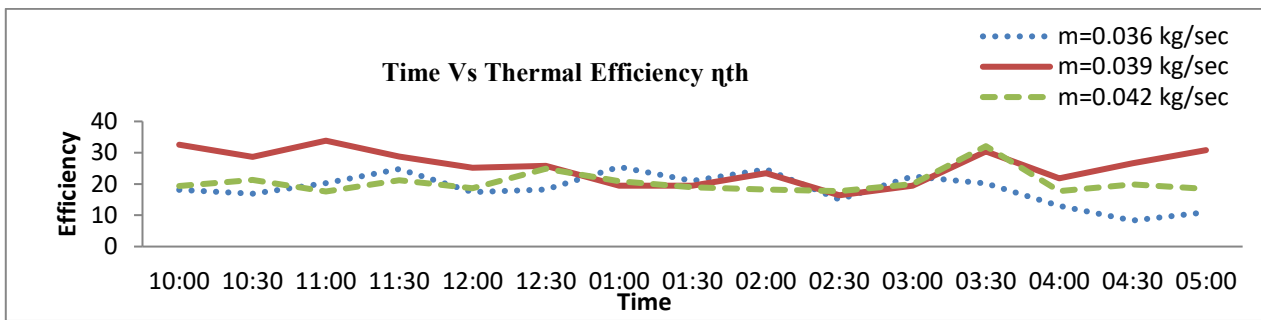


Figure 7 Plot of energy efficiency V/s day time with different mass flow rate

Fig. 6 depicts plot of collector efficiency, with three mass flow rates verses time of day in (hr). As expected, minor variation is observed on account of overall & average collector mass flow rate. The estimated average, collector efficiency in all different three mass flow rates is obtained same as plot reflects. Fig. 7 predicts impact of thermal efficiency at the different mass flow rates, (0.036 kg/s, 0.039kg/sec and 0.042 kg/s) V/s day span. As mass flow rate, increased from (0.036 kg/s to 0.042 kg/s ) improvement in energy efficiency as 10.84%. It is found that as mass flow is higher the energy efficiency is also getting higher. In fact, due to increase in mass flow rate the impact of convective mode of heat transfer is more on-air flow at exit.

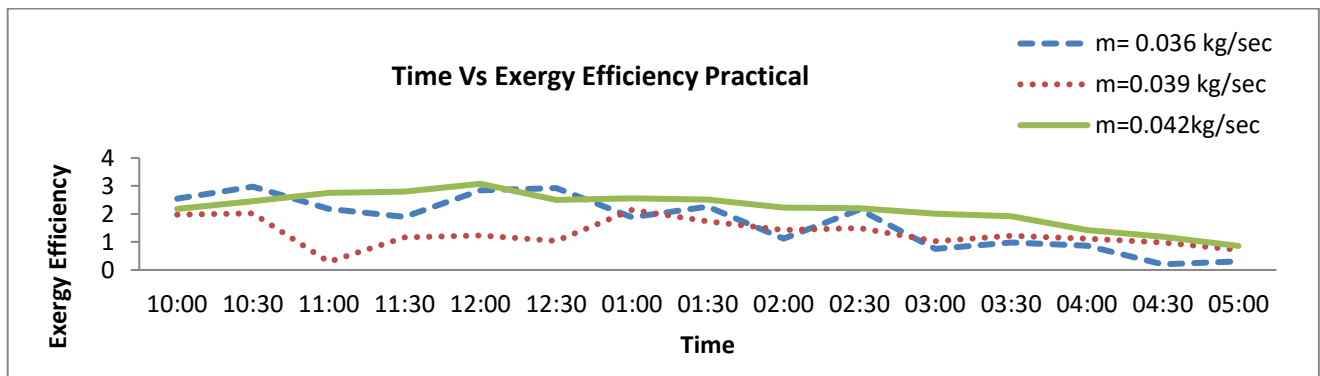


Figure 8 Plot of exergy efficiency (practical) V/s time (hr) with different mass flow rate.

As fig 8 depicts, practical exergy efficiency is higher at higher mass of flow rate. As mass flow rate , increases from (0.036 kg/s to 0.042 kg/s ) exergy efficiency also increases by 51%. Average practical (exergy efficiency) could be achieved by 1.724 % , 1.307 & 2.17 % at different (mass flow rate) of 0.036, 0.039 & 0.042 Kg/sec. Correspondingly.

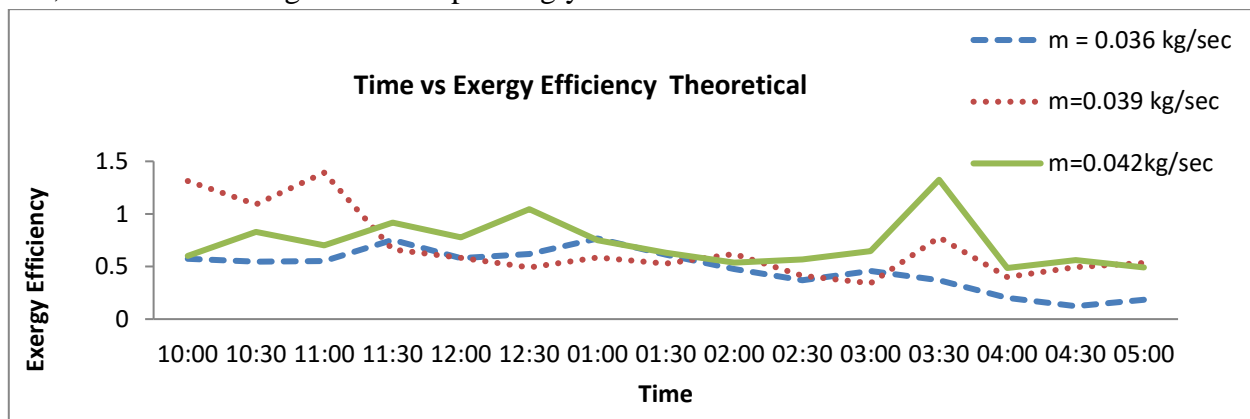


Figure 9 Plot of (exergy efficiency theoretical) V/s time Span (hr) with different mass flow rate

As fig 9 reflects, theoretical exergy efficiency is correspondingly higher at higher value of mass flow. At higher mass flow rate losses in exergy is reduced. As mass flow rate is enhanced from (0.036 kg/s to 0.042 kg/s ) exergy efficiency is also increases to 46%. The average practical (exergy efficiency) could find as (0.4785 %, 0.681 % & 0.7242 %) at mass flow rate (0.036 Kg/sec, 0.039 Kg/sec & 0.042 Kg/sec.) respectively.

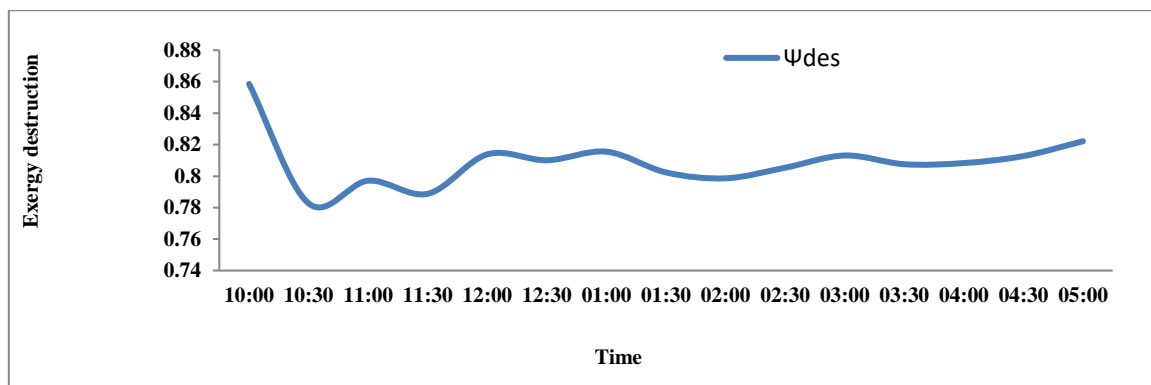


Figure 10 Plot (Exergy destruction) V/s time

Fig 10 shows the trend, exergy destruction v/s time of the day. The highest average (instantaneous destruction) found be 0.86 & overall average (destruction) is found 0.88.

## V. CONCLUSION

The presented mathematical model which is used as a tool to calculate or determine different incorporated heat transfer coefficients, which impacts on the STC performance. Through mathematical tool, thermal performance on STC over unlimited range of operating range such as (solar intensity & inlet air temperature) are trialed. Middling collector efficiency of 43.32 % & maximum (instantaneous thermal efficiency) approx 36.42 % is obtained. Exergy analysis Predicts maximum (exergy loss) & (exergy destruction) in the proposed STC. Average (exergy efficiency) of 0.74% is analyzed in the present study & the (average destruction) is about 0.88.

## REFERENCES

- [1] TERI, Energy and environment data directory and year book (TEDDY) 2013/2014. 28<sup>th</sup> ed. New Delhi: The Energy and Resources Institute; 2014.
- [2] Grag P, Energy Scenario and vision 2020 in india. J Sustain Energy and Environment 2012;3:7-17.
- [3] Ghosh D, Shukla P, Garg A, Ramana P.V. Renewable energy technologies for the Indian power sectors: mitigation potential and operational strategies. Renew sustain energy Rev 2002;6(6):481-512.
- [4] Panwar NL, Kaushik SC, Kothari S. Role of Renewable energy sources in environmental protection: a review. Renewable And Sustainable Energy Reviews2011; 15: 1513-24.
- [5] Srivastava Ravish and Rai Ajeet Kumar. Studies on the thermal performance of a solar air heater. International Journal of Mechanical Engineering and Technology. 2016;7(6):518-527.
- [6] Torres-reyes E, et al. A design method of flat plate solar collectors based on minimum entropy generation. Exergy 2001;1(1):46-52.
- [7] Dincer I, et al. Thermodynamic, exergy and environmental impact. Energy sources 2000;22:723-32.
- [8] Petela R. An approach to the exergy analysis of photosynthesis. solar energy2008;82:311-28.
- [9] Petela R. Exergy of undiluted thermal radiation. solar energy2003;74:469-88.

[10] M. Augustus Leon, S. Kumar. Mathematical modeling and thermal performance analysis of unglazed transpired solar collectors, Solar Energy 2007, 81: 62-75.  
 [11] Kalogirou, solar energy engineering: process and systems 2009; 121-180.  
 [12] Duffie JA, Beckman WA. Solar engineering of thermal processes. New York : 1974;17:79-80.  
 [13] Chamoli sunil, Exergy analysis of a flat plate solar collector, Journal of energy in south Africa 2003, 24:8-13.  
 [14] Karim Md.Azharul, et al. Performance investigation of a flat plate, v- corrugated and finned collectors. Energy 2006;31:452-70.  
 [15] Srivastava Ravish kumar and Rai Ajeet Kumar. Thermal performance investigation of a finned absorber plate solar air heater. International Journal of Mechanical Engineering and Technology. 2017; 8(6): 622-630.  
 [16] Srivastava Ravish kumar and Rai Ajeet Kumar. A review on solar air heater technology. International Journal of Mechanical Engineering and Technology. 2017; 8(7): 1122-1131.

**APPENDICES -**

<p><b>Nomenclature:</b>                  A Area (m<sup>2</sup>)                  C<sub>p</sub> Specific heat capacity of the fluid ( K j /Kg k)                  F' Finned collector efficiency factor                  F<sub>R</sub> Heat removal factor                  I<sub>T</sub> Incident Solar radiation (W/m<sup>2</sup>)                  U<sub>L</sub> Over all heat loss coefficient (W/m<sup>2</sup>-K)                  T Temperature (K)                  Q Heat transfer rate (Watt)                  D Hydraulic diameter (m)                  U Loss Coefficients(W/m<sup>2</sup>-K)                  T Temperature °K                  E,H, Value Contant (W/m<sup>2</sup>-K)                  h<sub>1</sub>, h<sub>2</sub>, h<sub>3</sub>, h<sub>c</sub> ,convective Heat transfer coefficient (W/m<sup>2</sup>-K)                  S Absorbed solar radiation (W/m<sup>2</sup>)</p>	<p>Re Reynolds's No.                  N<sub>u</sub> Nusselt No                  Pr Prandtl No                  L Collector length (m)                  W Collector width (m)                  s Depth of air channel (m)                  ṁ Mass flow rate (Kg/sec)                  h<sub>w</sub> Convective heat transfer due to wind.                  F Fin efficiency  <b>Greek symbols :</b>                  a absorptance                  η Efficiency                  τ Transmittance                  (τα) Transmittance-absorptance                  σ Stefan-Boltzman constant                  ε emittance                  μ Dynamic viscosity (Kg/m-s)                  k Thermal conductivity ( W/m-k)                  ψ Exergy</p>	<p><b>Subscripts:</b>                  a ambient                  o outlet .optical                  i inlet                  exp exponential                  p plate , petla                  c collector                  u useful                  f fin                  t<sub>h</sub> Thermal                  s Sun ,Depth of channel                  g Glass                  c Convective                  r Radiative                  t Total ,top                  b Back                  e End                  r Radiation                  abs Absorber                  conv Convective</p>
---	--	---

$\Delta T = (T_i - T_a)$	$F'_o = \frac{E}{[H + U_b(h_2 + h_r U_i) + U_i(h_r + h_3)]}$	$F_F = \frac{\tanh(mW_2)}{mW_2}$	$U_b = \frac{K}{l}$
$\varpi = [S - u_L(T_i - T_a)]$	$E = H + h_2 U_b$	$m = \sqrt{\frac{h_2}{k\delta}}$	$U_e = \frac{(UA)_{edge}}{A_c}$
$\Upsilon = \left[ 1 - \exp \left\{ -\frac{A_c u_L F'}{m C_p} \right\} \right]$	$H = (h_2 h_3 + h_2 h_r + h_3 h_r)$	$\eta_p = \frac{4T_a}{3T_s} + \frac{1}{3} \left( \frac{T_a}{T_s} \right)^4$	$A_c = s \times W$
$F_R = \frac{m C_p}{A_c u_L} \Upsilon$	$F_p = \frac{h_1}{h_1 + U_i}$	$h_w = 5.7 + 3.8 \times V$	$D = 4 \left[ \frac{W \times s}{2W} \right] = 2s$

**FLOW CHART:**

