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Performance Analysis of a Parabolic Trough Collector with Modified Receiver

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ABSTRACT

Solar energy is the primary source of all types of renewable energy, from which all types of energy are derived. Solar constant on the earth's surface is 1.357 kW/m^2. The current non-conventional sources of energy are satisfying only 6.9% of the total potential of renewable sources in India. Parabolic trough collector (PTC) is preferred to achieve high temperature. It is a low cost implementation of concentrated solar power technology, in which incident solar rays reflected and concentrated onto a receiver tube filled with a heat transfer fluid (HTF) by using parabolic trough reflector. Improvement of parabolic trough solar collector system (PTSC's) can be achieved through the design criteria, process parameters, type of technology, concentration ratio, solar intensity, and flow rate, etc. Typically, the concentration ratio ranges from 30 to 80, depending on the radius of the parabolic solar energy concentrator.The solar receiver is the key component of a PTSC's, which plays a prominent role in the gross system efficiency. In order to improve the efficiency of the system heat gain of the system should increase. The useful heat gain of the PTC system is directly dependent on the heat loss from the receiver at its operating temperature. The receiver is designed to improve the energy conversion efficiency of concentrated sunlight to the thermal energy of HTF inside the absorber tube. Evacuated glass tube with the selective coating is employed to control radiative and convective heat losses. An increase in the efficiency of the PTSC's is done by adopting a modified evacuated tube and selecting efficient HTF. It creates a counter flow of HTF by inserting copper tube inside the evacuated tube, which will support to enhance heat flux handling capacity of the system as it has a large effect on overall performance. The performance of PTC hot fluid generation system is determined by obtaining the values of collector instantaneous efficiency, overall thermal efficiency, and the hourly thermal efficiency for different combinations of solar intensity of radiations, ambient temperature and the inlet HTF temperature. Other than above cited objectives, the current work includes detailed thermal model of PTC's modified receiver by studying the already developed thermal models for various receivers. During thermal analysis of the collector receiver, all modes of heat transfer are considered.

***Keywords*— Concentrated solar power, evacuated tube, heat flux, heat transfer fluid, parabolic trough collector, thermic fluid.**

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I. INTRODUCTION

The greenhouse gas (GHG) concentration in 2010 was 39% above the pre-industrial level. Therefore, the warming trend has increased significantly over the last 50 years. Still GHG emissions associated with the provision of energy services are the major cause of climate change. Both world total final energy consumption and world CO_2 emissions have doubled in the last 35 years. The limited supply of fossil hydrocarbon resources and the negative impact of CO_2 emissions on the global environment dictate increased usage of renewable energy resources [1].

India is one of the few countries with long days and plenty of sunshine, especially in the Thar Desert region. On average, the country has 300 sunny days per year and receives an average hourly radiation of $200 MW/km^2$. The India Energy Portal estimates that around 12.5% of India's land mass, or 413,000 km^2, could be used for harnessing solar energy. India receives solar energy equivalent to over 5000trillionkWh/year, which far more than the total energy consumption of the country. The maximum power production of the solar energy is from the state of Gujarat with 654.8MW i.e. 66.4% contribution. The second best power producingstate is Rajasthan with 197.5MW with a 20.5% contribution [2].

The interest in solar concentrating technology was negligible for almost 60 years. However, in reaction to the oil crisis of the seventies, international attention was drawn to alternative energy sources to supplement fossil fuels, and the development of a number of parabolic-trough systems was sponsored [3].

A. Fernandez-Garcia. et al. [3] paper present an overview PTSC's that have been built and marked during past century as well as currently under development.H.P. Garg.et al. and S. P. Sukhatme[5], [6], gives detail study about solar radiation, sun-earth geometry, different types of collectors, solar energy principlesand various application of solar energy.Govindarajet. al. and Amirtham et. al. [7], [8], The presented work is based on the experimental study to investigate the performance of the PTC with a storage unit. A. S. Pidaparthiet. al. [9], The 3 MW PTC field built by Abengoa, is the first parabolic trough power plant in India. Plant is equipped with the HTF and sun tracking system. K. Senthil et al. [10], gives the theoretical performance study an existing PTC systemwith the change in parameters, to observe variation of the system efficiency.Alok Kumar and AvadheshYadav, et al.report presents the comparative study of the instantaneous efficiency of the system with different types of receiver covers and with the various reflectors by experimentally and mathematically.

From references [13]-[18], summarises different HTF candidates used and under development in recent years, (liquid metals, therminol oil, water, molten salt, ionic liquid, sulphur and CO_2) their comparative study is done with respect to their, operation temperature, system operation, storage concept, safety aspects, stability, thermal properties with respect change in temperature and cost. References [19]-[24] present study and analysis of various heat losses from receiver tube and from the PTSC's. Also numerical study and investigation of parabolic trough receiver performance with different receiver arrangement presented. A detailed study of different thermal models for various receiver arrangements with considering all modes of heat transfer presented.

PTSCs focus direct solar radiation (Direct Normal Irradiance (DNI)) onto a focal line of the collector axis. A receiver tube coated with the solar radiation absorbing material, usually covered with a totally or partially vacuumed glass tube to minimize the heat losses, with a fluid flowing inside that absorbs concentrated solar energy from the tube walls and raises its enthalpy is installed in this focal line. The collector provided with one-axis solar tracking to ensure that the solar beam falls parallel to its axis. PTSCs can only use direct solar radiation the fraction of solar radiations which are not deviated by clouds, fumes or dust in the atmosphere and that reaches the Earth's surface as a parallel beam.Typically, the concentration ratio range is from 30 to 80 depending on the radius of the parabolic trough concentrator. The working fluid can reach a maximum temperature up to 400°C, depending on the concentration ratio, solar intensity, working fluid flow rate and other parameters. Hence, such collectors are an ideal device for power generation and/or water desalination applications [4].

II. PTSC SYSTEM DESCRIPTION

A. *Experimental set-up*

PTSC's is concentrating type solar collector system. The systemmade by bending a sheet of stainless steel into a parabolic shape by using PARABOLA-2 software for locating the co-ordinate and focal point accurately. A modified evacuated (vacuum is created between the absorber coated glass and outer glass cover) receiver tube to reduce heat losses, is placed along the focal lineof the receiver (Fig. 1).

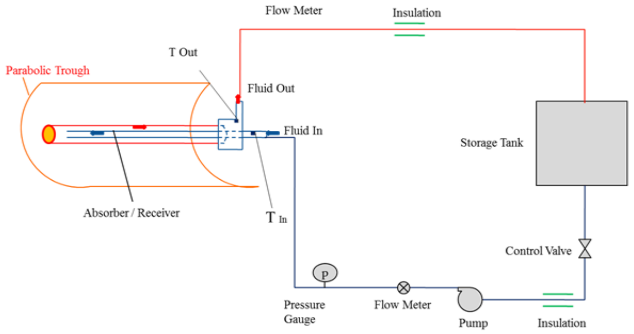


Fig.1 A line diagram of experimental set-up of PTSC's

The storage tank in the experimental setup is filled with the HTF, which is a working fluid. HTF is circulated to the receiver tube with the help of a pump for changing the various mass flow rates.During circulation, it gains heat in the receiver tube while coming back in the storage tank and recirculated throughout the whole day. The temperature at the inlet and outlet is measured by the thermocouple. A single axis manual solar tracking system is used for tracking of the sunon an east–west direction by keeping the focal axis fixed in N-S direction; also, readings taken ata fixed tilt angleof the collector facing towards the south direction. The advantages of the tracking mode areto increase collector performance during the early and late hours ofthe day by reducing a large incidence angles (cosine loss) and concentrating the solar rays by always facing the aperture towards the sun at noontime.

B. *Modified Evacuated Receiver Tube*

The solar receiver is the key component of a PTSC's, which plays a prominent role in the gross system efficiency. In order to improve the efficiency of the system heat gain of the system should increase. The useful heat gain of the PTC system is directly dependent on the heat loss from the receiver at its operating temperature. The receiver is designed to improve the energy conversion efficiency of concentrated sunlight to the thermal energy of HTF inside the absorber tube. Evacuated glass tube with the selective coating employed to control radiative and convective heat losses. Normally receivers of the PTSC's are single pass flow design, but in this system by inserting, the copper tube inside the evacuated tube creates a counter flow of HTF.

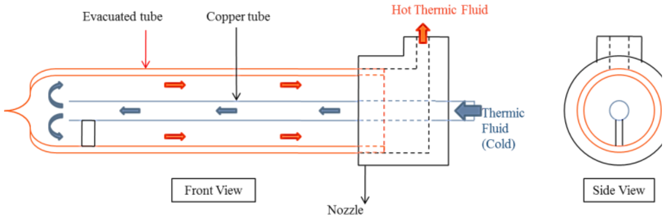


Fig. 2Aschematic diagram of modified evacuated receiver tube

Which has significant advantages like uniform temperature difference between the two fluids minimizes the thermal stresses, inlet temperature of the cold fluid can approach outlet temperature of hot fluid, and uniform temperature difference produces a uniform rate of heat transfer. It will support to enhance heat flux handling capacity of the system as it has a large effect on overall performance.

TABLE I

SPECIFICATION OF EVACUATED TUBE

C. *Selection of The HTF*

Heat carried from the solar receiver to the heat storage tank by HTF. HTF improves the heat flux handling capacity of the system and thermal storage capacity of the system. For selection of the HTF fluid as per required application, following criteria consider for selection of an optimumHTF.

1) Temperature range
2) Specific heat
3) Thermal conductivity
4) Viscosity
5) Density
6) Environmental impact
7) Toxicity
8) Flash point
9) Corrosiveness
10) Compatibility
11) Stability
12) Cost

DOWTHERM* A heat transfer fluid is a eutectic mixture of two very stable organic compounds, biphenyl ($C_{12}H_{10}$) and diphenyl oxide ($C_{12}H_{10}O$). DOWTHERM A fluid is used in systems employing in liquid phase in the temperature range 60°F to 750°F (15°C to 400°C).It is stable, does not decompose readily at high temperatures, and can be used effectively in either liquid or vapor phase systems. The low viscosity throughout the entire operating range results in efficient heat transfer; start-up and pumping problems are minimized. The fluid is noncorrosive to common metals and alloys.

TABLE III

SPECIFICATION OF DOWTHERM* A HTF

Temperature applicationrange	60°F to 750°F (15°C to 400°C) Liquid phase
	Maximum recommended film temperature is 800°F (425°C).
Freezing point	53.6°F (12°C)
Pressure range is from	Atmospheric to 152.5 psig (10.6 bar)
High flash point	236°F (113°C) (SETA)
Fire point	245°F (118°C)
Autoignition temperature	1110°F (599°C)(ASTM)
Lower flammable limit	0.6% (volume) at 175°C
Upper limit	6.8% (volume) at 190°C
Critical Temperature	927°F
Critical Pressure	30.93 atm

III.PERFORMANCE TESTING

The performance of the system is determined by obtaining the values of collector instantaneous efficiency, overall thermal efficiency and the hourly thermal efficiency for different combinations of solar intensity of radiations, ambient temperature and the inlet heat HTF temperature. All parameters are measured as a function of time over one hour period under steady state conditions. The steady state equation describes the energy balance Equation for system [6]:

$$dq_u = [I_b r_b (w - D_0)\rho\gamma(\tau\alpha)_b + I_b r_b D_0 (\tau\alpha)_b \\ - U_L \pi D_0 (T_p - T_a)]dx$$

Where,

dq_u = Useful heat gain rate for a length dx

ρ = Specular reflectivity of the concentrator surface

γ = Intercept Factor = 0.90

$(\tau\alpha)_b$ = Average value of the transmissivity - absorptivity product for beam radiation

U_l = Overall loss coefficient

T_p = Local temperature of the absorber tube

T_a = Ambient temperature

Tube structure		All- glass double tube co-axial structure
Glass material		Borosilicate 3.3 glass
Outer tube diameter x inner tube diameter x tube length		58mm x 47mm x 1800mm
Glass thickness		2 mm
Pressure		0.6 Mpa
Absorber coating	Coating material	Cu/SS-AIN
	Sediments method	Three targets magnetron sputtering plating
	Absorptivity	α ≥ 0.93 (AM 1.5)
	Emmitance	ε ≤ 6.5% (80°C ± 5°C)
Vacuum degree		P ≤ 5x10-3 pa
Transmittance of glass tube		T ≥ 0.89
Thermal conductivity at 90 °c		1.2 W/mK

The first Term of the Right hand side in above Eq. ($I_b r_b (w - D_0)\rho\gamma(\tau\alpha)_b$) represent the incident beam radiation absorbed in the absorber tube after reflection and the second term ($I_b r_b D_0 (\tau\alpha)_b$) represent the absorbed incident beam radiation which falls directly on the absorber tube. The second term is small in comparison with the first, but cannot be ignored when the concentration ratio is small. The third term ($U_l \pi D_0 (T_p - T_a)$) represents the loss by convection and re-radiation.

D. *Concentration Ratio (C)*

Concentration ratio of the collector is given by:

$$C = \frac{Effective\ aperture\ area}{Absorber\ tube\ area} = \frac{(W - D_{po})L}{\pi D_{po} L}$$

E. Absorbed Flux (S)

Absorbed fluxby the receiver tubeis given by:

$$S = I_b r_b \rho\gamma(\tau\alpha)_b + I_b r_b \left(\frac{D_{po}}{(w - D_{po})}\right)(\tau\alpha)_b$$

F. Collector Efficiency Factor (F')

Collector efficiency factor of the system is given by:

$$F' = \frac{\frac{1}{U_L}}{\frac{1}{U_L} + \frac{D_{po}}{h_f \text{x} D_{pi}}\left[\frac{D_{po}}{2\ \text{x} K_f} \text{x}\ ln\frac{D_{po}}{(D_{pi})}\right]}$$

G. Heat Removal Factor (F_r)

$$F_r = \frac{(\dot{m}\ \text{x}\ Cp)}{(\pi\ \text{x} D_{po} \text{x} U_L\ \text{x}\ L)}$$

H. Useful Heat Gain (Q_u)

$$Q_u = F_r(W - Do)L\left[S - \frac{U_L}{C}(T_{fin} - T_a)\right]$$

I. Instantaneous Efficiency Of Collector (N_i)

$$n_i = \frac{Q_u}{[(I_b \text{x} r_b) + (I_d\ \text{x} r_d)]WL}$$

J. Instantaneous Efficiency Of Collector (N_{ib})

Instantaneous efficiency (n_{ib}) is calculatedbased on the beam radiation by neglecting the reflected radiation.

$$n_{ib} = \frac{Q_u}{(I_b \text{x} r_b)WL}$$

IV. THERMAL ANALYSIS

I. *A*

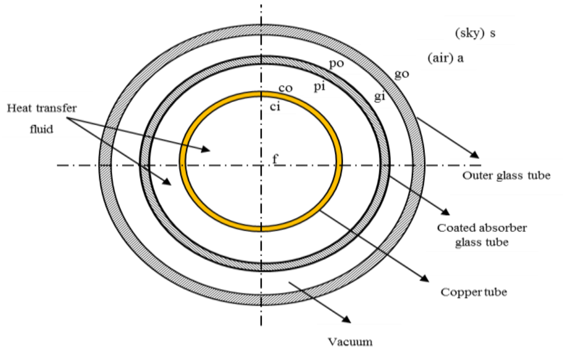


Fig. 3 Nomenclature

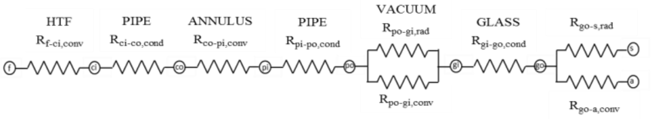


Fig. 4 Thermal Resistance Model

The Energy Balance equations are determined by considering that the energy is conserved at each surface of the energy is conserved at each surface of the receiver cross-section [19].

$$q_{f-ci;conv} = q_{ci-co;cond} = q_{co-pi;conv} = q_{pi-po;cond}$$

$$q_{po;SolAbs} = q_{po-gi;conv} + q_{po-gi;rad} + q_{pi-co;cond}$$

$$q_{po-gi;conv} + q_{po-gi;rad} = q_{gi-go;cond}$$

$$q_{gi-go;cond} + q_{po;SolAbs} = q_{go-a;conv} + q_{go-s;rad}$$

$$q_{Heatloss} = q_{go-a;conv} + q_{go-s;rad}$$

K. Convection Heat Transfer between the HTF and the Receiver Pipe:

$$Q_{f_{in}-ci;\,conv} = h_{f\,ci}\pi D_{ci}(T_{ci} - T_{f_{in}})$$

$$h_{f\,ci} = \frac{Nu_{D_{ci}}\ \text{x}\ K_f}{D_{ci}}$$

Turbulent and transitional cases occur at Reynolds number > 2300

$$Nu_{D_{ci}} = \frac{\frac{f_{ci}}{8}\text{x}\left(Re_{D_{ci}} - 1000\right)Pr_f}{1 + 12.7\sqrt{f_{ci}/8}(Pr_f^{2/3} - 1)}\left(\frac{Pr_f}{Pr_{ci}}\right)^{0.11}$$

For $0.5 < Pr_f < 2000$ and $2300 < ReD_{ci} < 5\text{x}10^6$

L. Conduction heat transfer through the receiver pipe wall:

$$q_{ci-co;\,cond} = \frac{2\pi k_{pipe}(T_{ci} - T_{co})}{ln\left(\frac{D_{co}}{D_{ci}}\right)}$$

M. Heat transfer from the receiver pipe to the glass envelope:

Heat transfer between the receiver pipe and the glass envelope occur by convection and radiation. Convection heat transfer depends on the annulus pressure.

1) *Convection Heat Transfer:* When annulus is under vacuum (pressure < 0.013 Pa)), the convection heat transfer between the receiver pipe and glass envelope occurs by free-molecular convection and is given by:

$$q_{po-gi;conv} = \pi D_{po} h_{po-gi}(T_{po} - T_{gi})$$

Where,

$$h_{po-gi} = \frac{k_{std}}{\frac{D_{po}}{2\ ln\left(\frac{D_{gi}}{D_{po}}\right)} + b\lambda\left(\frac{D_{po}}{D_{gi}} + 1\right)}$$

For $Ra_{D_{gi}} < \left(D_{gi}/(D_{gi} - D_{po})\right)^4$

2) *Radiation Heat Transfer:* Theradiation heat transfer between receiver pipe and glass envelope is estimated with the following equation:

$$q_{po-gi;rad} = \frac{\sigma\pi D_{po}(T_{po}^4 - T_{gi}^4)}{\left(\frac{1}{\varepsilon_{po}} + \left(\frac{(1-\varepsilon_{gi})D_{po}}{\varepsilon_{gi}D_{gi}}\right)\right)}$$

3) *Heat Transfer from the glass envelope to the atmosphere:* The heat transfer from the glass envelope to the atmosphere occurs by convection and radiation. Depending on whether there is wind, the convection will either be forced or natural. Radiation heat loss occurs due to the temperature difference between the glass envelope and sky.

N. Heat Transfer from the glass envelope to the atmosphere:

The heat transfer from the glass envelope to the atmosphere occurs by convection and radiation.

1) *Convective heat transfer:* The convection heat transfer is determined by knowing the Nusselt number, which depends on whether the convection heat transfer is natural (no wind) or forced (wind case).

$$q_{go-a;\,conv} = h_{go-a}\pi D_{go}\left(T_{go} - T_a\right)$$

$$h_{go-a} = \frac{k_{air}}{D_{go}} Nu_{D_{go}}$$

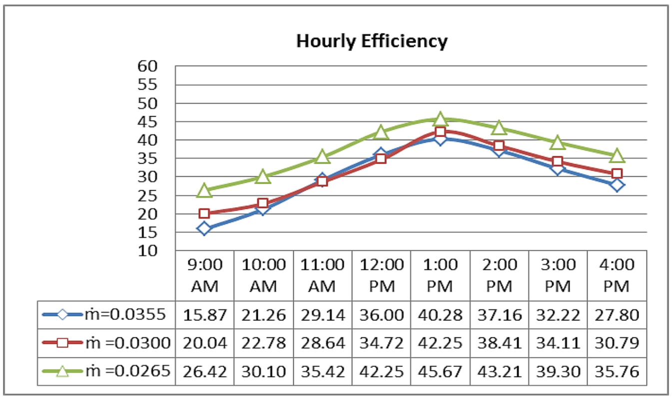
When there is no wind, the convection heat transfer from the glass envelope to the environment occurs by natural convection

2) *Radiation heat transfer:* The In this case, net radiation transfer between the glass envelope and sky is given by:

$$q_{go-s;\,rad} = \sigma\varepsilon_{go} D_{go}\left(T_{go}^4 - T_s^4\right)$$

V.RESULT & DISCUSSION

The study of above-mentioned system is carried out from 9.00AM to 4.00PM in a couple of months, during which the solar radiation varied between 400M/m^2 and 1000M/w^2. The flow rate of water and HTF are chosen as 0.02 and 0.05kg/s respectively.

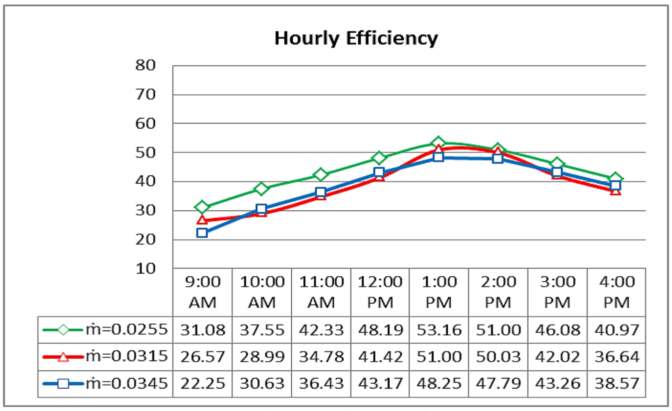


	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM
ṁ=0.0355	15.87	21.26	29.14	36.00	40.28	37.16	32.22	27.80
ṁ =0.0300	20.04	22.78	28.64	34.72	42.25	38.41	34.11	30.79
ṁ =0.0265	26.42	30.10	35.42	42.25	45.67	43.21	39.30	35.76

Fig. 5Variation of hourly efficiency for day hours.

Fig. 5 shows the hourly efficiency variation Vs. day hours for system facing towards south.

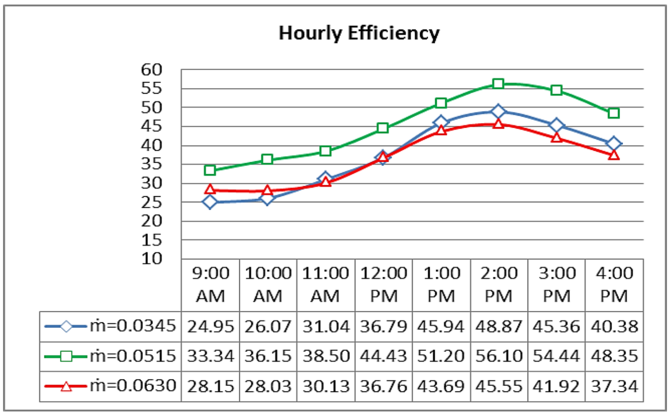
It results efficiency of the system increases drastically up to 1.00PM and then decreases slowly. It is also observed that at low mass flow rate (ṁ = 0.0265) efficiency is maximum (45.67%) and it decreases with increasing mass flow rate.



	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM
ṁ=0.0255	31.08	37.55	42.33	48.19	53.16	51.00	46.08	40.97
ṁ=0.0315	26.57	28.99	34.78	41.42	51.00	50.03	42.02	36.64
ṁ=0.0345	22.25	30.63	36.43	43.17	48.25	47.79	43.26	38.57

Fig. 6 Variation of hourly efficiency for day hours.

Fig. 6 shows the hourly efficiency variation Vs. day hours for manual tracking of sun E-W direction by keeping focal axis in N-S plane. It is observed that at low mass flow rate (ṁ =0.0255) efficiency is maximum (53.67%) and it decreases with increasing mass flow rate. Comparison of fig. 5 and fig. 6 is shows that system efficiency is increased by tracking the sun after interval of 1hr. Also overall day efficiency of the system is increased from 37.26% for south facing to 43.79% by manual tracking for the same mass flow rate (ṁ = 0.0255).

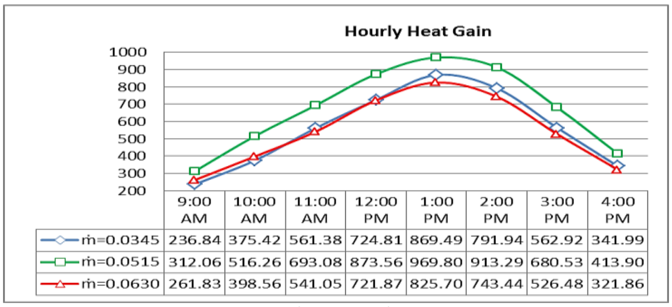


	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM
ṁ=0.0345	24.95	26.07	31.04	36.79	45.94	48.87	45.36	40.38
ṁ=0.0515	33.34	36.15	38.50	44.43	51.20	56.10	54.44	48.35
ṁ=0.0630	28.15	28.03	30.13	36.76	43.69	45.55	41.92	37.34

Fig.7 Variation of hourly efficiency for day hours.

Fig. 7 shows the hourly efficiency variation Vs. day hours for manual tracking by using HTF (Dowtherm A). It is observed that at optimum mass flow rate (ṁ = 0.0515) efficiency is maximum (56.10%) and it decreases with increasing and decreasing mass flow rate. As the specific heat capacity of the HTF is increases with increasing temperature, it results that maximum efficiency is at 2.00PM and decreases slowly thereafter.

From the experiment it is clear that heat gain, inlet and outlet temperature difference and specific heat of the HTF is important parameters that will affects the efficiency of the system. Maximum temperature difference and heat gain is observed in fig.7 and fig.8, which will increase the system efficiency.



	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM
$\dot{m}=0.0345$	236.84	375.42	561.38	724.81	869.49	791.94	562.92	341.99
$\dot{m}=0.0515$	312.06	516.26	693.08	873.56	969.80	913.29	680.53	413.90
$\dot{m}=0.0630$	261.83	398.56	541.05	721.87	825.70	743.44	526.48	321.86

Fig. 8Heat gain of the HTF for day hours.

VI.CONCLUSION

From above experimentation, it is found that system with hourly manual tracking and HTF gives better results than south facing. In addition,increase of specific heat with increase in temperature of HTF will help to increase mass flow rate for HTF and operational temperature range of working fluid, which will increase the system efficiency. There is scope for improvement to avoid heat losses by improving storage system and by using automatic solar tracking system.

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