Estimation of Changes in the Effectiveness of Parabolic Trough Solar Collector Due to Dust Particles

Khushaboo Singh[1], Pooran Meena[2],
[1]PG Student, *Mechanical Engineering Department, MBM Engineering,JNVU University-Jodhpur, India*
[2]*Professor, Mechanical Engineering Department, MBM Engineering,JNVU University-Jodhpur, India*

Abstract

Present work provides the insight of dust particle effect on the overall efficiency of collector-receiver tube water heating used in the power plant. Since the characterisation of dust particles deposited on collector plate and its controlled effect on plant efficiency has limitation for field scale study, we have proposed a new methodology to carry lab scale experimentation to characterise dust concentration followed by simulation to estimate the plant performance. Present study showed the effect of dust with respect to the clean surface efficiency. It should be noted that thermal efficiency of the system against clean surface is 20.59% and due to dust deposition efficiency of system reduced to 8.91 % at dust concentration 26.637 x 10-6gm/m2. Comparatively change in maximum thermal efficiency is reduced upto 56.726 %. Efficiency curve with dust concentration suggests that cleaning of the collector should be done in an optimised time interval rather than fixed time interval for better efficiency.

Keywords - *Solar radiation, Solar parabolic trough concentrator, Image J, Plot Digitizer, Optical properties.*

I. INTRODUCTION

In modern world, energy is primary requirement for human culture. All the energy sources we are using today can be classified into two groups; renewable and non-renewable. Renewable and non-renewable energy sources can be used to produce secondary energy sources as electricity. The release of large amounts of waste heat from power plants has caused thermal pollution in lakes and rivers leading to the destruction of many forms of plant and animal life. In the case of nuclear power plants, there is also concern over the possibility of radioactivity being released into the atmosphere and long term of problems of disposal of radioactive wastes from these plants.

So, solar energy is alternative source of energy. A worthy investment option is concentrating solar power (CSP) technology which has the capacity to provide for about 7% of the total electricity needs projected for the world by 2030 and 25% by 2050 (Izquierdo et al., 2010).

The performance of a parabolic trough solar collector measured experimentally differs slightly from the simulation results due to inaccurate prediction of absorbed solar energy. The amount of absorbed energy of such systems mainly depends on various parameters like reflector/collector, absorptivity of absorber tube and transmissivity of glass cover of absorber tube etc. The optical properties of these systems are strongly affected by the dust deposition Singh et al., [1]. Solar absorption and thermal power production are strongly related to the optical properties of the collectors (Yaghoubi et al., 2011 and Sahin, A.D., 2007) [2,3].

Several authors have tried to quantify the effect of dust deposition on flat plate collectors at field scale as well as in laboratory setups with some assumptions. Garg (1974) investigated the effect of dust on the transmittance of solar radiation through various inclined glass plates and plastic film [4]. Sayigh et al., (1985) observed 64, 48, 38, 30 and 17% reduction in the transmittance of the glass plates after 38 days of exposure to the environment with tilt angles of 0, 15, 30, 45 and 60° [5]. El-Shobokshy and Hussein (1993) investigated the effect of dust on the performance of photovoltaic cells [6]. Goossens and Van Kerschaever (1999) investigated the effect of wind velocity and airborne dust concentration on the drop of photovoltaic (PV) cell performancecaused by dust accumulation on such cells. Performance drop and I-V characteristics were investigated at four wind velocities and four dust concentrations [7]. Hegazy (2001) investigated dust accumulation on glass plates with different tilt angles and associated reductions in solar transmittance experimentally over a period of one year under the climate conditions of the Minia region, central Egypt. His results show that the fractional reduction in glass normal transmittance depends strongly on dust deposition in conjunction with plate tilt angle, as well as on the exposure period and site climate conditions [8]. El-Nashar (2009) studied the seasonal effect of dust deposition on a field of evacuated tube collectors of a solar desalination plant. The system is located near the city of Abu

Dhabi, UAE, and the results are therefore relevant to this region. It was found that dust deposition can cause a monthly drop in glass tube transmittance of 10–18%.The drop in transmittance of the glass tubes due to dust deposition can cause a large drop in plant production [9].

Although various studies have been performed to study dust effect on the performance of different solar systems, very limited published studies on dust effects are available for parabolic trough collectors (PTC) of solar thermal power plants. Deffenbaugh et al., (1985) studied the effect of dust and found that any long term thermal performance should include a factor to account for degradation effects on the optical surface as a result of local dust and dirt accumulation [10]. Vivar et al., (2010) conducted experiments at different site of IES-UPM in Madrid and found that losses due to dust accumulation in ISC(short circuit current) of about 14% on average in three different tests. Moreover, some concentrators reached losses up to 26% when the system was soiled for 4 months of exposure. He found that Concentrating Photovoltaic systems with high concentration ratio are more sensitive to dust [11]. Nikinia et al., (2013) observed that an amount of 1.5 gm/m^2 dust can reduce the instantaneous performance of collectors up to 60% and the average performance during the dust deposition up to 37% [12].

In this paper effect of dust on the solar parabolic trough collector is determined by using artificially created environmental dust. Reduction at the receiver surface is obtained experimentally which served as an input for further processing and software handling. Simulations are done by using ANSYS 13.0 version. FVM based solver using fluent module is used to simulate the heat transfer to water in order to rise its temperature. Equations used in the calculation of losses during the processes of incident rays and up to receiver end are based on Tzivanidis et al., (2015) [13].

II. MATERIALS AND METHODOLOGY

This experiment has been carried out in Jodhpur which is blessed with high value of irradiance; latitude and longitude at the place of experiment were found to be 26.23^o N and 73.02^o E respectively. First of all we have taken an industrial grade of Kaolinite powder clay as a dust and it is deposited on the mirror slices of dimension (75mm ×25mm) for a fixed time intervals. We have taken six mirror sample of different dust deposition. Dust is deposited by means of blower. For this purpose some quantity of dust was kept at the bottom surface of a confined box with circular holes to blow the air dust in to the artificial environment Mirror stripes were placed at an angle of 6o from the main stream of dust air. Dust deposition assembly is shown in fig.1.

The blower used to provide fixed dusty air velocity. The glass stripes were deposited by means of blower air for 1, 2,3,4,5, and 6 min respectively. So, six samples were obtained of different dust deposition concentration

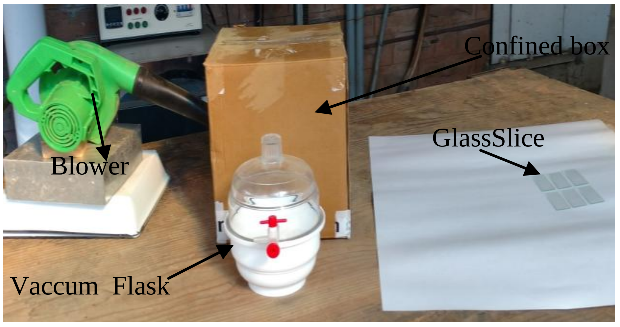


Figure 1: Dust deposition assembly

After collecting different dust samples, we have taken these samples under the optical microscope and found the images of dust particles (accumulated particles) by optical zooming of 50 times of their actual size, after that these images are carried out into the image processing software Image J to study the particle topology along with its particle count in order to derive the ways dust concentration on each samples have been determined. Additional software Plot digitizer is used to convert particle data into concentration values.

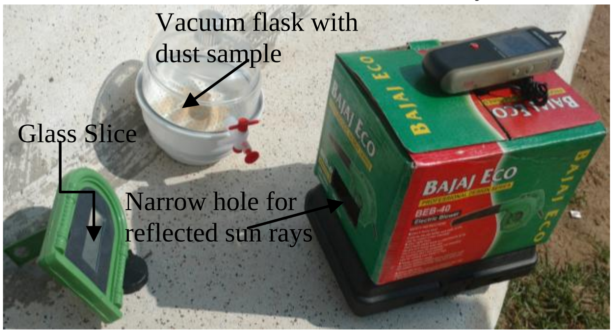


Figure 2: Reflectivity measurement arrangement

In order to assess the effect of dust deposition on the reduction of reflectivity of the sample impregnated with dust particle at the surface, we have designed an assembly shown in figure 2. Assembly consist of close box open at one side by a narrow hole only for allowing reflected sun ray and obstructing the diffuse radiations, a pyranometer and dust sample slice. We have kept the samples synchronised with latitude of Jodhpur and placed the box such that the sun rays after reflection from the sample goes into the box through the open portion of box where pyranometer kept as shown in fig.2 is used to record the incident irradiation value projected on it. In this way reduced reflection was determined w.r.t. different dust deposition.

III. SIMULATION CASE SETUP

. Once the experimental data is obtained for the reduced irradiation, it is used as an input for simulation. Simulation setup consists of a parabolic trough and a single glass tube receiver with no vacuum envelop as shown in fig. Length of receiver tube is taken as 5.78 m, Aperture of parabolic trough is taken as 5 m, Tube internal and external diameters are 6.6 cm and 7.0 cm respectively. Running fluid in tube is considered as air with Thermal conductivity of 0.0242 W/m-K, specific heat of 1006.43 J/Kg-K and density of 1.225 Kg/m^3. Material for receiver tube is taken as glass and trough material is Aluminium with thermal conductivity of 202.4 W/m-K, Specific heat of 871J/Kg-K and density of 2719 Kg/m^3. Trough direction was aligned with latitude and longitude of Jodhpur. Incident irradiation values are put as a parallel rays after computing from the actual incident irradiation on the day of 28 August 2016, 2:30 PM minus the losses computed. After incorporating all the losses, trough surface in simulation is assumed to be ideal reflective surface. Air inlet at the receiver has the temperature of 25^o C. Solar loading is applied in the simulation and energy equation is in on mode for the calculation. Set up for simulation is shown in figure 3. Equation of curvature for trough surface can be given by equation.

$$y = \frac{1}{4f} x^2$$

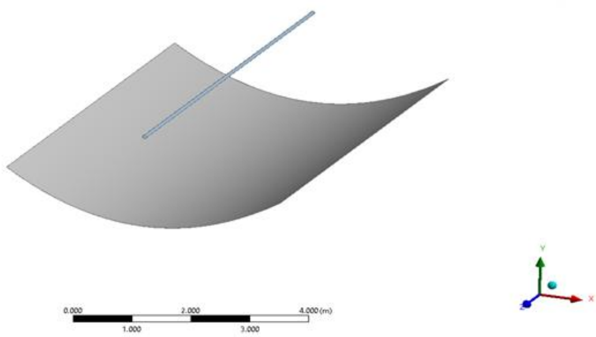


Figure 3: Simulation setup for numerical solution

A. *Data Processing:*

In this part the basic mathematical equations used for the analysis of Parabolic Trough Systems are given. PTC utilize only direct radiation of the sun. Solar energy in trough aperture is given by Eq. (3.1) and the useful energy can be calculated by Eq. (3.2)

$$Qa = Aa \cdot Gb, \quad (3.1)$$

$$Qu = m \cdot cp \cdot (Tout - Tin), \quad (3.2)$$

The thermal efficiency of collector is calculated as:

$$\eta = \frac{Q_u}{Q_a}, \quad (3.3)$$

Thermal losses of the collector can be calculated by many ways, by using different reference temperatures. These are:

$$Q_{loss} = U \cdot Aro \cdot (Tr - Tam), \quad (3.4)$$

$$Q_{loss} = A_{co} \cdot h_{ca} \cdot (T_c - T_{am}) + \varepsilon_c \cdot A_{co} \cdot \sigma \cdot (T_c^4 - T^4_{am}), \quad (3.5)$$

$$Q_{loss} = \frac{\sigma \cdot A_{ro} \cdot (T_c^4 - T_{am}^4)}{\frac{1}{\varepsilon_r} + \frac{1-\varepsilon_c}{\varepsilon_c}}, \quad (3.6)$$

The convection coefficient between pressurized water and receiver is an important parameter which affects the efficiency of the system. The theoretical calculation of this is done by calculating the Nusselt number. For laminar flow inside the tube, which means that the Reynolds number is lower than 2300; the mean Nusselt number is given by the Eq. (3.7):

$$Num = 3.66 + \frac{0.0668.Re.Pr.D_{ri}/L}{1+0.04.(Re.Pr.\frac{D_{ri}}{L})^{2/3}}, \quad (3.7)$$

This equation has the assumption of an isothermal tube which is not quite accurate under our circumstances but it is a very close approximation The Nusselt number is correlated with the convection coefficient according to the Eq. (3.8):

$$Num = \frac{h.D_{ri}}{k}, \quad (3.8)$$

It is essential to calculate the equation of the Reynolds number. This number is determined by the flow conditions (temperature and velocity) and geometry. Eq. (3.9) presents Reynolds number for the tube internal flow:

$$Re = \frac{4.\dot{m}}{\pi.D_{ri}.\mu}, \quad (3.9)$$

Eq. (3.10) presents the way that the convection coefficient is calculated.

$$h_w = \frac{Q_u}{(\pi.D_{ri}.L).(T_r - T_{fm})}, \quad (3.10)$$

IV. RESULT AND DISCUSSION

A. *Particle Concentration Measurement*

At first the images acquired from confocal microscope are analysed using plot digitizer to correlate the pixel data to spatial data, image quality acquired was 3136 × 2022 pixels. Resolution is found to be 7.028754 micron/pixel as can calculated using data available in fig.4 by dividing the scaled length (mm) to the pixel length (pixels).

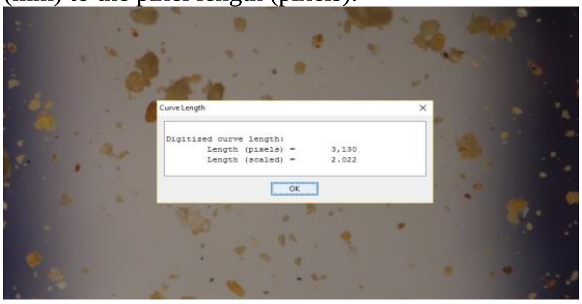
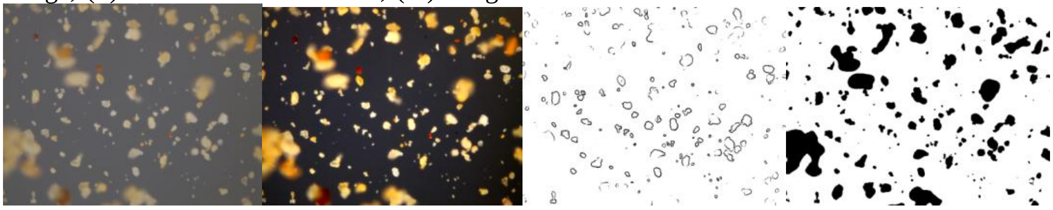


Figure 4: Pixel to micron relation as in plot digitizer

Next attempt is to quantify the concentration of dust particles in each slab by image processing using ImageJ software. Typical steps involved are (i) import image, (ii) Remove artefacts/noise, (iii) image enhancement, (iv) segmentation using threshold value of grey value based on histogram after that Data acquisition. Some typical steps involved in image processing are shown in fig.5



(i) (ii) (iii) (iv)

Figure 5: Different image processing steps involved in Image J software

Once the data is processed, particle size distribution and concentration can be derived as in fig. 6. It should be keep in mind that area calculated using image processing provides the projected area of 3-D particle in 2-D plane which is required for the calculation of exposed area for reflectivity of the surface.

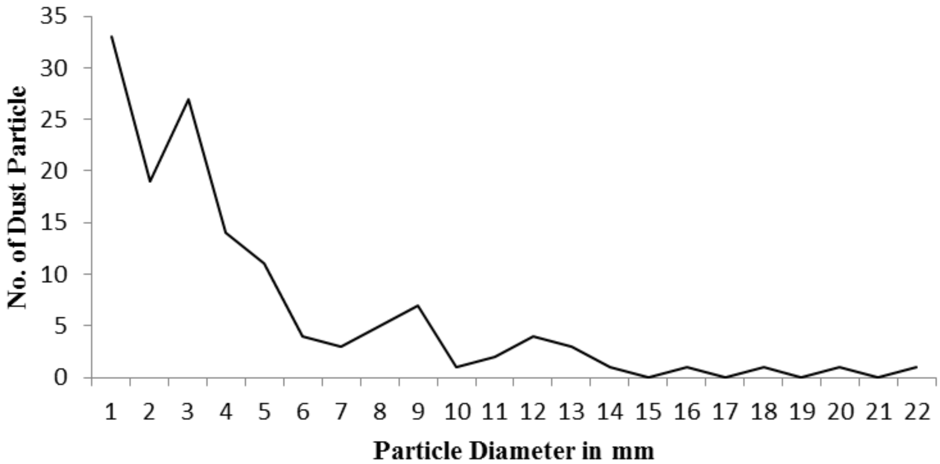
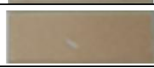
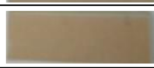


Figure 6: Particle size distribution

Dust concentration for each case is provided in Table 1 along with original slide sample and binarised image processed using Image J.

Table 1: Dust particle concentrations

Time exposure to artificial environment (in min)	Concentration value of dust particle(in % of total area)	Concentration of dust particle (in gm/m^2)	Original slide sample	Binary image
1	10.46246	4.84772E-06		
2	14.73	6.82505E-06		
3	20.8	9.63755E-06		
4	22.987	1.06509E-05		
5	46.819	2.16933E-05		
6	57.898	2.63768E-05		
7	56.927	2.68267E-05		

B. Radiation losses calculation

During the whole cycle of power absorption, it is evident to incorporate the losses involved in the process. Some of these losses are constant and does not depend on the equipment design and experimental strategies while others are susceptible to the technique simulation as an input value of radiation for the absorption in receiver tube. Finally temperature of outlet water from the receiver is determined using simulation and overall efficiency is estimated and effect of dust particle on efficiency is calculated.

Reduction in radiation through a reflective surface is determined by experiments and Fig. 7 represents the relation between dust particle concentrations with the reduction in irradiation value.

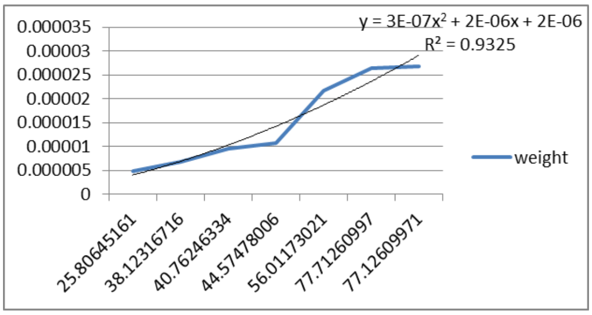


Figure 7: Reduction in Radiation with dust concentration

Eq. 3.11 can be used for determining the reduction in radiation value with concentration of dust particles.

$$y = 3E\text{-}07x2 + 2E\text{-}06x + 2E\text{-}06 \qquad (4.1)$$

Where y is concentration of dust particle in gm/m^2 and x shows the percentage reduction in radiation value.

Thermal losses can be calculated from equation 3.4 to 3.6. Similarly convective losses can be calculated from equation 3.7 to 3.10.

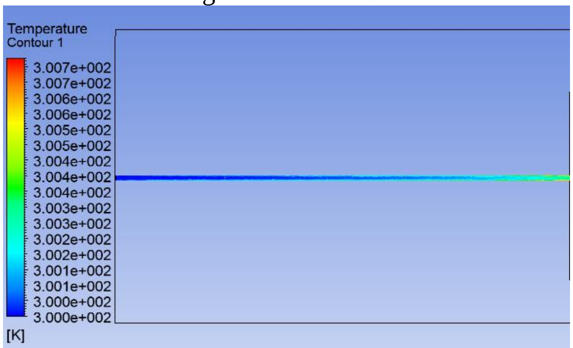
C. Simulation results

In the simulations radiation value received after the reflection as provided in table 2 is used as an input for the heating of water inside the receiver tube.

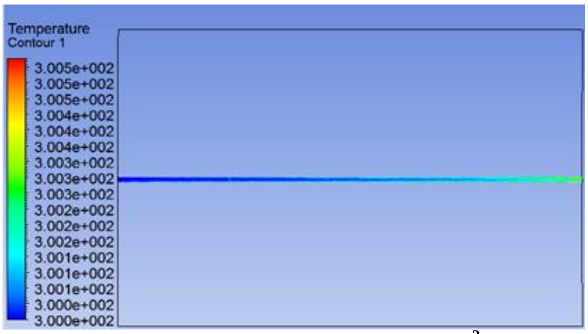
Table 2: Radiation value and outlet water temperature after the receiver

S.No.	Dust concentration weight(in gm/m^2)	Radiation received after reflection(in W/m^2)	Outlet water temperature (in ^{0}C)
1.	4.84772E-06	253	304.65
2.	6.82505E-06	211	303.86
3.	9.63755E-06	202	303.54
4.	1.06509E-05	189	303.27
5.	2.16933E-05	150	302.49
6.	2.63768E-05	76	301.12
7.	Clean	341	306.55

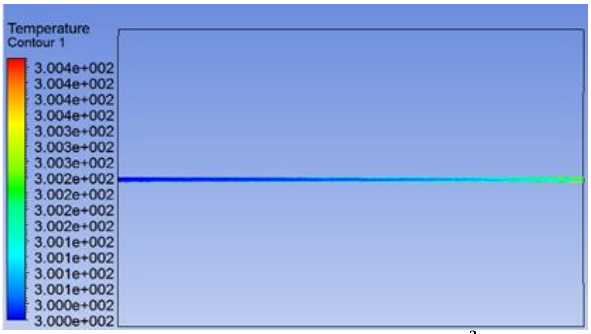
applied to the experimentation. In our study, we have assumed all other kind of losses to be constant except the variation in dust deposition and corresponding changes in absorption values. Once the all types of losses have been accounted, these values are used for Results from the simulation in Ansys are shown in fig. 8 (a to g). Left corner in each figure is showing tube inlet and right as outlet of the tube.From figure it is clear that as the fluid flows through the receiver tube, its temperature gets rise due to two factors. First one is absorption of radiation energy received from collector plate which increases the temperature of fluid. Once this heated up fluid flows further along the receiver tube, it again receives the radiation energy resulting in further heating. Finally outlet temperature at the end of receiver tube is given in table 2.



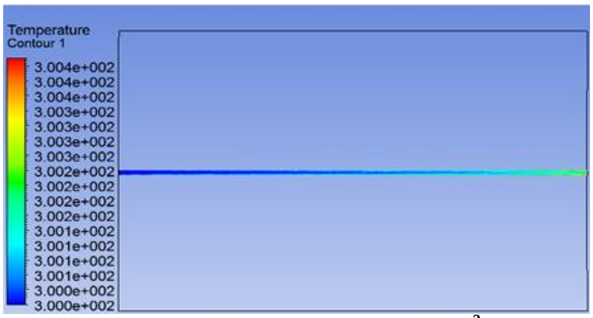
(a) Clean surface with radiation 341 W/m^2



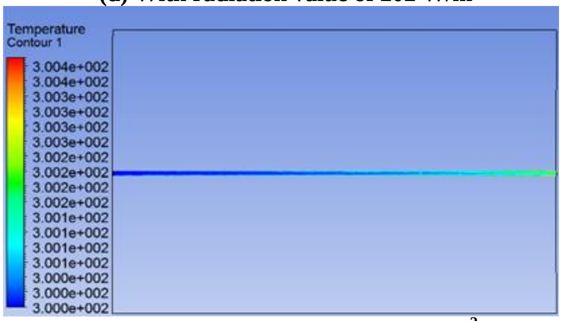
(b) With radiation value of 253 W/m^2



(c) With radiation value of 211 W/m^2

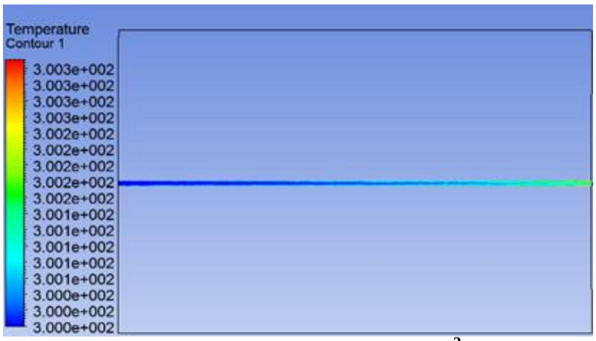


(d) With radiation value of 202 W/m^2



(e) With radiation value of 189 W/m^2

(f) With radiation value of 150 W/m^2



(g) With radiation value of 78W/m^2

Temperature variation of fluid not only varies along the receiver length but also across the cross section of the receiver tube. Lower portion of the tube is heated more in comparison to the upper part of the receiver. Since the flow is laminar with fluid velocity being 0.02 m/s, mixing is prohibited and at the end section of the receiver tube one gets the temperature variation in 2 Dimensions. This 2 dimensional variation is shown in fig. 9 at 9 cross sectional area locations for radiation value of 343 W/m^2. And a reference cross sectional variation is shown in fig. 10 to show the variation of temperature r-θ direction at the outlet of receiver tube for radiation value of 343 W/m^2.

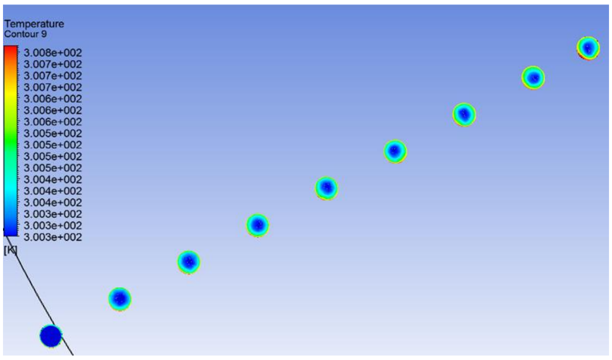


Figure 9: Temperature variation along cross section area of receiver tube

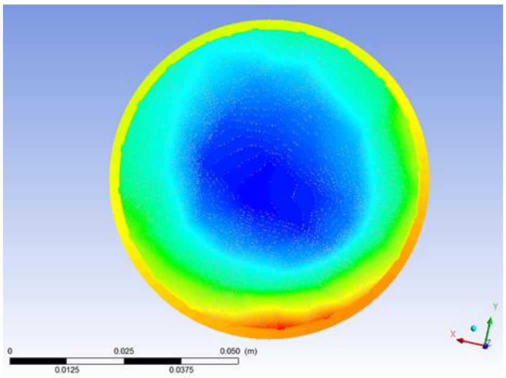


Figure 10: Typical cross sectional variation of temperature in a receiver tube

D. Effectiveness assessment

Effectiveness of the system can be calculated by total energy absorbed by the system with respect to energy incident on the system. Energy absorbed by the water at the outlet can be calculated by using the formula 3.2.

$$Q_u = m \cdot c_p \cdot (T_{out} - T_{in})$$

T_{in}= 297 K is a water inlet temperature used in the simulation

C_p = 4182J/Kg-K and m is a mass flow rate in the receiver tube.

m = ρ A v = 0.0291 kg/s.

Effectiveness of the system and its response due to dust concentration can be calculated by comparing the energy absorbed by the water in receiver and energy incident on the system and also with the temperature gain due to clean surface. Data is provided in Table 3.

To compare with clean surface parameter is defined by equation 3.12 and to compare with total energy incident equation 3.13 is used.

$$\eta_1 = Q_u / A_a \cdot G_b \qquad (4.2)$$

$$\eta_2 = \Delta T_{unclean} / \Delta T_{clean} \qquad (4.3)$$

where G_b = 341 W/m^2

Results are shown in Table 3

S.No.	Dust concentration weight (gm/m^2)	Comparing with energy incident (η_2)%	Comparing with clean surface(η_1) %
1.	4.84772E-06	16.51	80.10471
2.	6.82505E-06	14.82	71.83246
3.	9.63755E-06	14.12	68.48168
4.	1.06509E-05	13.54	65.65445
5.	2.16933E-05	11.8	57.48691
6.	2.63768E-05	8.91	43.14136
7.	Clean Surface	20.59	-

Efficiencies defined in Table 3 are designed so that η_2 shows the efficiency of the system due to dust concentration losses as well as the thermal losses whereas $\eta_1$incorporates the effect of dust concentration only on the radiation absorbed by the receiver tube. Thus and η_2 represents the overall effects during the energy conversion from radiation energy to absorbed sensible energy to the fluid flowing through receiver tube and η_1 represents the dust effect. η_2 is specific to the thermal efficiency of flowing fluid field and can be used only for specific flow parameters and system design parameters whereas η_1 can be used to find the effect of dust concentration on reflected surface while. Efficiency of the system with dust concentration is shown in fig. 11 and fig.12.

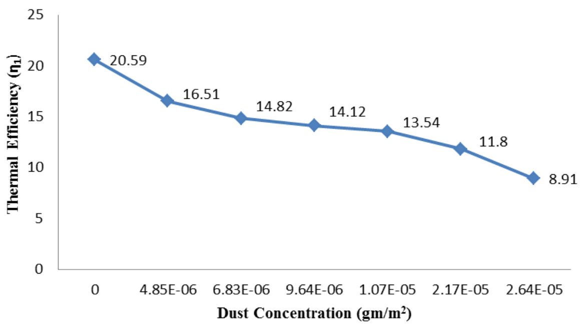


Figure 11: Thermal Efficiency Vs Dust Concentration

It is shown that due to dust deposition efficiency reduces drastically from 20.59 to 8.91% as the amount of dust increased in the reflective surface. It should be noted that thermal efficiency of the system against clean surface is 20.59% and due to dust deposition efficiency of system reduced to 8.91 % at dust concentration 26.637 x 10-6 gm/m^2 which was maximum dust concentration. Maximum percentage thermal comparatively efficiency reduced upto 56.726 %. Results show that increasing adverse effects on the plant performance as the dust concentration increases, which suggests that cleaning of collector should be done on an optimising time interval rather than fixed time interval depending on time and spatial situation of the location.

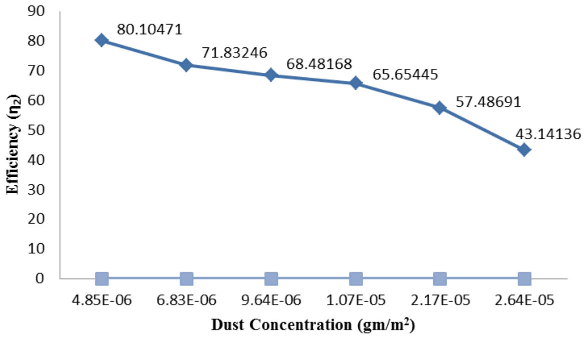


Figure 12: Efficiency Vs Dust Concentration

This is the graph between dust concentration and reduced efficiency due to dust deposition only. The efficiency obtained is 80.1, 71.8, 68.48, 65.65, 57.48, and 43.14% at dust concentration 4.85E-06, 6.83E-06, 9.64E-06, 1.07E-05, and 2.17E-05 and 2.64E-05 gm/m2 respectively.

V. CONCLUSION

It is obtained that due to dust deposition efficiency reduces drastically as the percentage of dust increases in the reflective surface. It should be noted that thermal efficiency of the system against clean surface is 20.59% and due to dust deposition efficiency of system reduced to 8.91 % at dust concentration 26.637 x 10-6 gm/m^2 which was maximum dust concentration. Maximum percentage thermal comparatively efficiency reduced upto 56.726 %. Efficiency curve with dust concentration suggests that cleaning of the collector should be done in an optimised time interval rather than fixed time interval for better efficiency. From curve it is clear that in summer days when dust concentration in atmosphere is more, it requires to clean the collector more frequently than usual days. At the time of storm it is better to shut down the plant since high concentration of dust drastically decreases the plant efficiency. Similarly plants situated in desert location are required to be clean more frequently than places with fertile or good biding soil. Reduction in efficiency comparing to clean surface shows the reduction of more than 50% in efficiency, which suggests that proper cleaning provision should be provided so that plant can be operated successfully. Temperature distribution in cross sectional area suggests that if working fluid is oil or more specifically single phase flow then recirculation of fluid along the θ – direction of tube may increase the efficiency since colder surface at the bottom of the tube will be available for the absorption of energy. But in the same time if fluid is water or more specifically multiphase flow with phase change during flow, it is advisable to maintain the laminar flow since the accumulation of vapour bubbles near the bottom surface will hinder the further heat transfer from the surface.

ACKNOWLEDGMENT

Authors are indebted for the instrument facility provided by IIT Jodhpur to conduct the experiment and access provided to the central library. Authors are also thankful to Sandeep Gupta, research scholar at IIT Jodhpur for his valuable input for the solver development and image processing technique.

A. Nomenclature

A	area, m^2
C_p	specific heat capacity, kJ/kg-K
T	Temperature, K
U_L	Losses coefficient, W/m2K
W	Width, m
D	diameter, m
G_b	solar beam radiation, W/m^2
h	convection coefficient, W/m^2K
k	thermal conductivity, W/m-K
K	Angle efficiency modifier
L	tube length, m
m	mass flow rate, kg/s
Nu	mean Nusselt number
Pr	Prandtl number
Q	Heat flux, W
Re	Reynolds number

B. Greek symbols

ε	emittance
η	efficiency
θ	angular displacement in longitudinal direction,°
μ	dynamic viscosity, Pas
ρ	reflectance
σ	Stefan–Boltzmann constant[= 5.67 × 10^{-8} W/ m^2 K^4]
μ	dynamic viscosity, Pas

C. Subscripts and superscripts

a	aperture
abs	absorbed
am	ambient
c	cover
ca	Cover-ambient
ci	inner cover
co	outer cover
fm	Mean fluid
in	inlet
loss	losses
m	mean
opt	optical
out	outlet
r	receiver

REFERENCES

[1] Singh K, Purohit K, Meena P M, Review Paper on Effect of Dust on the Solar Parabolic Trough and Applications. IJIREM, 3 (2016) 249 – 254.

[2] Yaghoubi, M., Niknia, I., Kanaan, P. and Mahmoodpoor, A.R., 2011. Experimental study of dust deposition effect on the performances of parabolic trough collectors. In: Solar PACES 2011: Proceedings of 17th Solar Paces Conference,20–23 September 2011, Granada, Spain.

[3] Sahin, A.D., A new formulation for solar irradiation and sunshine duration estimation. International Journal of Energy Research, 31(2) (2007) 109–118.

[4] Garg, H.P., Effect of dirt on transparent covers in flat plate solar energy collectors. Solar Energy, 15 (1974) 299 – 302.

[5] Sayigh, A., Al-Jandal, S. and Ahmed, H., Dust effect on solar flat surfaces devices in Kuwait. In: C. Furlan, NA. Mancini, A. Sayigh and B. Seraphin (Eds) Proceedings of the Workshop on the Physics of Non- Conventional Energy Sources and Materials Science for Energy, 2 (20) (1985) 353–367.

[6] El-Shobokshy, M.S. and Hussein, F.M., Effect of the dust with different physical properties on the performance of photovoltaic cells. Solar Energy, 51 (6) (1993) 505–511.

[7] Goossens, D.V. and Kerschaever, E., Areolian dust deposition on photovoltaic solar cells: the effects of windvelocity and airborne dust concentration on cell performance. Solar Energy, 4 (1999) 277–289.

[8] Hegazy, A.A., Effect of dust accumulation on solar transmittance through glass covers of plate-type collectors. Renewable Energy, 22 (2001) 525–540.

[9] El-Nashar, A. M., Seasonal effect of dust deposition on a field of evacuated tube collectors on the performance of a solar desalination plant, Desalination, 239 (2009) 66-81.

[10] Danny M. Deffenbaugh, Steve T. Green and Steve J Svedeman, The effect of dust accumulation on line-focus parabolic trough solar collector performance, Solar Energy. 36 (2) (1985) 139-146.

[11] M. Vivar, R. Herrero, I. Antón, F.Martínez-Moreno, R. Moretón, G. Sala, A.W. Blakers and J. Smeltink, Effect of soiling in CPV systems,

[12] I. Niknia, M. Yaghoubi and R. Hessami, A novel experimental method tofind dust deposition effect on the performance of parabolic trough solar collectors, International Journal of Environmental Studies. 69 (2) (2012) 233-252.

[13] C. Tzivanidis, E. Bellos, D. Korres, K. A. Antonopoulos, G. Mitsopoulos, Thermal and optical efficiency investigation of a parabolic trough collector, Case Studies in Thermal Engineering 6 (2015) 226–237.