Predict the Decay of the Thermal Performance of Solar Parabolic Trough Concentrators Due to Dust Accumulation

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Abstract- The accumulation of dust on solar collectors and concentrates surfaces is one of the most important problems and challenges suffered by solar energy devices. The effect of the dust accumulation on the mirror surface and transparent cover of the receiver tube for the parabolic trough concentrator on the energy gained and the outlet temperature were studied theoretically. The change in the outlet temperature and the thermal energy gained were predicted at different dust concentration factor using the transient simulation system TRNSYS. The average value of the outlet temperature reduced from 465.3 to 366.1 ºC with decreasing the cleanliness factor for the mirror only from 1 to 0.4, respectively. Also, the daily thermal energy gained was reduced from 52.78 to 18.14 GJ respectively. While for a cleanliness factor range from 1 to 0.4 for both reflecting mirror surface and the glass cover of the receiver, tube the decay of the outlet temperature and the daily solar energy gained were more ill where the outlet temperature the daily energy gained were reduced to 318.4 °C and 4.496 GJ, respectively. The energy consumed by the auxiliary heater to compensate for the shortage of solar collected energy increased from 9.46 to 33.7 GJ for a decrease in a cleanliness factor range from 1 to 0.6 respectively. From the study, it is evident that the accumulation of dust has a significantly bad effect on the solar energy gained, where a decrease in the cleanliness factor by about 0.1 decreases the collected energy by about 19.9 %.

Keywords Solar energy, parabolic trough collector, dust accumulation, cleanliness factor.

1. Introduction

With the increase in population and technological development, the demand for energy increases. Whereas conventional energy such as coal and petroleum are on the way to depletion, in addition to the harmful impact of these sources on the environment, we find that renewable energy, especially solar energy, is the key to solve these problems. Solar energy applications and devices suffer from several problems. The accumulation of dust on the solar systems is one of the most important of these problems. Many researchers have made efforts to study this phenomenon [1, 2]. The accumulation of dust on the surfaces of the solar systems is affected by many variables and can be classified into geographical variables, and design variables [3]. The geographical variables are related to the location, nature of the soil, wind speed, precipitation, and also atmospheric moisture. The design variables are related to the surface shape, surface title angle, and material.

Sayigh studied the effect of dust on flat plate collectors for different tilt angles, the experimental result showed that a dust accumulation of about 2.5 g/m^2/day was observed from April and July [4]. Hakizabera et al. investigated theoretically and experimentally the effect of the dust accumulation on the evacuated tube collector [5]. They made a comparison between clean collector (0 mg/m^2) and dusty collector (2.6 x 10^{-5} mg/m^2), a reduction in the optical efficiency by about 17.6 % was recorded with the dusty collector. El-Shobokshy and Hussein investigated the effect of dust accumulation on the performance of the photovoltaic cell [6]. They have found that dust particles of small diameter have a destructive effect on solar cells compared to particles of large diameter.

Tsuboi et al. [7] investigated the photovoltaic output degradation by the effect of very small particles, the result showed that the output degradation for SiO_2 particles depends on particle size this degradation is a linear function of the SiO_2 weight. Tripathi et al. [8] present the performance decay on the PV due to the dust and temperature.

From the available references, it has been observed that a large number of researches have been conducted on the effect of dust on photovoltaic cells, while a few have studied this effect on solar concentrators [9]. Vivar et al. [10] found that the accumulation of dust on the reflective surfaces leads to absorb part of the sun's radiation and scattering of another part as well as reducing the area of the reflecting surface. Sarver et al. [11] concluded that the major effect of dust is scattering the radiation more than the absorption.

One of the most prominent challenges facing researchers to make an accurate simulation of the solar energy concentrator power plant is the accurate prediction of these plants, as the production of the solar power plant depends mainly on the optical performance of solar concentrators [12, 13]. The reflectivity of the mirrors and the transmissivity of the glass cover of the receiver tube in the solar concentrator plants are affected by the accumulation of dust on this surface, which leads to a decrease in the thermal output of the solar plants. Therefore, these stations have prepared and implemented different cleaning schedules for these surfaces consistent with the conditions surrounding these stations. The sun's radiation, which is dispersed by the action of dust particles on the reflecting surface, leads to a deviation of sun rays. This deviation, even if it is small, takes away the reflected beam from a collision with the receiver tube, especially in the solar concentrating power plant, resulting in a decrease in the collected energy [14]. We et al [15] studied the effect of dust on the cleanliness factor of the parabolic trough concentrator. From the study, it was concluded that the accumulation of dust on the bottom edge of the reflector causes the largest decrease in the reflectivity compared to the center and top edge.

The design of a cleaning schedule for solar concentrators depends on the permissible amount of decrease in the thermal energy produced due to the accumulation of dust. In this paper, the effect of the dust concentration factor for each of the reflecting mirrors and the glass cover of the receiver tube on the thermal energy gained and the output fluid temperature from the solar collector will be investigated theoretically under the Cairo climate. A simulation program was built using the Transient System Simulation program TRNSYS. The energy consumed by an auxiliary heater to compensate for the shortage of solar radiation due to the variation of the solar irradiance through the day and the dust accumulated on the surfaces of solar concentrators will be predicted with the variation of the cleanliness factor.

2. System Description

The accumulation of the dust on the solar concentrated collector affects two important surfaces which are the reflecting mirror surface and the surface of the transparent glass cover of the receiver tube. In this work, the simulation process focuses on studying the effect of dust accumulation on each part separately. Also, the effect of dust on the solar power plant was investigated by predicting the amount of auxiliary heating required to compensate for the reduction in solar energy collected due to dust. The solar power plant consists of 8 parabolic trough concentrators each collector has an aperture surface area of about 403 m^2, a stratified storage tank, auxiliary heater, steam generator, steam turbine, electric generator, steam condenser, and high-pressure pump.

A transit simulation program was built using the TRNSYS platform. The program used the components of the TRNSYS and the TESS to form a solar power plant for electricity generation as shown in Fig. 1. The solar power plant consists of serval components (types) which will be described in the following section.

3. Modelling and Simulation

In this work, a model of a solar power plant was developed using a parabolic trough concentrator and auxiliary heater to supply the steam turbine of the Rankine cycle with the required steam. The TRNSYS simulation program was used to model and simulate the performance of a solar power plant under the effect of dust. TRNSYS is the most used software by researchers to develop models of solar applications and systems. The program consists of several blocks called components or types; each component simulates the performance of a certain device. All of these components are connected to form a system. Figure 1 presents a layout of the solar power plant with all its components on the TRNSYS platform. The description of the components used in this work is explained as follow:

3.1. Solar Parabolic Trough Concentrators (PTC)

This component (type 1257) models and simulates the performance of a parabolic trough collector with 72 m collector length and 5.6 m parabolic width for 8 collectors connected in series. All optics and design parameters for the PTC were identified for the component. The parameters of the parabolic trough concentrator used in the simulation are presented in table 1. This component simulates the effect of

Table 1. the design parameter of the parabolic trough concentrator

Parameter	**Value**
Parabola width	5 m
Parabola length	36 m
No. of collectors in series	16 -
Inner diameter of absorber tube	0.07 m
The focal length of the collector	1.8 m
Mirror accuracy	0.98
Reflectivity of mirror	0.93
Glass transmittance	0.96
Absorptance of receiver coating	0.95

the dust of each of the mirror surfaces and on the transparent glass cover for the receiver tube. The model in this component is based on the following equations [16]:

$$\dot{Q}_u = R_1 R_2 A_{ap} N_{pa} [F_R (\tau\alpha)_n \, IAM \cdot I_b - \frac{F_R U_L}{conRat}(T_{in} - T_{amb})] \quad (1)$$

Where $\dot{Q}_u$ is the rate of heat energy gained, T_{in} and T_{amb} are the fluid inlet and ambient temperature respectively, A_{ap} is the concentrator aperture area, IAM is the incident angle modifier, F_R is the heat removal factor, R_1 and R_2 are modifier correlations, I_b is the solar beam radiation, $(\tau\alpha)_n$ is the transmittance absorptance product of the receiver tube, N_{pa} is the number of parallel collector arrays. The outlet temperature T_{out} of the parabolic trough concentrator is calculated from the following equation [16]:

$$T_{out} = T_{in} + \frac{\dot{Q}_u}{\dot{m} \cdot Cp_f} \quad (2)$$

Where $\dot{m}$ and Cp_f are the mass flow rate and specific heat of the heat transfer fluid. The heat loss coefficient for the parabolic trough concentrator under consideration is calculated from the following equation:

$$U_L = a_0 + a_1 T + a_2 T_2^2 + a_3 T_3^3 \quad (3)$$

Where T is the collector fluid temperature, a_0, a_1 a_2, a_3 are constants.

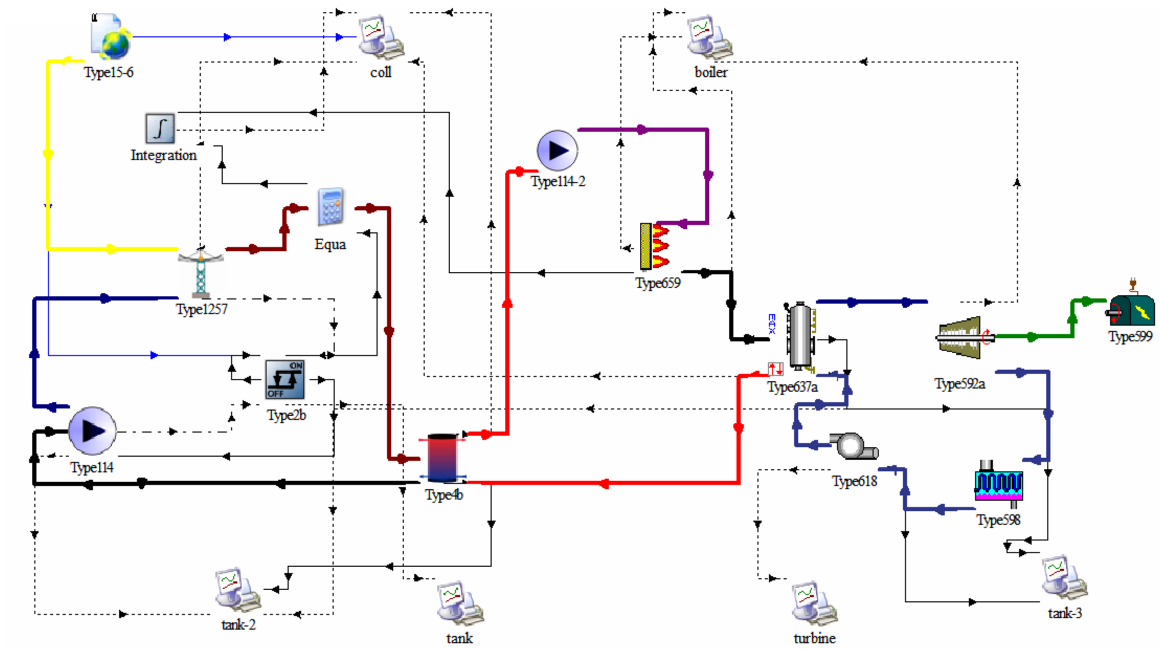

Fig. 1. Components layout of the solar power plant in the TRNSYS platform.

3.2. Circulating Pumps

This component (type 114) is used to circulate the heat transfer fluid, which is synthetic oil, from the solar concentrators to the storage tank. Another pump was used to circulate the heat transfer fluid from the storage tank to the backup heating unit and the steam generator.

3.3. Storage Tank

The storage tank component (type 4b) models and simulates the performance of a stratified storage tank. The storage tank was divided into 40 segments to satisfy good stratification. The following equation presents the general energy balance model for any of the tank's segments. [17].

$$M_i C_{p,f} \frac{dT_i}{dt} = \alpha_i \dot{m}_h C_{p,f}(T_h - T_i) + \beta_i \dot{m}_c C_{p,f}(T_c - T_i) + UA_i(T_{amb} - T_i) + \gamma_i (T_{i-1} - T_i) C_{p,f} + \gamma_i (T_{i-1} - T_i) C_{p,f} \quad (4)$$

Where T_i, T_h, and T_L are the temperature of the fluid in the i^{th} segment, the inlet hot fluid and outlet cold fluid respectively, $\dot{m}_h$ and $\dot{m}_c$ are the mass flow rate of the hot and cold fluids respectively, M_i is the mass of fluid in the i^{th} segment, UA is the overall heat transfer coefficient, while α, β, and γ are control functions.

3.4. Auxiliary Heater

The auxiliary heater component (type 659) was used to model and simulate an auxiliary heater to elevate the temperature of the synthetic oil to the required temperature. This component was inserted in the solar power plant to supply stable fluid temperature and consequently generate stable steam with a stable condition. The heat energy consumed by the auxiliary heater depends on the required outlet temperature, inlet temperature, and the fluid flow rate. The auxiliary rate of energy $\dot{Q}_{au}$ can be calculated from the following equation [18]:

$$\dot{Q}_{au} = \frac{\dot{m}_f Cp_{,f} \left(T_{out} - T_{in}\right) - UA\left(T_{av} - T_{amb}\right)}{\eta_{au}} \quad (5)$$

Where $\dot{m}_f$ is the mass flow rate of the fluid flow through the auxiliary heater, UA is the thermal loss coefficient, T_{av} is the average temperature inside the heater, η_{au} is the efficiency of the auxiliary heater and it is defined as the net heat gained by the fluid to the heat supplied to the fluid.

3.5. Steam Generator

This component (type 637) models and simulates the performance of a heat recovery steam generator that uses hot fluid heated by solar energy and the auxiliary heater to generate steam at a desired steam condition.

3.6. Electric Generator

This component (type 592) models and simulates the process of converting the mechanical work output from the steam turbine into electric energy.

3.7. Weather data reader

This compound generates hourly data for the weather in a specific location by taking the averages of the measured values at this location in terms of solar radiation of all types and ambient temperature, ratio humidity, wind speed, and solar angles. It can interpolate the data at any time steps.

The developed program simulates the performance of the solar power plant during one week in July under the climate condition for Cairo (30.02° N 31.13° E, 23 m above sea level), Egypt. The program simulates the performance of the plant every 15 minutes. Figure 2 present the beam solar radiation, wind speed, and ambient temperature for the location of the study.

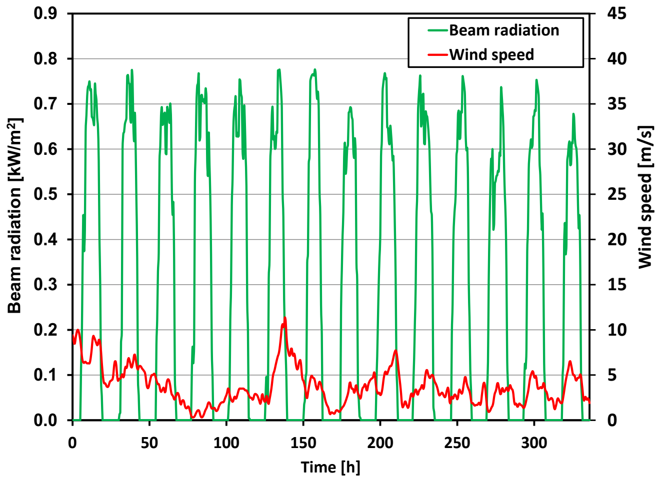

Fig. 2. Variation of the beam radiation and the wind speed for Cairo during the two weeks of

4. Results

The results of the simulation investigate the effect of the dust of the mirror reflector surface and the transparent glass cover of the receiver tube on the PTC outlet temperature and the daily energy gained. The cleanliness factor is definite as the ratio of the surface area uncovered by dust to the total surface area. The cleanliness factor varies from 1 to 0, where the value of 1 indicates a clean surface and the value of 0 indicates a total covering of the surface by dust. Figure 3 illustrates the effect of the cleanliness factor for the reflecting mirror surface of the PTC on the outlet temperature of the solar concentrator for the 1st week of July. The inlet fluid temperature of the solar collector was kept constant at 300 ºC. From the figure, it can be observed that by decreasing the cleanliness factor for the mirror only from 1 (completely clean) to 0.8, 0.6, and 0.4 the average value of the outlet temperature at solar noon decrease from 465.3 to 434.2, 399.6, and 366.1 ºC respectively, consequently, the percentage reduction of the temperature rise of the PTC was about 19.02 %, 40.5 %, and 61.4 % respectively. It can be attributed to the decrease in the solar radiation received by the receiver tube due to dust.

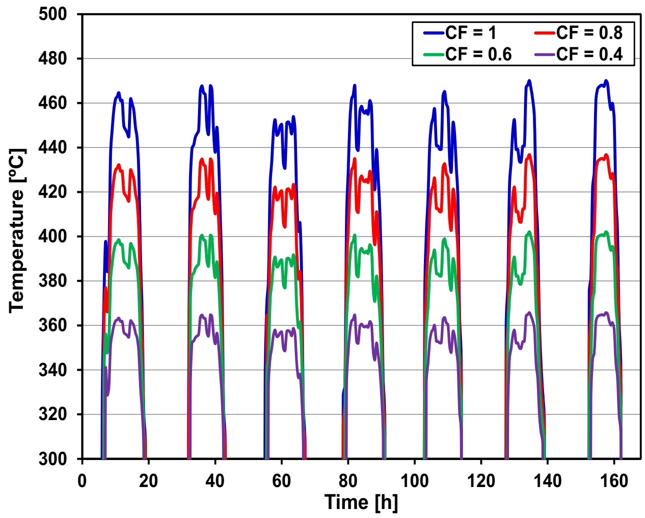

Fig. 3. Effect of the mirror cleanliness factor only on the PTC outlet temperature for the first week of July.

The effect of the cleanliness factor of both the mirror surface and the glass cover of the receiver tube together on the PTC outlet temperature was presented in Fig. 4. The figure shows a more ill effect, of course, since in this case the accumulation of dust on the glass surface of the receiving tube has been taken into consideration as well. It can be observed a dramatic decrease in the outlet temperature of the heat transfer fluid, and consequently in the value of the temperature rise. It can be observed that decreasing the cleanliness factor from 1 (completely clean) to 0.8, 0.6, and 0.4 reduce outlet temperature of the PTC from 465.3 to 403.1, 356.6, and 318.4 ºC, respectively, and the reduction in the outlet temperature and consequently the temperature rise became 36.3 %, 66.3 %, and 88.9 % respectively.

The daily energy gained from the parabolic trough collectors was affected by the cleanliness factor for both mirror surface and glass cover surface. The effect of the

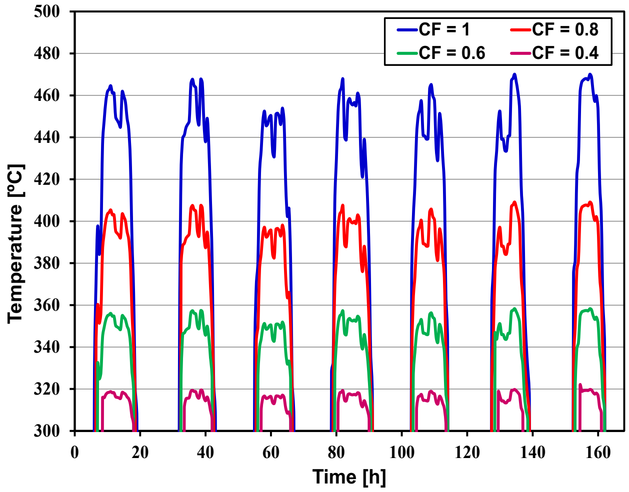

Fig. 4. Effect of the mirror and glass cover cleanliness factor on the outlet temperature of the PTC.

cleanliness factor of the reflecting mirror only on the energy gained from the parabolic trough collector is illustrated in Fig. 5. From the figure, it can be observed that the daily energy gained at the clean surface (CF =1) of the mirror is 52.78 GJ, while with a dusty mirror surface, the daily energy gained is reduced to 41.31, 29.79, and 18.14 GJ at cleanliness factor of 0.8, 0.6, and 0.4 respectively.

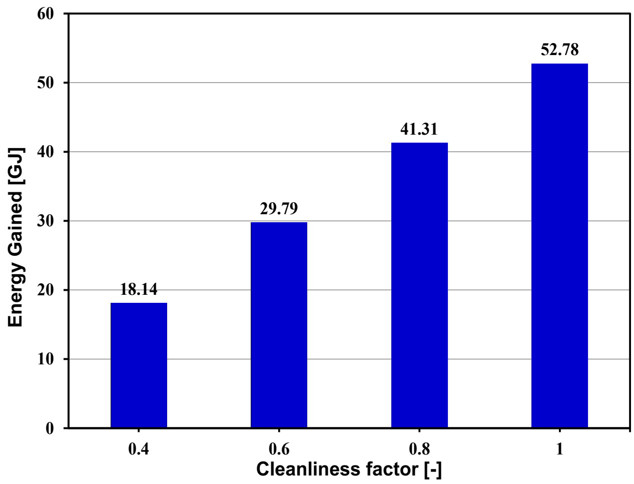

Fig. 5. Variation of the daily energy gained by the PTC with varied cleanliness of the mirror.

Figure 6 shows the effect of the cleanliness factor for both the reflecting mirror and the glass cover on the energy gained from the PTC. In the case of the dust accumulation on the mirror and glass cover, the daily energy gained is reduced to 32.12, 15.93, and 4.49 GJ at a cleanliness factor of 0.8, 0.6, and 0.4 respectively.

The decrease in the heat energy gained by the parabolic collector is compensated by the auxiliary heater, as the energy gained by the sun is varied throughout the day and from day to other. The auxiliary heater compensates for any shortage or instability in the energy collected by the solar collectors. Fig. 7 displays the variation of energy generated by the collector and the energy consumed by the auxiliary heater to compensate for the energy shortage due to dust.

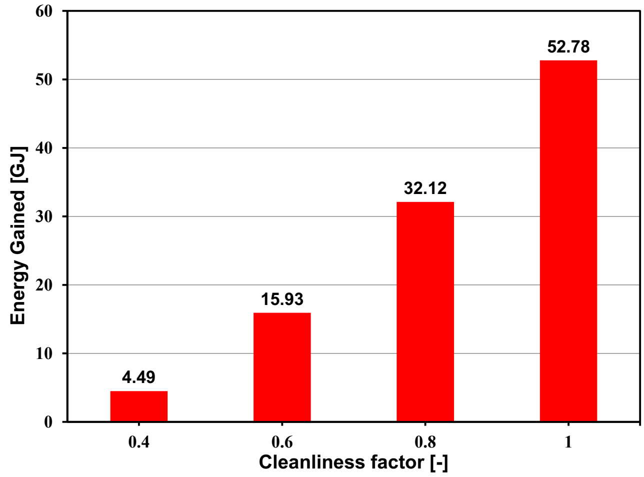

Fig. 6. Variation of the daily energy gained by the PTC with the cleanliness factor of both mirror and glass cover of the receiver tube

From the figure, it can be observed that there is an increase in the energy consumed by the auxiliary heater with decreasing the cleanliness factor from 1 to 0.6, the daily energy consumed change from 82.6 to 115.7 GJ. This increase is due to the shortage of solar collector energy because of dust. Where decrease the cleanliness from 1 to 0.9, 0.8, 0.7, and 0.6 lead to an increase in the energy consumed by the auxiliary heater by about 9.46, 18.3, 26.3, and 33.7 GJ, respectively. It can be seen also that the daily solar energy gained decreased from 56.4 to 18.8 GJ, with decreasing the cleanliness factor from 1 to 0.6 respectively. Also, a decrease in the cleanliness factor by about 0.1 decreases the collected energy by about 19.9 %.

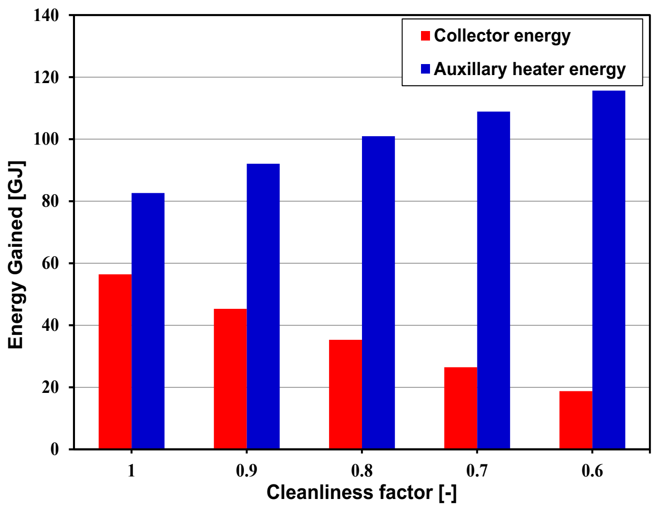

Fig. 7. Variation of the daily energy gained by the PTC with varied cleanliness of the mirror

The variation on cleanliness factor with time depends on the location of the solar plant and the environmental condition such as the wind speed and soil type. In this part of the study, it was assumed three rates of decreasing the cleanliness factor which are; fast drop (decreasing the cleanliness factor from 1 to 0 within two weeks), medium drop, (decreasing the cleanliness factor from 1 to 0 within four weeks) and slow drop (decreasing the cleanliness factor from 1 to 0 within six weeks) weeks. The outlet fluid temperature from the solar collector verses time is presented in Fig. 8 for fast, medium and slow drop of the cleanliness factor.

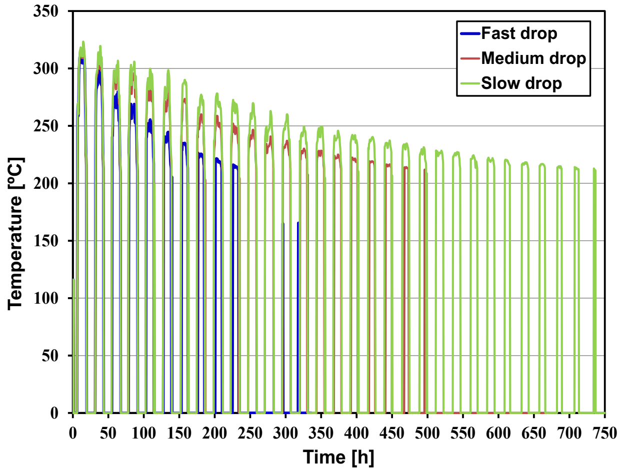

Fig. 8. Variation of the outlet collector temperatures for the fast, medium, and slow drop in the cleanliness factor varied.

From the figure, it can be concluded that the fast decrease in the cleanliness factor decreases the outlet temperature to its minimum value after 235 hours, where the temperature rise through the solar collector became very small to operate the pump. For medium and slow drop in the cleanliness factor, the outlet temperature from the collector reaches its minimum values after 436 and 798 hours respectively.

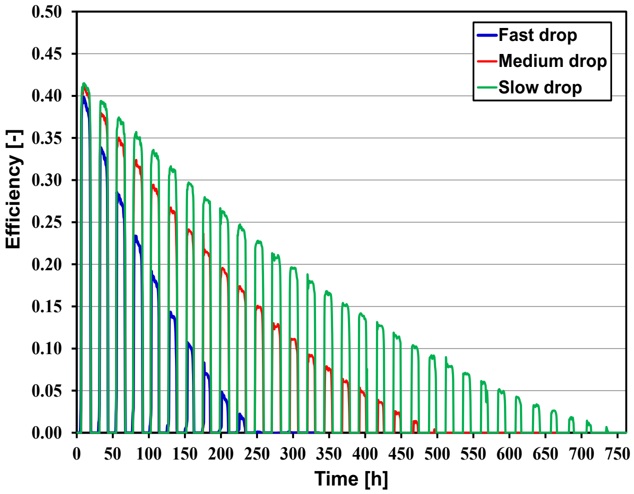

Fig. 9. Variation of the collector thermal efficiency at fast, medium, and slow drop of the cleanliness factor

The effect of the decay rate of the cleanliness factor on the thermal collector efficiency versus time is illustrated in Fig. 9. From the figure, it can be observed that the decrease in the thermal efficiency with time has the same trend as the outlet fluid temperature.

5. Conclusions

The effects of the dust on the mirror reflecting surface and the glass cover of the receiver tube of parabolic trough concentrator, as the main parts of a solar power plant, were investigated theoretically. The TRNSYS simulation program was used for carrying out the simulation. From the results, it can be observed a reduction in the outlet collector temperature by about 99.2 ºC as a result of increasing the dust accumulation on the reflecting mirror surface where the cleanliness factor decreases from 1 to 0.4., this decrease in the collector outlet temperature increases to about 146.9 °C as a result of increasing the dust accumulation on both of the reflecting mirror and the glass covers of the receiver tube.

With decreasing the cleanliness factor for both the reflecting mirror and the glass cover of the receiver tube from 1 to 0.4, the daily solar energy gained is reduced from 52.78 to 4.49 GJ, respectively. The energy consumed by the auxiliary heater to compensate for the shortage of solar collected energy due to dust range from 9.46 to 33.7 GJ and the daily solar energy gained decreased from 56.4 to 18.8 GJ, respectively. From the study, it is evident that the decrease in the cleanliness factor by about 0.1 decreases the collected energy by about 19.9 %. The effect of decreasing the cleanliness factor rate on fluid outlet temperature was identified as the time of operating the solar collector before stopping due to decay the temperature rise. where at fast, medium, and slow drop of cleanliness factor the collector operate for 235, 438 and 798 hours respectively.

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References

[1] H. Garg, “effect of dirt on transparent covers in flat-plate solar energy collectors”, Solar Energy, Vol. 15, No. 4, pp. 299- 302, April 1974.

[2] E. Nashar, “the effect of dust accumulation on the performance of evacuated tube collectors”, Solar Energy, Vol. 53, No. 1, pp. 105-115, July 1994.

[3] S.Biryukov, “Degradation of reflectivity of parabolic mirror caused by dust on its surface”, Journal of Aerosol Science, Vol. 31, pp. 985–986, sept. 2000.

[4] A. A. M. Sayigh, “Sun: Mankind's future source of energy”, in Proceedings of the International Solar Energy Congress, New Delhi, India, Vol. 2, pp. 960-964, 16-21 January 1978

[5] O. Hakizabera, J. Li, J. Yang, and Y. Heli, “Dust effect on evacuated tube solar collector in Minquin, China”, International Journal of Energy and Environmental Research, Vol. 6, No.2, pp.1-11, July 2018.

[6] M. S. El-Shobokshy and F. M. Hussein, “Effect of the dust with different physical properties on the

performance of photovoltaic cells", Solar Energy, Vol. 51, No. 6, pp. 505–511, Dec. 1993.

[7] K. Tsuboi, T. Matsuoka, T. Yachi, "An output degradation of photovoltaic module by fine particles deposition", International Conference on Renewable Energy Research and Applications (ICRERA), Nagasaki, pp. 1-5, 11-14 November 2012.

[8] A. K. Tripathi, M. Aruna, Ch. S. N. Murthy, 2017, "Output Power Loss of Photovoltaic Panel Due to Dust and Temperature", International Journal of Renewable Energy Research, Vol. 7, No. 1, pp. 439-442, January 2017.

[9] R. Conceiç~ao, H. G. Silva, M. Collares-Pereira, "CSP mirror soiling characterization and modeling", Solar Energy Material and Solar Cell, Vol. 185, pp. 233-239, October 2018.

[10] 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", Solar Energy, Vol. 84, No. 7, pp. 1327–1335, July 2010.

[11] T. Sarver, A. Al-Qaraghuli, and L. L. Kazmerski, "A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches", Renewable and Sustainable Energy Reviews, Vol. 22, pp. 698–733, June 2013.

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

[13] A. D. Şahin, "A new formulation for solar irradiation and sunshine duration estimation", International Journal of Energy Research, Vol. 31, No. 2, pp.109–118, 2007.

[14] B. K. Bergeron, and J. M. Freese, "Cleaning strategies for parabolic-trough solar collector fields; guidelines for decisions", SAND81-0385, 1981.

[15] Z. Wu, S. Yan, Z. Wang, T. Ming, Xi. Zhao, R. Ma, Y. Wud, "The effect of dust accumulation on the cleanliness factor of a parabolic trough solar concentrator", Renewable Energy, Vol. 152, pp 529-539, June 2020.

[16] J. A. Duffie, and W. A. Backman, Solar Engineering of Thermal Processes, Wiley, New York, 1991.

[17] S. A. Klein, "A Design Procedure for Solar Heating Systems", Ph.D. Thesis, Department of Chemical Engineering, University of Wisconsin-Madison, (1976).

[18] J.W. Thornton, D.E. Bradle, T.P. McDowell, N.J. Blair, M.J. Duffy, N.D. LaHam, A.V. Naik, "TESS libs17, HVAC Library mathematical Reference" TESS– Thermal Energy Systems Specialists http://www.tess-inc.com.