Advances in Energy Research, *Vol. 3, No. 3 (2015) 157-165*
DOI: http://dx.doi.org/10.12989/eri.2015.3.3.157

Dust accumulation effect on solar thermal energy systems performance

Mohammad A. Alsaad*

Department of Mechanical and Industrial Engineering, The University of Applied Sciences,
5 Ibrahim Alaqqani Street, Amman 11190, Jordan

(Received June 18, 2015, Revised August 3, 2015, Accepted August 19, 2015)

Abstract. This research investigates the effect of natural dust accumulation on the glass cover of solar thermal energy conversion systems. Four similar, locally manufactured, flat plate solar collectors are used. All collectors are South oriented with tilt angle of 40°. The glass cover of one collector is kept clean of dust during the experimental period while the second collector is cleaned at the beginning of each month. The third collector is cleaned every two months while the fourth collector is kept un-cleaned throughout the experimental period of four months. The calculated parameters are the solar heat gain rates and the corresponding values of the thermal efficiency. The result of the present work indicates that the percentage of fractional reduction of the useful heat gain rate due to dust accumulation during a period of one and two months is 11.4% and 17.0%, respectively. The percentage decrease of thermal efficiency during the same duration periods is 4.0% and 6.1%, respectively. The percentage of fractional reduction of the useful heat gain rate due to dust accumulation during a period of three and four months is 27.8% and 31.9%, respectively. The percentage decrease of monthly thermal efficiency during the same duration period is 10.2% and 11.3%, respectively.

Keywords: dust accumulation; heat gain rate; thermal efficiency; solar system; energy conversion; conversion system

1. Introduction

Middle East countries, which are in the middle latitudes, such as Jordan, receive large amounts of solar energy throughout the year. Jordan is considered as a temperate country that is characterized by dry and dusty climate. In addition, the sunshine duration hours are longer in spring, autumn and summer seasons. This fact makes solar radiation utilization to be more economical and more efficient in such countries.

Jordan is blessed with renewable energy resources such as solar and wind energies. Several national programs are being pursued for promoting solar and wind energies involving monitoring and assessment of technological developments and pilot solar projects. Hrayshat and Al-Soud (2004) estimated the share of solar energy in the energy mix in Jordan for the years 2002 and 2007. They found that the share of solar energy in the energy mix in Jordan for the years 2002 is

*Corresponding author, Professor, E-mail: m_saad@asu.edu.jo

http://www.techno-press.org/?journal=eri&subpage=7 ISSN: 2287-6316 (Print), 2287-6324 (Online)

1.7 to 1.8% and that for the year 2007 is 2.1%.

Few studies considered the effect of dust accumulation on the performance parameters of solar thermal collectors, such as heat gain rate and thermal efficiency. The previous studies of dust accumulation on solar thermal systems focused on its effect on glazing transparency. Jiang *et al.* (2011) performed experimental study to examine the effect of dust accumulation onto different types of solar photovoltaic modules and determined the corresponding efficiency reduction. Sun simulator and test chamber were used for their study. Their results indicated that dust accumulated has significant impact on PV output. The reduction of PV efficiency reached 25% and has a linear relationship with dust accumulation density. Sulaiman *et al.* (2011) experimentally investigated the effect of dust accumulation on the performance of solar PV panels. Their results indicated that the accumulated dust on the surface of photovoltaic solar panels reduces the efficiency of PV panels by up to 50%. Duffie and Beckman (2006) indicated that dust accumulation on the glass cover of solar energy equipment reduces the glass transmission by 2.7%. They also indicated that the absorbed solar radiation is decreased by 2%. Hegazy (2001) investigated the effect of the dust accumulation on the transmittance of glass cover of flat plate solar collectors with different tilt angles and discussed the associated reduction in solar transmission over a period of one year under the climate conditions of Minia region, Egypt. The glass covers were never cleaned during experimental duration of one month to allow dust to accumulate. His results showed that the fractional reduction in glass transmittance depends on the glass cover tilt angle and exposure period. To reduce the negative effect of dust accumulation on the solar collector performance, he suggested that the tilt angle, β of the collector to be set such that it is equal to that of the site latitude angle, ϕ plus 30^o. i.e., $\beta=\phi+30^o$.

Mastekbayera and Kumar (2000) discussed the influence of dust accumulation on the transmittance of a 0.2 mm thick low density polyethylene (LDPE) glazing used commonly in solar air heaters. They measured the reduction in transmittance due to various dust accumulation periods. Their work represents experimental observations of natural dust accumulation on a 15^o inclined LDPE glazing at tropical climate condition.

Most of current flat plate solar energy conversion systems researches such as Alsaad (1999), Jubran and Alsaad (1994), Alsaad and Jubran (1994) performed their research with clean glass cover that is free of dust accumulation. The current research investigates the effect of dust accumulated during several months on the glass cover surface of flat plate solar collectors. The effect of the accumulated dust on the performance parameters of these solar collectors will be discussed and determined. The performance parameters to be investigated are the hourly, daily, weekly and monthly useful heat gain rates, thermal efficiencies and the efficiency ratios of the un-cleaned collectors.

2. Theoretical analysis

The hourly useful heat gain rate, $\dot{Q}_{u.h}$ of the solar collector is expressed as

$$\dot{Q}_{u.h} = \dot{m}c_p(T_o - T_i) \quad (1)$$

Where; $\dot{m}$ is the mass flow of water entering the collector, kg/s, c_p is the specific heat of water, kJ/kg.K, T_o is the outlet water temperature, ^{o}C and T_i is the inlet water temperature ,^{o}C.

The daily useful heat gain rate, $\dot{Q}_{u,d}$ of the solar collector is calculated as

$$\dot{Q}_{u,d} = \sum Q_{u,h} \tag{2}$$

The weekly useful heat gain rate, $\dot{Q}_{u,w}$ and the monthly heat gain rate, $\dot{Q}_{u,m}$ of each solar collector is calculated by summing up Eq. (2) over the number of days during the week and number of days of the month, respectively.

The hourly thermal efficiency, η_h of solar collector is expressed as follows

$$\eta_h = \frac{\dot{Q}_{u,h}}{A_c I_{T,h}} \tag{3}$$

Where, A_c is the effective collector surface area, m^2 and $I_{T,h}$ is the hourly solar total radiation incident on tilted collector surface, kW/m^2.

The daily thermal efficiency, η_d of solar collector is expressed as follows

$$\eta_d = \frac{\sum \dot{Q}_{u,h}}{A_c \sum I_{T,h}} \tag{4}$$

The weekly thermal efficiency, η_w of the solar collector is calculated by using the weekly heat gain rate and the weekly incident solar radiation values in Eq. (4) instead of the hourly values.

Similarly, the monthly thermal efficiency, η_m of solar collector is calculated by using the monthly heat gain rate and the monthly incident solar radiation values in Eq. (4) instead of the hourly values.

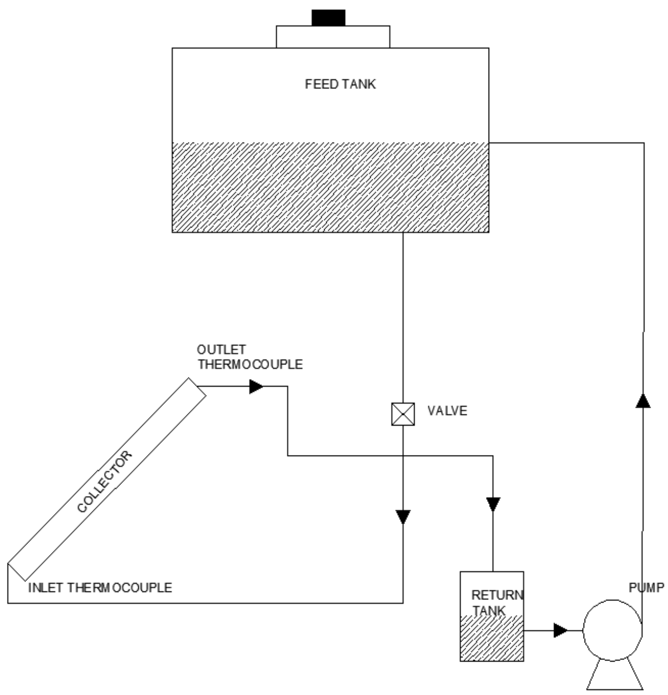

Fig. 1 Schematic diagram of the experimental rig

3. Experimental setup and instrumentation

The used experimental rig of the present paper is shown in Fig. 1. It consists of four identical, locally manufactured, flat plate solar collectors. All collectors are South oriented with fixed tilt angle of 40^o. A feed water tank of 1.0 m^3 capacity, located at a height of 2.0 m, is used to supply cold water to each of the four collectors at a fixed mass flow rate of 0.01 kg/s. A circulating pump is used for this purpose.

The effective surface area of each collector is 1.231 m^2.

The total solar radiation incident on the collector surface is measured using a calibrated CM5 Kipp and Zonen pyranometer and a ACC1 solar integrator. The pyranometer is installed on the plane of the tested solar collectors. The incident solar radiation was measured at regular intervals of one hour around solar noon during the experimental day.

The temperature of water entering and leaving each collector was measured by means of Copper-Constantan thermocouples. Eight thermocouples were placed at the inlet and outlet of each solar collector for this purpose. All thermocouples were connected to a digital microprocessor thermometer. The mass flow rate of circulating water was measured by recording the time needed to fill a certain volume of water of calibrated container. A valve is installed at inlet and outlet of each collector to control the mass flow of supply water for each collector at the specified flow rate of the circulating water.

The four collectors were installed on the roof of the Mechanical Engineering Department, Faculty of Engineering, Amman City (Latitude 32^o, Longitude 36^o E, Elevation 980 m), Jordan. The four collectors were tested during the months of January through April. All experiments were performed on clear days of each month except of the first week of January, where the weather turned to be dusty. The experimental data were spread equally around solar noon to eliminate the effect of solar incidence angle. The four collectors were tested at outdoor conditions during the months of January through April.

The hourly useful heat gain rate for each collector is calculated using Eq. (1), starting at 08:00 AM tell 16:00 PM standard time. The circulating mass flow rate through each collector was measured by recording the time needed to fill a certain volume of water of calibrated container. The temperatures of circulating water entering and leaving each collector were measured and recorded using the Copper and Constantan thermocouples and the microprocessor.

The glass covers of all collectors were cleaned from dust and dirt accumulation at the beginning of the experiments. The experiments of the present work were conducted under the following conditions:

(a) The glass cover of one collector **(A)** was kept clean and free of dust accumulation throughout the test period of four months.

(b) The glass cover of the second collector **(B)** was cleaned from accumulated dust at the first day of each month.

(c) The glass cover of the third collector **(C)** was cleaned from dust accumulated at the first day of each two months.

(d) The glass cover of the fourth collector **(D)** was never cleaned from accumulated dust during the four experimental months.

Three weekly additional experiments were carried out during the month of January to investigate the effect of weekly dust accumulation on the thermal efficiency of the solar collector.

Table 1 Calculated values $\dot{Q}_{u,m}$, η_m and efficiency ratios for January month.

	Collector (A) Clean	Collector (B)	Collector (C)	Collector (D)
$\dot{Q}_{u,m}$, kW	38.2	27.3	27.3	27.3
η_m, %	21.5	15.4	15.4	15.4
Efficiency Ratio, %	100	71.6	71.6	71.6

4. Results and discussion

The hourly, daily, weekly and monthly useful heat gain rates were calculated using Eq. (1) and Eq. (2). The hourly thermal efficiency of each solar collector was calculated using Eq. (3). The hourly solar radiation incident on the inclined surface of the solar collectors was measured using the pyranometer and the solar integrator. On the other hand, the daily, weekly, and monthly thermal efficiency of each collector is calculated using Eq. (4) during the months of January through April. The effect of the weekly dust accumulation on the useful heat gain rates and the thermal efficiencies of the solar collectors were obtained for the first three weeks of January month. Eqs. (1)-(3) were used for this purpose. The obtained results indicate that the thermal efficiency reduction due to dust accumulation during the first week is 3.1%. It has to be pointed out that this high value of thermal efficiency reduction is due to unusual dusty weather during the first week of January month. This value of thermal efficiency reduction reached 4.3% when the dust is allowed to accumulate for two consecutive weeks. When the dust is allowed to accumulate for three consecutive weeks, the thermal efficiency reduction reached 5.4%. This shows the importance of cleaning the glass cover at least once every one week.

Eqs. (1)-(2), and Eq. (4) were used to calculate the monthly total useful heat gain rates, $\dot{Q}_{u,m}$ for each collector during the four months of the experiments. The monthly efficiencies, η_m of each experimented collector were also calculated using Eq. (4) by using the monthly values of the useful heat gain rates and the monthly incident solar radiation for each month of the experiments.

The obtained results of useful heat gain rates, $\dot{Q}_{u,m}$ and collector thermal efficiencies, η_m of the present work for the four collectors are presented in Tables 1-4.

Table 1 shows the values of $\dot{Q}_{u,m}$ and η_m when collector (A) is kept free of dust accumulation throughout the month of January while the other three collectors (Collectors (B), (C), and (D)) were left un-cleaned throughout the days of this month. Therefore, the values of their performance parameters $\dot{Q}_{u,m}$ and η_m are similar, as indicated in Table 1. The values of the efficiency ratios are also included in Table 1. The efficiency ratio is defined as the efficiency of the dusty collector to that of the clean collector. It is a useful tool that indicates the influence of dust accumulation on the performance parameters of the unclean collector. Table 1 shows that the efficiency ratio dropped from the value of 100% to 71.6% due to dust accumulation during the month of January.

The data of Table 1 also indicate that the percentage reduction of both $\dot{Q}_{u,m}$ and η_m due to dust accumulation during a period of one month is 28.5% and 6.1%, respectively for January month. The efficiency ratio for this month is 71.6%.

Table 2 shows the obtained results of the four collectors for February month under the following conditions: Collector (A) is kept clean as planned for. Collector (B) is cleaned of the accumulated dust at the beginning of this month then it is kept un-cleaned during the month of February only, as that of the case of January month. Collectors (C) and (D) were kept un-cleaned

Table 2 Calculated values of $\dot{Q}_{u,m}$, η_m and efficiency ratios for February month

	Collector (A) Clean	Collector (B)	Collector (C)	Collector (D)
$\dot{Q}_{u,m}$, kW	89.4	78.2	68.5	68.5
η_m, %	43.9	38.4	33.6	33.6
Efficiency Ratio, %	100	87.5	76.5	76.5

Table 3 Calculated values of $\dot{Q}_{u,m}$, η_m and the efficiency ratios for March month

	Collector (A) Clean	Collector (B)	Collector (C)	Collector (D)
$\dot{Q}_{u,m}$, kW	76.3	69.2	69.2	55.1
η_m, %	36.9	33.5	33.5	26.7
Efficiency Ratio, %	100	90.8	90.8	72.4

Table 4 Calculated values of $\dot{Q}_{u,m}$, η_m and the efficiency ratio for April month

	Collector (A) Clean	Collector (B)	Collector (C)	Collector (D)
$\dot{Q}_{u,m}$, kW	73.7	65.3	61.2	50.2
η_m,%	35.5	31.5	29.5	24.2
Efficiency Ratio, %	100	88.7	83.1	68.2

for the two months of January and February as planned for. Therefore, their performance parameters values of $\dot{Q}_{u,m}$, η_m and the efficiency ratios are the same, as indicated in Table 2.

The data of Table 2 indicate that the percentage reduction of both $\dot{Q}_{u,m}$ and η_m due to dust accumulation during a period of one month is 12.5% and 5.5%, respectively for February month. On the other hand, the percentage reduction of both $\dot{Q}_{u,m}$ and η_m due to dust accumulation during the period of two months is 23.4% and 10.3%, respectively for January and February months. Table 2 also shows that the efficiency ratio dropped from 100% to 87.5% and to 76.5% due to dust accumulation duration of one and two months, respectively. This result indicates that the efficiency ratio dropped 23.5% due to dust accumulation period of two months.

Table 3 gives the calculated data for the four collectors for the month of March under the following conditions: Collector (A) is kept clean as required. Collectors (B) and (C) were kept un-cleaned of dust accumulation for one month until the end of March. Collector (D), on the other hand, is kept un-cleaned for three months duration of January, February and March as planned for

The data of Table 3 indicate that the percentage reduction of both $\dot{Q}_{u,m}$ and η_m due to dust accumulation during a period of one month is 9.3% and 3.4%, respectively for March month. On the other hand, the percentage reduction of $\dot{Q}_{u,m}$ and η_m due to dust accumulation during a period of three months is 27.8% and 10.2%, respectively for January, February and March months. Table 3 also indicates that the efficiency ratio dropped from 100% to 90.8% and to 72.4% due to dust accumulation during one and three months, respectively.

Table 4 shows the obtained results of the four collectors for the month of April under the following conditions: Collector (A) is kept clean of duct accumulation as usual, collector (B) is kept un-cleaned during the month of April as required, collector (C) is kept un-cleaned for the two months of March and April as planned, while collector (D) is kept un-cleaned for the four months duration of January, February, March and April

The data of Table 4 indicate that the percentage reduction of both $\dot{Q}_{u,m}$ and η_m due to dust accumulation on the glass cover of the experimented flat plate collector during a period of one month is 11.4% and 4.0%, respectively for April month. On the other hand, the percentage reduction of $\dot{Q}_{u,m}$ and η_m due to dust accumulation during a period of two months of March and April is 17.0% and 6.0%, respectively. Similarly, the percentage reduction of $\dot{Q}_{u,m}$ and η_m due to dust accumulation during a period of four month of January through April is 31.9% and 11.3%, respectively. The efficiency ratio dropped from 100% to 88.7% and to 83.1% due to dust accumulation of one and two months, respectively. On the other hand, the efficiency ratio dropped from 100% to 68.2% due to dust accumulation period of four months. This indicates that the efficiency ratio decreased by 31.8% due to dust accumulation during four months period.

Tables 1-4 indicate that the monthly useful heat gain rate, $\dot{Q}_{u,m}$ for the dust clean collector reached a maximum value of 89.4 kW for February month. This is due to the high value of the measured incident solar radiation during this month. On the other hand, the minimum value of useful heat gain rate of the dust free collector is 38.2 kW and occurred during the month of January. This is due to the low value of the measured incident solar radiation during this month. The maximum value of the monthly thermal efficiency, η_m for the clean collector reached a value of 43.9% for the month of February while the minimum value of the monthly efficiency, η_m of the cleaned collector reached a minimum value of 21.5% for the month of January.

Tables 1-4 also show that the maximum values of $\dot{Q}_{u,m}$ and η_m due to dust accumulation for one month duration is 78.2 kW and 38.4%, respectively and both occurred for the month of February. On the other hand, the minimum values of $\dot{Q}_{u,m}$ and η_m due to dust accumulation during one month reached 27.3 kW and 15.4%, respectively and both occurred for the month of January. Tables 1- 4 also indicate that the efficiency ratio dropped by 12.5% and 23.5% due to dust accumulation periods of one and two months periods. On the other hand, the efficiency ratio dropped by 27.6% and 31.8% due to dust accumulation periods of three and four months periods. This result indicates the importance of keeping the solar thermal systems free of dust accumulation throughout their operation period.

Tables 2-4 show that the maximum values of $\dot{Q}_{u,m}$ and η_m due to dust accumulation during two months is 68.5 kW and 33.6%, respectively. On the other hand, the minimum values of $\dot{Q}_{u,m}$ and η_m for two months duration due to dust accumulation are 61.2 kW and 29.5%, respectively. Table 3 indicates that the values of $\dot{Q}_{u,m}$ and η_m due to dust accumulation for three months duration are 55.1 kW and 26.7%, respectively. If the collector is allowed to accumulate dust for four months duration then Table 4 indicates that the values of $\dot{Q}_{u,m}$ and η_m are 50.2 kW and 24.2%, respectively.

The obtained results of the present work indicate that the influence of natural dust accumulation on the glass cover of the flat plate solar collectors have the following effects:

(a) The percentage of fractional reduction of the useful heat gain rate due to dust accumulation for one month is 28.5% for January month, 12.5% for February month, 9.3% for March month and 11.4% for April month.

(b) The percentage of fractional reduction of the useful heat gain rate due to dust accumulation for duration period of two months is 23.4% for January and February months and 17.0% for March and April months.

(c) The percentage of fractional reduction of the useful heat gain rate due to dust accumulation for duration period of three months is 27.8% for the months of January, February and March.

(d) The percentage of fractional reduction of the useful heat gain rate due to dust accumulation for duration period of four months is 31.9% for the months of January, February, March and April.

(e) The percentage decrease of monthly efficiency due to dust accumulation for duration period for one month is 6.1% for January month, 5.5% for February month, 3.4% for March month and 4.0% for April month. On the other hand, the efficiency ratio decrease for one month is 28.4% for January month, 12.5% for February month, 9.2% March month and 11.3% for April month.

(f) The percentage decrease of monthly efficiency due to dust accumulation for duration period of two months is10.3% for January and February months and 6.0% for March and April months. On the other hand, the efficiency ratio decrease for two months is 23.5% for January and February months and 9.2% for March and April months.

(g) The percentage decrease of monthly efficiency due to dust accumulation for duration period of three months is 10.2% for January, February and March months. On the other hand, the efficiency ratio decrease for three months is 27.6% for January, February and March months.

(h) The percentage decrease of monthly efficiency due to dust accumulation for duration period of four months is 11.3% for January, February, March and April months. On the other hand, the efficiency ratio decrease for four months is 31.8% for January, February, March and April months.

5. Conclusions

The present work discussed the influence of natural dust accumulation on the performance parameters of flat plate solar collector for various month durations at the climate conditions of Amman, Jordan. The following conclusions emerged from the present investigation:

- The percent range values of useful heat gain rate reduction for one and two months exposure to dust accumulation are 9.3% to 28.5 and 17.0% to 23.4%, respectively.
- The percent value of useful heat gain rate reduction for three and four months exposure is 27.8% and 31.9%, respectively.
- The percentage decrease ranges of thermal efficiency due to one and two months of dust accumulation exposure are 3.4% to 6.1% and 6.0% to 10.3%, respectively.
- The percentage drop ranges of efficiency ratio due to one and two months of dust accumulation exposure are 9.2% to 28.4% and 9.2% to 23.5%, respectively.
- The percentage decrease of thermal efficiency due to three and four months of dust accumulation is 10.2% and 11.3%, respectively.
- The percentage drop ranges of efficiency ratio due to three and four months of dust accumulation exposure are 27.6% and 31.8%, respectively.
- The dust effect value on the performance parameters of solar energy systems depends on the climate conditions of the location, exposure period of dust accumulation, and month of the year.
- The performance parameters of solar energy systems can be significantly improved if their glass covers are cleaned of dust accumulation at regular intervals of time, say one week or month.

Acknowledgments

The author is grateful to the Applied Science Private University, Amman, Jordan, for the financial support granted to this research (Grant No. DRGS-2014-2015-153).

References

Alsaad, M.A. (1999), "Transmitted solar Radiation through Jordanian windows of various orientations", *World Renewable Energy Congress*, Kuala Lampur , September.

Alsaad, M.A., Jubran, B.A. and Abu-Faris, N.A. (1994), "Development and testing of concrete solar collectors", *Int. Solar Energy*, **16**, 27-40.

Duffie, J. and Beckman, W. (2006), *Solar Engineering of Thermal Processes*, Wiley, New York, New York, USA.

Hai, J., Lin, L. and Ke, S. (2011), "Experimental investigation of the impact of air born dust deposition on the performance of solar photovoltaic (PV) power plant", *Atmosph. Environ.*, **45**, 4299-4304.

Hegazy, A. (2001), "Effect of dust accumulation on solar transmission through glass cover of flat-plate collectors", *Renew. Energy*, **22**(4), 525-740.

Hrayshat, E. and Al-Soud, M. (2004). "Solar energy in Jordan: current state and prospects", *Renew. Sustain. Energy Rev.*, **2**,193-200.

Jubran, B.A., Alsaad, M.A. and Abu-Faris, N.A. (1994), "Computational evaluation of solar energy systems using concrete solar collectors", *Energy Conver. Manage.*, **35**(12) 1143-1145.

Mastekbayera, G.A. and Kumar, S. (2000), "Effect of dust on the transmittance of a 0.2 mm thick low density polyethylene glazing in a tropical climate", *Solar Energy*, **68**(2), 135-141.

Sulaiman, S.A., Hussain, H.H., Leh, N.S.H.N. and Razali, M.S. (2011), "Effect of dust on the performance of PV panels", *World Acad. Sci. Eng. Tech.*, **58**, 588-593.

CC