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Effect of dust accumulation on solar transmittance through glass covers of plate-type collectors

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Abstract

Dust accumulation on glass plates with different tilt angles and associated reductions in solar transmittance have been experimentally investigated over a period of 1 year under the climate conditions of the Minia region, middle of Egypt. The glass plates were never cleaned during the experiment duration of 1 month to allow dust to accumulate. The results showed 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. Based on the data obtained, an empirical correlation, accurate to ±6%, is developed which allows for the calculation of the reduction in glass transmittance for a given tilt angle after a number of days of exposure to the atmosphere. For design purposes and in the absence of any specific data, the literature comparisons encourage the use of the correlation for other neighboring regions along the desert belt that extends from the Atlantic Ocean to the Persian Gulf. For moderately dusty places, weekly cleaning of the glass covers of solar panels is strictly recommended as part of the maintenance routine, but equipment should be cleaned immediately after a dust storm to retain nominal operating efficiency. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Dust effect; Transmissivity degradation; Suspended dust

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Nomenclature

D	day number since last cleaning
F_d	transmittance dust factor = τ/τ_{clean}
MABE	mean absolute error, $\sum\{\text{Abs}[x_{measured}-x_{predicted}]\}/N$
N	number of data points
RMSE	root mean square error, $\sqrt{\sum[x_{measured}-x_{predicted}]^2/N}$
x	dummy variable

Greek symbols

β	tilt angle from the horizontal (degrees)
τ	transmittance of dusty glass plate
ω	weight of dust deposition (g/m^2)

1. Introduction

Nowadays, solar energy is widely used in heating water, dehumidifying air and generating electrical energy for many domestic, agricultural and industrial applications. For these applications, the most important piece of the system equipment is the solar collector in which solar energy is converted into heat or electrical power. Although there are several designs for solar energy collecting devices, flat-plate collectors are the most common and popular type all over the world. They have the advantages of being simple to build, employing locally available materials, they are easy to operate and maintain, they have the ability to function even during cloudy or hazy days with diffuse solar radiation only, and they are capable of integration into a roof or a wall structure.

A search of the literature revealed that most published studies on flat-plate collectors have concentrated on the parameters which affect the performance such as: (a) geographical and climatological factors, (b) collector orientation, inclination and geometrical parameters, (c) the nature, rate and pattern of the working fluid, (d) collector fabrication and materials, etc. The publications on the subject now amount to several thousands of papers reported by a large number of investigators, who have analyzed and discussed in detail the performance characteristics (thermal and/or electrical) of the various models of such a type of collector. Also, information on this body of research is well documented in several comprehensive articles, e.g. [1–3]. Nevertheless, most of these studies were limited to clean transparent-cover conditions and few have attempted to examine the effects of dirt and dust accumulation.

Hottel and Woertz [4], in one of the earlier studies, carried out 3-month performance tests on collectors having a 30° tilt angle and located in an industrial district near a power plant and 92 m away from a four-track railroad. Experimentally they found that the effect of dirt on the collector's net performance was surprisingly small (4.7% max.), while the calculations indicated 2.7% maximum reduction in glass transmittance. They attributed these small values to the collector's self-cleaning action, incorporated due to snow and rainfall in Boston, MA. In a similar investigation, but for tilt angles between 0 and 50°, the data of Dietz [5] showed a reduction in the solar radiation reaching the collector by a factor of 5% due to dirt accumulation. This finding was recently affirmed by Michalsky et al. [6], when two pyranometers were sat side-by-side for 2 months in Albany, New York. One of the pyranometers was cleaned daily while the other was left unattended, but during this period the test site had some rain at least once every 10 days. Even so, less than 1% decrease in the values of the unclean pyranometer was observed.

On the other hand, there are a number of studies in the literature concerning the effect of dust on solar devices in rainless and arid regions. In a 30-day experiment in Roorkee, India, where dust storms are frequent, Garg [7] investigated the effect of dust on the transmittance of solar radiation through various inclined glass plates and plastic films. Dust accumulation on a glass plate tilted at 45° was found to reduce the transmittance by an average of 8% after an exposure period of 10 days, which is significantly different from the values reported above for rainy sites. Similar measurements were made in Kuwait by Sayigh et al. [8], who 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°, respectively. Also, Nimmo and Seid [9] reported 15 and 30% deterioration in the long-term efficiency of the thermic and photovoltaic panels tilted at an angle of 26° due to dust deposition over respective periods of 2 and 4 months in Dhahran, Saudi Arabia. Recently, El-Nashar [10] examined the effect of dust accumulation on the performance of evacuated-tube flat-plate type collectors over different time periods, extending from 1 month to a whole year, in the United Arab Emirates. It was found that the monthly percentage decline in glass transmissivity is seasonal in nature, between 10% during summer and 6% for winter. However, a 70% reduction in the collector performance is observed when the collector was left without cleaning for a whole year.

Wind tunnel simulations and field experiments were conducted by Goossens et al. [11] to investigate the deposition of atmospheric dust on photovoltaic collectors. They concluded that wind direction and collector orientation have a serious impact on dust deposition and distribution. Also, wind velocities greater than 2 m/s have only a small effect on the distribution of dust deposition. Recently, laboratory experiments of dust accumulation on the surface of photovoltaic panels were made by El-Shobokshy and Hussein [12] using five kinds of dust having different physical properties. The results indicated that fine particulate dust significantly deteriorates the performance of photovoltaic panels, more so than coarser particles.

The above literature survey indicates that the effect of the accumulation of atmospheric dust on the transparent covers of plate-type solar devices has not received much attention, especially in countries with dusty climates. The limited published studies, on the other hand, do not provide enough information about the dust deposition rate in the test site nor its physical properties. More data are, thus, required for design purposes and to generalize the reduction in glass solar transmittance due to dust accumulation. These are the motivations of the present investigation.

This paper reports on the intensive experiments which were carried out over a period of 1 year in the Minia region, middle of Egypt. This area is similar to the southern part of Egypt where the Nile Valley is narrow and runs through the Egyptian deserts. Accordingly, winds that originate either from the eastern or western deserts are relatively dry and laden with fine dust particles. Dust emissions from agricultural activities and operations such as soil cultivation and harvesting also contribute to ambient particulate levels. Since the Minia region has a latitude of 28° N (longitude of 30.5° E), the reported results may, thus, be used for other communities along the desert belt, which extends from the Atlantic Ocean (longitude 15° W) to the Persian Gulf (longitude 60° E). This is true in the absence of any specific data regarding dust accumulation in a particular location.

2. Site climate and data collection

Careful experiments were conducted on the roof of the solar energy laboratory, Minia Faculty of Engineering, which is surrounded by agricultural fields. Data were collected over a period of 1 year so that different weather conditions prevailing in the Minia region were adequately considered. Like most subtropical regions along the North African desert, the Minia site (latitude 28° N and longitude 30.5° E) has mainly two seasons: summer and winter, with a very short spring (March and April) and autumn (October and November). Summer (May to mid-October) is hot whilst winter (December to February) is cold as they are affected by the respective warm-law and cold-law barometric pressure systems that cross the eastern Mediterranean basin. The prevailing winds are mostly from the N–W sector trajectories, especially form the NW direction, with an average velocity of 1.5 m/s, but gusts of up to 3–4 m/s may be experienced in early morning and late afternoon. Dust storms also occur during April and May when the Khamsin winds blow over the Egyptian western desert with a wind speed of the order of 10 m/s or less.

The average summer temperature is 36°C while that of winter is 16°C, with an average difference between day and night of approximately 14°C. This great temperature difference promotes the formation of dew at dawn as the relative humidity of the air becomes generally high, especially during the winter season. Dew formation aids dust settling on collectors' flat surfaces, while evaporation, on the other hand, reinforces dust adhesion to these surfaces. Rainfall is rare and usually occurs during the months of October and March, with an annual average of less than 50 mm.

The experimental arrangement consisted simply of nine small square glass plates cut from a larger one: each 3 mm thick and with an exposed surface area of 0.09 m^2. One plate was kept constantly clean and was used as a base case, while the others were laid on wooden frames with 40×40 cm^2 flat surfaces facing south and having different inclination angles, β=0, 10, 20, 30, 40, 50, 60 and 90° from the horizontal. These specific tilt angles were chosen with the view that the optimum tilt angle of a collector in the Minia region is achieved by tilting the collector upwards towards the equator by the same number of degrees as the site latitude plus 0–30° during the period extending from mid-September to mid-March or minus 0–28° for the rest of the year [13]. The 90° inclination was chosen as the other extreme to the 0° horizontal plate case. The wooden frames were arranged side-by-side on a large table placed on the laboratory roof, thereby maintaining identical exposure to the environment. The inclined surface of each frame was covered with a commercial polyethylene sheet to protect the unexposed surface of the glass plate from “involuntary” scratches. Beside each glass plate was placed a small clean glass piece with a precisely known surface area ($7\times7 cm^2$) and weight (≈39 g) to determine the average dust quantity that settled on each plate. After a predetermined number of days of exposure to the atmosphere, each glass piece was weighed using a digital precision balance, accurate to within 0.0001 g. The difference between the measured and initial (clean condition) weight values was divided by the glass piece surface area to obtain dust deposition ω in g/m^2.

An Eppley pyranometer was incorporated in determining normal solar transmittance through clean and dusty glass plates. The pyranometer was placed inside a $30\times30\times15 cm^3$ wooden box painted “matt” black, while the required plate was situated atop of the box as a cover. The box was fastened to a table assembly that could be adjusted, and in turn the whole arrangement was normal to the incident solar radiation. The table board was equipped with a solid perpendicular rod, the shadow of which was used to judge if the table was normal to the sun radiation. Nevertheless, solar transmittance through the different glass plates, including the clean one (base case), were determined at noon time after 3, 10, 15, 18, 23 and 30 days of exposure to the environment. The glass plates were left without cleaning throughout the duration of the experiment, but at the end of the month all glass plates and pieces were cleaned with detergent and distilled water, then dried with soft paper. For a particular day, the dust transmittance factor F_d was determined as the ratio between dusty and clean normal solar transmittance values of a particular glass plate or

$$F_d=\tau/\tau_{clean} \tag{1}$$

where τ is the solar transmittance of the dusty plate.

An uncertainty analysis was carried out to determine the uncertainties in the experimental data using the method described by Kline [14]. The maximum uncertainties in the values of the dust deposition ω and the transmittance factor F_d were estimated to be 5% and 3%, respectively.

3. Results and discussion

Extensive experimental data regarding the effect of dust accumulation on solar transmittance through inclined glass covers have been obtained. Seven glass plates were tilted at different angles between 0 and 60° in steps of 10°, while the eighth plate was placed vertically, i.e. β=90°. These plates were exposed to the ambient conditions and left without cleaning for a period of 30 days. Measurements of normal transmittance through these dusty plates were, however, made during this period and compared with that of a clean plate. Dust accumulation over the various glass plates was in general uniform, forming a thin yellowish brown dust layer by the end of the month. Nonetheless, the thinness of the dust layer and in turn the quantity of dust deposition were strongly dependent on plate tilt, as discussed later. Examination of the dust particles that accumulated on the different glass pieces under the microscope revealed a similar correlation between particle size and tilt angle. Only fine particles with a mean diameter of about 1 μm had settled on the vertical plates, while a mixture of both fine and relatively coarse particles was found to be deposited on the horizontal plates, giving rise to a particle mean diameter of up to 3 μm.

Fig. 1 shows the degradation in the glass normal transmittance due to dust accumulation, F_d, in terms of the days of exposure since the last cleaning. To avoid massive data overlap, the figure encompasses eight individual curves which pertain respect-

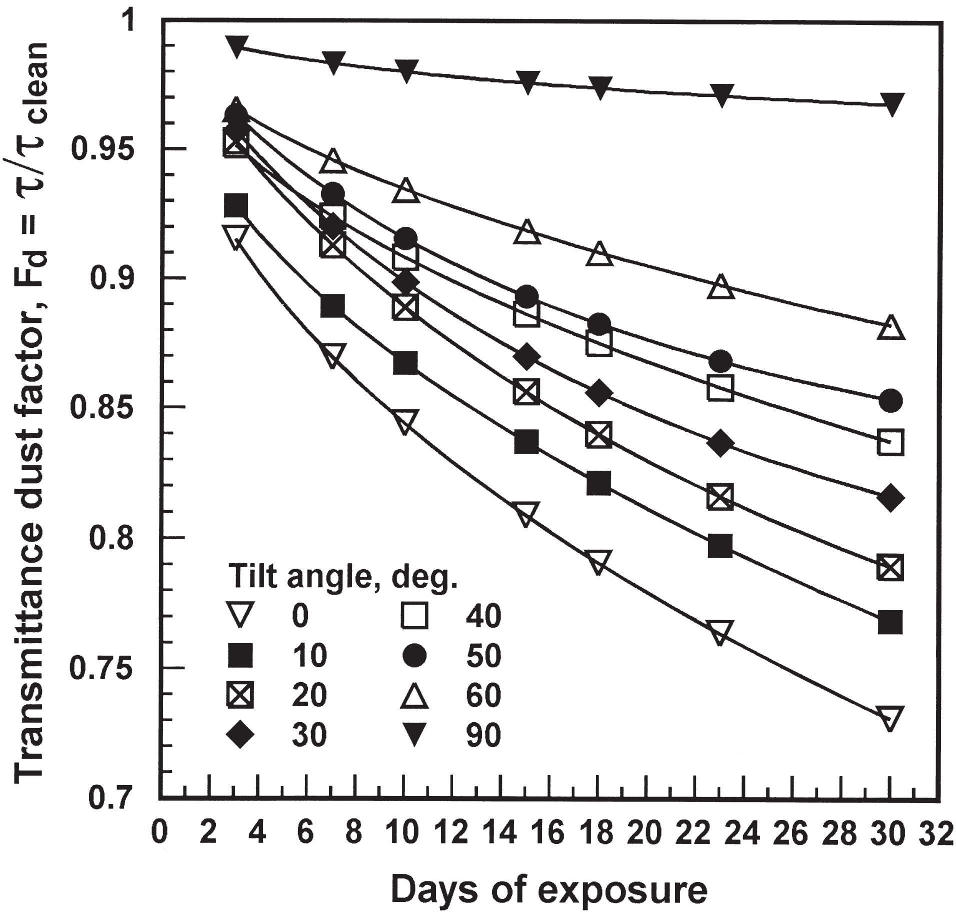

Fig. 1. Degradation in solar transmittance of the various tilted glass plates versus the days of exposure to atmospheric dust.

ively to fixed tilt angles of β=0, 10, 20, 30, 40, 50, 60 and 90° from the horizontal. Each curve represents the least-squares fit of the actual data-set of a particular tilt angle. In this format, the effects of tilt angle and the exposure period are readily identified. From a careful examination of Fig. 1, a number of dust-related effects can be distinguished. First of all, the general level of transmittance deterioration increases as the number of exposure days increases. This is due to the continuous accumulation of dust particles on the plate's surface. Second, deterioration persists due to smaller tilt angles and long exposure periods as more coarse and fine particles are caught by the semi-horizontal surfaces. Finally, deterioration sensitivity to exposure period diminishes at tilt angles $\beta \geq 50°$ after 2 weeks of exposure to the environment.

Another basic issue of the research is the role of dust deposition in the Minia region in reducing solar transmittance through glass covers. This issue is addressed in Fig. 2, where the experimental data are plotted as the percentage reduction in glass transmittance $(1-\tau/\tau_{clean})$% versus dust deposition ω, g/m^2. Clearly, dust deposition has a decisive effect on solar transmittance through the various inclined glass plates. Also, the variation in the data is consistent, showing a continuous reduction in glass transmittance with dust deposition, irrespective of the tilt angle β. However, it is obvious that the rate of transmittance reduction is relatively higher at lower dust deposition. In fact, as dust deposition increases, transmittance reduction increases too, but with a progressively decreasing rate until reaching its upper limit of 100%, whereafter the effect of dust deposition vanishes. Accordingly, it is reasonable to seek the following simple correlation form

$$(1-\tau/\tau_{clean})\% = d_1 \,\mathrm{erf}(d_2 \omega^{d_3}) \tag{2}$$

to reflect this natural behavior between dust deposition and transmittance reduction. The empirical coefficients d_1, d_2 and d_3 are evaluated from a nonlinear regression analysis of the experimental data and the resulting expression for an exposure period of 1 month is

$$(1-\tau/\tau_{clean})\% = 34.37 \,\mathrm{erf}(0.17\omega^{0.8473}) \tag{3}$$

A statistical error analysis was also carried out which gave a MABE of 1.29 and a RMSE of 1.54. The comparison between the correlation predictions and the data is shown by the solid line in Fig. 2.

Fig. 3 displays the correlated dust quantities (g/m^2) that settled on the different glass pieces, having tilt angles β between 0 and 90°. The data in the figure are parameterized by the exposure period and are connected with different lines to provide continuity. As shown in Fig. 3, the biggest amount of dust is attained at the smallest tilt angle, β=0°, irrespective of the number of exposure days. As β increases, however, dust deposition starts to decrease, but gradually, until it levels off at a maximum tilt of 90°, with the leveling-off taking place in the range of $\beta > 40°$, depending on the exposure period. The striking feature in Fig. 3 is the decrease in the rate of dust deposition of a particular tilt angle after 2 weeks of exposure to weather conditions. This is attributed to the wind "blowout" action, which reduces the deposited amount of dust fall. Actually, some dust particles which have accumu-

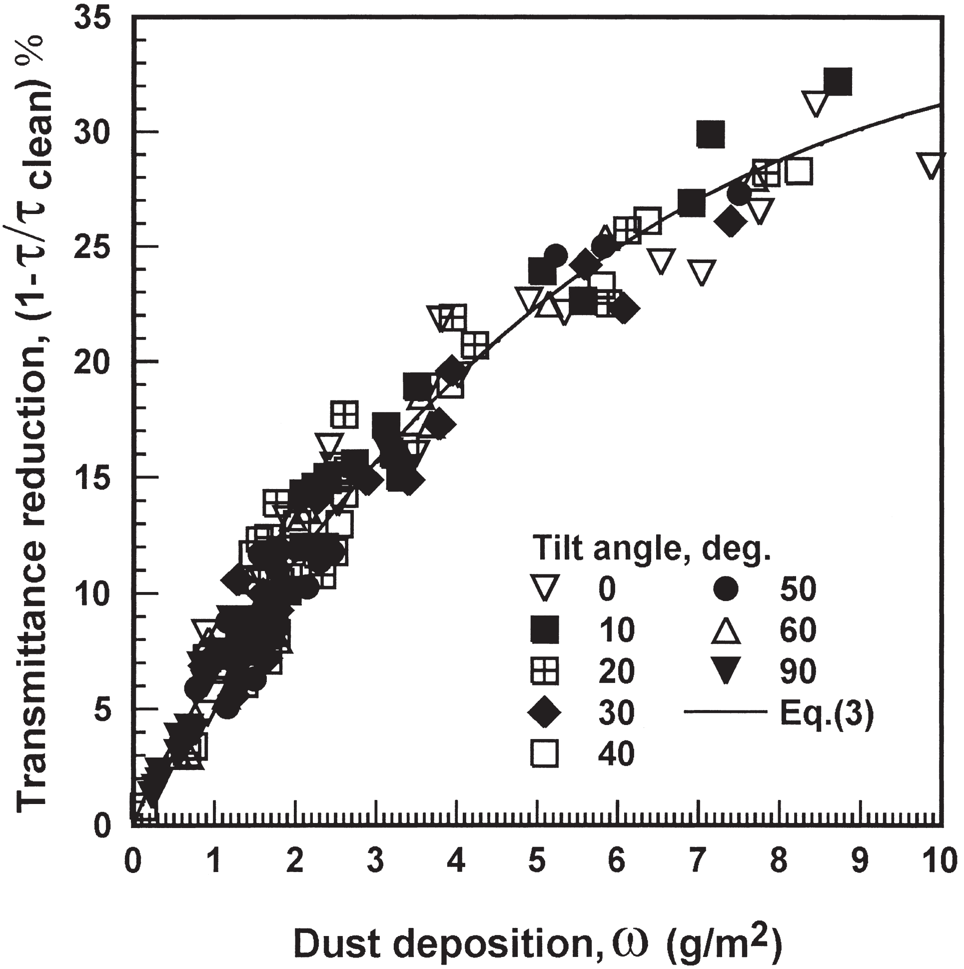

Fig. 2. Observed reduction in glass transmittance versus dust deposition and best fit as given by Eq. (3).

lated on the plate's surface during the period of light winds do not remain until the end of the experiment because subsequent stronger winds will cause them to be re-suspended in the air flow and undergo aerial transportation.

To explore in greater detail the relationship between dust deposition, tilt angle, exposure period and transmittance reduction, Fig. 4 has been prepared. The format of the figure is identical to that of Fig. 3, but the ordinate shows the least-squares values of the reduction in glass transmittance instead of dust deposition. Aside from some minor differences in detail, it is clear that the qualitative characteristics already identified for dust deposition appear to be re-produced for transmittance reduction data. Obviously, large transmittance reductions are encountered as the tilt angle is decreased, which is directly attributed to the increase in dust deposition on the plate's

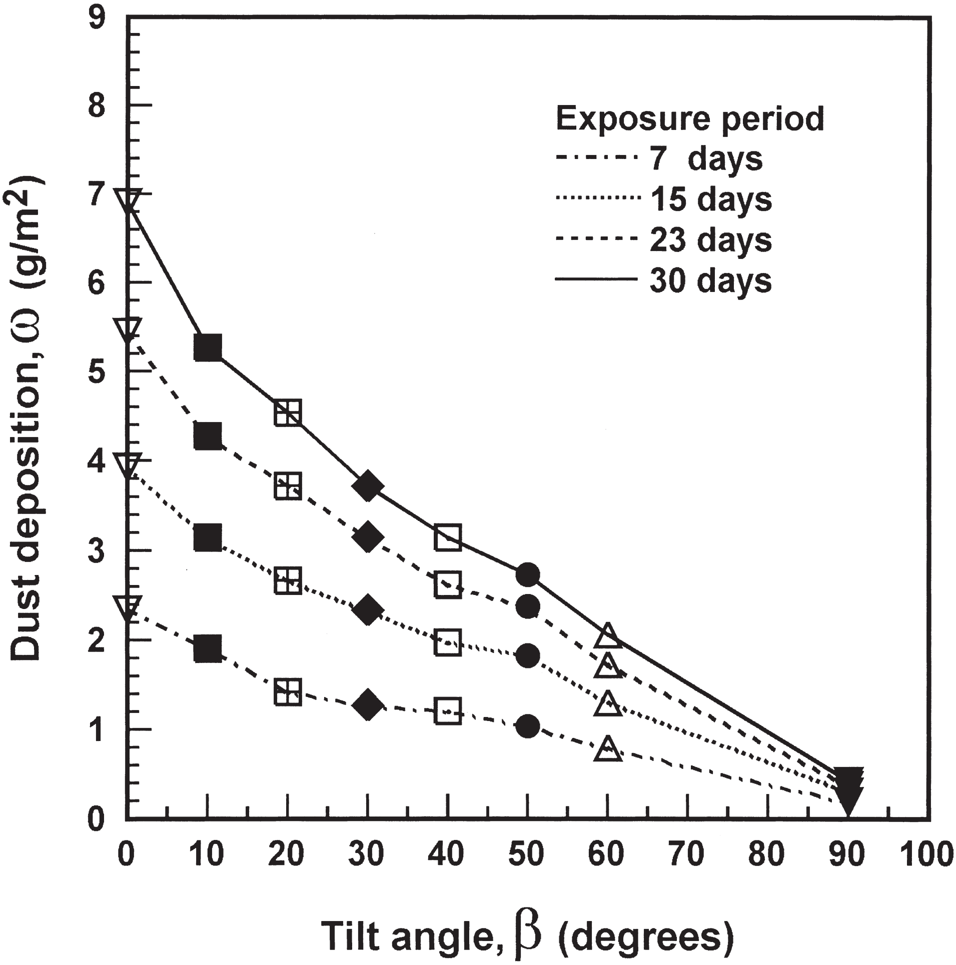

Fig. 3. Variation of dust deposition with tilt angle for different exposure periods.

surface, as displayed in Fig. 3. Furthermore, there is a significant degradation in glass solar transmittance for longer exposure periods and smaller tilt angles $\beta<40°$. However, transmittance degradation decreases much more rapidly upon increasing β (as the dust deposition decreases to) with a definite tendency for all curves to come together at larger tilt angles, $\beta\geq50°$.

4. Literature comparisons

The present data of Minia (latitude 28°N and longitude 30.5° E), Egypt and the data reported by Garg [7] for Roorkee (latitude 29° N and longitude 77° E), India and by Sayigh et al. [8] for Kuwait (latitude 29° N and longitude 47.5° E) are

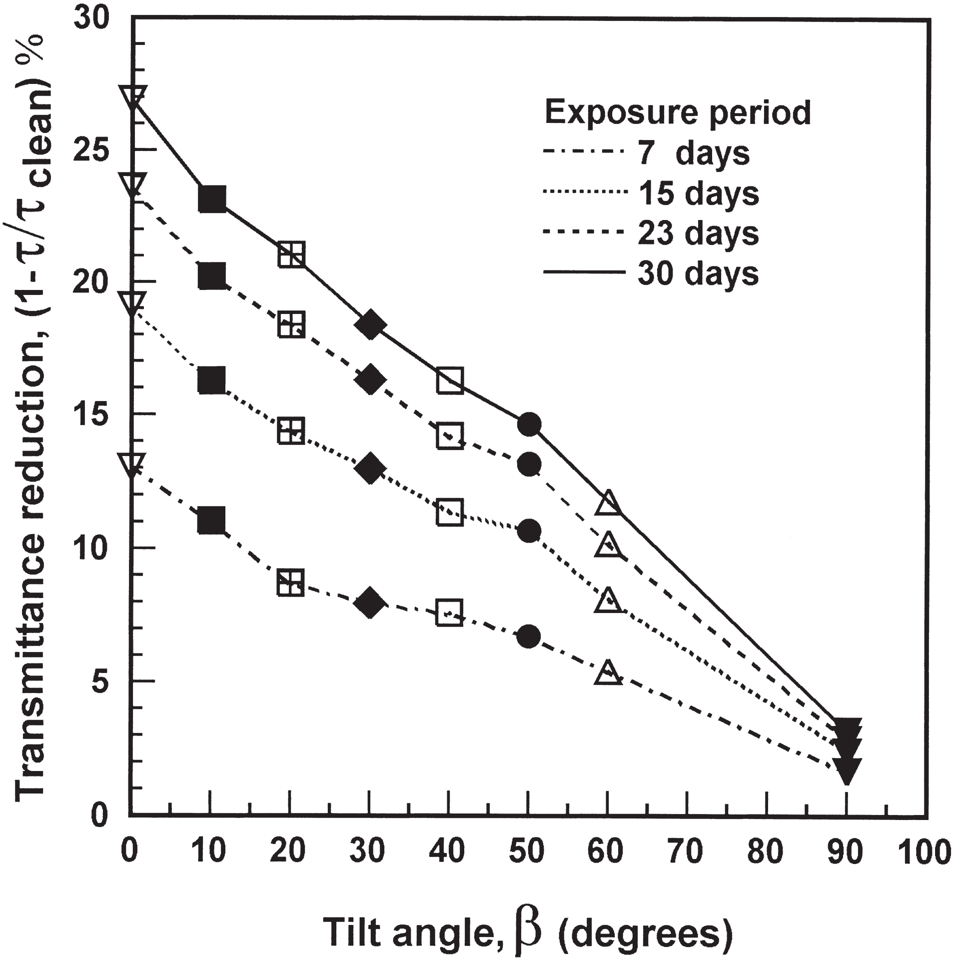

Fig. 4. Reduction in glass transmittance with tilt angle for different exposure periods

compared in Figs. 5 and 6. Fig. 5 shows the dust transmittance factor F_d for various inclined glass plates after 10 days of exposure to the environment in these three different countries. Clearly the data of Kuwait exhibit a similar behavior to those of Egypt, but the degradation in transmittance is higher by approximately 17% at β=0°, down to 7% at β=60°. In contrast, the data of India is within ±3.5% of the Minia data in the range of 35°≤β≤90°, but the deviation increases with decreasing tilt angle, reaching approximately 26% at β=0°. Accordingly, it can be concluded that for tilt angles β≤30°, dust deposition and accumulation and in turn the transmittance factor F_d are very site-dependent as they are greatly affected by the prevailing climate conditions. This point is further discussed later in this section.

In general, each particular set of data shown in Fig. 5 exhibits a noticeable change in the variation of the dust factor F_d with tilt angle for β>50°. This is in line with

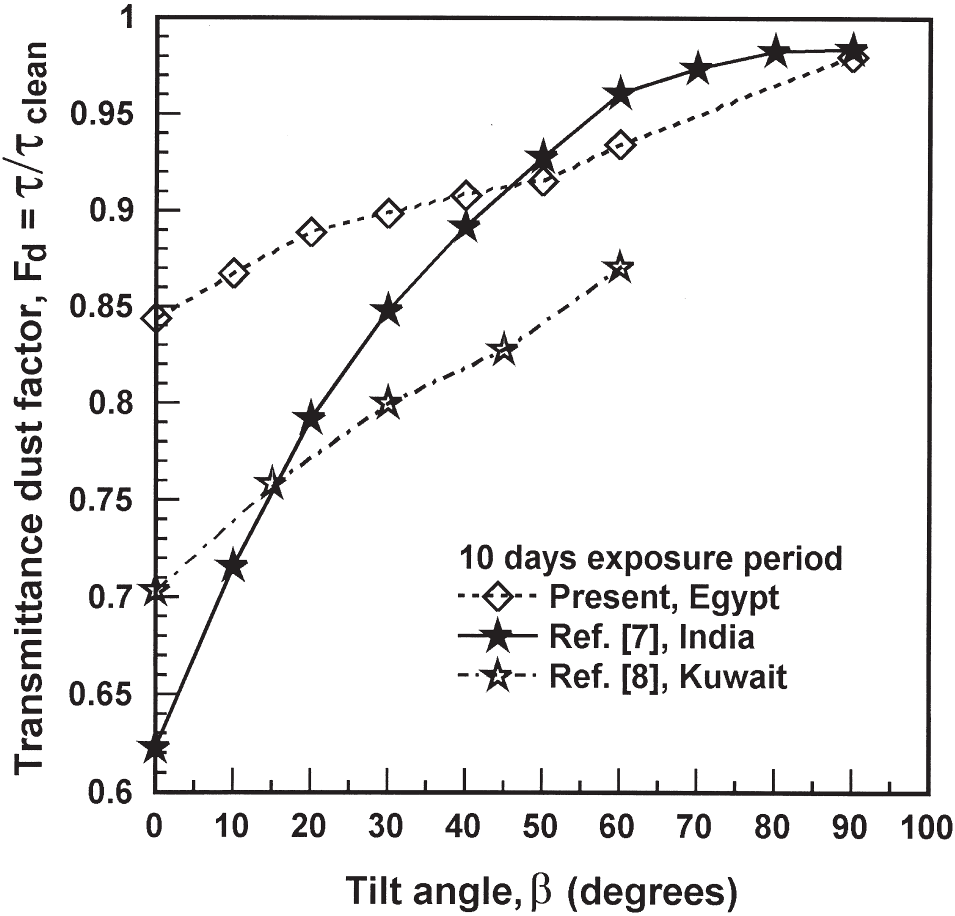

Fig. 5. Comparison of dust transmittance factors for various tilted glass plates after 10 days of exposure in different countries.

the finding that both coarse and fine particles are observed to accumulate on various inclined glass plates having $\beta<40°$, while fine dust particles are the only particulates that settled on these plates when $\beta>50°$.

Fig. 6(a, b) shows the variation in the dust factor F_d with the days of exposure under the climate conditions of the above-mentioned three countries for two tilt angles β=30° and 60°. Although there is no reason to expect very close agreement between these different results, the data of India [7] are within ±3% after 1 week of exposure, while the data of Kuwait [8] are always below the Minia data by 8% and 5% for β=30° and 60°, respectively. With increasing exposure period, however, the deviation between the various sets of data is found to increase only for smaller tilt angles, but remains almost constant and within experimental uncertainty for $\beta\geq60°$, as shown in Fig. 6(b, c).

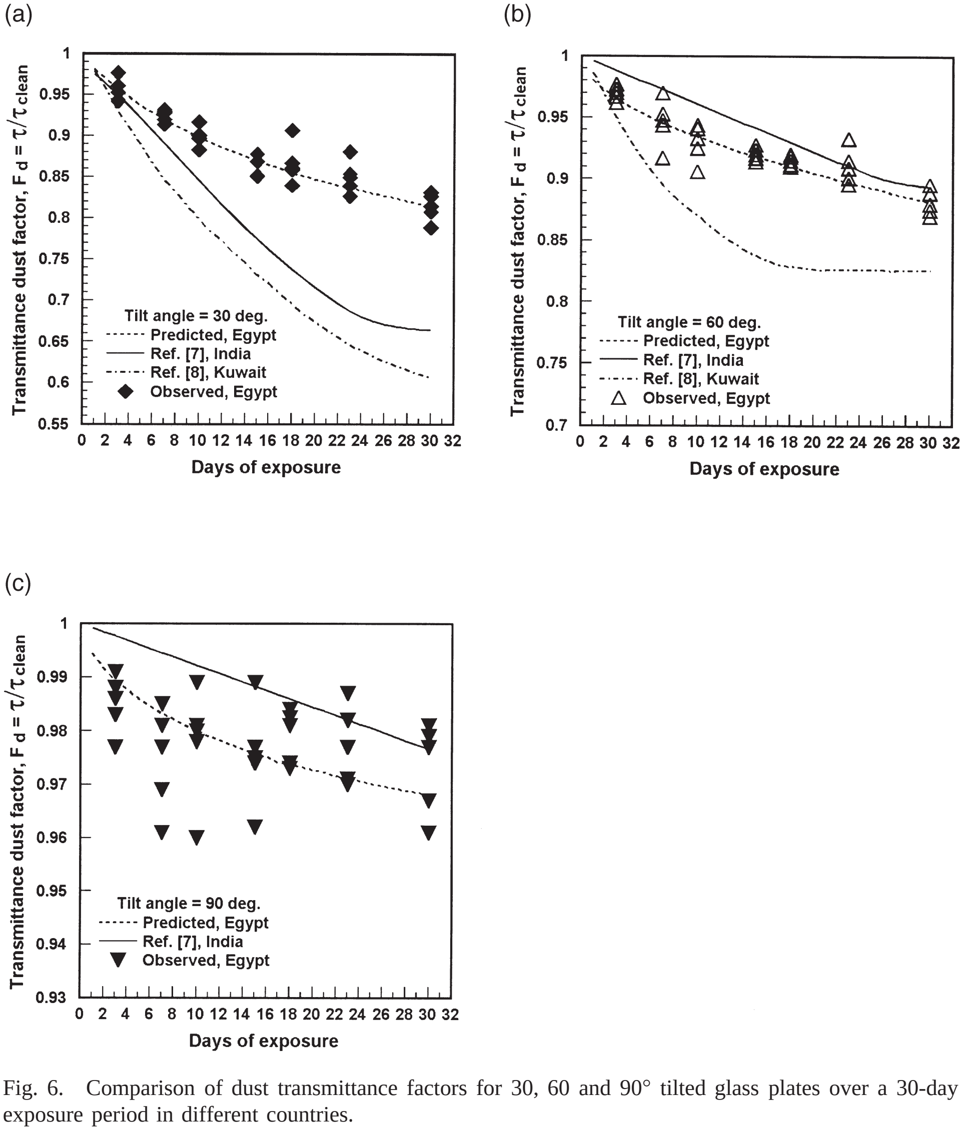

Fig. 6. Comparison of dust transmittance factors for 30, 60 and 90° tilted glass plates over a 30-day exposure period in different countries.

The noteworthy feature of Fig. 6(c) is that the data set of Egypt corresponds well with the data of India [7] and shows approximately 4% maximum degradation in glass transmittance for 90° tilt angle over a 30-day exposure period. Considering the fact that very fine dust particles were the only particulates adhered to the surfaces of nearly vertical plates, it can thus be concluded that for moderately dusty places, dust accumulation and associated effects are largely determined by particle size and weight, in addition to local climate conditions. This conclusion is supported by the results of Feuermann and Zemel [15], who found only 3% reduction in the pyranometer's response after 30 days of exposure under the desert conditions prevailing at Sede Boqer (≈latitude 30.5° N and longitude 35° E), Israel. In fact, dust deposition on the concave dome of the pyranometer is approximately the same as the amount accumulated on the flat surface of a vertical plate, which resulted in only a 1% difference in the values of the dust factor.

Finally, it should be pointed out that although the above comparisons may be regarded as supporting the present measurements, they also suggest some kind of generalization for the effect of dust accumulation on solar transmittance through glass plates used in solar energy devices. Furthermore, the results indicate that for moderately dusty places, weekly cleaning of solar panels is strictly necessary for smaller tilt angles, $\beta<60°$, but while desirable, it is dispensable for larger tilt angles.

5. Design correlations

Although the data presented in Fig. 1 provide good information about the dust factor for tilted glass plates, they may be cumbersome for design purposes. We have, therefore, derived simple correlations in terms of the exposure days D for each data set of a particular tilt angle in the form of

$$F_{\mathrm{d}}=(1-a)+a\exp(bD^{c}) \quad (4)$$

which is easiest to use and incorporate. The empirical coefficients a, b and c, which appear in Eq. (4), were determined for each tilt angle and are given in Table 1 along with the corresponding MABE and RMSE values.

Moreover, correlation attempts were carried out to generate a more comprehensive relation for the overall data in terms of the exposure period in days, tilt angle and the three coefficients a, b and c indicated in Eq. (4). Consideration of this large number of variables coupled with close examination of the data indicated the improbability of achieving a really tight correlation of a simple form. After a number of attempts utilizing equations of varying complexity, Eq. (4) was finally adopted,

Table 1
Values of the empirical constants a, b and c of Eq. (4) and error analysis results

Tilt angle (degrees)	$10^2\times a$	$-10^2\times b$	$10^2\times c$	MABE	RMSE
0	219.3	2.215	52.20	0.011	0.015
10	664.6	0.616	51.44	0.009	0.011
20	33.96	6.085	81.31	0.012	0.015
30	25.26	7.276	84.77	0.010	0.012
40	167.1	1.622	54.20	0.009	0.012
50	18.98	8.561	83.74	0.008	0.012
60	996.6	0.191	53.76	0.007	0.010
90	4.954	11.84	63.53	0.005	0.007

but the three coefficients a, b and c were permitted to depend on the tilt angle β as follows:

$$a=0.596-6.076\times10^{-3}\beta \quad (5)$$

$$b=-6.802\times10^{-2}+4.042\times10^{-4}\beta-1.056\times10^{-5}\beta^{2} \quad (6)$$

$$c=0.6413 \quad (7)$$

The analysis was carried out using a multivariable non-linear regression routine with a least-squares objective function. Eq. (4) in conjunction with Eqs. (5)–(7) correlate all the data of the present study to within ±6%, as shown in Fig. 7. The resulting MABE of 0.01 and RMSE of 0.013 confirm the accuracy of the general correlation.

To complement this section, it should be mentioned that dust deposition over a

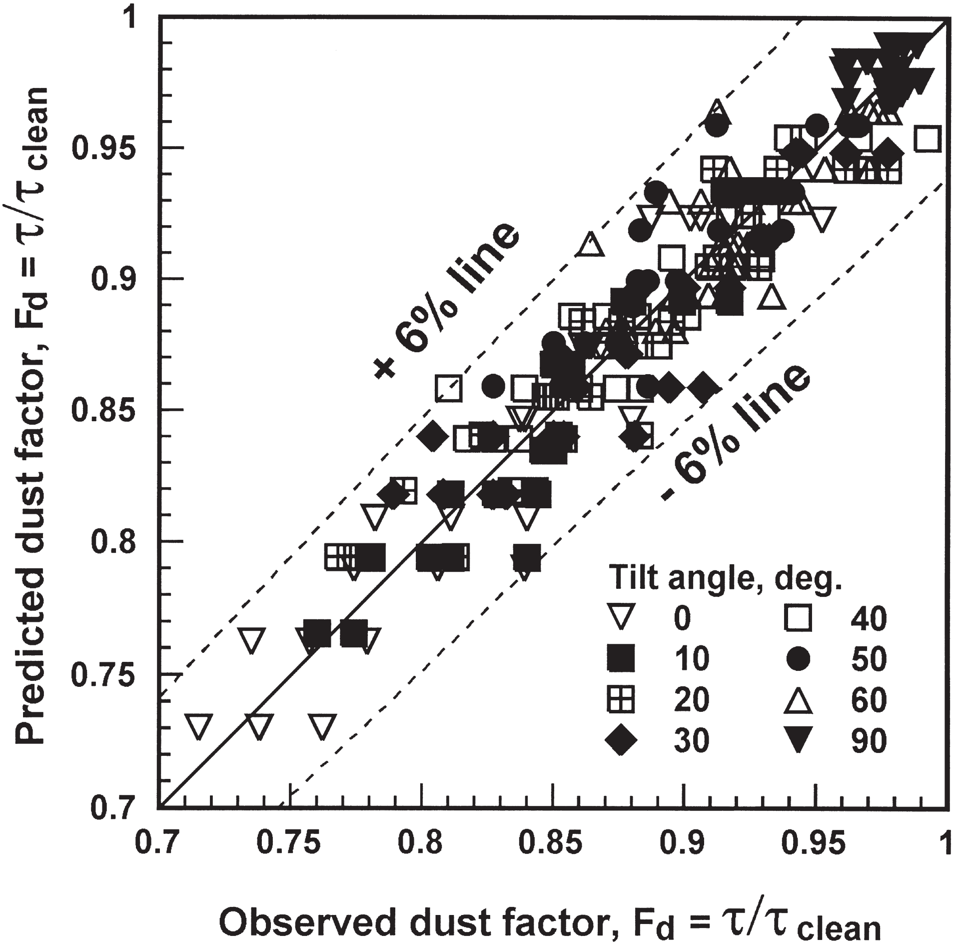

Fig. 7. Comparison of observed and predicted dust transmittance factors.

tilted glass plate after a certain exposure period, D, can be estimated by incorporating expressions (3) and (4). First, use correlation (3) to calculate dust factor F_d after employing the appropriate empirical coefficients a, b and c reported in Table 1 corresponding to the specific plate tilt angle β. Second, substitute the computed dust factor in correlation (4) and solve for the value of dust deposition ω, which necessitates information about the inverse of the Gauss error function $\mathrm{erf}^{-1}(x)$.

6. Conclusions

Dust accumulation effects on solar transmittance through glass plates with different tilt angles have been determined experimentally. The reduction in glass transmittance showed a strong dependence on the amount of dust that had settled on the plate's surface. Dust deposition is also found to be closely related primarily with the tilt angle and to a lesser degree with the exposure period and site climate conditions. Horizontal plates were the most contaminated, with a mixture of fine and coarse dust particles. In contrast, vertical plates caught the least amount of dust, consisting only of fine particles 1 μm in diameter. Data concerning reduction in glass transmittance have been summarized in terms of a global correlation between dust factor, tilt angle and number of exposure days since last cleaning. The correlation has a spread of ±6% and it is a step towards the generalization of the effect of dust accumulation on glass transmittance, although it is developed under the climate conditions of the Minia region, middle of Egypt. For design purposes, however, the literature comparisons encourage the use of the correlation for other neighboring regions along the desert belt, which extends from the Atlantic Ocean to the Persian Gulf. This is true in the absence of any specific data. For moderately dusty places, weekly cleaning of solar panels is strictly recommended as part of the maintenance routine. Nevertheless, equipment should be cleaned immediately after a dust storm to retain nominal operating efficiency.

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