Investigation on Dustfall and Rainfall to Cover Transmittance of Flat-plate Solar Collectors in Beijing

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Abstract

Nature dustfall influences on transmittance of flat-plate solar collectors cover and will furtherly influences on its working efficiency. A 12-month experiment of dustfall and cover transmittance has been conducted in Beijing. A dust deposition model describing the effect of rain on dust deposition has been studied. And the correlation of environmental factors, such as dustfall and rainfall, on cover transmittance has also been established. The maximum relative deviation between calculated and experiment transmittance is 6.42%. Therefore, the correlation is accurate enough and can be used for further analysis such as maintenance strategy of solar thermal system operating in Beijing or other areas with similar climate.

Keywords: dustfall, rainfall, flat-plate solar collector, cover transmittance, rainfall facto, extinction coefficient

1. Introduction

Flat-plate solar collector (FPC) is getting higher installed capacity in China due to its better safety performance and advantage of integrating with buildings. Normally, effect of environmental factors, such as dust deposition, rainfall and wind, would not be considered when calculating the thermal performance of FPC. That results in a significant difference between designing output and actual operation, especially in the special area with severe dust or wind. El-Nashar (2009) pointed out that in arid regions such as the United Arab Emirates, collector's thermal performance will drop by 40% in a year without cleaning. Elminir et al. (2006) proposed that the transmittance of glass fell 52.5%~12.4% according different slope and azimuth in Egypt. Research in China showed that thermal performance of flat-plate collector would drop 9.69% after 3 months in Lanzhou, the transmittance would fall 12.3% after 12 days in Xi'an (Liu, 2014; Hou, 2015).

Based on the analysis of effect mechanism of dustfall and rainfall on cover transmittance, A 12-month experiment of dustfall and cover transmittance has been conducted in Beijing. A dust deposition model describing the effect of rain on dust deposition has been studied. And the correlation of environmental factors, such as dustfall and rainfall, on cover transmittance has also been established. With the correlation, further analysis, such as maintenance strategy of solar thermal system operating in Beijing or other areas with similar climate, could be analyzed.

2. Effect mechanism

2.1. Working principle

The working principle of flat-plate solar collectors can be described as following:

- Solar radiation through the glass cover is absorbed by the absorber panel with selective coating;
- The temperature of the absorber panel increases, and the heat transfer to fluid in tubes;
- Fluid is heated and deliver heat to outside.

Heat transfer process between components is showed in Fig. 1.

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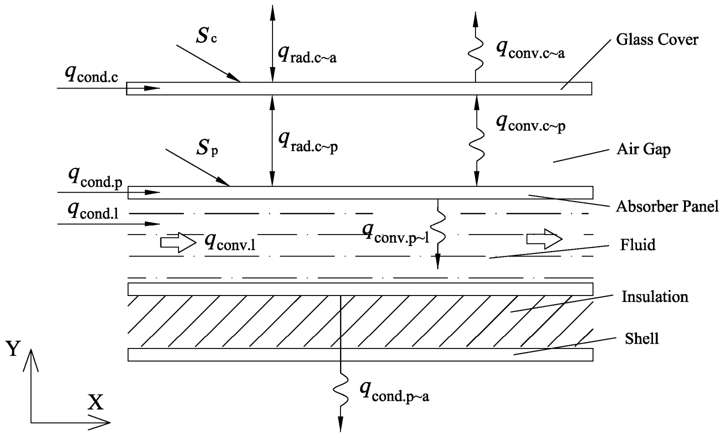

cond	Conductive heat transfer	c	Glass cover	a	Ambient
conv	Convective heat transfer	p	Absorb panel	S	Solar radiation
rad	Radiation heat transfer	l	Fluid	q	Heat transfer

Fig. 1: Schema of heat transfer in flat-plate solar collector

According to the working principle, transmittance of the glass cover has significant effect on collector's thermal performance. Decrease of the transmittance would reduce heat received by the absorber panel, which eventually leading to decline of heat gain and thermal efficiency.

For a flat-plate solar collector in operation, the cover transmittance is affected by the dustfall and rainfall. The effect mechanism could be described as following:

- Dust falls and deposited on the collector cover.
- Then it is washed by the rainfall.
- If the transmittance of clean glass cover is τ_c , transmittance of dust layer is τ_d, Then the transmittance of glass cover with dust is down to $\tau_m=\tau_c\cdot\tau_d$.

To describe the effect of dustfall and rainfall on cover transmittance, a dust deposition model has been studied as following.

2.2. Dust deposition

By deposition mechanism, the dustfall on the tilted collector cover could be divided into 2 parts: the gravity settling dust and particulate matter. The dust deposition on the tilted collector cover can be calculated from the following equation:

$$D_{d,\theta} = d_{1,\theta} + d_{2,\theta} = d_d \cos\theta + v_{d,\theta} C_{dp} T \times 10^{-3} \quad \text{(eq. 1)}$$

Where, θ is the titled angle of inclination surface; $D_{d,\theta}$ is the total dust mass on titled surface, g/m^2; $d_{1,\theta}$ is gravity settling dust mass on titled surface, g/m^2; $d_{2,\theta}$ is particulate matter mass on titled surface, g/m^2; d_d is daily gravity settling dust mass, g/m^2; v_d is particulate matter settling velocity, m/s; C_{dp} is particulate matter concentration, mg/m^3; T is calculation period of particulate matter, 86400s.

2.3. Effect of rainfall on dust deposition

The rain will wash away part of the dust on the collector cover, but part of the sticky dust will still remain on the collector cover. Therefore, when describing the effect of rainfall on dust deposition, four different scenarios are proposed:

1) No rain, dust on the cover is not affected;

2) Little rain, but the rain is not strong enough to wash away the dust on the cover;

3) Small rain, the rain can only wash away part of the dust on the cover;

4) Heavy rain, the rainfall exceeds a certain threshold. Almost all the dust is washed away, but there will be a small part of sticky dust still stay on the cover.

Rainfall factor R is introduced as eq. 2 to describe the effect of rainfall on dust deposition. And the dust deposition model including rainfall effect has been established as eq. 3 ~ eq. 5.

$$R = \begin{cases} 1 & r_{24} \le b_1 \\ r' & r_{24} = b_2 \\ r'' & r_{24} \ge b_3 \\ 1 + (r'-1)\dfrac{r_{24}-b_1}{b_2-b_1} & b_1 < r_{24} < b_2 \\ r' + (r''-r')\dfrac{r_{24}-b_2}{b_3-b_2} & b_2 < r_{24} < b_3 \end{cases} \qquad \text{(eq. 2)}$$

Where, b_1, b_2, b_3 are different rainfall threshold, mm; r', r'' are the left dustfall proportion after rainfall flush, %.

$$D_r(i) = D_{r,1}(i) + D_{r,2}(i) \qquad \text{(eq. 3)}$$

$$D_{r,1}(i) = R(i)\left[D_{r,1}(i-1) + d_d(i)\cos\theta\right] \qquad \text{(eq. 4)}$$

$$D_{r,2}(i) = R(i)\left[D_{r,2}(i-1) + v_d C_{dp}(i) T \times 10^{-3}\right] \qquad \text{(eq. 5)}$$

Where $D_r(i)$ is the total dust mass after rainfall flush on i day, g/m^2; $D_{r,1}(i)$ is the total gravity settling dust mass after rainfall flush on i day, g/m^2; $D_{r,2}(i)$ is the total particulate matter after rainfall flush on i day, g/m^2.

2.4. Transmittance of collector cover with dust

According to Zhao (2006) and Katzan's (1991) research, the correlation between cover transmittance and dust deposition could be described as eq. 6 by defining the extinction coefficient of dust deposition K_d :

$$\tau = \tau_c \cdot \exp\left[K_d\left(\frac{D_{r,1}}{\phi_1} + \sum_{j=1}^{n}\frac{D_{r,2,j}}{\phi_{2,j}}\right)\right] \qquad \text{(eq. 6)}$$

Where τ is the transmittance of dirty cover; τ_c is the transmittance of clean cover; φ_1 is equivalent diameter of gravity settling dust mass, m; $\varphi_{2,j}$ is equivalent diameter of particulate matter j, m.

To determine the rainfall factor R and extinction coefficient K_d in the correlation of dustfall and rainfall on cover transmittance of flat-plate solar collector, a 12-month experiment of dustfall and cover transmittance has been conducted in Beijing.

3. Experiment methods

3.1. Location

The dustfall and cover transmittance experiment has been carried out on the roof of a 3-floor building in Shunyi District, Beijing. There is no high-rise building around, and there is no obvious source of pollutants. The latitude of experimental site is 40°, longitude is 116°, average elevation of 35 m. Experimental site is 50 km away from city center.

The climatic character in Beijing is rainy and hot in summer, cold and dry in winter. 75% of the annual rainfall is in summer. Average annual rainfall is 571.3 mm. In January the average temperature is -4°C, and monthly rainfall is 2.8 mm. In July the average temperature is 26.3°C, and monthly rainfall is 177 mm.

3.2. Method

Experiment included 2 parts: dustfall measurement and cover transmittance measurement. Experiments period was 12 months, from April 2015 to March 2016. The dustfall measurement and cover transmittance measurement were carried out at the same time in each month. The rainfall data and daily PM_{10} concentration from China Meteorology Data Center is recorded at the same time.

3.2.1. Dustfall measurement

The experiment was carried out according to the national standard GB/T 15265-94 "Ambient air -Determination of dustfall - Gravimetric method". The glycol water (Mixture of 100 mL $C_2H_6O_2$ and 100 mL water) was placed in a glass collection tank to collect the dustfall. The inner diameter of glass collection tank was 15 cm, and the height was 30 cm, the mass of dustfall was measured by gravimetric method. The glycol water was collected every 30±2 d. After evaporation, drying at 105°C, cooling at room temperature, the dust was weighted by analytical balance. The experimental site and equipment for dustfall measurement is showed in Fig. 2.

a. experimental site b. glass collection tank c. crucible d. Drying oven f. analytical balance

Fig.2: Experimental site and equipment of dustfall experiment

3.2.2. Cover transmittance measurement

Glass pieces were used as the sample of collector cover during the experiment. The glass pieces' size is 50 mm × 50 mm × 3 mm. The glass pieces were placed at three tilted angles of 0°, 40° and 90°. Monthly transmittance changes of glass pieces were measured every month, and the cumulative transmittance changes from the 1st month were also measured. As shown in Fig. 3, the transmittance was measured by a spectrophotometer, the transmittance of each glass pieces was tested twice to reduce the test error.

a. spectrophotometer b. glass pieces

Fig.3: Spectrophotometer and glass pieces

3.3. Uncertainty analysis

Measuring instruments used in the experiment included analytical balance, Vernier caliper, spectrophotometer. Main parameters of these instruments are showed in Tab. 1.

Tab. 1: Test instrument list

Item	Instrument	Model	Range	Resolution	Accuracy
Dust weight	analytical balance	JJ224BC	0~220g	0.1mg	±0.2mg
Inner diameter of glass collection tank	Vernier caliper		0~150mm	0.02mm	-
Transmittance	spectrophotometer	Cary-5000	300~2500nm	0.0001	0.0008

3.3.1. Uncertainty of dustfall

The relative synthetic uncertainty of dustfall was calculated by eq.7:

$$U(\mathrm{d}) = \sqrt{U(\mathrm{S})^2 + U(\mathrm{w})^2} \quad \text{(eq. 7)}$$

Where, U(d) was the synthetic uncertainty of dustfall; U(S) was the uncertainty of opening area of glass collection tank; U(w) was the uncertainty of dust weight.

The resolution of the Vernier caliper used to measure the inner diameter was 0.02 mm. Considering the average distribution, the confidence probability p= 95% was taken, and the corresponding inclusion factor k = 1.65. For the inner diameter of glass collection tank, the standard uncertainty u(L) of measurement results was 0.006 mm. Inner diameter of glass collection tank was 139 mm. After calculation, the uncertainty of opening area of glass collection tank was 0.0062%.

The accuracy of the analytical balance used to measure the dust weight was 0.2 mg. Considering the normal distribution, the probability of confidence is 95.45% and the corresponding inclusion factor k = 2. The standard uncertainty of the measurement results u(w) was 0.1 mg. The relative uncertainty U(w) was 0.25% when the measured dust was about 40 mg.

Therefore, the relative synthetic uncertainty of dustfall U(d) = 0.25%.

3.3.2. Uncertainty of transmittance

According the uncertainty analysis method, the relative uncertainty of transmittance $U(\tau)$ = 0.0667 %.

4. Experiment results

According to the experimental results shown in Fig. 4, total amount of dustfall at the experimental site was 58.653 t/km^2. And the maximum monthly dustfall was 9.718 t/(km^2·30d) in April, the minimum monthly dustfall was 2.254 t/(km^2·30d) in September. Seasonal changes of rainfall was obvious. There was rare rainfall in winter (December ~ March), while there was rich rainfall in summer (July ~ September). The maximum monthly rainfall is in July.

The transmittance of glass piece was affected by dustfall and rainfall. Monthly transmittance changes were different in different season. During December to March, there was rich dustfall and rare rainfall. The transmittance decreased obviously according to the increase in dustfall (Except February). From July to September, there was little dustfall and rich rainfall. The transmittance decreased a little and the glass kept clean. Relative change of transmittance was only 1.9%. In the first transition season (from October to November), there was little dustfall and rainfall. The transmittance decreased slowly. In the second transition season (from April to June), there was lot dustfall and rainfall. The transmittance fluctuated greatly.

Based on the annual experimental data, the cumulative transmittance in June and February increased significantly comparing with previous month, but the rainfall did not change significantly. Therefore the effect of rainfall needed further analysis.

Fig. 5 shows the maximum 24h rainfall in each month. It could be seen that the maximum 24h rainfall in June and February was 12.1 mm and 7.3 mm respectively. During February, the maximum 12h rainfall was 7.3 mm. And the maximum 24h rainfall in May and January was 3 mm and 0 mm, respectively. In meteorology, if 12 hours rainfall (*r*12) was more than 5mm and less than 15 mm, 24 hours rainfall (*r*24) was more than 10mm and less than 25 mm, the rain was called moderate rain. If 12 hours rainfall (*r*12) was more than 15 mm and less than 30 mm, 24 hours rainfall (*r*24) was more than 25 mm and less than 50 mm, the rain was called heavy rain. According the analysis above, the increase of transmitters in June and February could be attributed to the occurrence of moderate rain or heavy rain in that month. As the monthly rainfall didn't reflect the rainfall intensity, it was more reasonable to use 24h maximum rainfall (*r*24) in eq. 2 when analyzing the impact of dustfall and rainfall on the cover transmittance.

During the experiment, the monthly and cumulative transmittance changes of the 0°, 40° and 90° glass pieces are shown in Fig. 6 and Fig. 7. The transmittance of clean glass piece (τ_m) was 0.8497. The decrease in the transmittance of the glass piece decreased with the increase of the tilted angle θ, and the change trend was non-linear. Transmittance of 40° glass piece was more like that of 0° glass piece.

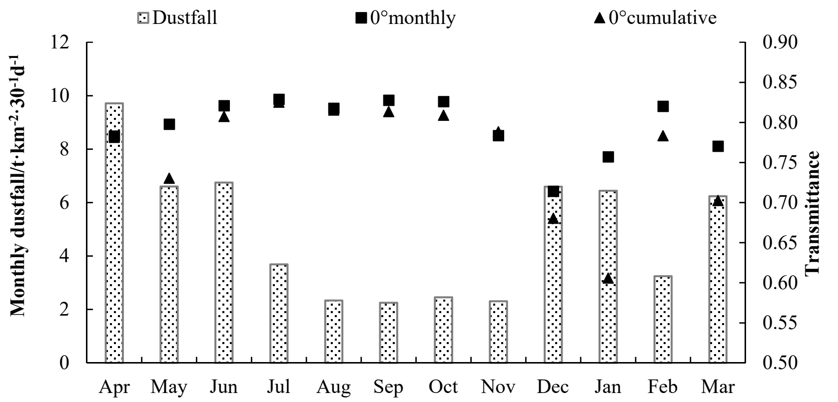

Fig.4: Results of monthly dustfall and transmittance on horizontal surface

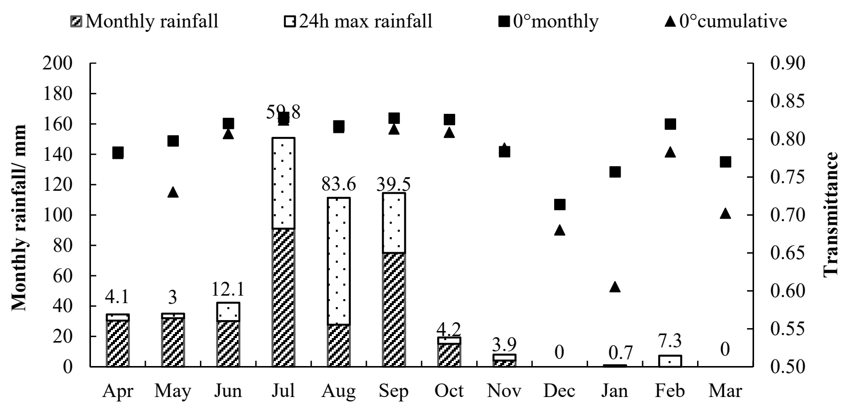

Fig.5 Results of monthly rainfall and transmittance on horizontal surface

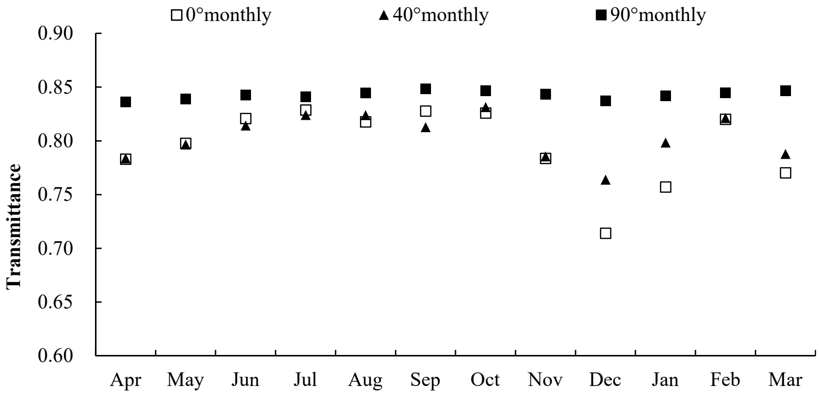

Fig.6: Results of monthly transmittance on different tilted surface

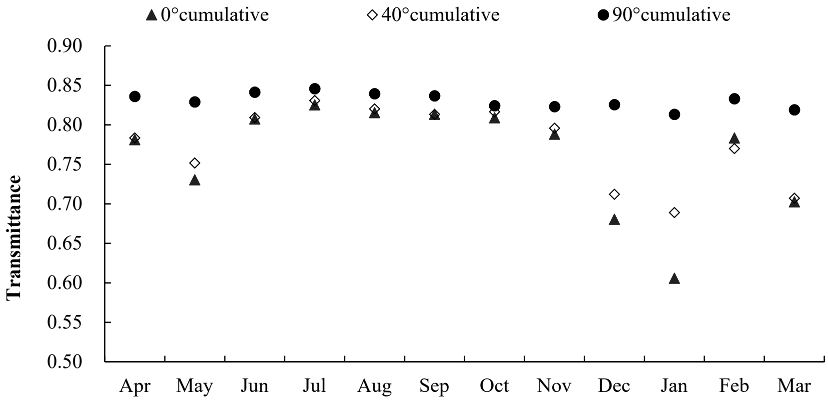

Fig.7: Results of cumulative transmittance on different tilted surface

5. Discussion

5.1. Dust deposition

The dust deposition could be calculated by eq. 1. In the equation, daily gravity settling dust mass could be achieved from experiment results.

Assuming that PM_{10} is composed of 4 kinds of particulate matter with diameter of 10μm, 5μm, 2.5μm and 1μm, the volume ratio of the 4 kinds of particulate matter are 72.2%, 15.3%, 8.3% and 4.2%, according to the results of Wu G. et al. (2005) and Wu C. et al. (2006). As a result, the amount of daily dust deposition can be calculated by eq. 8.

$$\tau_j = \tau_c \cdot \exp\left[K_d \sum_{j=1}^{n} R_j \left(D_{r,j-1} + \frac{d_d \cos\theta}{d_{p40}} + v_{dR,\theta,\mathrm{pm10}} C_{PM10,j} T \times 10^{-3} \right) \right] \quad \text{(eq. 8)}$$

$$v_{dR,\theta,pm10} = \frac{0.722 v_{d,\theta,\mathrm{dp10}}}{d_{p10}} + \frac{0.153 v_{d,\theta,\mathrm{dp5}}}{d_{p5}} + \frac{0.083 v_{d,\theta,\mathrm{dp2.5}}}{d_{p2.5}} + \frac{0.042 v_{d,\theta,\mathrm{dp1}}}{d_{p1}} \quad \text{(eq. 9)}$$

Where, j is days in a month; C_{PM10} is outdoor daily PM_{10} concentration, mg/m^3; $v_{dR,\theta,\mathrm{pm10}}$ is ratio of settling velocity to diameter of particulate matter; $v_{dR,\theta,\mathrm{dp}}$ is settling velocity of particulate matter with diameter of 10μm, could be calculated by equation proposed by Zhao (2006), You (2012) and Chen (2011); d_p is the diameter of particulate matter, m.

5.2. Regress of R and K_d

With the data of dustfall, rainfall, daily PM_{10} concentration and measured transmittance by above experiment in Beijing, the Rainfall Factor R and extinction coefficient K_d could be regressed, and the following equations are obtained:

$$\tau_j = \tau_c \cdot \exp\left[-5.146\times10^{-7} \sum_{j=1}^{n} R_j \left(D_{r,j-1} + \frac{d_{d,\mathrm{d}}\cos\theta}{d_{p40}} + v_{dR,\theta,\mathrm{pm10}} C_{PM10,j} T \times 10^{-3} \right) \right] \quad \text{(eq. 10)}$$

Where, $$R = \begin{cases} 1 & r_{24} \le 2 \\ 0.13 & r_{24} \ge 6 \\ 1 - 0.218\times(r_{24}-2) & 2 < r_{24} < 6 \end{cases} \quad \text{(eq. 11)}$$

It can be seen from eq. 11 that the rainfall factor R is divided into three stages. And b_1= 2, b_2= b_3= 6, $r'$and r is 1 and 0.13, respectively in eq. 2. The function is graphically shown in Fig. 8.

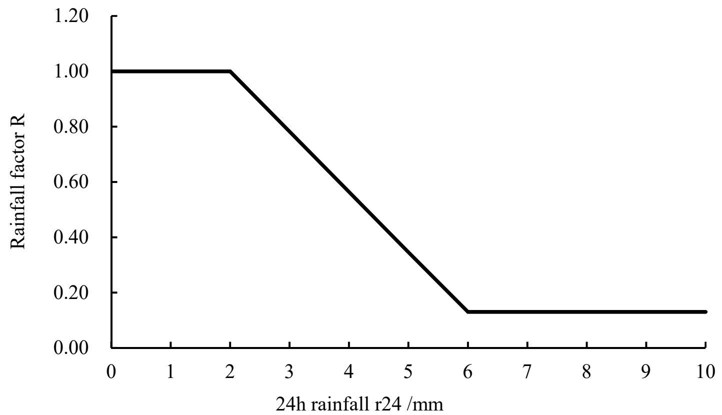

Fig. 8: Regressed rainfall factor *R*

With eq. 9, eq. 10 and eq. 11, the cover transmittance on titled surface can be calculated. The calculated and measured transmittance are compared in Fig. 9. It can be seen that the maximum relative deviation between calculated and experiment transmittance is 6.42%. Therefore, the correlation can fit the influence of environmental factors such as dustfall and rainfall on the transmittance of the collector cover. The fitting result is accurate enough and can be used for further analysis such as maintenance strategy of solar thermal system operating in Beijing or other areas with similar climate.

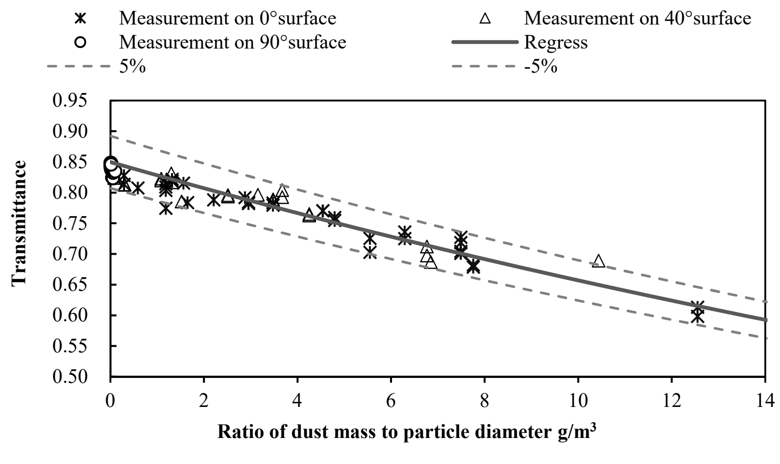

Fig. 9: Comparison of regress data and experimental data

6. Conclusion

A dust deposition model, as well as the correlation of environmental factors, such as dustfall and rainfall, on cover transmittance have been proposed in this paper. With a 12-month experiment of atmospheric dust and cover transmittance in Beijing, an empirical formula has been established to evaluate the effect of dustfall and rainfall on the cover transmittance of solar flat-plate under natural environment. The detailed results are summarized as follows:

1) The dust deposition on the surface of collector cover is affected by the dustfall and rainfall. The correlation of dustfall and rainfall on cover transmittance has also been established as the following equation:

$$\tau_j = \tau_c \cdot \exp\left[K_d \sum_{j=1}^{n} R_j \left(D_{r,j-1} + \frac{d_d \cos\theta}{d_{p40}} + v_{dR,\theta,\mathrm{pm10}} C_{PM10,j} T \times 10^{-3}\right)\right]$$

2) A 12-month experiment in Beijing has been conducted. During December to March, there was rich dustfall and rare rainfall. The transmittance decreased obviously according to the increase in dustfall. From July to September, there was little dustfall and rich rainfall. The transmittance decreased a little and the glass kept clean.

3) The K_d and R were got by regress of experimental result as: K_d = -5.146×10^{-7} and

$$R = \begin{cases} 1 & r_{24} \le 2 \\ 0.13 & r_{24} \ge 6 \\ 1 - 0.218 \times (r_{24} - 2) & 2 < r_{24} < 6 \end{cases}$$

4) The maximum relative deviation between calculated and experiment transmittance is 6.42%.Therefore, the correlation is accurate enough and can be used for further analysis such as maintenance strategy of solar thermal system operating in Beijing or other areas with similar climate.

7. Acknowledgment

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