Experimental study of a single-pass flat plate solar air collector with severe dust deposition on the transparent glass cover

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Abstract

The present study analyzes the thermal performance of a single-pass flat plate solar air collector (SAC) in the case of severe dust deposition surface. Experiments of the SAC with both severe dust deposition surface and clean cover surface are conducted using the steady-state test (SST) method, in order to show a contrast. The mathematical relation between the combined standard uncertainty of the predicted thermal efficiency and the uncertainties of the experimental results is presented. And the collector characteristic parameters, such as the collector heat removal factor, the collector flow efficiency factor, the total heat loss coefficients, etc. are obtained. The results show that, the predicted thermal efficiency in the case of severe dust deposition surface is decreased by 10.7% - 21.0% when the normalized temperature difference ranges from 0 to 0.04. And the optical efficiency of the SAC with severe dust deposition surface is decreased by 8.39% in contrast with the case of clean cover surface.

1. Introduction

Solar air collectors (SACs) are more and more popular used for space heating and drying processes, due to their advantages of simple manufacturing and maintenance, freeze resistance and less corrosion compared with solar hot water heating systems. Because of lower thermal efficiencies of general flat plate SACs, research has been done to
improve thermal performances of SACs. In order to enhance the convective heat transfer between the flowing air and the absorber plate, various types of absorber plates are used in the studies, such as roughness elements [1], cross-corrugated plates [2, 3], v-groove absorber plate [4], or using fins attached over and under the absorber plate to provide extended surfaces [5, 6]. Besides, double pass is another way to enhance air-side heat transfer of SACs, by inserting the absorber plate into the air conduit to divide it into two channels so as to extend heat transfer area [7-9]. Furthermore, El-Sebaii and Al-Snani [10] presented the effect of selective coating on thermal performance of flat plate SACs from the view point of radiation heat transfer. Most of the previous studies focused their attention on the absorber plates of SACs. And it seems heat transfer between the absorber and the air conduit is the primary impact factor on the thermal performance of SACs.

Actually, several physical phenomena are taking place in the SACs – optical, thermal and hydrodynamic phenomena. In the present study, we will focus on the optical aspect. The optical properties of the transparent cover can play a key role on the collector thermal performance. Eq.(1) depicts the useful energy gain ($Q_u$) of a collector with aperture area ($A_a$), which is the difference between the absorbed radiation and the collector thermal loss. The optical property of the transparent cover directly determines the absorbed solar radiation per area ($S$) by the collector absorber plate. In the practical application of flat plate SACs, transparent covers of the collectors are exposed to ambient and are easily deposited by dust and ash in the atmosphere. Thus, transmittances of transparent covers can be decreased by dust deposition and it directly reduces absorbed radiation $S$ of the SACs. It results in the decrease of the collector thermal performances. However, little attention was paid on the dust deposition surface of SACs. The present study analyzes the thermal performance of a single-pass flat-plate SAC with multi-louvered fin structure in the case of severe dust deposition. Experiments of the collector with both clean cover surface and severe dust deposition surface are conducted, in order to show a contrast. The steady-state test (SST) method is used to obtain the collector characteristic parameters of the two cases.

$$Q_u = A_a [S - U_b(T_b - T_a)]$$

### Nomenclature

- $A_a$ transparent frontal area or aperture area of a collector, m$^2$
- $A_g$ gross collector area, m$^2$
- $c_p$ specific heat, J/(kg·K)
- $\triangle E_{b,f}$ enthransy dissipation of convective heat transfer process between absorber plate and flowing air, W·K
- $F'$ solar collector flow efficiency factor, dimensionless
- $F_h$ solar collector heat removal factor, dimensionless
- $G_g$ global solar irradiance of inclined surface, W/m$^2$
- $h$ enthalpy, J/kg
- $m_f$ mass flow rate of flowing air, kg/s
- $m_\uparrow$ upstream air mass flow rate, kg/s
- $m_\downarrow$ downstream air mass flow rate, kg/s
- $m_L$ air leakage mass flow rate of a solar air collector, kg/s
- $N$ number of data points, dimensionless
- $Q_u$ useful heat gain of the collector, W
- $S = (\alpha m)G_g$, absorbed solar radiation per area, W/m$^2$
- $T$ temperature, °C
- $T_{fi}$ collector inlet temperature, °C
- $T_{fo}$ collector outlet temperature, °C
- $T_n$ $=(T_{fo} - T_{fi})/G_g$, normalized temperature difference, (m$^2$·°C)/W
- $U_{b,f}$ heat transfer coefficient from the absorber to the flowing air, W/(m$^2$·°C)
- $U_L$ total heat loss coefficient of a solar collector, W/(m$^2$·°C)
- $u(x)$ uncertainty of the measured quantity $x$, different units
- $V_f$ volume flow rate of the flowing air at the collector inlet, m$^3$/h
- $V_p$ volume flow rate of the flowing air at the collector outlet, m$^3$/h
2. Methodologies of the experiments and error analysis

2.1. The steady-state test (SST) method and experimental data handle

The collector test procedures of the SST are illustrated in detail by ASHRAE standard 93-2003 [11]. The thermal performance of the nonconcentrating collector operating under the steady-state conditions can be described by Eq. (2). And the collector thermal efficiency ($\eta_g$) based on gross collector area ($A_g$) can be calculated by Eq. (3) in terms of the collector heat removal factor ($F_R$) and the collector efficiency factor ($F'$).

The relation between the factors $F_R$ and $F'$ is given by Eq. (4) [12].

$$Q_u/A_g = G_x F_x (\alpha)_{\alpha \beta} - F_x U_x (T_\beta - T_x) = m_f c_f (T_\beta - T_x) / A_g \tag{2}$$

$$\eta_g = Q_u/A_g G_x m_f c_f c_g (T_\beta - T_x) / A_g G_x (A_x / A_g) \left[ F_x (\alpha)_{\alpha \beta} - F_x U_x (T_\beta - T_x) / G_x \right] = (A_x / A_g) \left[ F'(\alpha)_{\alpha \beta} - F' U_x (T_\beta - T_x) / G_x \right] \tag{3}$$

$$F' U_x = -m_f c_f / A_g \ln \left[ 1 - F_x A_x U_x / (m_f c_f) \right] \tag{4}$$

It is unavoidable to have certain amount of air leakage during the thermal performance test of the flat-plate SAC. Different volume flow rates in the collector inlet and exit streams are usually obtained in measuring the useful heat gain ($Q_u$). Defining the air leakage mass flow rate $m_l$ positive for in-leakage, i.e., $m_l = m_\beta - m_\beta'$. The useful heat gain $Q_u$ is then expressed as Eq. (5), according to ASHRAE Standard 93-2003 [11]. $T_x$ denotes the measured inlet temperature of the collector upstream airflow. While the corrected inlet temperature is taken as the mass-weighted mean temperature of the in-leakage and inlet flow rates, viz., $(m_\beta' T_x + m_\beta T_\beta) / m_\beta$. The mass flow rate $m_\beta'$ at the exit is taken as $m_f$ (see Eq. (6)). And the collector thermal efficiency $\eta_{g,exp}$ in the SST is calculated by Eq. (7). The normalized temperature difference ($T_{\alpha \beta,exp}$) should be calculated by Eq. (8). Every SST data point ($T_{\alpha \beta,exp}$, $\eta_{g,exp}$) can be obtained by the averaged values through a certain time interval (5min is taken in the present work). The effective transmittance-absorptance product ($\alpha \beta$) of single glazing flat-plate SAC is calculated by Eq. (9) [12].

$$Q_u = m_f h_f - (m_\beta h_\beta + m_\beta' h_\beta') = c_f m_\beta (T_\beta - T_x) + c_f (m_\beta - m_\beta') (T_\beta - T_x) = c_f \frac{\rho \dot{V}_\beta}{3600} (T_\beta - T_x) + c_f \frac{\rho \dot{V}_\beta'}{3600} (T_\beta - T_x) \tag{5}$$
\[\dot{m}_f = \dot{m}_i + (\dot{m}_i - \dot{m}_o) / (T_f - T_o) / (T_f - T_o) = \dot{m}_i + (\rho_{\nu_0} \dot{V}_{\nu_0} - \rho_{\nu_o} \dot{V}_{\nu_o}) / (T_f - T_o) / (T_f - T_o) \]  \hspace{1cm} (6)

\[\eta_{\text{exp}} = c_f \dot{m}_i / A_{\text{e}} G_e = c_f / (A_{\text{e}} G_e) / (\rho_{\nu_0} \dot{V}_{\nu_0} / (T_f - T_o) - \rho_{\nu_o} \dot{V}_{\nu_o} / (T_f - T_o)) / (T_f - T_o) / (T_f - T_o) \]  \hspace{1cm} (7)

\[T_{\text{e,exp}} = \left[\left(\dot{m}_i T_f + (\dot{m}_i - \dot{m}_o) T_o / \dot{m}_i - T_o\right) / G_e = \rho_{\nu_0} \dot{V}_{\nu_0} / (\rho_{\nu_o} \dot{V}_{\nu_o} / (T_f - T_o) / G_e \right) \right] \]  \hspace{1cm} (8)

\[\left(\tau x\right)_{\text{e}} = \tau x \left(\alpha_n \sum_{n=0}^{\infty} (1 - \alpha_n)^{\frac{1}{2}}\right) = \tau x / 1 - (1 - \alpha_n) \rho x \]  \hspace{1cm} (9)

### 2.2. Error analysis of the experimental results

The uncertainties of the direct measured quantities can be obtained by the general principles for the determination of Type A and Type B uncertainties. In the collector SST test, Type A uncertainties derive from the statistical analysis of the repeated measurements at each SST data point [13]. For each data point, the best estimate of a quantity \(X\) (e.g., the collector thermal efficiency \(\eta_{\text{exp}}\)) is the arithmetic mean \(x\) of the observations \(x_i\) \((i=1,2,\ldots,N)\) and its Type A uncertainty is the standard deviation of the mean, as shown in Eq. (10) [14]. Type B uncertainties \(u_B, X\) derive from the calculation of uncertainties over the whole measurement, taking into account all instrument uncertainties. The standard uncertainty \(u_B, X = \sigma_{x} / \sqrt{N}\), where \(\sigma_{x}\) is the stated accuracy for Type B. The general law of uncertainties combination is given as Eq. (11) [14, 15]. \(u_i\) denotes independent sources of uncertainties. Tables 1 and 2 gives the stated accuracies of the direct measured quantities in the test and the standard uncertainties of the direct measured quantities, respectively.

\[\sigma_{x, X} = \sqrt{\sum_{i=1}^{N} (x_i - x)^2 / N} / (N - 1) \]  \hspace{1cm} (10)

\[u = \left(\sum u_i^2\right)^{0.5} \]  \hspace{1cm} (11)

### Table 1. Accuracy levels of the testing instruments compared with those required by ASHRAE Standard 93-2003

<table>
<thead>
<tr>
<th>Direct measured quantities</th>
<th>Measuring instruments or sensors (type)</th>
<th>Measuring range</th>
<th>Accuracy Required by ASHRAE 93-2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector area</td>
<td>Tape measure</td>
<td>0-10m</td>
<td>±0.005m</td>
</tr>
<tr>
<td>Global / diffuse solar irradiance</td>
<td>Pyranometer (TBQ-2-B)</td>
<td>0-2000 W/m²</td>
<td>±1.633% (for steady-state) 2.0% (for steady-state)</td>
</tr>
<tr>
<td>Collector inlet / outlet temperature</td>
<td>Thermocouple</td>
<td>-50°C -450 °C</td>
<td>±(0.3+0.005×</td>
</tr>
<tr>
<td>Ambience temperature</td>
<td>Thermocouple</td>
<td>-50°C -450 °C</td>
<td>±(0.3+0.005×</td>
</tr>
<tr>
<td>Volume flow rate at collector inlet</td>
<td>Gas turbine flowmeter</td>
<td>10-300 m³/h</td>
<td>±1.0% of reading ±0.5% of reading</td>
</tr>
<tr>
<td>Volume flow rate at collector exit</td>
<td>Vortex Flowmeter</td>
<td>10-300 m³/h</td>
<td>±1.0% of reading ±1.5% of reading</td>
</tr>
<tr>
<td>Outdoor wind speed</td>
<td>Anemometer (FB-1)</td>
<td>0.15-30.0 m/s</td>
<td>±5% of reading ±0.8 m/s</td>
</tr>
</tbody>
</table>

### Table 2. Standard uncertainties of the direct measured quantities in the solar collector test

<table>
<thead>
<tr>
<th>Number</th>
<th>Measured quantities</th>
<th>Symbols of uncertainties</th>
<th>Units</th>
<th>Type-B Standard Uncertainties</th>
<th>Relative errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(\dot{V}_{\nu_0})</td>
<td>(u_B, X)</td>
<td>m³/h</td>
<td>1.0%×(\dot{V}_{\nu_0}) / \sqrt{3}</td>
<td>0.577%</td>
</tr>
<tr>
<td>2</td>
<td>(\dot{V}_{\nu_o})</td>
<td>(u_B, X)</td>
<td>m³/h</td>
<td>1.0%×(\dot{V}_{\nu_o}) / \sqrt{3}</td>
<td>0.577%</td>
</tr>
<tr>
<td>3</td>
<td>(T_{\nu_0})</td>
<td>(u_B, X)</td>
<td>°C</td>
<td>0.3+0.005×(T_{\nu_0}) / \sqrt{3}</td>
<td>0.48%-1.15%</td>
</tr>
<tr>
<td>4</td>
<td>(T_{\nu_o})</td>
<td>(u_B, X)</td>
<td>°C</td>
<td>0.3+0.005×(T_{\nu_o}) / \sqrt{3}</td>
<td>0.48%-1.15%</td>
</tr>
<tr>
<td>5</td>
<td>(T_a)</td>
<td>(u_B, X)</td>
<td>°C</td>
<td>0.3+0.005×(T_a) / \sqrt{3}</td>
<td>0.74%-1.15%</td>
</tr>
<tr>
<td>6</td>
<td>(G_e)</td>
<td>(u_B, X)</td>
<td>W/m²</td>
<td>1.633%×(G_e) (SST) 1.633% (SST)</td>
<td>1.633% (SST)</td>
</tr>
<tr>
<td>7</td>
<td>(A_e)</td>
<td>(u_B, X)</td>
<td>m²</td>
<td>0.863×10⁻¹</td>
<td>0.043%</td>
</tr>
<tr>
<td>8</td>
<td>(w)</td>
<td>(u_B, X)</td>
<td>m/s</td>
<td>5% / \sqrt{3}</td>
<td>2.887%</td>
</tr>
</tbody>
</table>
The combined standard uncertainty \( u_c(y) \) of an indirect measured quantity \( y \) is given by the law of error propagation [13, 15], as shown in Eq.(12). When all the measured quantities \( x_j \) \((j = 1,2,\ldots,M)\) are independent to each other. The uncertainties of the experimental results in the SST method can be depicted by the uncertainties of the scattered testing data points \( (T_{n,\exp}, \eta_{g,\exp}) \). Using Eq.(12), the combined standard uncertainty \( u_c(T_{n,\exp}) \) of the averaged normalized temperature difference and the combined standard uncertainty \( u_c(\eta_{g,\exp}) \) of the averaged thermal efficiency can be calculated by Eqs. (13) and (14), respectively. Where \( u_c(x_j) \) \((j = 1-7)\) are listed in Table 2.

\[
\frac{1}{N} \sum_{j=1}^{N} \left( \frac{\partial T_{n,\exp}}{\partial x_j} \right) u(x_j) \right)^2 \right)^{0.5} \tag{12}
\]

\[
\frac{1}{N} \sum_{j=1}^{N} \left( \frac{\partial T_{n,\exp}}{\partial x_j} \right) u(x_j) \right)^2 \right)^{0.5} \tag{13}
\]

\[
\frac{1}{N} \sum_{j=1}^{N} \left( \frac{\partial \eta_{g,\exp}}{\partial x_j} \right) u(x_j) \right)^2 \right)^{0.5} \tag{14}
\]

The combined standard uncertainty \( u_c(\eta_{g,\exp}) \) of the predicted collector thermal efficiency \( (\eta_{g,pred}) \) is correlated with the uncertainties of the experimental results and the uncertainties of the fitting coefficients. Set the two-parameter collector SST model to be Eq.(15), where \( \eta_0 = (A_1/A_2)F_0(\pi)\alpha, U_i = (A_1/A_2)F_0U_i \). The combined standard uncertainty \( u_c(\eta_{g,\exp}) \) is calculated by Eq.(16). \( u^2(\eta_0), u^2(U_i) \) represents the squared standard uncertainties of \( \eta_0 \) and \( U_i \), respectively. Calculating formulas of \( u^2(\eta_0), u^2(U_i) \) will be given in the following text.

\[
\eta_{g,\exp} = \eta_0 - U_i T_{n,\exp} \tag{15}
\]

\[
u_c(\eta_{g,\exp}) = \left( u^2(\eta_0) + T_{n,\exp}^2 u^2(U_i) \right)^{0.5} \tag{16}
\]

The best estimation parameter \( \eta_0 \) by linear square fitting in the SST model can be expressed as the statistical average of \( N \) data points, viz., \( \eta_0 = \bar{\eta} + U_i \bar{T} \) (\( \bar{x}, \bar{y} \) is given in Eq.(17)).Thus \( u^2(\eta_0) \) is calculated by Eq.(18) using Eq.(12). Where the combined squared standard uncertainties \( u^2(\bar{x}), u^2(\bar{y}) \) are determined by the error propagation of the measuring and the standard deviation of the statistical mean. According to Eqs. (10) and (12), \( u^2(\bar{x}), u^2(\bar{y}) \) can be calculated by Eqs.(19) and (20), respectively. The parameter \( U_i \) can be rearranged as \( U_i = (\eta_0 - \bar{y}) \bar{x} \). Thus \( u^2(U_i) \) is calculated by Eq. (21), considering the independence of \( U_i \) and \( \eta_0 \).

\[
\bar{x} = \frac{1}{N} \sum_{j=1}^{N} T_{n,\exp}(j) / N, \bar{y} = \frac{1}{N} \sum_{j=1}^{N} \eta_{g,\exp}(j) \tag{17}
\]

\[
u^2(\bar{x}) = u^2(\bar{x}) + U_i^2 u^2(\bar{y}) \tag{18}
\]

\[
u^2(\bar{x}) = \frac{1}{N} \sum_{j=1}^{N} \left( \frac{\partial \bar{x}}{\partial T_{n,\exp}(j)} u(T_{n,\exp}(j)) \right)^2 + \frac{1}{N(N-1)} \sum_{j=1}^{N} \left( T_{n,\exp}(j) - \frac{1}{N} \sum_{j=1}^{N} T_{n,\exp}(j) \right)^2 \tag{19}
\]

\[
u^2(\bar{y}) = \frac{1}{N} \sum_{j=1}^{N} \left( \frac{\partial \bar{y}}{\partial \eta_{g,\exp}(j)} u(\eta_{g,\exp}(j)) \right)^2 + \frac{1}{N(N-1)} \sum_{j=1}^{N} \left( \eta_{g,\exp}(j) - \frac{1}{N} \sum_{j=1}^{N} \eta_{g,\exp}(j) \right)^2 \tag{20}
\]
Substituting \( u'(\eta_0) \), \( u'(U_i) \) in Eq. (16) with Eqs. (18) and (21), the combined standard uncertainty \( u_c(\eta_{g,\text{pred}}) \) of the predicted collector thermal efficiency is calculated by Eq.(22). Eq.(22) reveals the mathematical relation between the combined standard uncertainty \( u_c(\eta_{g,\text{pred}}) \) and the uncertainties of the experimental results in the SST method. Where the first term in the brace \{ \} stands for the error propagations of the arithmetic mean \( \bar{y} \), \( y \) of the observations \( (\bar{q}_{g,\text{exp}}) \), with the sensitivity coefficient of error \( 1 + T_m^2 / \bar{x}_i^2 \). The second term represents the error propagations of the arithmetic mean \( \bar{x} \), \( x \) of the observations \( (T_{m,\text{exp}}) \), with the sensitivity coefficient of error \( U_i^2 + T_m^2 (\eta_0 - \bar{y})^2 / \bar{x}_i^2 \).

\[
\begin{align*}
u'(U_i) &= \left( \frac{\partial U}{\partial y} u(y) \right)^2 + \left( \frac{\partial U}{\partial x} u(x) \right)^2 = \left( \frac{-1}{\bar{x}} \right) u(\bar{x})^2 + \left( \frac{\eta_0 - \bar{y}}{\bar{x}} \right) u(\bar{x})^2 \\
\end{align*}
\]

\[ (21) \]

3. Experimental procedures

Schematic of the flat-plate SAC test rig is given in Fig. 1. The gross collector area \( A_g \) is 1.985m\(^2\) with a contour size of 1.995m by 0.995m. The collector aperture area \( A_a \) is 1.896m\(^2\). Thickness of the collector is 135mm, consisting of 3.2mm thickness tempered glass cover (normal incident transmittance 0.92), 30mm-thickness closed air layer between the upper surface of the absorber plate and the transparent glass cover, 0.65mm selective coating absorber plate (absorptance 0.92; emittance 0.05), 50mm height airflow channel with multi-louvered fins (0.4mm aluminum alloy sheet) structure, 50mm insulation material of fluffy glass fiber cotton and 1mm steel outer frame. In the SST process, global solar irradiance, diffuse irradiance, inlet and outlet volume rate of airflow, inlet temperature, outlet temperature, ambient temperature were measured. The measuring instruments and their errors are listed in Table 1. All the instruments were calibrated before experiments. And the standard uncertainties of the direct measured quantities are listed in Table 2.

Fig. 1. Schematic layout of the solar air collector test rig. Fig. 2. The cases of the flat-plate SAC (a) clean surface; (b) severe dust deposition.

Thermal performance test of the flat-plate SAC was conducted in Beijing, China. The tilted angle \( \beta \) of the SAC was 45°. The exit mass flow rate \( \dot{m}_{\text{ext}} \) of the flowing air through the inner of the collector was controlled to be near constant, viz., 0.0403 kg/s with a deviation of ±1%. The time interval of data acquisition was 10s. The wind speed scope during the test was 0 - 2 m/s, measured by a portable anemoscope at random times. Both the cases of the flat-plate SAC with clean cover surface and severe dust deposition surface are considered, in order to show a contrast. The case of clean cover surface is shown in Fig. 2(a). Fig. 2(b) represents the case of severe dust deposition on the
transparent cover of the SAC. The dust deposition surface was artificially implemented by spreading dust on the transparent cover surface in advance. During the test period, the SAC was instantaneously adjusted to be near normal incidence by adjusting the rotating rack of the test rig. Moreover, in order to get different scopes of \((T_\beta - T_a)\), four different inlet temperature conditions were realized by an electrical heater (see Fig.1), controlling the temperature of the upstream air flow both for the two cases.

4. Results and discussion

4.1. Parametric analysis in SST method

Both for the cases of dust deposition surface and clean cover surface, a minimum of sixteen data points at four different inlet temperatures are obtained using SST method. Fig. 3 shows the collector thermal efficiency curves and \(\pm 95\%\) confidence limits for the cases of clean cover surface and dust deposition surface. The combined standard uncertainty \(u_c(\eta_{E,\text{pred}})\) for the two cases are obtained using Eq.(22), as expressed by Eqs. (23) and (24), respectively.

\[
u_c(\eta_{E,\text{pred}}) = \sqrt{0.0003102 + 0.772387T_m^2}
\]

(23)

\[
u_c(\eta_{E,\text{pred}}) = \sqrt{0.0008482 + 1.85515T_m^2}
\]

(24)

Fig. 4 gives the thermal efficiency decrease percentages for the cases of severe dust deposition surface and clean cover surface by fitting. The predicted thermal efficiency in the case of severe dust deposition surface is decreased by 10.7\% - 21.0\% when the normalized temperature difference \((T_m')\) ranges from 0 to 0.04.

4.2. Collector characteristic parameters

The thermal efficiency curves for the two cases as shown in Fig. 3. Comparing the least squares (LS) fitting curves with Eq. (3) and eliminating \(A/A_g\), the heat loss coefficients \(F'U_L\) in the cases of clean cover surface and severe dust deposition surface are 5.271 and 5.453, respectively. For the case of clean surface, the optical efficiency \((\tau a)_{\text{on}}\) is 0.8495 by Eq. (9) with the transparent cover transmittance \(t_g = 0.918\), the absorptance \(a_e = 0.92\) and the reflectance \(\rho_e = 0.05\) for the absorber plate. And the collector heat removal factor \(F_R\) is obtained by \(F_R(\tau a)_{\text{on}}/F_R, F_R=0.567\). Then, \(U_L\) is separated from \(F_RU_L\) in the case of clean cover surface. The coefficient \(F'U_L\) is calculated by Eq. (4). The parameters \(F'U_L, F', F_R, U_L\) for the case of clean cover surface are given in Table 3. Similarly, the coefficient \(F'U_L\) for the case of severe dust deposition surface can be calculated by Eq.(4). But the parameters \(F', F_R, U_L\) of the case cannot be separated from each other. In order to determine the optical efficiency \((\tau a)_{\text{on}}\) for the case of severe dust deposition surface, the equivalent thermal resistance of the convective heat transfer process between the absorber plate and the flowing air is analyzed using the entransy analysis. And the underlying correlation among the two cases is illustrated in the next section.

![Fig. 3. Collector thermal efficiency curve and 95% confidence limits for the cases of: (a) clean surface; (b) dust deposition surface.](image-url)
Fig. 4. Thermal efficiency decrease percentages for the cases of severe dust deposition surface and clean cover surface by fitting.

Table 3. Collector characteristic parameters of the cases with clean surface and dust deposition surface by the SST method

<table>
<thead>
<tr>
<th>Cases</th>
<th>Collector characteristic parameters</th>
<th>FR</th>
<th>(IJĮ)en</th>
<th>FRUL</th>
<th>AF</th>
<th>UL</th>
<th>F'</th>
<th>Uuf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean surface</td>
<td></td>
<td>0.495</td>
<td>5.271</td>
<td>6.053</td>
<td>0.8495</td>
<td>0.567</td>
<td>9.032</td>
<td>0.6698</td>
</tr>
<tr>
<td>Dust deposition surface</td>
<td></td>
<td>0.442</td>
<td>5.453</td>
<td>6.296</td>
<td>0.7782</td>
<td>0.561</td>
<td>9.797</td>
<td>0.6565</td>
</tr>
</tbody>
</table>

4.3. Relations of the collector characteristic parameters

The entransy dissipation of the convective heat transfer between the absorber plate ‘b’ and the flowing air ‘f’ is \( \Delta E_{b-f} = \frac{Q_s}{(T_b - T_f)} \), according to the entransy theory [16, 17]. The equivalent thermal resistance of the convective heat transfer process \( R_{b-f} \) is defined as \( R_{b-f} = \frac{1}{U_{b-f} A_s} = (T_b - T_f) / Q_s = \frac{\Delta E_{b-f}}{Q_s} \) [17]. Using simple mathematical transformation of Eq.(3) and eliminating \( T_b \), the entransy dissipation \( \Delta E_{b-f} \) can be rearranged to Eq. (25).

\[
\Delta E_{b-f} = Q_s \left[ \frac{(1 - F') S}{U_L} + (F' - 1)(T_f - T_b) \right] = \frac{(1 - F')}{F'} \frac{Q_s^2}{A U_L}
\]

Combining the equivalent thermal resistance \( R_{b-f} \), it can be expressed as Eq. (26). And the convective heat transfer coefficient between the absorber plate and the working fluid \( U_{b-f} \) is calculated by Eq.(27). It is remarked that, the convective heat transfer coefficient \( U_{b-f} \) is based on the collector aperture area \( A_s \).

\[
R_{b-f} = \frac{1}{U_{b-f} A_s} = \frac{(1 - F')}{F'} \cdot \frac{1}{(A U_L)}
\]

and \( U_{b-f} = F' U_L / (1 - F') \) (27)

In the present study, \( U_{b-f} \) is reckoned as a constant for a given airflow channel with the same air flow rate. Hence, the two cases of clean surface and severe dust deposition surface has the same \( U_{b-f} \), as given by Eq.(28).

\[
\left( \frac{F' U_L / (1 - F')} {U_{b-f}} \right)_{\text{Clean surface}} = \left( \frac{F' U_L / (1 - F')} {U_{b-f}} \right)_{\text{Dust deposition surface}}
\]

The parameter \( F' U_L \) for the case of severe dust deposition surface is already obtained. Thus the factor \( F' \) for the case of severe dust deposition surface can be obtained by Eq. (28). And the parameters \( U_L, F_R \) and \( (\tau a)_{on} \) are obtained. The optical efficiency \( (\tau a)_{on} \) in the case of severe dust deposition surface is 0.7782, which is decreased by 8.39\% in contrast with the case of clean cover surface (0.8495).
5. Conclusions

Experiments of the flat-plate SAC both in the cases of severe dust deposition surface and clean cover surface were conducted using the SST method, in order to show a contrast. According to the general law of uncertainties combination and the law of error propagation, the mathematical relation between the combined standard uncertainty of the predicted thermal efficiency by the fitting model and the uncertainties of the experimental results in the SST method is presented. In order to obtain the collector characteristic parameters in the case of dust deposition surface, the underlying correlation of the parameters are derived using the entransy analysis of the convective heat transfer process between the absorber plate and the flowing air. Then the collector characteristic parameters both for the two cases are obtained. The results show that, the predicted thermal efficiency in the case of severe dust deposition surface is decreased by 10.7% - 21.0% when the normalized temperature difference ranges from 0 to 0.04. And the optical efficiency (effective transmittance-absorptance product) of the SAC is decreased by 8.39% when the collector transparent glass cover is under the condition of severe dust deposition.

Acknowledgements

This work was financially supported by Beijing Municipal Science and Technology Projects (Grant No. 141100002714001 and No. D131100003713002).

References