

# *A quick measurement method for determining the incidence angle modifier of flat plate solar collectors using spectroradiometer*

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3 **A quick measurement method for determining the incidence angle**  
4 **modifier of flat plate solar collectors using spectroradiometer**

5

6 Zhiyong Tian <sup>a</sup>, Jie Deng <sup>b,\*</sup>, Shicong Zhang <sup>c</sup>, Runming Yao <sup>b</sup>, Li Shao <sup>b</sup>

7 <sup>a</sup> Department of Civil and Environmental Engineering, Norwegian University of  
8 Science and Technology, Trondheim, Norway

9 <sup>b</sup> School of The Built Environment, University of Reading, Whiteknights, Reading,  
10 Berkshire, RG6 6DF, UK

11 <sup>c</sup> China Academy of Building Research, Beijing 100013, China

12

13

14 \* Corresponding author:

15 E-mail address: [deng-jie2@163.com](mailto:deng-jie2@163.com), [j.deng@reading.ac.uk](mailto:j.deng@reading.ac.uk) (J. Deng)

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17

18 **A quick measurement method for determining the incidence angle**  
19 **modifier of flat plate solar collectors using spectroradiometer**

20

21 **Abstract**

22 In real engineering of solar thermal applications, it needs considerable effort to  
23 determine the incidence angle modifier (IAM) of flat plate solar collectors, according  
24 to the test standards (BS EN ISO 9806, 2017; ASHRAE 93-2010, 2014). And the  
25 available method in the test standards is usually inapplicable to measure thermal  
26 performance of installed solar collectors with dust deposition effect in service. A quick  
27 measurement method is therefore presented to identify the IAM of flat plate solar  
28 collectors with less effort using a spectroradiometer. The quick method developed was  
29 validated with optical tests of a solar panel under the conditions of different incidence  
30 angles. It is inferred that the method not only helps to determine the IAM of flat plate  
31 solar collectors quickly without needing to run the collectors by energy power input,  
32 but also provides a pathway for assessing dust deposition effect on the thermal  
33 performance of installed flat plate solar collectors in service, as well as for determining  
34 the optical property attenuation of solar collectors in the long-term running.

35

36 *Keywords:* Flat plate solar collector; Incidence angle modifier (IAM);  
37 Spectroradiometer; Reflectance spectrum; Irradiance spectrum

38

39

40 **List of symbols**

<b>Nomenclature</b>	
$A_a$	collector aperture area or transparent cover area, $m^2$
$A_g$	collector gross area, $m^2$
$b_0$	constant of the incidence angle modifier of flat plate solar collectors, dimensionless
$F_R$	heat removal factor of a solar collector, dimensionless
$G_g$	global solar irradiance on tilted solar collector surface, $W/m^2$
$Irr_{50^\circ}(\lambda)$	solar spectral irradiance with a tilted angle of $50^\circ$ at $\lambda$ nm wavelength, $W/(m^2 \text{ nm})$
$Irr_{90^\circ}(\lambda)$	solar spectral irradiance with a tilted angle of $90^\circ$ at $\lambda$ nm wavelength, $W/(m^2 \text{ nm})$
$K_{\theta b}(\theta)$	incidence angle modifier of solar beam radiation for a solar collector with an incidence angle of $\theta$ degree, dimensionless
$Q_u$	useful heat gain of solar collector, $W/m^2$
$T_{amb}$	ambient temperature, $^\circ\text{C}$
$T_{fi}$	collector inlet temperature, $^\circ\text{C}$
$T_m^*$	$=(T_{fi} - T_{amb})/G_g$ , normalised temperature difference, $(m^2 \text{ }^\circ\text{C})/W$
$U_L$	collector total heat loss coefficient, $W/(m^2 \text{ }^\circ\text{C})$
<i>Greek symbols</i>	
$\eta_a$	collector thermal efficiency based on collector aperture area, dimensionless
$\eta_g$	collector thermal efficiency based on collector gross area, dimensionless
$\theta$	incidence angle of solar beam radiation on a solar collector, $^\circ$
$\lambda$	wavelength, nm
$\rho_{tot}$	total reflectance at the top of a solar collector, dimensionless
$\rho_{tot,c}(\lambda)$	corrected total reflectance at $\lambda$ nm wavelength, dimensionless
$\rho_{tot,m}(\lambda)$	measured total reflectance at $\lambda$ nm wavelength with the vertical reference plane, dimensionless
$(\tau\alpha)_{en}$	effective transmittance-absorptance product of a solar collector at normal incidence (or optical efficiency), dimensionless
$(\tau\alpha)_\theta$	effective transmittance-absorptance product of a solar collector at an incidence angle of $\theta$ degree, dimensionless
<i>Abbreviations</i>	
<i>IAM</i>	incidence angle modifier

## 42 **1 Introduction**

43 Dynamic or transient thermal characteristics of flat plate solar collectors in naturally  
44 variable meteorological conditions are widely concerned in low-temperature solar  
45 thermal applications (Rojas et al., 2008; Deng et al., 2015a; Deng et al., 2016; Deng et  
46 al., 2017; Tian et al., 2018; Aleksiejuk et al., 2018). The incidence angle modifier (IAM)  
47 of the flat plate solar collectors plays an important role in the collector dynamic thermal  
48 performance due to diurnal motion of the sun. It is therefore indispensable to determine  
49 the collector IAM in assessing and predicting collector dynamic thermal performance  
50 in real engineering. Following the solar collector test standards (BS EN ISO 9806, 2017;  
51 ASHRAE 93-2010, 2014), however, it usually takes considerable efforts to obtain the  
52 IAM of flat plate solar collectors through thermal performance tests recommended. The  
53 collector thermal performance at fixed incidence angles (e.g. 0°, 30°, 45°, 60°) is  
54 needed to test in order to get the IAMs. The solar collectors need to be run under specific  
55 incidence angle conditions over a period of time by power energy input and the test  
56 requirement is relatively rigorous in the steady-state. Particularly, determination of the  
57 IAM of solar collectors with variable geometries is more complicated because there are  
58 more than one direction of dependence for the IAM (Sallaberry et al., 2015; Hertel et  
59 al., 2015). The present study aims to introduce a quick measurement method for  
60 identifying the collector IAM using a spectroradiometer. The collector IAM can be  
61 obtained through executing a couple of quick optical test sequences without running  
62 the solar collectors by energy power input, meaning that less effort is taken to obtain  
63 the IAM compared to the thermal performance test method recommended in the

64 existing test standards. More than that, the quick method is expected to assess dust  
 65 deposition effect on the thermal performance of installed flat plate solar collectors in  
 66 service on-site of solar fields, as well as to determine optical performance attenuation  
 67 of the solar collectors in the long-term running in terms of optical tests. Table 1 gives  
 68 a comparison between the available methods in the test standards and the presented  
 69 method, which indicates the advantages of the latter.

70

71 Table 1. Comparison between the method available in the test standards and the  
 72 presented method

Comparison of test conditions	Thermal performance test method available in the test standards	The presented method using spectroradiometer
Running solar collectors by energy input	Need thermal power	No need
Test conditions of incidence angles	Fixed incidence angles (e.g. 0°, 30°, 45°, 60°) which are restricted	Flexible incidence angles can be chosen as long as it covers a wide range from 0° to 60°.
Test duration	Considerable efforts with restricted conditions (tends to cover several sunny days)	Less effort (usually can be completed on one sunny day)
Applicability in determining optical property of installed solar collectors with surface dust deposition	Unable to determine dust deposition effect without intervention of the solar collectors	Applicable to determine dust deposition effect and optical property attenuation of on-site solar collectors

73

74 **2 Fundamentals of the measurement method**

75

76 **2.1 Thermal performance test method available in the test standards for**  
77 **determining the collector IAM**

78 Usually, the collector thermal efficiency ( $\eta_a$ ) based on collector aperture area ( $A_a$ ) is  
79 defined as (Duffie and Beckman, 2013):

80 
$$\eta_a = \frac{Q_u}{A_a G_g} = \frac{A_g}{A_a} \eta_g \quad (1)$$

81  
82

83 Concerning the collector thermal efficiency curve correlating  $\eta_g$  (or  $\eta_a$ ) with the  
84 normalised temperature difference ( $T_m^* = (T_{fi} - T_{amb})/G_g$ ), a simple linear model in  
85 equation (2) is commonly used to describe the collector steady-state thermal  
86 performance (Duffie and Beckman, 2013; BS EN ISO 9806, 2017; ASHRAE 93-2010,  
87 2014).

88

89 
$$\eta_g = \frac{A_a}{A_g} \cdot \left[ F_R (\tau\alpha)_{en} \cdot K_{\theta b}(\theta) - F_R U_L \frac{(T_{fi} - T_{amb})}{G_g} \right] \quad (2)$$

90

91 where  $K_{\theta b}(\theta)$  – the collector IAM of solar beam radiation is described as (BS EN  
92 ISO 9806, 2017):

93 
$$K_{\theta b}(\theta) = 1 - b_0 \cdot \left( \frac{1}{\cos\theta} - 1 \right) \quad (3)$$

94

95 where  $\theta$  is the incidence angle of solar beam radiation on the collector surface, °;  $b_0$   
96 is a constant of the IAM of the flat plate solar collector, dimensionless.

97

98 In the solar collector test standards ( BS EN ISO 9806, 2017; ASHRAE 93-2010, 2014),

99 the thermal performance test method is recommended in determining the collector IAM  
100 by testing the collector thermal efficiency at different incidence angles.

101

## 102 **2.2 Fundamental of determining the collector IAM using spectroradiometer**

103 Essentially, the optical efficiency  $((\tau\alpha)_\theta)$  of the flat plate solar collectors can be  
104 separated from the collector thermal efficiency curve in Equation (2), as shown in  
105 Equation (4).

106

$$107 \quad (\tau\alpha)_\theta = (\tau\alpha)_{en} \cdot [1 - b_0 \cdot (1/\cos\theta - 1)] \quad (4)$$

108 where the optical efficiency  $(\tau\alpha)_\theta$  represents the transmittance-absorptance product  
109 of the collector at an incidence angle of  $\theta$  (Duffie and Beckman, 2013).

110

111 The total reflectance  $(\rho_{tot})$  of the solar collectors is calculated in Equation (5), since  
112 the sum of the transmittance-absorptance product and the total reflectance equals one  
113 in terms of energy conservation. As the total reflectance  $(\rho_{tot})$  at the top of the collector  
114 surface in equation (5) can be measured directly using a spectrometer with a white  
115 reflectance standard, it is convenient to obtain the transmittance-absorptance products  
116  $((\tau\alpha)_\theta)$  of a flat plate solar collector at different incidence angles by measuring the total  
117 reflectance. Then the IAM is readily identified through linear fitting of  $(\tau\alpha)_\theta$  versus  
118 the incidence angle  $(\theta)$ . It is reckoned as a quick measurement method to identify the  
119 collector IAM, since there is no need to run the collectors for thermal performance tests

120 by energy power input and it can be completed on one sunny day.

$$121 \quad \rho_{tot} = 1 - (\tau\alpha)_\theta \quad (5)$$

122

### 123 **3 Method validation with real tests and merit explanation**

#### 124 **3.1 Test facilities and procedures of implementing the quick method**

125 A Black-Comet-SR concave grating miniature spectrometer (CXR-SR, StellarNet Inc.,  
126 USA) was used to measure the total reflectance at the top of a flat plate solar panel at  
127 different incidence angles, in order to determine the constant ( $b_0$ ) of the IAM in  
128 Equation (4). The miniature spectrometer has a spectroradiometer mode by fitting the  
129 fiber-optic cable with a cosine receptor ( $180^\circ$  field of view), which allows measuring  
130 solar spectral irradiance in a range of wavelengths from 350 to 1000 nm. The fiber-  
131 optic tip of the spectrometer with a white reflectance standard RS50 is shown in Figure  
132 1(a). A solar panel with a tilted angle of  $40^\circ$  shown in Figure 1(b) was used for optical  
133 tests under a clear sky. Manufacturing information of the panel was not available and  
134 disregarded, as the [quick method did not require detailed information of the optical](#)  
135 [system and its components.](#) There was a technical problem of directly measuring the  
136 total reflectance in Equation (5), because the white reference standard had to be tilted  
137 at the same angle as the solar panel ( $40^\circ$  in the case), while the fiber-optic tip pointing  
138 at the white reference standard would shade the reference standard on a sunny day. To  
139 avoid the technical problem, a vertical reference plane ( $90^\circ$  tilted angle) was taken in  
140 the tests of the total reflectance at different incidence angles. In the meanwhile, solar

141 irradiance spectra at the tilted angles of  $90^\circ$ ,  $50^\circ$  were recorded instantaneously with the  
142 fiber-optic tip upwards fitted with the cosine receptor. Thus, the original total  
143 reflectance measured based on the vertical reference plane can be corrected by  
144 conversions of solar spectral irradiances, as given in Equation (6).

145

$$146 \quad \rho_{tot,c}(\lambda) = \rho_{tot,m}(\lambda) \cdot Irr_{50^\circ}(\lambda) / Irr_{90^\circ}(\lambda) \quad (6)$$

147

148 where  $\rho_{tot,c}(\lambda)$  is the corrected total reflectance at  $\lambda$  nm wavelength.  $\rho_{tot,m}(\lambda)$  is  
149 the measured total reflectance at  $\lambda$  nm wavelength with the vertical reference plane.  
150  $Irr_{50^\circ}(\lambda)$  and  $Irr_{90^\circ}(\lambda)$  denotes the solar spectral irradiance at  $\lambda$  nm wavelength  
151 with tilted angles of  $50^\circ$  and  $90^\circ$ , respectively.

152

153 The average reflectance ( $\rho_{tot,ave}$ ) at a specific incidence angle can be calculated as

$$154 \quad \rho_{tot,ave} = \sum_{350}^{1000} \rho_{tot,m}(\lambda) \cdot Irr_{50^\circ}(\lambda) / \sum_{350}^{1000} Irr_{90^\circ}(\lambda) \quad (7)$$

155



156

157 (a)



(b)

158 Figure 1 Testing facilities (a) fiber-optic tip of the spectrometer and reflectance standard

159 RS50; (b) solar panel in test

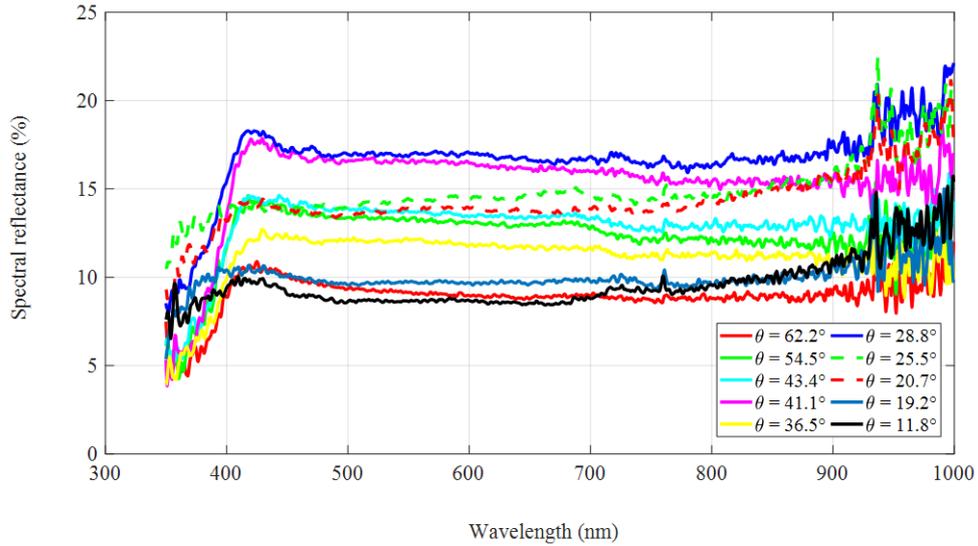
160

161 A set of test sequences was executed with the solar panel at different incidence angles  
162 to determine the IAM. In a test condition of a specific incidence angle, the total  
163 reflectance spectrum of the solar panel with the vertical reference plane, solar spectral  
164 irradiance at both tilted angles of  $50^\circ$  and  $90^\circ$  were measured in a quick succession. A  
165 ruler was used to measure the shadow length of a fixed-length rod perpendicular to the  
166 surface of the panel, giving rise to the incidence angle which was the arctangent value  
167 of the quotient of rod shadow length divided by rod length.

168

### 169 **3.2 Reflectance spectra of the solar panel at different incidence angles**

170 Through a group of optical tests with the solar panel at different incidence angles, the  
171 measured total reflectance spectrum of the solar panel with the vertical reference plane,  
172 the measured solar spectral irradiance at tilted angles of  $50^\circ$  and  $90^\circ$  were obtained on  
173 a sunny day. Figure 2 shows the measured reflectance spectrum of the tested solar panel  
174 with fiber-optic tip pointing in the normal direction of the solar panel and to a vertical  
175 reference plane, while Figure 3 gives the corrected reflectance spectra at different  
176 incidence angles using equation (6), combining the measured solar spectral irradiance  
177 at tilted angles of  $50^\circ$  and  $90^\circ$ .



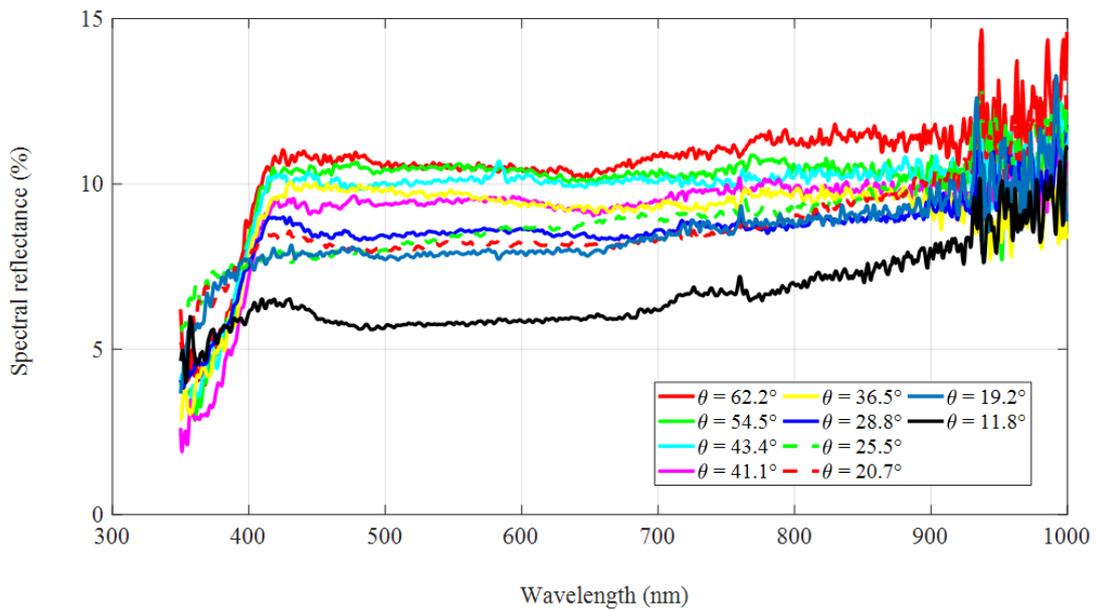
178

179 Figure 2 Measured reflectance spectrum of the tested solar panel with fiber-optic tip

180 pointing in the normal direction of the solar panel and to a vertical reference plane

181

182



183

184 Figure 3 Corrected reflectance spectra at different incidence angles for the solar panel

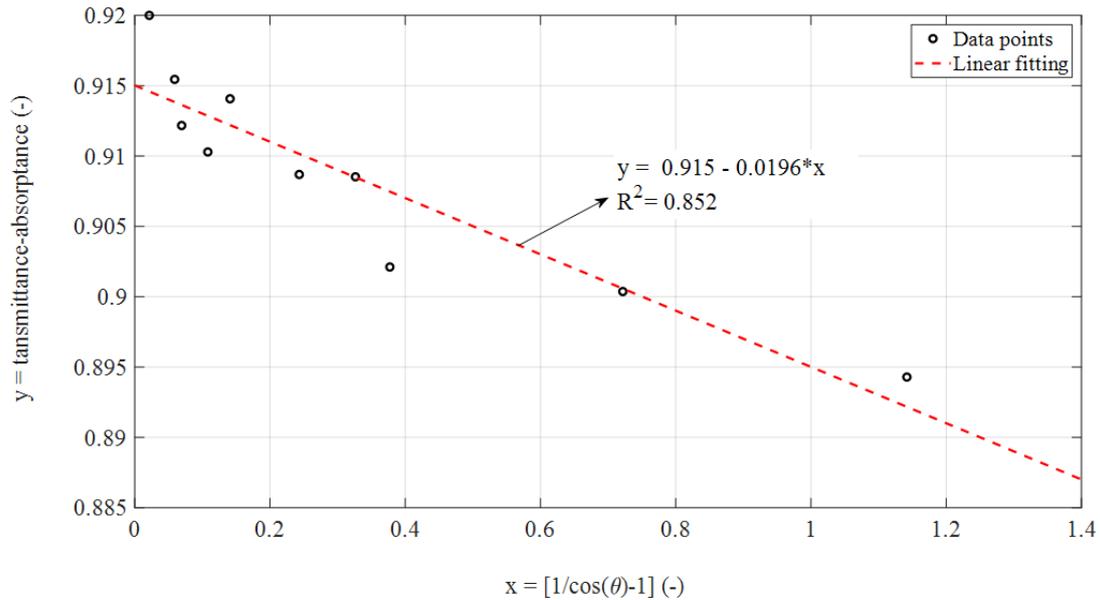
185 tested

186

### 187 3.3 Linear fitting of the IAM (incidence angle modifier)

188 Based on the corrected reflectance spectra at different incidence angles for the solar  
189 panel (see Figure 3), the total reflectance at the top of the solar panel surface was  
190 calculated in equation (7). Then the transmittance-absorptance products  $(\tau\alpha)_\theta$  at  
191 different incidence angles ( $\theta$ ) were obtained in equation (5). Figure 4 gives the linear  
192 fitting results of the transmittance-absorptance product  $(\tau\alpha)_\theta$  versus  $[1/\cos\theta - 1]$ ,  
193 in terms of the relations between each other described in equation (3). The coefficient  
194 of determination ( $R^2$ ) in the fitting was 0.852, indicating a high correlation of  $(\tau\alpha)_\theta$   
195 versus  $[1/\cos\theta - 1]$ . The root mean square error of the fitting was 0.31%. Fitting  
196 coefficients and their standard uncertainties in the linear fitting model were  $(\tau\alpha)_{en} =$   
197  $0.915 \pm 0.0015$  and  $-b_0 \cdot (\tau\alpha)_{en} = 0.0196 \pm 0.0032$ , respectively. Thus, the  
198 coefficients  $(\tau\alpha)_{en}$  and  $b_0 \cdot (\tau\alpha)_{en}$  and their standard uncertainties result in  $b_0 =$   
199  $\frac{0.0196}{0.915} = 0.0214 \pm 0.0035$ . At here, the constant  $b_0$  of the IAM was lower than  
200 presented in the literature (Tesfamichael and Wäckelgård, 2000; Tian et al., 2017; Tian  
201 et al., 2018), mainly due to the fact that a solar photovoltaic panel was used for the tests.  
202 For flat plate solar thermal collectors, the constant  $b_0$  tends to be in the range of 0.1–  
203 0.3 according to the literature. Nonetheless, it confirms that applying the optical tests  
204 by using a spectroradiometer is feasible to determine the IAM of flat plate solar  
205 collectors.

206



207

208 Figure 4 Linear fitting of transmittance-absorptance product  $(\tau\alpha)_\theta$  versus  $[1/\cos\theta -$   
 209  $1]$  ( $x = b_0 \cdot (1/\cos\theta - 1)$ ,  $y = (\tau\alpha)_\theta$ )

210

### 211 3.4 Merits of the presented quick measurement method

212 As the presented method decouples the IAM from measuring the collector thermal  
 213 efficiency and directly applies tests of collector optical efficiency, it helps to save lots  
 214 of effort comparing with the available method in the test standards (see Table 1). More  
 215 than that, the method is applicable to determine the collector optical efficiency in some  
 216 other scenarios in real engineering. Specifically, dust and ash in the air might be  
 217 deposited on the installed flat plate solar collectors in service. The effect of dirt can  
 218 degrade the transmittance of transparent covers of flat plate solar collectors to some  
 219 extent (Garg, 1974). It was argued in Deng et al. (2015b) that the optical efficiency  
 220 (effective transmittance-absorptance product) of a flat plate solar air collector was  
 221 decreased by 8.39% when the transparent cover of the collector was under the condition

222 of artificially severe dust deposition. Tanesab et al. (2019) presented the effect of dust  
223 with different morphologies on the performance degradation of various photovoltaic  
224 technologies. Nevertheless, the aforementioned methods used to quantify the dust  
225 deposition effect were limited to the case of installed solar collectors in service, as it  
226 was difficult to separate the solar collectors from operating systems. On this occasion,  
227 the quick measurement method provides a pathway for assessing the dust deposition  
228 effect on the collector thermal performance. The transmittance-absorptance products of  
229 the solar collectors in different degrees of cleanness can be obtained by quick optical  
230 tests. The dust deposition effect of the solar collectors can be assessed compared to the  
231 collector zero-loss optical efficiency  $((\tau\alpha)_{en})$  with a clean surface.

232

233 On the other aspect, for the flat plate solar collectors serviced in solar thermal fields  
234 and exposed to sunlight in the long-term running, optical performance of the collector  
235 coating surfaces might be attenuated due to aging (Tian et al., 2019). It is difficult to  
236 quantify the thermal performance attenuation of the installed solar collectors without  
237 damaging the panels. The quick measurement method is expected to determine the  
238 collector optical property attenuation after a long period of running.

239

#### 240 **4 Conclusion**

241 A quick measurement method using a spectroradiometer was presented to identify the  
242 incidence angle modifier (IAM) of flat plate solar collectors with less effort by using a  
243 spectroradiometer, compared to the thermal performance test method recommended in

244 existing test standards. To testify the quick method, an installed solar photovoltaic panel  
245 was used to conduct optical tests under conditions of different incidence angles. The  
246 IAM coefficient of the flat solar panel was obtained with a relatively high  $R^2$ ,  
247 confirming the applicability of the quick measurement method. Last but not the least,  
248 the method not only helps to determine the collector IAM quickly without needing to  
249 run the collectors by energy power input, but also provides a pathway for assessing the  
250 dust deposition effect and optical property attenuation of installed solar collectors in  
251 the long-term running.

252

253 **Declaration of interest:** none.

## 254 **Acknowledgment**

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257

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