Energy Conversion and Management 95 (2015) 304–313

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A new anisotropic diffuse radiation model

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ARTICLE INFO

Article history:
Received 14 November 2014
Accepted 7 January 2015
Available online 28 February 2015

Keywords:
Diffuse radiation
Anisotropic
Integral solution
New model

ABSTRACT

Through the analysis of distribution of diffuse radiation in the sky, the sky diffuse radiation is divided into four zones. Based on the concept of radiation intensity and solid angle, the corresponding integral equation is established in each zone to build a new theoretical model of anisotropic diffuse radiation. Radiation enhancement coefficients in the new theoretical model are solved from the instantaneous diffuse radiation data received by 30°, 45°, 60° inclined planes, then new model and existing models are compared with the diffuse radiation data received by 90° inclined planes. The results demonstrate that for existing models, Perez model is the most accurate, followed by Liu and Jordan model. Among the second generation models, Klucher model, Hay model, Skartveit and Olseth model are relatively accurate. While compared with existing models, NADR model is more consistent with the measured values. Further comparative analysis shows that for east and north orientations, Perez model and NADR model are more accurate; for south and west orientations, Liu and Jordan model and NADR model are more accurate. Klucher model is well agreed with the measured data in different inclinations. Hay model and Skartveit and Olseth model are relatively accurate on 30° tilt surface, and Temps and Coulson model is also relatively accurate on 45° tilt surface. NADR model is in good agreement with the measured data on 60° and 90° tilt surface. On the whole, NADR model is more accurate than the existing models.

1. Introduction

Solar radiation on inclined planes of different orientation for solar photovoltaic [1–3] and solar thermal [4–6] conversion is extremely important, and it is also essential for building heat gain calculations [7]. The solution of beam solar radiation is relatively simple, while solving the diffuse radiation is more complex because of its anisotropy. Therefore solving the diffuse radiation through diffuse radiation models is very important [8,9]. Diffuse radiation models can be divided into three generations [10]. The first generation models are isotropic diffuse radiation models, represented by the Hottel and Woertz model [11], Liu and Jordan model [12], Koronakis model [13], Tian et al. model [14] and Badescu model [15]. For the second generation, anisotropic diffuse radiation models are got from various modifications based on the isotropic diffuse radiation models. The typical models are Temps and Coulson model [16], Klucher model [17], Hay model [18], Skartveit and Olseth model [19] and Reindl model [20]. The third generation anisotropic diffuse radiation models are obtained by integrating solving diffuse radiation integral equation, and the typical models are Perez model [21], Gueymard model [22] and Muneer model [10,23]. These models can be used to calculate the diffuse radiation on different orientations and tilt surfaces. Lots of simulation softwares (TRNSYS, Energyplus, eQUEST and so on) use these models to calculate the heat gain of buildings, solar photovoltaic, solar thermal, etc. In addition, it can also be used for the research of plant growth.

The first generation models assumed the diffuse radiation from the sky is isotropic, and the study of Klucher [17] indicated that the isotropic models (e.g. Liu and Jordan model) provide a good fit to empirical data under overcast skies but underestimate the amount of solar radiation incident on tilted surface under clear and partly cloudy conditions. For cloudy weather conditions, direct solar radiation is blocked, and the sky is close to isotropic. So the first generation diffuse models can be better matched. For partially cloudy and sunny weather conditions, the direct solar radiation causes diffuse radiation enhancement in circumsolar zone, and glow effect causes diffuse radiation enhancement in sky horizontal zone. All of these factors result in the first generation of isotropic diffuse radiation models are inconsistent with the measured data under partially cloudy and sunny weather conditions.

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http://dx.doi.org/10.1016/j.enconman.2015.01.016
0196-8904/

Nomenclature

A, B, C are the intermediate variables (dimensionless)
F_1 Circumsolar radiation coefficient (dimensionless)
F_2 Orthogonal radiation coefficient (dimensionless)
F_3 Horizon radiation coefficient (dimensionless)
$F_{11}, F_{12}, F_{13}, F_{21}, F_{22}, F_{23}, F_{31}, F_{32}, F_{33}$ are the intermediate variables (dimensionless)
k_d diffuse ratio, $k_d = I_{h,d}/I_h$ (dimensionless)
k_t clearness index, $k_t = I_h/I_{h,0}$ (dimensionless)
I_s diffuse radiation from the sky dome (W/m^2)
$I_{h,0}$ extraterrestrial radiation on a horizontal surface (W/m^2)
I_h global solar radiation on a horizontal surface (W/m^2)
$I_{h,d}$ diffuse solar radiation on a horizontal surface (W/m^2)
$I_{h,b}$ beam solar radiation on a horizontal surface (W/m^2)
$I_{h,d1}$ diffuse radiation on a horizontal surface from circumsolar zone (W/m^2)
$I_{h,d2}$ diffuse radiation on a horizontal surface from orthogonal zone (W/m^2)
$I_{h,d3}$ diffuse radiation on a horizontal surface from the sky horizontal zone (W/m^2)
$I_{h,d4}$ diffuse radiation on a horizontal surface from the sky dome (W/m^2)
$I'_{h,d4}$ diffuse radiation on a horizontal surface from hemispherical (W/m^2)
$I_{t,d}$ diffuse radiation on a tilted surface (W/m^2)
$I_{t,d1}$ diffuse radiation on a tilted surface from circumsolar zone (W/m^2)
$I_{t,d2}$ diffuse radiation on a tilted surface from orthogonal zone (W/m^2)
$I_{t,d3}$ diffuse radiation on a tilted surface from the sky horizontal zone (W/m^2)
$I_{t,d4}$ diffuse radiation on a tilted surface from the sky dome (W/m^2)
$I'_{t,d4}$ diffuse radiation on a horizontal surface from hemispherical (W/m^2)
$u(m_a)$ uncertainty of the test values (W/m^2)
$u_a(m_a)$ relative uncertainty of the test values (dimensionless)
α the half angle of the circumsolar zone (°)
β tilt angle (°)
γ solar azimuth angle (°)
δ solar declination (°)
φ latitude (°)
ω hour angle (°)
θ the incident angle of the tilted surface (°)
θ_z zenith angle (°)
ζ half vertex angle of orthogonal spherical cap (°)
ξ the angular thickness of the horizon band (°)
$\chi_h(\theta_z)$ the fraction of the circumsolar zone which is seen by horizontal (dimensionless)
$$\chi_h(\theta_z) = \begin{cases} \psi_h \cos\theta_z, 0 \leqslant \theta_z < \frac{\pi}{2} - \alpha \\ \psi_h \sin(\psi_h \alpha), \frac{\pi}{2} - \alpha \leqslant \theta_z \leqslant \frac{\pi}{2} \end{cases}$$
ψ_h the fraction of the circumsolar zone which is not shadowed (dimensionless) $\psi_h = \begin{cases} 1, 0 \leqslant \theta_z < \frac{\pi}{2} - \alpha \\ \frac{\pi/2-\theta_z+\alpha}{2\alpha}, \frac{\pi}{2} - \alpha \leqslant \theta_z \leqslant \frac{\pi}{2} \end{cases}$
$\chi_h(\frac{\pi}{2} - \theta_z)$ the fraction of the orthogonal zone which is seen by horizontal (dimensionless)
$$\chi_h(\tfrac{\pi}{2} - \theta_z) = \begin{cases} \psi'_h \sin(\psi'_h \zeta), 0 \leqslant \theta_z < \zeta \\ \psi'_h \sin\theta_z, \zeta \leqslant \theta_z \leqslant \frac{\pi}{2} \end{cases}$$
ψ'_h The fraction of the orthogonal zone which is not shadowed (dimensionless)
$$\psi'_h = \begin{cases} \frac{\theta_z+\zeta}{2\zeta}, 0 \leqslant \theta_z < \zeta \\ 1, \zeta \leqslant \theta_z \leqslant \frac{\pi}{2} \end{cases}$$
$\chi_c(\theta)$ the fraction of the circumsolar zone which is seen by tilt (dimensionless)
$$\chi_c(\theta) = \begin{cases} \psi_h \cos\theta, 0 \leqslant \theta < \frac{\pi}{2} - \alpha \\ \psi_h \frac{\pi/2-\theta+\alpha}{2\alpha} \sin\left(\frac{\pi/2-\theta+\alpha}{2}\right), \frac{\pi}{2} - \alpha \leqslant \theta \leqslant \frac{\pi}{2} + \alpha \\ 0, \frac{\pi}{2} + \alpha < \theta \leqslant \pi \end{cases}$$
$\chi_c(\frac{\pi}{2} - \theta)$ the fraction of the orthogonal zone which is seen by tilt (dimensionless)
$$\chi_c(\tfrac{\pi}{2} - \theta) = \begin{cases} \psi'_h \frac{\theta+\zeta}{2\zeta} \sin\left(\frac{\theta+\zeta}{2}\right), 0 \leqslant \theta < \zeta \\ \psi'_h \sin\theta, \zeta \leqslant \theta < \frac{\pi}{2} \\ \psi'_h \sin(\pi - \theta), \frac{\pi}{2} \leqslant \theta < \pi - \zeta \\ \psi'_h \frac{\pi-\theta+\zeta}{2\zeta} \sin\left(\frac{\pi-\theta+\zeta}{2}\right), \pi - \zeta \leqslant \theta \leqslant \pi \end{cases}$$

The second generation models are generally based on modifying the first generation models to be suitable for partially cloudy and sunny weather. The assumption of these models is the diffuse radiation from the sky is anisotropic, but these models are often unable to explain how anisotropic diffuse radiation distributed in the sky. For example, Temps and Coulson model [16] increases the horizon radiation coefficient and circumsolar radiation coefficient to describe the anisotropic diffuse radiation under clear weather conditions. Klucher model [17] is adapted to sunny, cloudy and clear weather condition by introducing a correction factor related to diffuse ratio based on Temps and Coulson model. So this model in cloudy conditions is close to Liu and Jordan model, and in sunny conditions close to Temps and Coulson model. Moreover, diffuse radiation is divided into diffuse radiation from circumsolar zone, sky horizontal zone and sky dome by Hay [18], Skartveit and Olseth [19], Reindl [20] and other researchers. The second generation models have relatively simple forms and some practical values, but they do not have clear physical meaning and are relatively low accuracy because they are only adjusted from isotropic models.

The third generation models remedy the defect of the aforementioned models, and the assumptions of these models are the diffuse radiation from the sky is anisotropic. The sky is divided into several zones, and then the equations of diffuse radiation from the sky element are solved by integration in each zone respectively. Among these models, Gueymard model [22] and Muneer model [10,23] are developed from Steven and Unsworth model [24] which is gained by integrating Moon and Spencer model [25]. The radiation distribution index is the core indicator of these models, and it has significant impact on accuracy of diffuse radiation calculation. Perez model [21] is strictly in accordance with the definitions of the radiation intensity and the solid angle. The source of diffuse radiation is divided into circumsolar zone, sky horizontal zone and sky dome zone by radiation intensity, and assuming each zone is isotropic. On the basis of these hypotheses, diffuse radiation from these three zones is solved by integration respectively. The performance of these models is evaluated by Gueymard and other researchers [26–28] with measured diffuse radiation data. The result shows that the calculated values are not well agreed with the measured data. This is due to the deviation between the hypothesis of models and the actual distribution of diffuse radiation. For Perez model, the distribution of diffuse radiation on the sky dome zone is actually not isotropic. Many observations and studies [16,24,29–31] show that diffuse radiation from a zone located at 90° angles with the Sun (hereinafter referred to as orthogonal diffuse radiation) is weakened. Mcarthur and Hay [29] mapped the distribution of diffuse solar radiation over the sky hemisphere. Justus and Paris [30] gave the measured and computed diffuse radiance distribution. Brunger and Hooper [31] used