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Effects of atmospheric aerosol on the direct normal irradiance on the earth's surface

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ABSTRACT

Direct normal irradiance (DNI) plays a key role on the quantity and rate of hydrogen production. The accurate calculation of DNI has very important significance for low-cost hydrogen economy and efficient utilization of solar energy. This study mainly takes account of the influence of atmospheric aerosol on DNI and the experimental tests. The main idea of this paper is: obtaining the distribution characteristics of aerosol particles in the atmosphere and the optical depth of aerosol spectrum based on inversion method of ground observation station data; calculating the attenuation coefficient of solar spectrum with classical Mie scattering theory and particle system radiation characteristics; calculating aerosol attenuation coefficient under full spectrum, namely the aerosol correction factor (defined as the ratio of the attenuation coefficient of aerosol atmosphere to standard atmosphere under full spectrum) with Planck model, Rosseland model and Planck–Rosseland model respectively; choosing with the theoretical calculation model of aerosol correction factor based on the solar spectrum radiation calculated by SMARTS software; verifying the accuracy of this theoretical model with experimental DNI in city Harbin. The results show that there is a good agreement with a minimum variation of 3.08% and a maximum variation of 9.97%.

1. Introduction

Hydrogen can be generated by a wide range of technologies, that is: gasification of coal and biomass; electrolysis of water; photo-electrochemical/photo-catalytic splitting of water; thermolysis and thermochemical cycles [1]. But to respect the environment, the solution of renewable energy sources, particularly solar energy, appears most appropriate for a future industry [2–4]. The main four types of solar hydrogen production systems are follows: PV, photo-electrochemical, photo-biological and solar thermal reaction [5]. The PV-based solar hydrogen production mainly utilizes electricity energy produced by the PV cells. In photo-electrochemical process, semiconductor or other materials are adopted to convert the solar energy to hydrogen [6]. For photo-biological system, photosynthesis is a main mode of solar hydrogen production. The most important method of solar hydrogen

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Nomenclature

L	aerosol optical depth
C_a	absorption cross section
C_e	attenuation cross section
C_s	scattering cross section
h	Planck constant
k	Boltzmann constant
n	refractive index
κ_a	aerosol correction factor
$\kappa_{e,\lambda}$	the spectral attenuation coefficient of atmosphere
$\kappa_{e,\lambda,A}$	spectral attenuation coefficients of aerosol
$\kappa_{e,\lambda,G}$	spectral attenuation coefficients of atmospheric gases particle
λ	wavelength (m)
I	DNI (W/m^2)
$Q_{e,\lambda}$	attenuation coefficient
$Q_{s,\lambda}$	scattering coefficient
$Q_{a,\lambda}$	absorption coefficient
$\omega_{\lambda,p}$	scattering albedo
$\phi_{\lambda,p}$	scattering phase function
m_λ	the particle spectrum complex refractive index
n_λ	spectral refractive index
k_λ	spectral absorption index
χ	scale parameter
G	geometric projected area of the particle
Re	the real part of a complex number
ω_p	scattering albedo of single particle
Φ_p	scattering phase function of single
Θ	angle between scattering direction and incident direction
κ_e	attenuation coefficient
κ_s	scattering coefficient

production is concentrated solar thermal system. The production of hydrogen from water using concentrated solar energy via a thermochemical cycle or other method. The key topic of solar hydrogen production is DNI, which affects the temperature of receiver/reactor and system's efficiency. Recently, experimental result shows that the temperature of 2300 K can be obtained from concentrated solar energy as the source of process heat [7]. A novel receiver/reactor driven by concentrating solar energy for hydrogen production was designed, constructed and tested [8–10]. It is found that the receiver/reactor temperature increased with the increment of DNI. Besides, the concentrating system, the efficiencies and application in solar hydrogen production progress have been investigated [4,11–15].

It is very obvious that DNI has an effect on the quantity and rate of solar hydrogen production [10]. As the instantaneous DNI on the earth's surface has characteristics of intermittent nature, dynamic, variable and companying with cloud, rain wind-sand, etc, affecting the non-uniform changing law of DNI, the calculation of DNI is very difficult [16,17].

There are a number of studies on DNI. Sun and Liu [18] summarized five kinds of calculation methods for DNI on the earth's surface using calculation of average radiation intensity with sunshine hours, sunlight transmission model, difference between total radiation intensity and scattering radiation intensity, satellite data acquisition and ground-based observations respectively, and this article analyzed the advantages and disadvantages of each calculation method, and proposed a simplified calculation method for transient DNI on the earth's surface considering a variety of weather conditions. Janjai et al. [19] established a monthly average of hourly global radiations based on satellite data and this article considered the influence of aerosol, atmospheric relative humidity, ambient temperature, the total column ozone on the solar radiation intensity. Senkal and Kuleli [20] calculated DNI in Turkey with an artificial neural network model and the satellite observation data. Escobedo et al. [21] calculated hourly average and daily average values of total sunlight radiation intensity under different band conditions using data in city Botucatu, and combining with an empirical model calculation. This paper proposed an atmospheric cleanness correction factor κ_T (the ratio of the global-to-extraterrestrial solar radiation). In addition, in order to calculate the solar irradiance of the earth's surface, there are some researches focused on the radiation transfer progress of the sunlight (i.e. reflection, emission, absorption, and scattering) in the atmospheric layer [22,23].

The literature review shows that aerosol of the atmosphere is an important composition of atmosphere environment, with a great influence on DNI but the current studies are limited. In order to obtain DNI on the earth's surface, a calculation model of aerosol correction factor is established in this paper. Meanwhile, the experimental test located at city Harbin is investigated.

2. Aerosol correction factor

The solid particles or small liquid substances suspended in the atmosphere are usually called as atmospheric aerosol, with general diameter range of $10^{-3}\sim10^{2}$ μm. It is more likely to produce radiation forcing effect for the aerosol particles with diameter ranging 0.1–10 μm. Obviously, as different regions have different characteristics properties, and aerosol is an important indicator of atmosphere radiation balance with a direct influence on DNI on the earth's surface.

Supposed that the spectral radiation intensity of wavelength λ outside the earth's atmosphere is $I_{\lambda,0}$, the aerosol optical depth is L, the spectral attenuation coefficient of atmosphere (containing particle medium) is $\kappa_{e,\lambda}$, the spectral radiation intensity of solar energy after atmosphere attenuation observed on the earth's surface $I_{\lambda,L}$ is expressed as:

$$I_{\lambda,L} = I_{\lambda,0}\exp(-\kappa_{e,\lambda}L) \tag{1}$$

The spectral attenuation coefficient of atmospheric medium $\kappa_{e,\lambda}$ consists of two parts: one part is aerosol and the other part is atmospheric gases, which can be calculated by:

$$\kappa_{e,\lambda} = \kappa_{e,\lambda,A} + \kappa_{e,\lambda,G} \tag{2}$$

where, $\kappa_{e,\lambda,A}$ and $\kappa_{e,\lambda,G}$ represent spectral attenuation coefficients of aerosol and atmospheric gases respectively.