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A simple model to predict solar radiation under clear sky conditions

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Abstract

Solar radiation is one of the major factors that dominate the thermal behaviors of aerostats in the daytime and the primary energy source of high altitude long endurance aerostats. Therefore, it is necessary to propose an accurate model to predict the solar irradiances. A comprehensive review of the well-known solar radiation models is conducted to help develop the new model. Based on the analysis of the existing models and the available radiation data, the extensive computer tests of the regression and optimization are conducted, from which the new solar radiation model for direct and diffuse irradiances under clear sky conditions is proposed. The new model has excellent prediction accuracy. The coefficient of determination for direct radiation is 0.992, with the root mean square error (RMSE) of 16.9 W/m^2 and the mean absolute error (MAE) of 2.2%. The coefficient of determination for diffuse radiation is 0.86, with RMSE = 8.7 W/m^2 and MAE = 9.9%. Comparisons with the well-known existing models show that the new model is much more accurate than the best existing ones.

Keywords: Solar radiation; Direct radiation; Diffuse radiation; Aerostat; Altitude

1. Introduction

An aerostat is a lighter than air vehicle whose lift derives from the buoyancy resulted from the density difference between the inner gas and the surrounding air. Its distinguishing features of long endurance, station keeping, and low cost-effectiveness make it suitable for transportation, surveillance, telecommunication relay, broadcasting, and military roles, which attract interests all over the world.

In order to predict the thermal performance of an aerostat, it is important to consider its surrounding thermal environment carefully. The solar radiation is one of the major factors that dominate the thermal behaviors of an aerostat in the daytime. Meanwhile, the solar radiation is the primary energy source of a high altitude long endurance aerostat. The good estimation of solar radiation is crucial for modeling the thermal performance of an aerostat.

Several studies were carried out for modeling solar radiation on aerostats. Carlson and Horn (1983) and Wang et al. (2007) assumed the total solar irradiance reaching an aerostat to be constant. Kreith and Kreider (1974) and Farley (2005) neglected the diffuse and reflected irradiance. This assumption is unacceptable for low altitude conditions, where the magnitude of sum of diffuse and reflected irradiance can be as high as 400 W/m^2. Wang and Yang (2011) employed semi-empirical corrections related to the ground measurements which may lead to under-prediction of the solar irradiance for a high altitude aerostat. Xia et al. (2010) used a semi-empirical direct solar model which takes the effect of altitude into account, but they neglected the influence of altitude on diffuse and reflected irradiance. Dai et al. (2012) employed an empirical solar model, where the atmospheric transmittance was highly simplified.

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The operational altitude of aerostats covers a wide range, from 0 km for tethered aerostats to over 30 km for high altitude aerostats. The differences of direct and diffuse solar irradiances predicted by spectral analysis at different altitudes may as high as 500 and 300 W/m^2 (Knaupp and Mundschau, 2004), respectively. In the foregoing solar radiation models, except for Xia et al. (2010) and Dai et al. (2012), all of them do not consider altitude, i.e., they are only suitable for ground applications. On the other hand, Xia et al. (2010) and Dai et al. (2012) consider only the effect of altitude on direct solar irradiance, while the effect of altitude on diffuse solar irradiance is neglected. Therefore, the above-mentioned solar models may lead to remark errors at high altitude. Meanwhile, all of the above mentioned solar radiation models do not consider the effect of atmospheric conditions, such as aerosol and water vapor. The values of aerosol and water vapor vary dramatically. At a given altitude, the differences of direct and diffuse solar irradiances predicted by spectral analysis at different atmospheric conditions may as high as 300 and 200 W/m^2, respectively. Therefore, the solar models using constant aerosol and water vapor are not reasonable.

The heat load caused by solar radiation contributes a major fraction for high altitude aerostats. For a near space aerostat with a diameter of 40 m and a solar absorptivity of 0.33, its solar absorption can be as high as 400 W/m^2 at the operational altitude of 20 km, where the direct solar irradiance is about 1300 W/m^2, while its forced convective heat load is only around 100 W/m^2 at the temperature difference of 50 K and the forced convective heat transfer coefficient of 2 W/m^2 K. If the mean absolute errors (MAEs) caused by the convective load calculation and the direct solar load calculation are required to be equivalent and the MAE of the convective load calculation is 20%, the MAE of the direct solar radiation calculation should be lower than 5%. All of the above mentioned solar radiation models have an MAE greater than 5%.

From the above brief introduction, it can be seen that an accurate solar radiation model that considers the factors of altitude and atmospheric conditions is needed. It is the purpose of this paper to propose an accurate model to predict the direct and diffuse solar irradiances which takes into account of altitude and meteorological parameters. A comprehensive survey of the well-known solar radiation models is conducted. Based on the analysis of the existing models and the radiation data from National Renewable Energy Laboratory (NREL) (http://www.nrel.gov/midc/srrl_bms), the extensive computer tests of the regression and optimization using the commercial software 1stOpt (7D-Soft High Technology Inc., 2010) are conducted to develop the new solar radiation model for clear sky conditions. The new model is compared to the existing models and reference code to assess its accuracy.

2. Review of solar radiation models

2.1. *Bird and Hulstrom (1980, 1981) model*

The Bird and Hulstrom model has gained wide acceptance in the last three decades. The algorithms for each attenuation process were the basis of the Iqbal (1983) model and the METSTAT model (Maxwell, 1998). The model is of the form

$$I_{DN} = 0.9662 I_{SUN} T_R T_O T_{MG} T_W T_A \quad (1)$$

$$I_d = 0.79 I_{SUN} T_O T_W T_{MG} T_{AA} \sin h [0.5(1 - T_R) + 0.84(1 - T_{AS})]/(1 - m_R + m_R^{1.02}) \quad (2)$$

where I_{DN} is the direct irradiance, I_d is the diffuse irradiance, I_{SUN} is the solar constant, T_R, T_O, T_{MG}, T_W and T_A are the individual transmission coefficient for Rayleigh scatting, ozone, mixed gases, water vapor and aerosol, T_{AA} is the transmittance of aerosol absorption, T_{AS} is the transmittance of aerosol scattering, and X_O and X_W are the amount of ozone and water vapor in a slant path. The relative air mass m_R is determined by the following Kasten (1965) equation:

$$m_R = \left[\sin h + 0.15(3.885 + h)^{-1.253}\right]^{-1} \quad (3)$$

where h is the solar elevation angle. The absolute air mass can be determined by

$$m_A = m_R(p/1013) \quad (4)$$

where p is the atmospheric pressure.

2.2. *Heliosat-1 model (Dumortier, 1995; Page, 1996)*

The clear sky Heliosat-1 model consists two separate models for direct radiation (Page, 1996) and diffuse radiation (Dumortier, 1995). They can be written as:

$$I_{DN} = I_{SUN} \exp(-m_A \sigma T_L) \quad (5)$$

$$I_d = I_{SUN}[0.0065 + (0.0646 T_{L2} - 0.045)\sin h - (0.0327 T_{L2} - 0.014)\sin^2 h] \quad (6)$$

where T_L and T_{L2} are the turbidity factors, and σ is the optical depth of clean atmosphere. The relative air mass is calculated using an expression introduced by Kasten and Young (1989):

$$m_R = [\sin h + 0.506(h + 6.08)^{-1.636}]^{-1} \quad (7)$$

2.3. *MAC model (Davies, 1987; Davies et al., 1988)*

The MAC model provided a different treatment of the extinction process involved by water vapor, as expressed in the following:

$$I_{DN} = I_{SUN}(T_R T_O - a_W) T_A \quad (8)$$