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A new model for atmospheric radiation under clear sky condition at various altitudes

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Abstract

Atmospheric radiation is one of the major factors that dominate the thermal behaviors of aerostats. A high-performance model is needed to evaluate the atmospheric radiation. Based on the atmospheric radiation database containing 24,862 data points compiled from 7 stations with the elevation from sea level to 2373 m and the reference code MODTRAN, a new atmospheric radiation model is proposed using regression and optimization software. It has excellent prediction accuracy with the coefficient of determination of 0.94, the root mean square error of 15.1 W/m^2, and the mean absolute percentage error of 4.13% for the database. Comparison with the well-known existing model shows that the new model has the highest prediction accuracy. The new model predictions agree with the MODTRAN calculations at various altitudes very well, and thus it can be used for estimating the thermal performances of a high altitude aerostat.

Keywords: Atmospheric radiation; Sky equivalent temperature; Sky emissivity; Altitude; Aerostat

1. Introduction

An aerostat is a light-than-air vehicle whose lift is derived from buoyancy gas. This unique feature makes aerostat have a huge hull and be sensitive to the thermal environment, for which an accurate estimation of the thermal behaviors of the aerostat is especially important.

Solar radiation and longwave radiation play a key role in the thermal behavior of aerostats (Farley, 2005; Li et al., 2011; Li et al., 2012; Dai and Fang, 2014). Longwave radiative heat transfer occurs during the full daily cycle and is the only radiative heat transfer during the night. The good estimation of the atmospheric radiation is crucial for modeling the thermal performance of aerostats, especially at high altitude and low wind velocity conditions. On the contrary to the infrared heat transfer between ground and an aerostat, the longwave radiative heat transfer between atmosphere and an aerostat is more complicated.

Several studies were carried out for modeling atmospheric longwave radiation on aerostats. Carlson and Horn, (1983) used a blackball temperature to present the longwave radiative heat transfer. The blackball temperature is assumed to be 5.5 K below the ambient temperature in the troposphere and constant at 214.4 K in the stratosphere under clear sky. Farley (2005) considered a simple longwave atmospheric radiation model as a function of altitude. Dai et al. (2012) employed an empirical model based on the ground measurement.

Atmospheric radiation is mainly caused by the absorption and emission of the water vapor, carbon dioxide, and ozone in the sky, among which the water vapor plays

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the most important role (more than 90% at sea level). Therefore, an empirical model that contains the ambient temperature and water vapor pressure may be suitable for estimating the thermal behavior of an aerostat. Most existing atmospheric radiation models were developed using a limited temporal and spatial data set and thus suffered from being specific to a site or region. The environment where an aerostat works in is different from the ground measurement station. Therefore, the effect of altitude on atmospheric radiation of an aerostat needs to be carefully considered.

The purpose of this paper is to propose an empirical correction of the atmospheric radiation that may useful for high altitude aerostats. Based on regression and optimization using commercial software 1stOpt (First Optimization), a new atmospheric radiation model is proposed using the radiation data from the Baseline Surface Radiation Network (BSRN, 2013). The dataset containing hourly meteorological data (screen level temperature, screen level relative humidity, pressure and atmospheric radiation) from 7 stations are used in this work. Statistical parameters are used to measure the accuracy of the new model, and the comparisons of the new model with the existing models are conducted. The results show that the new model is feasible to provide an accurate prediction of atmospheric radiation under cloudless sky conditions.

2. Atmospheric radiation

The atmospheric radiation can be expressed in two ways (Ramsey et al., 1982):

(a) The sky is assumed to behave like a black body, so that the atmospheric radiation can be written as:

$$R_{sky} = \sigma T_{sky}^4 \tag{1}$$

(a) The sky is considered to be a gray body, with a sky emissivity of ε_{sky}, so that it follows

$$R_{sky} = \varepsilon_{sky} \sigma T_a^4 \tag{2}$$

where R_{sky} is the downward integral radiative flux, T_{sky} is the sky equivalent temperature in K, T_a is the ambient temperature in K, and σ is the Stefan–Boltzmann constant.

The concepts of sky equivalent temperature and sky emissivity are widely accepted to determine the atmospheric radiation. Many semi-empirical or empirical correlations are available in the literature to calculate the sky emissivity or sky equivalent temperature. Some simple semi-empirical models were obtained by integration of radiative transfer equation with some assumptions that allow an approximation for analytical solution in terms of screening-level variables (Brutsaert, 1975; Prata, 1996), while most empirical models were based on the statistical fit between the atmospheric radiation and the screening-level parameters, such as air temperature, water vapor pressure and/or dew point temperature (Brunt, 1932; Melchior, 1982; Bliss, 1961; Clark and Allen, 1978; Martin and Berdahl, 1984; Berger et al., 1992). Table 1 shows an exhaustive list of the models available to calculate the atmospheric radiation under clear sky conditions.

Most of the empirical models were developed for only one region or climatic zone. The altitude's contribution to the atmospheric radiation was only represented in the Martin and Berdahl model (1984) and the Berger et al. model (1992). The additive terms in the Martin and Berdahl model (1984) have limited effect on the adjustment at high altitude. Meanwhile, the Martin and Berdahl model (1984) exceeds the applicable range at stratosphere where the dew point temperature is below –40 °C. The polynomial form involved in the Berger et al. model (1992) may lead to remarkable error at the altitude higher than 5 km.

At high altitude where aerostats work in, the dew point temperature is more difficult to establish than water vapor pressure. Therefore, the Brunt model (1932) which uses the water vapor pressure as input is employed. By incorporating a pressure fraction into the Brunt model (1932), a new model is proposed as the following:

$$\varepsilon_{sky} = (a + b p_w^c)\left(\frac{p}{1013}\right)^d \tag{3}$$

where a, b, c and d are the best fit parameters, and p is the ambient pressure in mbar.

3. Experimental stations and database

Hourly data from 7 different stations around the world were used. There data can be obtained from BSRN (2013). The atmospheric radiation data used in this paper include date, time, screen level temperature, screen level relative humidity, pressure, direct radiation, and downward long-wave radiation. The data are recorded automatically every minute. Table 2 summarizes the main geographic characteristics of the stations as well as the time period of the measurements.

The screen level temperature and screen level relative humidity can be used to determine the water vapor pressure and dew point temperature, as given below (Fang, 1995):

$$p_w = \begin{cases} R_h \exp\left(29.06 - \frac{6211.88}{t_a + 274.35}\right) & -100^\circ\mathrm{C} < t_a < 0^\circ\mathrm{C} \\ R_h \exp\left(23.3 - \frac{3890.94}{t_a + 230.4}\right) & 0^\circ\mathrm{C} \leqslant t_a < 300^\circ\mathrm{C} \end{cases} \tag{4}$$