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# The analysis on applicability of hourly horizontal diffuse radiation estimation model of Shanghai Zone

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# The analysis on applicability of hourly horizontal diffuse radiation estimation model of Shanghai Zone

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**Abstract:** For shading design and energy consumption simulation, hourly diffuse radiation data is necessary. In order to estimate the total solar radiation on surfaces with different spatial orientations, the knowledge of all components on the horizontal plane is required. Available measured data is, however, typically less. The 2004-2013 year's measured data of Shanghai were localized revising of three categories models, comparing the measured data and estimation data by the correlation coefficient and error index. The results show that the three types of models have high accuracy at higher solar altitude and the accuracy of multi parameter logistic function is best. For stations with only daily solar radiation data, the third types of models can be used to calculate hourly diffuse solar radiation.

**Keywords:** hourly global solar radiation; hourly diffuse solar radiation; clearness index; daily diffuse radiation; solar altitude angle

## 1. Introduction

To analysis buildings' energy performance under the effect of solar radiation and calculate solar radiation on a titled surface, it is necessary to know the direct and diffuse solar radiation. Moreover, design and sizing of solar energy systems (e.g. photovoltaic cells, solar-thermal collectors) needs accurate solar radiation data. The most accurate way to obtain solar radiation data is to establish station to collect in real time using high-precision measurement equipment. However, due to cost and maintenance, concurrent measured data of global and diffuse radiation on horizontal or inclined surface are available only for a limited number of locations in China. Therefore, it is necessary to established mathematical method using radiation-related parameters.

The diffuse fraction model, which is the ratio of the hourly horizontal diffuse solar radiation to the hourly horizontal global solar radiation, was first derived from Origill's study [1]. Origill divided the hourly clearness index (ratio of horizontal global radiation and extra-terrestrial radiation) into three intervals and established the relationship between diffuse fraction and hourly clearness index in each interval. Erbs et al. [2] fitted the fourth degree polynomial functions between them. Then, many scholars studied the regional adaptability of the Origill´ and Erbs´ model, and made revised to this model, in terms of first to fourth degree polynomial functions, first to three paragraph curve and other variables such as air temperature, relative humidity, cloud amount, sunshine hours ratio, air quality, and daily clearness index [3-11]. Other forms [12-14], with hourly clearness index, apparent solar time, solar altitude angle, and daily clearness index, are the Gompertz function and Logistic function. Some researches were about the relationship between the ratio of the diffuse rate[15](the ratio of the hourly diffuse solar radiation to the hourly horizontal extra-terrestrial solar radiation) and clearness index. Daily diffuse radiation[16] were decomposed, according to the changing rules of the sun from sunrise to sunset. This article calls daily diffuse decomposition model.

Many scholars verified the applicability of the diffuse fraction model in different regions[17-19]. The results showed the calculated are closed to the measured values. However, the diffuse fraction model needs hourly global horizontal radiation data as a support. There are more daily radiation data in

China. Compared with this, the development of the daily diffuse decomposition model has more development, but its accuracy remains to be verified.

This paper localizes the diffuse fraction, diffuse rate, and daily diffuse decomposition model and verifies the daily diffuse decomposition model with meteorological elements based on the Baoshan station of Shanghai.

## 2 Data Sources and Quality Control

### *2.1 Data Sources*

For this research, hourly and daily global, diffuse radiation data were recorded in Baoshan(latitude: 31.24°, longitude: 121.46°, altitude: 8 m) form January 2004 to December 2013. Other parameters such as hourly extra-terrestrial radiation and clearness index can be calculated.

### *2.2 Quality Control*

Measurement technology and equipment accuracy will bring errors, so it is necessary to quality control the measured data. The steps are as follows [20]:

①The first test proceeds by eliminating entries that show a solar altitude angle less than 7°.

②The second test: clearness index and the diffuse ratio are positive and have values between zero and one(inclusive)

③The third test: global and diffuse irradiation are compared with their corresponding Page model upper and lower boundaries.

④A fourth test involves the construction of $k_d$-$k_t$ quality control envelope. This is a statistical procedure that requires estimation of $k_t$ banded mean, weighted mean and standard deviations of "$k_d$" values (Δ). Typically the $k_t$ range of data may be divided in, say, ten bands of equal width. For each band the above mentioned statistics is obtained. From this information an envelope may be drawn that connects those points that, respectively, represent the top ( $\overline{k}_d+2\Delta$) and bottom ( $\overline{k}_d-2\Delta$) curves. The data lying within this envelope represent quality data—free of any measurement related errors.

Though the four steps, the final database consist of about 37413 hourly values.

## 3 Method

### *3.1 Statistical Tests and Comparison Indices*

To compare the performance of the models, five statistical indicators were employed[6,13], namely the correlation coefficient ($R^2$), the mean deviation (MBE), the relative mean absolute error (MABE%), the relative root mean square error (RMSE%), and the relative error (RE). The closer $R^2$ is to 1, the more accurate the model is. The remaining parameters is to zero, the more accurate the model is.

### *3.2 Used Models*

Based on the measured radiation data after the quality control between 2004 to 2009, a total of nine models were fitted and represented by M1-M9, as shown in formula (1) to (16). Meteorological parameters, such as Temperature (T), Relative Humidity (RH), Atmospheric Pressure (P), have a complex relationship with solar radiation. Using SPSS to analysis the correlation between hourly diffuse radiation and temperature, relative humidity and Atmospheric pressure, the correlation coefficients were 0.367, -0.427, and -0.191, respectively. The relative humidity, which is the most relevant factor, was selected to modify M9. The modified model was represented by M10, as shown in formula (17).

1）M1

$$k_d = 0.946k_t^3 + 1.05k_t^2 - 4.93k_t + 3.28 \quad (1)$$

2）M2

$$k_d = 5.816k_t^4 - 6.726k_t^3 + 0.667k_t^2 - 0.058k_t + 1.0 \qquad 0 \le k_t \le 0.85 \quad (2)$$

$$k_d = 0.4 \qquad 0.85 < k_t \le 1 \qquad (3)$$

3）M3

$$k_d = 1.0 \qquad k_t \le 0.1 \qquad (4)$$

$$k_d = 5.801k_t^4 - 6.578k_t^3 + 0.49k_t^2 + 0.008k_t + 0.993 \qquad 0.1 < k_t \le 0.8 \qquad (5)$$

$$k_d = 0.35 \qquad 0.8 < k_t \le 1 \qquad (6)$$

4）M4

$$k_d = 1.0 \qquad k_t \le 0.1 \qquad (7)$$

$$k_d = -1.235k_t + 0.022t + 0.974 \qquad 0.1 < k_t \le 0.85 \qquad (8)$$

$$k_d = 0.4 \qquad 0.85 < k_t \le 1 \qquad (9)$$

5）M5

$$k_d = 1.0 \qquad k_t \le 0.1 \qquad (10)$$

$$k_d = -1.242k_t + 0.037\sin\alpha + 0.023t - 0.946 \qquad 0.1 < k_t \le 0.85 \qquad (11)$$

$$k_d = 0.4 \qquad 0.85 < k_t \le 1 \qquad (12)$$

6）M6

$$k_d = \frac{1}{1 + \exp(6.554k_t - 4.127)} \qquad (13)$$

7）M7

$$k_d = \frac{1}{1 + \exp(8.174k_t - 0.195t - 2.572)} \qquad (14)$$

8）M8

$$k_D = 1.187k_t^3 - 2.683k_t^2 + 1.761k_t - 0.044 \qquad (15)$$

9）M9

$$\frac{I_{dh}}{I_d} = \frac{\pi}{24} \cdot \frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s} \qquad (16)$$

10）M10

$$\frac{I_{dh}}{I_d} = 0.021 + 0.986 \cdot \frac{\pi}{24} \cdot \frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s} - 0.032RH \qquad (17)$$

## 4 Results

The above-mentioned 10 models were validated using data from the 2010 to 2013 period in Shanghai, and the error indicators of each model were calculated. Fig. 1 shows the $R^2$, MBE, MABE%, and RMSE% of M1-M9. The cumulative distribution function of RE (in %) for M1 to M9 are showed in Fig.2. Figure 3 show the relationship between model accuracy and solar altitude. Table 1 shows, for both original(M9) and modified by the RH(M10), the $R^2$, MBE, MABE% and RMSE%. In the evaluation of the merits of the model, the method of reference [21], that is, the MBE<10%, RMSE <30% means good model; the 10% <MBE <20%, 30% <RMSE <40% means good enough model; the MBE> 10%, RMSE> 40% means bad model.

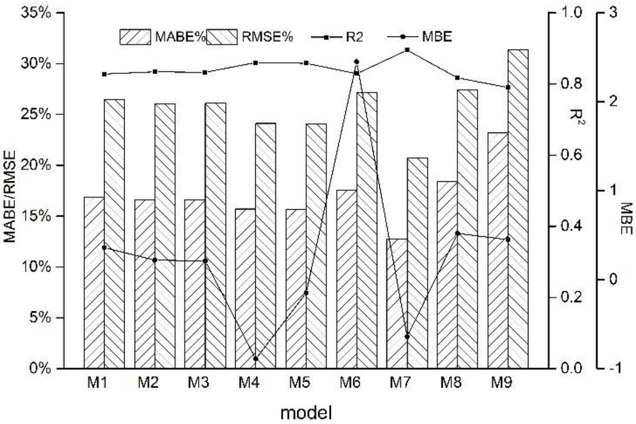



**Fig.1** The $R^2$、MBE、MABE% and RMSE% of M1-M9

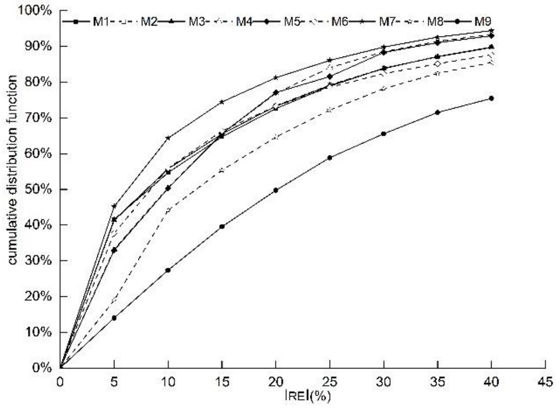
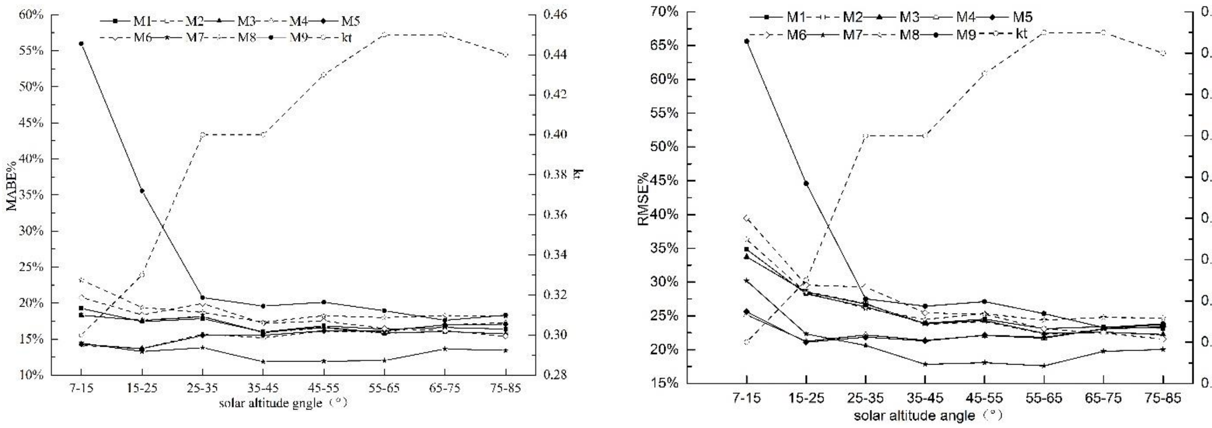



**Fig.2** The cumulative distribution function (CDF) of the relative errors(in ±%) for the eight models with the original coefficients.




a MABE% b RMSE%

**Fig.3** MABE%、RMSE% and $k_t$ of M1-M9 with solar altitude

**Table 1** The $R^2$、MBE、MABE% and RMSE% of M9 and M10

| model | R2 | MBE | MABE% | RMSE% |
|---|---|---|---|---|
| M9 | 0.79 | 0.45 | 23.17% | 31.36% |
| M10 | 0.83 | 0.79 | 22.82% | 31.16% |

## 5 Discussion

(1) The $R^2$ of the diffuse fraction models' value is the highest, the diffuse rate models' is next and the daily diffuse decomposition models' is the smallest in Fig.1. The MABE% and RMSE% have the opposite changing tendency. This shows that the diffuse fraction model has the highest accuracy, followed by the diffuse rate model and the daily diffuse decomposition model.

(2) The $R^2$, MABE% and RMSE% of the univariate model (M1-M3, M6) with the clearness index as variable are 0.82 to 0.85, 16% to 18% and 26% to 28%, respectively; while, the multivariate model (M4, M5, M7) is greater than 0.85, 12% to 16.3%, and 20% to 24.2%, respectively. This indicates that the accuracy of the multivariate model is higher than that of the univariate model.

(3) The values of $R^2$, MABE% and RMSE% of M6 is smallest and biggest in the univariate model, which indicates that the accuracy of the piecewise polynomial model is higher than the logistic function model. The values of $R^2$, MABE% and RMSE% of M7 is biggest and smallest in the multivariate model, which indicates that logistic function is better than the linear function. The error

indexes of M4 and M5 are basically the same, indicating that the solar altitude angle has no obviously effect on its accuracy. Based on the principle of simple calculation, M4 is priority than M5.
(4) Figure 2 shows that the results of M1 to M9 with a relative error less than 10% are about 50%, 55%, 56%, 56%, 56%, 50%, 64%, 44%, 44%, respectively, implying the accuracy of M7 is higher than others.
(5) The MABE% and RMSE% of M1 to M9 decrease with the increase of the solar elevation angle, while, the change of the clearness index is opposite, indicating that the accuracy of these models is increasing with the solar altitude angle and clearness index increasing. The trend of M9 is more obvious. When the solar altitude angle is ≥25°, the MABE%, RMSE% are 17% to 21%, 23% to 28%, respectively. According to the literature [21], the solar elevation angle is bigger, the accuracy is better.
(6) In the revised model (Table 1), $R^2$ increased by 0.4, MABE% decreased by 0.35%, and RMSE% decreased by 0.2%, indicating that the model´ accuracy can be improved by adding the correction of the relative humidity.

## 6 Conclusion
(1) The accuracy of the three types of models increases with the increase of the solar altitude.
(2) For the hourly diffuse radiation of Shanghai and its similar areas, the multi-parameter logistic function model (M7) is recommended, followed by the multi-parameter diffuse fraction model (M4) added with apparent solar time correction.
(3) The diffuse rate model (M8) could not improve the accuracy of the model. In case of the hourly global solar radiation data, this model is not recommended.
(4) Although the accuracy of M9 is slightly lower when the solar elevation angle is low, it can be used to calculate the hourly diffuse radiation to compensate the lack of hourly radiation data. The correction of relative humidity improves the accuracy of the model, but it is not obvious and more stations are needed to be verified.

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## Nomenclature
$I_{\mathrm{Gh}}$： hourly horizontal global solar radiation, MJ/m$^2$;
$I_{\mathrm{Gh,o}}$： hourly horizontal extra-terrestrial solar radiation, MJ/m$^2$;
$I_{\mathrm{dh}}$： hourly horizontal diffuse solar radiation, MJ/m$^2$;
$I_{\mathrm{d}}$： hourly horizontal daily solar radiation, MJ/m$^2$;
$k_t$： hourly clearness index, $k_t = I_{\mathrm{Gh}} / I_{\mathrm{Gh,o}}$ ;
$k_d$： diffuse fraction, $k_{\mathrm{d}} = I_{\mathrm{dh}} / I_{\mathrm{Gh}}$ ;
$k_D$: diffuse rate, $k_D = I_{\mathrm{dh}} / I_{\mathrm{Gh,o}}$
$t$： apparent solar time, h;
$\alpha$： solar altitude angle, deg;
$\omega$： hour angle, deg;
$\omega_s$： sunset angle, deg;
RH： relative humidity, %;
T： temperature, ℃;
P： atmospheric pressure, Pa;

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