A STATISTICS-BASED METHOD FOR HOURLY SOLAR RADIATION ESTIMATION

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ABSTRACT

A statistics-based method for hourly solar radiation estimation is introduced in the paper. On the basis of hourly extra-atmospheric horizontal solar radiation calculation, a statistical method is adopted to find out the relationship between solar radiation in normal direction and total solar radiation on extra-atmospheric horizontal, as well as the relationship between diffuse solar radiation and solar radiation in normal direction from typical meteorological year data. By these two relationships and other relative data found in hourly real meteorological year data, the hourly solar radiation data of real meteorological year can be calculated.

INTRODUCTION

It is more and more popular to adopt computer simulation for annual energy consumption analysis in recent years. This method in design stage can forecast how many energy the new building will consume, thereby guide the design of total building energy system to match with national building energy saving code. For existing buildings, this method can evaluate and estimate their energy consumption, and estimate the possibility and expected results of energy saving reconstruction or retrofitting in advance. The software often used for these purposes is DOE-2, VisualDOE, EnergyPlus, eQUEST and DeST, etc.

Because of a large amount of energy consumed by HVAC system in a building, it should certainly be involved in the total building energy consumption analysis. Moreover, the energy consumed by HVAC system is closely related to local weather conditions, especially the temperature, humidity and solar radiation. Usually the typical meteorological year data are adopted to estimate the energy consumption in design stage of new buildings. However, the real meteorological year data should be adopted to analyze the annual energy consumption of existing buildings. Because of the real energy consumption data of an existing building can be obtained easily, it is usually to be adopted to calibrate the computer model with real meteorological year data to ensure a certain precision of the model. And then the building energy consumption will be recalculated with typical meteorological year data and the calibrated model for evaluation and comparison purposes. This molding-calibration-calculation and estimation method is also recommended by International Performance Measurement & Verification Protocol (IPMVP Committee, 2002).

BASIC METHOD

According to the demands of DOE-2, 14 parameters are required for load calculation: wet-bulb temperature, dry-bulb temperature, atmospheric pressure, cloud cover, snow, rain, wind direction, humidity, atmospheric density, enthalpy, total horizontal solar radiation, solar radiation in normal direction, type of cloud and wind speed. Every of them, except the two parameters related with solar radiation, can be straight obtained from hourly weather records published by local observatories, or through certain calculation and quantization.

Solar radiation will heavily influence indoor heat environment and influence air-conditioning load consequently. Unfortunately, comprising with other meteorological parameters the hourly solar radiation data can hardly be found in China due to local observatories usually not publishing solar radiation data. At some cases without higher precision, solar radiation data of typical meteorological year are straight adopted. However, in those precisely cases, some methods based on calculation are introduced for solar radiation estimation. Generally, daily model is adopted in these methods but hourly model is rarely adopted. Thus, it is more significant to establish a model for practical hourly solar radiation estimation.

The hourly observation data of solar radiation composes of a random time series with strong randomicity. However, some determinacy rules with relative stable sects can still be found after a carefully analyzing. So the models for solar radiation estimation could be divided into two types of determinacy model and random model. There are many types of these

mathematical models, some are from theoretical deduction, some are empirical formulae, and others are semi-empirical, semi-theoretical formulae.

For instance, Zhang Suning and Tian Shenyuan combined determinacy model and random model to establish an hourly solar radiation calculation model ARIMA (Zhang et al, 1997). It firstly calculated the determinacy part of total solar radiation with C-P & R model, and then simulated the random part with white noise model by software to calibrate the determinacy model, and the final results obtained were much better than that through C-P & R model alone.

Lang Siwei developed a mathematical model of hourly solar radiation estimation for building energy analysis (Lang, 2002). This method was similar as the method issued by Matsuo Y (Matsuo et al, 1993), but the variables in it were total cloud cover, dry-bulb temperature, relative humidity and wind speed. And some coefficients in the model were determined based on observation data by regression.

The method issued by Kurt Spokas and Frank Forcella (Spokas et al, 2006) firstly calculating the solar radiation by astronomy formulae, and then determining a coefficient of atmospheric transmitivity according to daily temperature difference, precipitation and the trend of precipitating to finally figure out hourly solar radiation data.

Moreover, Qingyuan Zhang, Joe Huang, et al developed a model (Zhang et al, 2003) with three variables, say cloud cover, dry-bulb temperature on the time and dry-bulb temperature three hours before, and seven place dependent regression coefficients to estimate hourly global solar radiation on the horizontal surfaces. The only deficiency of this model is that it didn't give a way to estimate solar radiation in normal direction (sun direct beam radiation in normal direction) which is required by DOE-2.

To meet the demands of DOE-2, authors tried to find a solution to estimate both total solar radiation and solar radiation in normal direction in a simpler way. It is known that the hourly extra-atmospheric horizontal solar radiation data are merely related to longitude, latitude, calendar day and time, and all these can be precisely calculated by astronomy formulae (Wang, 1999). This means that the extra-atmospheric horizontal solar radiation is constant on certain time and in certain place. As authors' opinion, this could be a "jumping-off point" for solar radiation estimation.

Total solar radiation can be divided into two parts: solar radiation in normal direction and diffuse solar radiation, and the extra-atmospheric horizontal solar radiation is the source of both of them. So, if the relationship and influence factors between solar radiation in normal direction and total solar radiation on extra-atmospheric horizontal, as well as the relationship and influence factors between diffuse solar radiation and solar radiation in normal direction were found, the solar radiation in normal direction could be calculated from total solar radiation on extra-atmospheric horizontal, and diffuse solar radiation could be calculated from solar radiation in normal direction. And then the total solar radiation can also be calculated.

According to authors' opinion, these relationships and influence factors can all be found from local typical meteorological year (TMY) data by proper statistical methods. For description expediently, following are all based on the solar radiation estimation of year 2004 in Shanghai as an example.

DATA ANALYSIS, CALCULATION, FITTING AND APPLICATION

The relationship between solar radiation in normal direction and total solar radiation on extra-atmospheric horizontal (N/E for short in following) was considered in the very beginning.

First of all, three influence factors upon N/E relationship, say cloud cover in one-tenth, angle of sun incidence and humidity, were assumed. The reason of assuming them as influence factors was that they seemed no correlation one another, and this was important to a "pure statistics" method.

In these factors, the cloud cover influences the solar radiation directly, and its influence is self-evident; the angle of sun incidence will influence solar radiation in normal direction, and the smaller of the angle of sun incidence, the less of solar radiation in normal direction will reach ground surface; the vapor in air will disperse and absorb solar radiation, so the more vapor the air contained (means higher humidity), the less of solar radiation in normal direction will reach ground surface. Besides, of course the air pollution should also be an independent influence factor. But this factor has to be omitted now due to there has been no test or estimation about the influence of air pollution on solar radiation yet.

Based on such a consideration, the hourly typical meteorological year data of Shanghai quoted from "Chinese Standard Meteorological Database for Buildings" (Zhang et al, 2004) were adopted, and cloud cover, angle of sun incidence and humidity were as variables inputted to SPSS software to analyze the relationship between N/E and these three factors. The results showed that N/E was only related to cloud cover, and the influences of angle of sun incidence and

humidity tended to zero.

Referring to the result of factor analysis, it could be explained as follows: cloud cover as a main influence factor was expected; the influence of angle of sun incidence tending to zero only showed that the influence of this factor was already included in the alteration of extra-atmospheric horizontal solar radiation, in which a time factor was involved; and it might be two reasons of that humidity was also almost no influence on N/E: first was that there was not so significant disperse and absorb effects on solar radiation by vapor in Shanghai region, and the second was that the humidity was more or less related to cloud cover, so the influence of this factor was partly included in the factor of cloud cover already.

Thus, the calculation of N/E relationship can be simplified to calculate the average coefficients of proportionality corresponding to different cloud cover in a precondition of omitting the influence of air pollution.

Because of there were total 4385 hours in 2004, Shanghai when sun was above horizontal, so there were hundreds or more than one thousand N/E ratios corresponding to every cloud cover, and these data distributed in a wide range (See Figure 1, in which the red areas were 50% confidence interval).

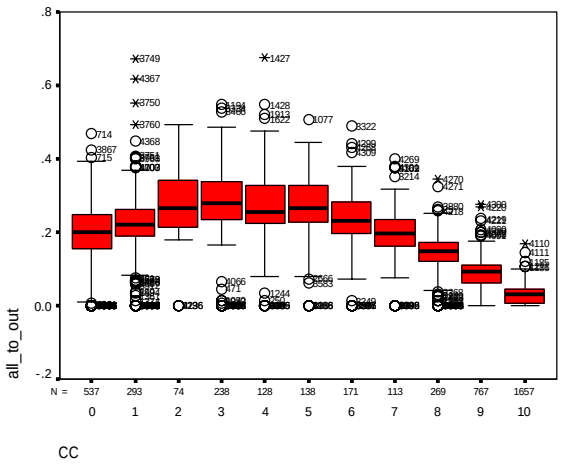

Figure 1 The distribution of N/E ratio corresponding to different cloud cover

According to authors' point of view, the reason of wide range distribution of the ratio was that the cloud cover only showed the percentage of sky shaded by cloud, but it didn't involve any information about the relative positions between sun and cloud. So, the solar radiation in normal direction would be quite different under same cloud cover condition because of the sun maybe, or maybe not, shaded by cloud. This situation would be more prominent when cloud cover was few.

If the consideration mentioned above were correct, the distribution of N/E ratios should obey normal distribution (Gaussian distribution) because of the randomicity of relative positions between sun and cloud. So, a test for checking whether the N/E ratios satisfying with normal distribution in different cloud cover should be done before calculating the average coefficients of proportionality.

Also by SPSS, the tests to check that if the N/E ratios satisfying with normal distribution in every cloud cover were implemented. The results showed that all N/E ratios satisfied normal distribution perfectly, and this provided a good basis for next step to calculate the average coefficient of proportionality. Figure 2 shows one of the normal distribution checking results.

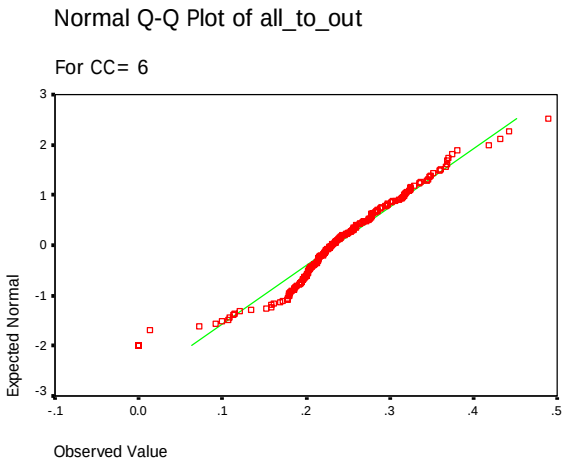

Figure 2 N/E ratio normal distribution checking result (cloud cover = 6)

The methods and procedures to find out N/E relationship can also be used to analyzing the relationship between diffuse sun radiation and solar radiation in normal direction (D/N for short in following). As the same methods as N/E relationship analyzing, it was found that the cloud cover was the only influence factor. So the way to find out D/N relationship was simplified to calculate the average coefficients of proportionality corresponding to different cloud cover as well. Although there were only 3845 hours that sun shining on ground surface directly in 2004, Shanghai, the D/N ratios were still hundreds or thousand. According to the same reason mentioned above, a normal distribution checking was also required. The checking results showed that the D/N ratios corresponding to every cloud cover also presented a

good normal distribution. The distribution of D/N ratios corresponding to different cloud cover was showed in Figure 3 and one of the normal distribution checking results was showed in figure 4.

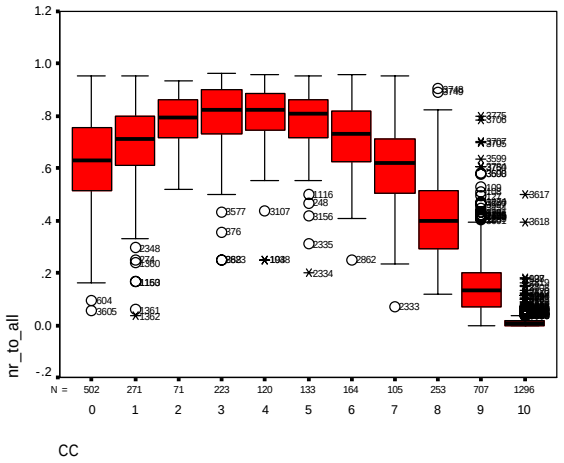

Figure 3 The distribution of D/N ratio corresponding to different cloud cover

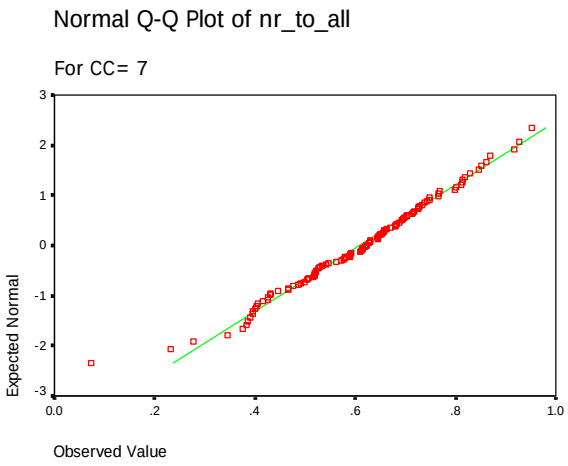

Figure 4 D/N ratio normal distribution checking result (cloud cover = 7)

Although both of the N/E ratio and D/N ratio corresponding to every cloud cover satisfied normal distribution perfectly, it would still lead to an unacceptable error if their arithmetic mean value were simply adopted as average coefficients of proportionality. This was because of the wide range of data distribution and the existing of some extreme values. To minimize calculation error, a maximum likelihood mean value estimating algorithm, called Hampel's redescending M-estimator provided in SPSS, was adopted. This algorithm is able to figure out a mean value which will be more closely to true value than arithmetic mean value while the data obey normal distribution but widely spread and some extreme values exist (Xue, 2004). The results of the mean values of N/E ratios and D/N ratios corresponding to every cloud cover from typical meteorological year data calculated by Hampel's redescending M-estimator were showed in table 1

Table 1 The maximum likelihood mean values of N/E and D/N corresponding to every cloud cover

Cloud cover	N/E	D/N
0	.201996	.629582
1	.225952	.707603
2	.279112	.794809
3	.286788	.821102
4	.273717	.821468
5	.276085	.796764
6	.238903	.723629
7	.199643	.612589
8	.146616	.399326
9	.089103	.134332
10	.028377	.006261

The data in table 1 showed: (1) solar radiation in normal direction only takes a part of less than 30% of total solar radiation on extra-atmospheric horizontal; and (2) while cloud cover is 2, 3, 4 or 5 the most solar radiation (include direct and diffuse) reaches ground surface.

By normal regression method, two fitting formulae can be found from the data in table 1:

$$k_1 = -0.0063cc^2 + 0.0442cc + 0.2022 \quad (1)$$

$$k_2 = -0.0199cc^2 + 0.1344cc + 0.6107 \quad (2)$$

where k_1 is the maximum likelihood mean value of N/E, k_2 is the maximum likelihood mean value of D/N, and cc is cloud cover in one-tenth.

The R^2 values of formula (1) and formula (2) are 0.9899 and 0.9873 respectively, and the fitting curves are showed in Figure 5.

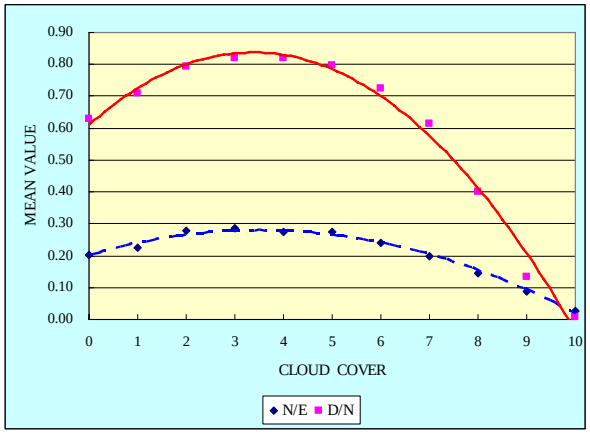

Figure 5 N/E and D/N mean values fitting curves

Now it is easy to calculate hourly solar radiation for real meteorological year data after the fitting formulae found:

1) Adopting astronomy formulae to calculate the local hourly total solar radiation on extra-atmospheric horizontal, and all the period that the solar radiation is 0 (means sun location is under horizontal) were then eliminated;

2) Obtaining and quantization hourly cloud cover according to real time weather from local real meteorological year data, and a manual smoothing processing may be required in those period when cloud cover changes tempestuously;

3) Adopting formula (1) or straight citing the values in table 1 with the results of step 1) and 2), the hourly solar radiation in normal direction of real meteorological year can be calculated;

4) Adopting formula (2) or straight citing the values in table 1 with the results of step 3), the hourly diffuse sun radiation of real meteorological year can be calculated.

5) Adding the hourly solar radiation in normal direction and hourly diffuse solar radiation correspondently to figure out the hourly total solar radiation of real meteorological year to match with the demands of DOE-2.

The monthly sums of total solar radiation and direct solar radiation of year 2004 and 2005 calculated by the procedures mentioned above were listed in table 2 respectively, and showed in Figure 6.

Table 2 Monthly sums of total solar radiation and direct solar radiation of 2004 and 2005 (MJ/m^2)

	Total solar radiation		Direct solar radiation	
	2004	2005	2004	2005
Jan	206.92	187.56	119.86	112.18
Feb	268.86	155.85	153.38	96.78
Mar	311.73	304.62	183.82	181.26
Apr	359.82	415.64	209.26	240.91
May	373.73	396.85	221.00	231.59
Jun	366.15	473.97	219.51	270.79
Jul	432.36	393.82	258.84	235.89
Aug	378.83	354.95	232.86	208.75
Sep	291.03	285.98	176.61	173.42
Oct	326.19	242.57	189.38	145.27
Nov	229.94	210.10	133.83	124.09
Dec	172.67	196.67	102.18	117.02
Sum	3718.23	3618.59	2200.54	2137.95

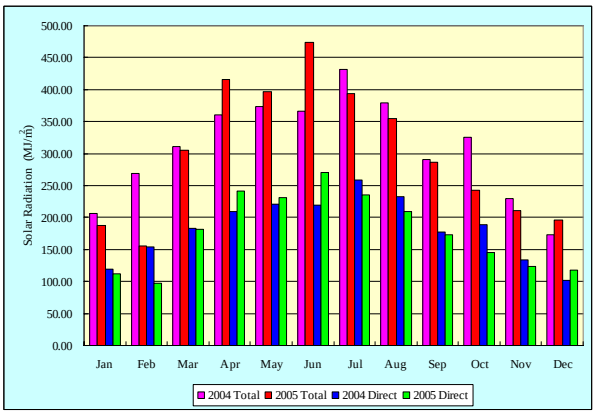

Figure 6 Monthly sums of total solar radiation and direct solar radiation of 2004 and 2005

All hourly solar radiation data calculation procedures were implemented by a program developed by authors because of there are huge amount of data require to be processed. The solar radiation data of year 2004 and 2005 calculated by the method introduced above has been adopted as a part of hourly real meteorological year data of Shanghai for a high-rise commercial buildings energy consumption computer simulation research project. The simulation results were satisfactory (Pan et al, 2006), and the details of simulation were expatiated in authors' another paper

titled “The Application of Building Energy Simulation and Calibration in Two High-Rise Commercial Buildings in Shanghai”.

CONCLUSION

1. The extra-atmospheric horizontal solar radiation, which can be calculated precisely by astronomy formulae, is the source of solar radiation in normal direction and diffuse solar radiation.

2. According to the results of influence factor analysis, the relationship between solar radiation in normal direction and total solar radiation on extra-atmospheric horizontal was only related to cloud cover, and the relationship between diffuse sun radiation and solar radiation in normal direction wais only related to cloud cover as well.

3. Although the ratio of solar radiation in normal direction and total solar radiation on extra-atmospheric horizontal corresponding to every cloud cover, as well as the ratio of diffuse sun radiation and solar radiation in normal direction corresponding to every cloud cover distributed in a rather wide range, but these values obeyed the normal distribution perfectly.

4. The mean values of the two ratios corresponding to every cloud cover mentioned above should be calculated by Hampel's redescending M-estimator algorithm. While the data obeyed normal distribution but widely spread and some extreme values existed, with this maximum likelihood mean algorithm can figure out a mean value (maximum likelihood mean value) which would be more closely to true value than arithmetic mean value. And the maximum likelihood mean value of these two ratios can be well fitted by two two-degree trinomials respectively.

5. Adopting the two mean values mentioned above with the hourly total solar radiation on extra-atmospheric horizontal calculated by astronomy formulae and the hourly cloud cover obtained from local hourly meteorological year data, the hourly solar radiation data of real meteorological year can be obtained.

6. Because of this estimation method was based on the local hourly solar radiation data of typical meteorological year and the local hourly cloud cover of real meteorological year, it is expected that this method could be extended to calculate hourly solar radiation data of any given place and any given year.

7. Up to now, the hourly solar radiation observation records of certain real meteorological year of Shanghai could not be found yet. So, although the solar radiation data figured out by the method introduced in this paper has been adopted in a building energy consumption computer simulation project with satisfactory results, its accuracy still needs further inspection.

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