Climatic Zoning for the Thermal Design of Residences in China Based on Heating Degree-Days and Cooling Degree-Hours

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Abstract
In this paper, using the integrated surface observations for 430 Chinese locations, equations for estimating heating degree-days and cooling degree-hours were developed. The distribution of heating degree-days and cooling degree-hours was clarified and contour maps of heating degree-days and cooling degree-hours were created. Based on these maps, a new climatic zoning was proposed for the thermal design of residences in China.

Keywords: China; climatic zoning; observation; heating degree-days; cooling degree-hours

Introduction
In order to save energy in residential sectors and improve indoor thermal comfort, the Chinese Ministry of Construction established a regulation for thermal design called the Thermal Design Code for Civil Buildings in 1993\(^1\). In this regulation, the climatic zoning in China was demonstrated (see Table 1.) and the level of thermal insulation and air-tightness for each region was given. The zoning was based on the average temperatures of the coldest and warmest months. As shown in Fig.1., there are five regions (very cold, cold, hot-summer-cold-winter, hot-summer-warm-winter and mild regions) and China is divided into nine blocks. The advantage of this zoning is that it reflects the climatic and geographic characteristics of each region. There are some problems with this zoning. First, the heating load can be very different within the same region even with the same type of housing, especially in the very cold region. A study by the author et al.\(^2\) demonstrated that with the same level of insulation and air-tightness, the heating load for Mohe is 1040 MJ/m\(^2\), which is almost twice that of Shenyang (528 MJ/m\(^2\)). There is also a big gap between the heating load of the southern and northern sides of Jiayuguan, although both sides belong to the same very cold region. The main reason for the big differences in heating load within the same very cold region is that the zoning is too approximate and the very cold region covers areas that are too extensive.

Heating degree-days are the integration of indoor-outdoor temperature difference over the heating season; therefore, the heating degree-day is a better parameter for describing the heating load than the average of the coldest month. As for cooling load, the cooling degree-hour is a better parameter than degree-days because cooling is usually conducted for only a few hours during the day. Up to now, very few studies have been carried out on zoning in China based on heating degree-days and cooling degree-hours.

In this paper, using the observational weather data for 430 locations over the period of 1995-2003, the heating degree-days and cooling degree-hours were calculated. The geographic distribution of heating degree-days and cooling degree-hours was clarified, based on which, new climatic zoning was proposed.

Table 1. Criteria for Climatic Zoning by Reference\(^3\)

| Region                  | Main criteria                                                                 | Additional criteria                                                                 |
|-------------------------|------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Very cold               | The average temperature in the coldest month is lower than -10°C             | The days when the average daily temperature is lower than 5°C are more than 145.    |
| Cold                    | The average temperature in the coldest month is between 0 and -10°C         | The days when the average daily temperature is lower than 5°C is between 0 and 145.|
| Hot-summer-cold-winter | The average temperature in the coldest month is between 0 and 10°C, and the average temperature in the warmest month is between 25 and 30°C | The days when the average daily temperature is lower than 5°C is between 0 and 90 days, the days when the average daily temperature is higher than 25°C is between 40 and 110. |
| Hot-summer-warm-winter | The average temperature in the coldest month is over 10°C, and the average temperature in the warmest month is between 25 and 29°C | The days when the average daily temperature is higher than 25°C is between 110 and 200. |
| Mild                    | The average temperature in the coldest month is between 0 and 13°C, and the average temperature in the warmest month is between 18 and 25°C | The days when the average daily temperature is lower than 5°C is between 0 and 90. |

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The Integrated Surface Hourly Data
The database used for this study is the global surface hourly observations integrated from the NCDC (National Climatic Data Center) observations and Navy Surface Hourly Data\(^3\). Although it is called Integrated Surface Hourly (ISH) observations, the intervals for most Chinese locations are three hours instead of one hour. Therefore, a procedure for interpolating the three-hour data to one-hour data is necessary. A computer program was developed by the author, in which double interpolation with the Fourier Series was conducted\(^4\). The period covered by the observations is from 1995 to 2003. The observations for 430 Chinese locations included in the ISH database were used for this study.

The Distribution of Heating Degree-Days in China
Because heating load is strongly related to heating degree-days, the distribution of heating degree-days is useful for estimating the energy consumption for residential heating. The average heating degree-days based on 18°C were calculated for the 430 locations over the period of 1995 - 2003. By plotting the values of the average heating degree-days to a Chinese map, and using linear interpolation, a contour map of heating degree-days was developed as shown in Fig.2. The maximum heating degree-days appears in Mohe, the northernmost city in China, whose heating degree-days are as many as large as 7,888. The heating degree-days for Shenyang is 3,905, which is about half that of Mohe, although both Mohe and Shenyang belong to the same very cold region. The minimum heating degree-days appear in Hainan Province, where the value of heating degree-days is less than 40. There is a large difference between the heating degree-days for southern and northern Xinjiang. In northern Xinjiang, the number of heating degree-days are usually more than 4,000, while the values for southern Xinjiang are about 3,000. It is clear that the degree-days are strongly related to the geographical features in the western part of China, especially around the Kunlun Mountains, where there are three contour lines close to each other. The geographical features on the Tibet Plateau are very complicated; therefore, more meteorological observatories are needed in order to make more accurate contour maps.

To understand the similarities and differences between the temperature-based and degree-day based

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Fig.1. The Climatic Regions for the Thermal Design of Civil Buildings (Created by the author based on reference \(^1\))
zonings, it is helpful to clarify the relation between heating degree-days and the average temperature of the coldest month. Because elevations significantly influence the temperature, the locations were divided into two groups when discussing the relations between the heating degree-days and the average temperature of the coldest month: one group contains locations above 3,000 m and the other below 3,000 m. As shown in Fig.3, degree-days have a strong relationship with the average temperature in January for both groups. The values of the degree-days are larger for the high elevation group, which means the heating season is longer at higher elevations than the lower locations when the average temperature in January is the same.

Using the least squares method, latitude, elevation, average temperature and relative humidity in January were used as parameters. To estimate the heating degree-days locations whose elevations are lower than 3,000 m, the equation is as follows:

\[
HDD = 33614 - 14.417\psi + 68.467 \log(h) - 17833.9 \log(50.0 + \theta_J) - 13.36\phi
\]

(1)

where \(\psi\) is the latitude, \(\phi\) is relative humidity in percent, \(\theta_J\) is the average temperature in January in °C, and \(h\) is the elevation in meters.

For locations whose elevations are above 3,000 m, heating degree-days HDD should be calculated using the following equation:

\[
HDD = 43822 - 79.66\psi + 2002.46 \log(h) - 26705.6 \log(50.0 + \theta_J) + 10.07\phi
\]

(2)

The relation between the heating degree-days and the average temperature in January is more logarithmic than linear, so the term of temperature in January is in the form of a logarithm. To avoid the antilogarithm being negative, a temperature of 50°C was added to the average temperature in January. The correlation between heating degree-days from estimation and observation is shown in Fig.4. The root mean square error (RMSE) from the estimation using Equations (1) and (2) is 207, which implies that heating degree-days can be estimated using Equations (1) and (2) for the locations where detailed observational data are lacking.
The Distribution of Cooling Degree-Hours

Heating is usually conducted continuously. During the cooling seasons, however, cooling is usually conducted for a few hours during the day; therefore, the cooling load is strongly related to cooling degree-hours rather than degree-days. This paper discusses the distribution of cooling degree-hours in China. Using the interpolated ISH database, the average cooling degree-hours were calculated over the period of 1995-2003.

The base temperature of cooling degree-hours is somewhat subjective and not as clear as that of the heating degree-days, which is usually fixed at 18°C. The relationship between cooling degree-hours based on different temperature and that based on 24°C are shown in Fig.5. The cooling degree-hours based on 25, 26, 27 and 28°C are about 70%, 46%, 28% and 16% as large as those based on 24°C, respectively. These relations can be expressed by the following equation:

\[ CDH_\theta = k \cdot CDH_{24} \] (3)

\[ k = 0.03\theta^2 - 1.77\theta + 2.62 \] (4)

where CDH is the cooling degree-hour based on 24°C, and CDH is the cooling degree-hour based on \( \theta \)°C.

The relations between coefficient \( k \) and base temperature \( \theta \) is shown in Fig.6.

The relationship between 24°C-based degree-hours and the average temperature in July is shown in Fig.7. The data can be classified into three groups by their locations: a. locations north of 28N; b. locations south of 28N and east of 107E and c. locations south of 28N and west of 107E. The relationship between cooling degree-hours and the average temperature in July can be expressed using polynomial expressions.
By using the least squares method, a function for estimating cooling degree-hours was established for locations north of latitude 28°N:

\[ CDH_{24} = -108.6 + 3.46\psi + 334.85\log(h) - 502.84\theta + 87.51\theta^2 - 5.745\theta^3 + 0.1279\theta^4 - 6.14\varphi \]  \hspace{1cm} (5)

For locations south of 28°N and east of 107°E:

\[ CDH_{24} = 1113 - 1071.2\psi - 350.1\log(h) + 1817.8\theta - 789.754\theta^2 + 57.534\theta^3 - 1.0527\theta^4 - 139.8\varphi \]  \hspace{1cm} (6)

For locations south of 28°N and west of 107°E:

\[ CDH_{24} = -4.1 - 32.9\psi + 1237.3\log(h) - 141.23\theta + 12.88\theta^2 - 3.642\theta^3 + 0.1281\theta^4 + 95.59\varphi \]  \hspace{1cm} (7)

The relationship between cooling degree-days from the estimation using Equations (5), (6) and (7) and the observations are shown in Fig.8. The RMSE from this estimation is 590, which shows that the cooling degree-hours can be estimated using Equations (5)-(7) for the locations where detailed data are lacking.

By combining Equations (3) – (7), cooling degree-hours can be calculated for any location at any base temperature between 24 and 28°C with minor error.

The distribution of cooling degree-hours based on 25°C is derived mainly by observations as shown in Fig.9. Most of the cooling degree-hours are distributed in the south-east and the Takla Makan Desert. The cooling degree-hours at the Tibet Plateau are equal to zero. The area with the largest cooling degree-hours is Hainan Province where the degree-hours are usually above 10,000. Although the cooling degree-hours are concentrated in the area cornered by 40°N and 105°E, the energy consumption for residential cooling cannot be underestimated because about 85% of the total Chinese population lives in this area.
Climatic Zoning Based on Heating Degree-days and Cooling Degree-hours

Because the energy consumed for heating is much larger than that for cooling, climatic zoning should be mainly based on heating degree-days. Another reason for this zoning is that thermal insulation is less effective for cooling than for heating. Based mainly on the distribution of heating degree-days, the climatic zoning for thermal design is given in Fig.10. The criteria for the zoning are shown in Table 2. The intervals of degree-days between the neighboring regions are 1,000, which means the region covers a smaller area than the ongoing thermal design code (Fig.1).  

Region 1 covers an area with heating degree-days of over 5,000, including the north-east part of China and the north part of the Tibet Plateau. Regions 5 and 6 almost agree with the hot-summer-cold-winter and hot-summer-warm-winter regions shown in Fig.1, respectively.  

Cooling degree-hours are also considered in deciding Region 7. Because both heating degree-days and cooling degree-hours are small in this area, basically neither cooling nor heating are necessary, which means that thermal insulation and air-tightness for residences are not as important as in other regions. In this zoning method, however, it is possible that in some local areas, the heating degree-days may exceed the criteria shown in Table 2. For example, the heating degree-days at Mount Tai in Shandong Province reach 4,348, which is far above the criterion for Region 4. In order to solve this problem, more detailed zoning is necessary; therefore, more detailed observations are required.
Table 2. Criteria for Climatic Zoning

| Regions | Criteria                  | Provinces                                                                 |
|---------|---------------------------|---------------------------------------------------------------------------|
| ①       | HDD>5000                  | Heilongjiang, Inner Mongolia, Xinjiang, Qinghai, Tibet, etc              |
| ②       | 4000<HDD≤5000             | Heilongjiang, Inner Mongolia, Jilin, Liaoning, Xinjiang, Gansu, etc      |
| ③       | 3000<HDD≤4000             | Liaoning, Hebei, Shanxi, Shaanxi, Gansu, Ningxia, Inner Mongolia, Xinjiang, etc |
| ④       | 2000<HDD≤3000             | Beijing, Tianjin, Hebei, Shanxi, Henan, Shandong, Anhui, Jiangsu, Hubei, etc |
| ⑤       | 1000<HDD≤2000             | Anhui, Jiangsu, Zhejiang, Shanghai, Huibei, Jiangxi, Sichuan, Chongqing, etc |
| ⑥       | HDD≤1000                  | Fujian, Guangdong, Guangxi, etc                                          |
| ⑦       | HDD>2000, CDH<1000        | Yunnan, Guiyang, Sichuan, etc                                           |

Conclusions
1. The distribution of heating degree-days and cooling degree-hours was clarified using the interpolated ISH observations and maps of heating degree-days and cooling degree-hours that were created.
2. Equations to estimate heating degree-days and cooling degree-hours were developed using the observations of 430 Chinese locations.
3. A new climatic zoning was proposed for the residential thermal design based on the contour maps of heating degree-days and cooling degree-hours.

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