HEATING/COOLING/POWER LOAD CHARACTERISTICS IN CHINA'S SEVERE COLD REGION

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ABSTRACT

This paper deals with typical residential buildings constructed according to the national energy-efficiency standard in China's severe cold region. Dynamic heating/cooling loads of residential building models were simulated via a factorial experiment. The electricity consumption of residential buildings was investigated, and the characteristics of the power load were analyzed statistically. The results show the cooling/heating/power load indexes of S–N- and E–W-oriented multi-story residential buildings in China's severe cold region. In addition, notable factors of heating/cooling load were obtained via a factorial experiment analysis. Besides, simplified formulae were obtained, which can be used to calculate heating/cooling load indexes for multi-story residential buildings in China's severe cold region. Furthermore, the heating/cooling/power load index can be applied to calculate the maximum load of a residential building in planning and design stage. According to the maximum load, equipment capacity can be determined. And the key variables can be used in building energy-saving design.

INTRODUCTION

With the improvement of Chinese living standards and the rapid pace of residential construction, centralized heating and cooling systems are being increasingly used in residential developments. Heating/cooling load characteristics of buildings are of great significance in architectural design, and can inform equipment and system selection, including operational strategies.

Many studies have examined the load characteristics and load indexes of residential buildings, both in China and across the world. For example, Huang et al (1999) used DOE-2 to simulate heating/cooling load of 175 families. Those family homes have individual heating and cooling systems. They obtained the heating/cooling ratios for different parts of the building envelope, indoor heat sources, and infiltration. Because residential buildings, building materials, and indoor comfort standards in the U.S. vary greatly from those in China, the results are not directly transferable. Nevertheless, the simulation method and building models are relevant to wider research. Hot et al (2008) utilized DeST to calculate heating/cooling loads of residential buildings in Beijing. However, dynamic data is still scarce.

Current research in this field faces a number of problems, as follows. Firstly, most load indexes and characteristics were obtained in the 1990s (Haider et al., 1988). Therefore, considering recent developments in building envelope materials, indoor lighting and equipment, and new energy-efficiency standards, the application of past load indexes and characteristics are of limited value. Secondly, the existing research examined building loads in different regions and countries. As heating/cooling load are affected by outdoor and indoor comfort conditions, researchers should be cautious of generalizing such results to other locations. Thirdly, previous studies rarely considered the specific characteristics of different types of buildings.

This paper deals with heating/cooling/power load characteristics of typical multi-story residential buildings in China's severe cold region. In this region, the average temperature of coldest month is less than -10℃. It's the coldest region of China. Heating is needed for every family. There are many cities in this area in China, such as Harbin, Shenyang, etc. In addition, the climate of Chicago and some cities of Korean Peninsula are similar to the severe cold region. Shenyang is the capital of Liaoning province; it is located in the center of the China's severe cold region, and was therefore chosen to represent heating/cooling/power load. Some simplified formulae were obtained to calculate load; these provide data for the design of centralized residential heating/cooling systems in the study region.

HEATING/COOLING/POWER LOAD SIMULATION METHOD

Heating/cooling load simulation method

This paper uses EnergyPlus software to simulate the annual dynamic heating/cooling load of buildings.

Many factors affect the heating/cooling load of buildings, including the shape coefficient (the ratio of external surface area to volume), window–wall ratio, building envelope type, indoor and outdoor conditions, and air change rate. Because of the low population density of residential buildings and limited working period of indoor lighting and equipment, simulation is based on the shape coefficient, the window–wall ratio, and the type of building envelope.

It is well known that major residential buildings are oriented south and east in China's severe cold region. Therefore, this paper examined residential buildings oriented S–N and E–W. The basic conditions were determined via statistics for residential buildings in severely cold regions of China, and national and local energy-efficiency design standards.

Simulations of dynamic heating/cooling load of residential building models used a factorial experimental design, which examines each level of each factor in the test. A large amount of information is obtained, by which the direct and indirect effects can be accurately estimated.

Each factor in the study has exactly two levels, represented by 0, 1 , as shown in Table 1. The values of other factors are shown in Table 2. The values used were obtained from the relevant guidance (China Academy of Building Research, 2010; Liaoning Province Academy of Building Research, 2011). Factors in Table 2 have less effect on heating/cooling load of residential buildings than factors in Table 1. In order to reduce the number of simulation, factors in Table 1 were chosen to be variables in simulations.

In China's severe cold region, most of multi-story residential buildings are six-story buildings. And the height of each floor is 3 meters. Then building models can be made according to the shape coefficient, window–wall ratio, height of each floor and the number of layers.

Power load calculation method

Although the function of residential buildings is simple, residents have unpredictable patterns of behavior, making it difficult to calculate power load in detail. Surveys are a relatively straightforward, simple and reliable method of obtaining such data (Yanqun Xie, 2007). Therefore, a questionnaire survey was conducted of electricity consumption in residential buildings in China's severe cold region.

The survey was conducted from June to July 2012, and interviewed families living in cities in China's severe cold region. A sample survey was used, considering that habits and customs vary significantly between families. The survey included 60 families from the Harbin Institute of Technology, and collected data on family areas, resident population, monthly power costs, electrical appliances, etc.

A face-to-face survey method was used. This approach enabled the researchers to explain the questionnaire directly to participants, and avoided delays in completing and returning questionnaires. The survey methodology thereby attempted to obtain reliable data to enable more accurate analysis. Statistical analyses were conducted on characteristics of residential building power load.

RESULTS OF HEATING/COOLING/POWER LOAD SIMULATION

Heating/cooling load simulation results

Shenyang is the capital of Liaoning province. It is located in the center of the China's severe cold region, and was therefore chosen to represent heating/cooling load. The heating/cooling loads calculated for S–N- and E–W-oriented multi-story residential buildings are shown in Figures 1 and 2, respectively.

According to Figure 1, the heating/cooling load of S–N long multi-story residential buildings is between the theoretical maximum and minimum values predicted by the model. In Figure 2, the heating/cooling load of E–W long multi-story residential buildings was within the intermediate zone contained by the curves representing heating/cooling load. Figures 1 and 2 show that annual heating/cooling load varies greatly according to outdoor meteorological parameters. The annual heating load is much greater than cooling load. The maximum heating/cooling loads occur in January and July, respectively.

Power load simulation results

The family survey obtained data on the type, quantity, rated power, and demand coefficient of electrical equipment. The resulting load is calculated by the rated power, multiplied by the demand coefficient, and coincidence factors. According to this method, demand coefficient refers to the ratio of actual power demand to rated power. To determine the demand coefficient, the load state of the electrical equipment, (continuous, short-term, repeated short-time work) and the probability of that kind of equipment operating at the same time are taken into consideration. The specific values are obtained from the literature (Yunfu Wu, 2006). Coincidence factors consist of: the probability of different equipment operating at one time within one household (n_1), and that of different households using equipment simultaneously within one building (n_2), as shown in Equation (1)

$$Q = n_1 * n_2 * \sum_{i=1}^{n}(q_i * Kx) \qquad (1)$$

where Q is the power load index, Kx the demand coefficient, q_i the rated power and n_1 and n_2 the coincidence factors. For $n_1 = 0.6—0.8$ and $n_2 = 0.65—0.75$ (Yunfu Wu, 2006), we find $Q = 40—65$ W/m², so the mean is 53 W/m². The annual power load characteristic is shown in Figure 3.

According to Figure 3, the annual power load of residential buildings is relatively stable, with small variations based on user habits. Compared with total heating/cooling load, the power load is greater than cooling load but far less than heating load.

Power load is closely related to users' habits, lifestyle and economic conditions, whereas it has little association with building orientation and outdoor meteorological parameters.

DISCUSSION AND ANALYSIS

Peak load index

Peak load refers to the maximum annual dynamic hourly load series, and is calculated according to the outdoor design temperature of the technical specification. The results are shown in Table 4. Table 5 shows that the peak heating load of S–N long multi-story residential buildings is approximately equal to that of E–W residential buildings; however, peak cooling load is quite different. As the study examined entire residential buildings, the heating/cooling loads of different orientations were not considered separately, so there is little difference in the peak load of the whole building. In addition, orientation influences heating load via infiltration of wind from different directions. In this paper, infiltration was determined by air-change rate, which is a fixed value. Therefore, the peak heating load is the same for different residential buildings. However, solar gain differs according to orientation, and has a great influence on cooling load; thus the cooling load is quite different between various residential buildings.

Furthermore, the maximum heating load was simulated according to the maximum values for shape coefficient, the window–wall ratio, and the building envelope, because such factors may greatly affect heating load. The heating load of residential buildings in China's severe cold region should be less than the theoretical maximum values predicted by the model. Minimum heating load was calculated based on the minimum shape coefficient, window–wall ratio and building envelope. In practice, very few residential buildings can achieve the minimum.

In addition, the maximum and minimum cooling loads were calculated for the maximum and minimum values of all factors individually. As the minimum shape coefficient is difficult to achieve, the minimum cooling load is rarely observed.

The majority of the heating/cooling load for long multi-story residential buildings occurs between the minimum and maximum thresholds, limited by construction technology and material.

The results can be applied in areas where the climate is similar to China's severe cold region. However the precondition is that the parameters of residential buildings are in accordance with Table 1. In fact, most multi-story residential buildings in China's severe cold region meet the conditions. The results can be used in preliminary design calculation for central heating/cooling system.

Notable factors of heating/cooling load

According to analysis of variance and F distribution, $\alpha = 0.01$ was taken as the significance level. Only the main effect was taken into consideration. The results (see Tables 5 and 6) show that the influence of shape coefficient is much greater than any other factors. Shape coefficient is the ratio of external surface area to volume; a higher shape coefficient represents larger heat-transfer area and therefore greater load. In addition, shape coefficient, indoor temperature and window–wall ratio all have considerable influence on heating/cooling load. The types of walls and windows also affect heating load. For S–N and E–W long multi-story residential buildings, shape coefficient and indoor design temperature have a greater influence on heating load than other factors. However, the significant factors differ between S–N and E–W long multi-story residential buildings.

The results can be used in building energy consumption. In addition, the notable factors can be taken into consideration to design energy-saving residential buildings. The results can be applied for most residential buildings without fresh air system.

Simplified linear regression of heating/cooling load index

As the influence of shape coefficient was found to be much greater than that of other factors, the relationships between shape coefficient and heating/cooling load were modeled numerically, using shape coefficient as the independent variable and heating/cooling load as the dependent variable.

In practice, the maximum and minimum values of each factor rarely occur in real building structures. The probability of the average occurrence is higher than that of the maximum and minimum. Therefore, heating and cooling loads were calculated for the average scenario rather than the extremes. The shape coefficient therefore ranged from 0.2—0.35 and was divided into six equal categories. Other factors used the mean as the constant value. Therefore, for an S–N long multi-story residential building, the south and north window–wall ratios are 0.35 and 0.2, respectively; the U-Factors of window, wall, and roof are 2.5, 0.45, and 0.4W/ (m^2•K), respectively; the indoor design temperatures in winter and summer are 20℃ and 24℃, respectively. Other parameters used the values shown in Table 2. For buildings oriented E–W, the east and west window–wall ratios were both 0.25; the type of building envelope, indoor design temperature and other parameters are the same as for buildings oriented S–N. The results are shown in Figures 4 and 5.

As seen in Figures 4 and 5, the relationships between shape and heating/cooling load index are approximately linear. The individual formulae for heating/cooling load indexes of S–N and E–W long multi-story residential buildings are given in Equations (2–5).

The simplified equations are as followings.

$$y_1 = 94.794x + 25.745 \quad (2)$$
$$y_2 = 169.18x + 6.5688 \quad (3)$$
$$y_3 = 109.24x + 24.692 \quad (4)$$
$$y_4 = 188.8x + 10.433 \quad (5)$$

Where x is shape coefficient of long multi-story residential buildings; y_1, y_2, y_3 and y_4 refer to heating/cooling loads of S–N and E–W long multi-story residential buildings.

In addition, according to the results in the section titled *Peak load index*, building orientation has little effect on heating load index. Therefore, we attempt to derive a single formula for heating load index, independent of orientation. Equations (2) and (4) can therefore be combined, as shown in Figure 6. However, the results for *Peak load index* show that orientation greatly influences cooling load; we therefore calculate cooling load index according to orientation.

The simplified formula for heating load index of long multi-story residential buildings is given by Equation (6).

$$y_5 = 102.02x + 25.218 \quad (6)$$

Where x is the shape coefficient and y_5 refers to heating load index of long multi-story residential buildings.

The values calculated by EnergyPlus are used to verify Equations (3, 5 and 6), evaluated according to relative error. The results are shown in Tables 7–9.

For Equation (3), the error is less than 3.3%; for Equation (5), the error is less than 1.1%; and for Equation (6), the error is less than 5.4%.

Therefore, Equation (3) is used as the simplified formula for cooling load index of S–N long multi-story residential buildings; Equation (5) is the simplified formula for cooling load index of E–W long multi-story residential buildings; Equation (6) is the simplified formula for heating load index of long multi-story residential buildings.

The application condition is that, for long multi-story residential buildings in severe cold regions, the values of the shape coefficient, the window–wall ratio, the building envelope, and the indoor design temperature are the mean values of levels 1 and 2 shown in Tables 1 and 2.

CONCLUSION

This paper estimated the heating/cooling/power load of long multi-story residential buildings in China's severe cold region. The conclusions are as followings.

(1) The cooling load index of S–N and E–W long multi-story residential buildings in China's severe cold region are 35—75W/m^2 and 45—85W/m^2, respectively (mean values are 53 W/m^2 and 63W/m^2). Heating load indexes are 40—70W/m^2, regardless of orientation (mean 54W/m^2). Power load index is 40—65W/m^2 (mean 53W/m^2).

(2) The heating and cooling load varies greatly throughout the year, whereas power load shows little variation. The maximum heating and cooling loads occur in July and January, respectively, whereas the monthly power load is relatively constant.

(3) Building shape coefficient has greater influence on heating/cooling load than other factors. In addition, heating load is affected by window–wall ratio, indoor design temperature and types of wall and window. Moreover, window–wall ratio and indoor design temperature have effect on cooling load.

(4) Taking shape coefficient as the independent variable, simplified linear regression formulae (3), (5) and (6) are derived, with relative errors of less than 3.3%, 1.1% and 5.4%, respectively. These equations can be used for load estimation during the architectural design process.

The results can be used in areas where the climate is similar to China's severe cold region. In fact, most multi-story residential buildings in China's severe cold region meet the conditions set in Table 1 and Table 2. The results can be applied in preliminary design calculation for central heating/cooling system.

NOMENCLATURE

Q = power load index
n_1 = probability of different equipment working at one time within a household
n_2 = probability of different households using equipment at the same time in one building
Kx = demand coefficient
q_i = rated power
x = shape coefficient for long multi-story residential buildings
y_1 = heating load index of S–N long multi-story residential buildings
y_2 = cooling load index of S–N long multi-story residential buildings
y_3 = heating load index of E–W long multi-story residential buildings
y_4 = cooling load index of E–W long multi-story residential buildings when calculating cooling index
y_5 = heating load index of long multi-story residential buildings

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Table 1 Simulation factors of multi-story residential buildings

FACTOR	LEVEL 1	LEVEL 2
Shape coefficient	0.2	0.35
South window–wall ratio (primary orientation)	0.3	0.4
North window–wall ratio (primary orientation)	0.15	0.25
East/West window–wall ratio (primary orientation)	0.2	0.3
U-Factor of Wall (W/(m^2•K))	0.4	0.5
U-Factor of Window (W/(m^2•K))	2.0	2.5
U-Factor of Roof (W/(m^2•K))	0.35	0.45
Indoor design temperature in winter (℃)	18	22
Indoor design temperature in summer (℃)	22	26

Table 2 Values of other factors

OTHER FACTORS	VALUE
Occupancy density (p/m^2)	0.03
Lighting heat dissipation (W/m^2)	6
Equipment heat dissipation (W/m^2)	10
South window–wall ratio (Non-primary orientation)	0.4
North window–wall ratio (Non-primary orientation)	0.15
East/west window–wall ratio (Non-primary orientation)	0.05
Infiltration (1/hr)	0.5

Table 3 Factorial equipment arrangements

TEST NO.	SHAPE COEFFICIENT	SOUTH WINDOW –WALL RATIO	NORTH WINDOW–WALL RATIO	WALL TYPE	WINDOW TYPE	ROOF TYPE	INDOOR DESIGN TEMPERATURE
1	1	1	1	1	1	1	1
2	2	1	1	1	1	1	1
3	1	2	1	1	1	1	1
4	1	1	2	1	1	1	1
5	1	1	1	2	1	1	1
6	1	1	1	1	2	1	1
7	1	1	1	1	1	2	1
8	1	1	1	1	1	1	2
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128	2	2	2	2	2	2	2

Table 4 Peak load index

BUILDING TYPE	MAXIMUM HEATING LOAD（W/㎡）	MINIMUM HEATING LOAD（W/㎡）	AVERAGE HEATING LOAD（W/㎡）	MAXIMUM COOLING LOAD（W/㎡）	MINIMUM COOLING LOAD（W/㎡）	AVERAGE COOLING LOAD（W/㎡）
S–N long multi-story residential building	70	40	54	75	35	53
E–W long multi-story residential building	70	40	54	85	45	63

Table 5 Factor significance for S–N long multi-story residential buildings

FACTOR	HEATING LOADF$_0$	COOLING LOADF$_0$	$F_{0.01}$（1,120）	SIGNIFICANT INFLUENCE ON HEATING LOAD	SIGNIFICANT INFLUENCE ON COOLING LOAD
Shape coefficient	557.79	1198.47	6.85	*	*
South window–wall ratio	4.85	59.32	6.85	-	*
North window–wall ratio	22.03	14.71	6.85	*	*
Roof type	0.08	1.95	6.85	-	-
Wall type	7.02	1.18	6.85	*	-
Window type	10.98	0.20	6.85	*	-
Indoor design temperature	76.14	29.18	6.85	*	*

Note: * refers to a significant effect and – refers to a non-significant effect.

Table 6 Factor significance for E–W long multi-story residential buildings

FACTOR	HEATING LOAD F$_0$	COOLING LOAD F$_0$	$F_{0.01}$（1,120）	SIGNIFICANT INFLUENCE ON HEATING LOAD	SIGNIFICANT INFLUENCE ON COOLING LOAD
Shape coefficient	1144.94	4252.04	6.85	*	*
East window–wall ratio	5.25	0.29	6.85	-	-
West window–wall ratio	33.37	435.31	6.85	*	*
Roof type	0.52	2.14	6.85	-	-
Wall type	7.90	0.33	6.85	*	-
Window type	27.26	0.96	6.85	*	-
Indoor design temperature	118.60	126.84	6.85	*	*

Note: * refers to a significant effect and – refers to a non-significant effect.

Table 7 *Error Analysis for* Equation (3)

TEST CASE	CALCULATED	PREDICTED	ERROR
x=0.20	40.04	40.40	0.9%
x=0.23	47.00	45.48	3.3%
x=0.26	49.73	50.56	1.7%

x=0.29	54.99	55.63	1.2%
x=0.32	60.17	60.71	0.9%
x=0.35	66.62	65.78	1.3%

Table 8 *Error Analysis for* Equation (5)

TEST CASE	CALCULATED	PREDICTED	ERROR
x=0.20	48.53	48.19	0.7%
x=0.23	54.15	53.86	0.5%
x=0.26	58.86	59.52	1.1%
x=0.29	64.75	65.19	0.7%
x=0.32	70.86	70.85	0.01%
x=0.35	76.97	76.51	0.6%

Table 9 *Error Analysis for* Equation (6)

TEST CASE	HEATING LOAD INDEX OF S–N MULTI-STORY RESIDENTIAL BUILDING			HEATING LOAD INDEX OF E–W MULTI-STORY RESIDENTIAL BUILDING		
	Calculated	Predicted	Error	Calculated	Predicted	Error
x=0.20	44.42	45.62	2.7%	46.13	45.62	1.1%
x=0.23	47.69	48.68	2.1%	49.78	48.68	2.2%
x=0.26	50.54	51.74	2.4%	52.95	51.74	2.3%
x=0.29	53.43	54.80	2.6%	57.96	54.80	5.4%
x=0.32	56.06	57.86	3.2%	59.10	57.86	2.1%
x=0.35	58.73	60.93	3.7%	62.48	60.93	2.5%

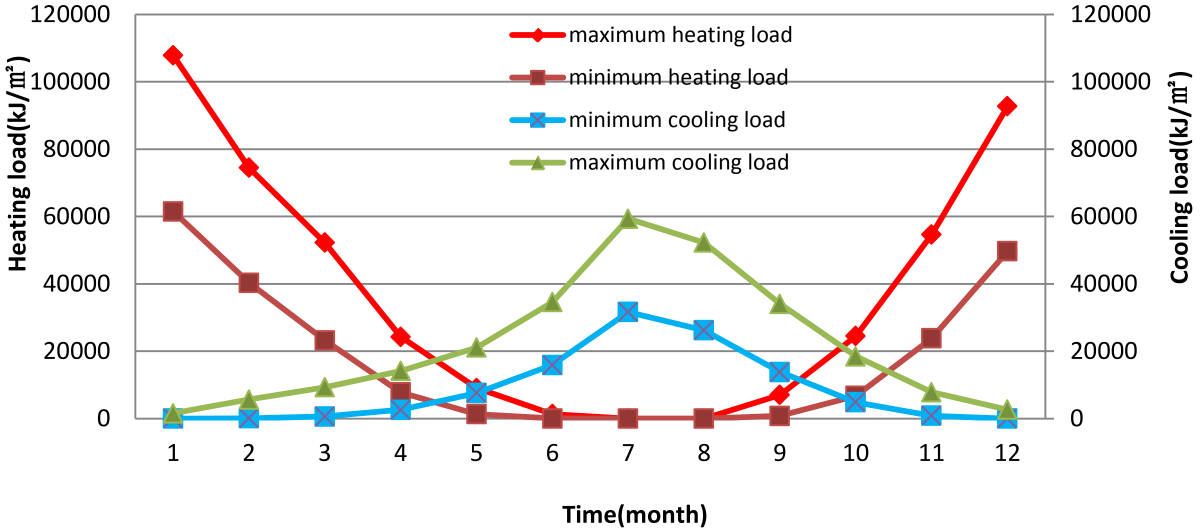

Figure 1 *Annual heating/cooling load characteristics of S–N long multi-story buildings*

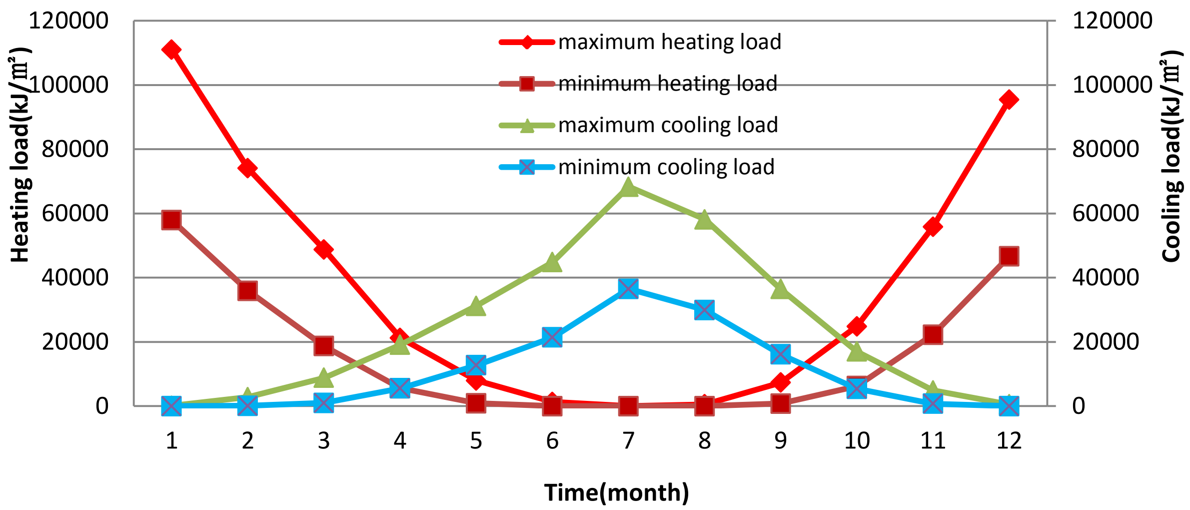

Figure 2 Annual heating/cooling load characteristics of E–W long multi-story buildings

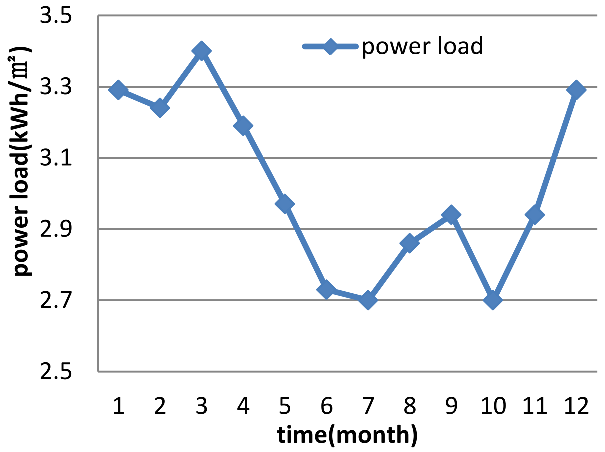

Figure 3 Annual power load characteristic

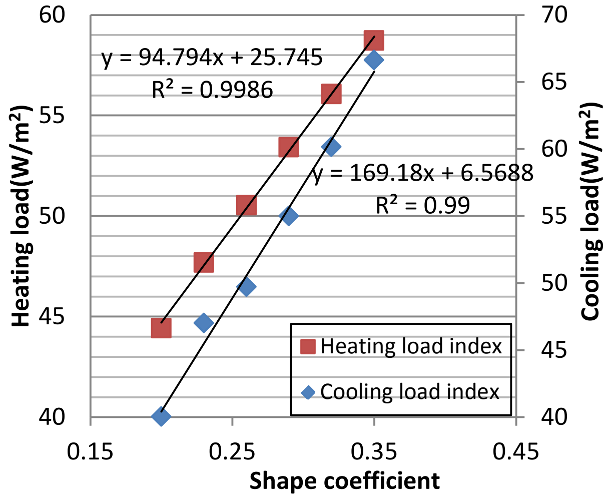

Figure 4 Regression formula of long multi-story residential building oriented S–N

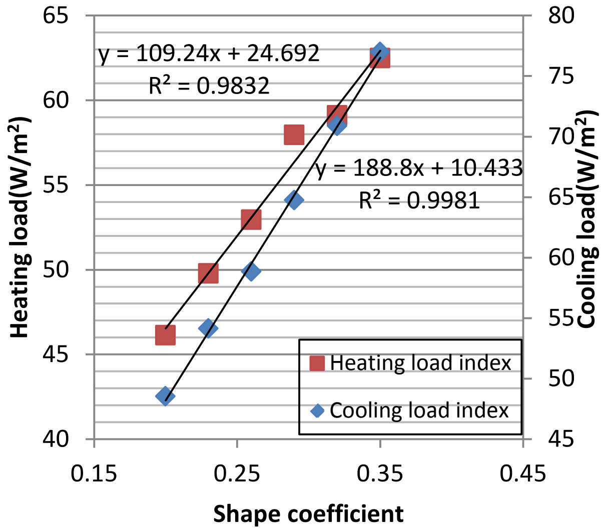

Figure 5 Regression formula of long multi-story residential building oriented E–W

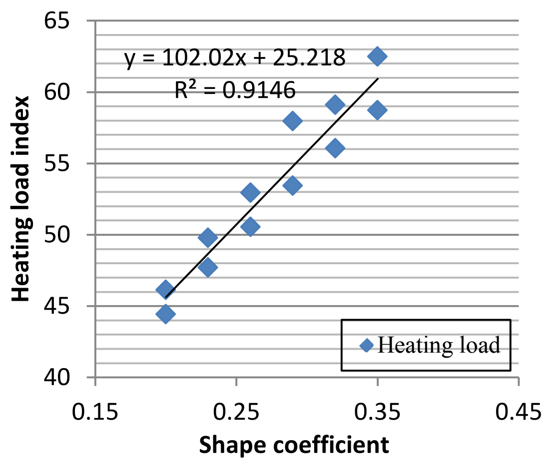

Figure 6 Regression formula for heating load index