Effect of Building Form on Energy Consumption of Academic Library Buildings in Different Climate Zones in China

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Abstract. This research focuses on the energy efficiency of academic library buildings with their shape in four major climate zones in China. According to their varieties in shapes and their representativeness in current constructions, eight hypothetical models of four types (point, slab, block, comb) are built based on the form of actual academic library buildings in recent years. The relationship between the building forms and building energy consumption is simulated and analysed with the software Design Builder. Results show that with the same construction area, different building forms can lead to variations in energy consumption in different climate zones. The slab-type is relatively energy-saving in most climate zones, while the block-type and E-shaped comb-type are more suitable for hot summer and warm winter zone. The building shape coefficient is an important parameter for reducing energy consumption in severe cold and cold zone, but the role of building depth is also sensitive. This information is dedicated to the architects at the early design stage of a project from the perspective of energy consumption.

1. Introduction

Energy issues have always been key aspects of global concern under the background of global climate change and energy crisis. By 2018, total construction area throughout China was about 60.1 billion m², of which 12.8 billion m² was for urban public buildings. In 2018, the primary energy consumption of civil building construction was 520 million tce, accounting for about 11% of the total primary energy consumption, among which public buildings accounted for 44% [1]. In addition to the fact that building consumes such a large fraction of energy, recent data indicates that with the improvement of people's living standards, the demand for energy in the living/working area continues to increase, resulting in the increase of the average energy intensity of buildings. The actual energy consumption of buildings in operation is much higher than the designed energy consumption index.

In recent years, in the context of vigorous development of green buildings, building energy efficiency has shifted from measure-oriented to effect-oriented, and refined design based on the improvement of green performance has been emphasized in the early stage of building design. A large part of the optimization method of building energy consumption performance depends on the early stage of architectural design. Research shows that more than 30% of the energy saving potential comes from the building plan design stage [2]. The initial stage of building design as a prerequisite for determining building energy consumption. Control the building form configuration and layout can effectively reduce energy consumption [3]. The energy consumption is inversely proportional to the compactness (with
low shape coefficient) in case of cold severe and scarcely sunny winters. However, it cannot be applied in case of mild climates [4]. According to different climate conditions and seasonal changes, reasonable consideration of different building forms and energy consumption performance, combined with passive design and active technologies, is an effective way to improve building space performance. Passive solar heat is particularly compatible with library functionality because it invites natural light into living spaces and eliminates noise that would otherwise exist with forced-air HVAC systems [5].

As a typical large-space public building type in educational buildings, academic library buildings have the characteristics of relatively simple function, stable energy consumption and large number of people staying for a long time. In recent years, with the expansion of campus construction scale, the number of university library buildings in China has increased rapidly. Compared with the type of modular library buildings built in the 1990s, academic library buildings in recent years emphasize more on the complex public space [6], with a trend of large volume and large depth in the building form. However, unreasonable architectural space design, such as building form, excessive volume and improper plane partition, will lead to a reduction in environmental comfort and an increase in energy consumption in building operations. A well-designed library building which cost less in terms of heating, cooling, or maintenance, is much healthier for the individuals who use them, because it offers more natural day lighting, consumes much less resources and energy, and enhances productivity and learning [7].

This article takes academic library building as the research object, through investigating the large-scale academic library building cases built in recent years, proposes 8 library building forms of four typical types. In order to achieve a balance between energy consumption, building forms and climatic conditions, the relationship between building forms and energy consumption under four major Chinese climate zones is simulated and analysed. This analysis will help to develop effective measures for building energy conservation and to reach higher energy efficiency standards from the early stage of a building design. Based on the simulation results, improvement measures are suggested for each climate zone from the perspective of architect's schematic design.

2. Methods

Based on survey data of 23 actual academic library buildings in different climate zones in China, this study summarizes four typical types of academic library buildings according to their varieties in shapes, namely, point, slab, block, and comb, and the morphological parameters of eight hypothetical models have been built on this basis. The annual energy consumption (heating, cooling and lighting) of each model is simulated and analyzed with the software Design Builder.

2.1. Prototypical buildings

The building model is divided into four typical types with a total of 8 kinds of building forms as shown in figure 1. The building form corresponds to different internal space organization. The point-type and slab-type are more common types of academic library buildings, which are usually connected with each functional area with the atrium as the core. The reading space of the point-type is arranged around the atrium, and it is mostly an open flowing space connected to each other. The reading space of slab-type is symmetrical along the central axis of the building. Compared with the point-type building with equal sides, the slab-type increases the southward area and reduces the negative factors of the east and the west sides. Model 1-1 and 1-2 are square planes with a length-width ratio of 1:1. The model 1-1 extends vertically and the standard floor area is less than Model 1-2. Model 2-1 is a rectangular plane with a length-width ratio of 3:1. The block-type is also widely used in academic library buildings. It solves the natural lighting and ventilation of large-scale buildings through the form of inner courtyard. The ratio of length-width of the two models is about 1.5:1. The three models of comb-type change the building shape to form an outdoor courtyard as a transition buffer between indoor and outdoor. The connection part will use as a public space, while the reading space can occupy a wing independently with good natural lighting conditions.
2.2. Morphological Parameter Settings
Based on the survey, the total floor area of the eight hypothetical models is all set to about 35000 m² as a quantification. Height between the floors is 4.2m, main facing direction is north-south. Window-wall ratio is 0.375 with single layer of glass. The floors and area of each floor will be changed according to different building forms. The building shape coefficient of the model is in the range of 0.09-0.14 as shown in figure 1.

2.3. Computer Software and Parameter Setting
The software Design Builder has been chosen for modeling and calculating the energy consumption throughout the year. The energy consumption simulation of Design Builder is based on the latest calculation engine by Energy Plus. After the 3D modeling in Design Builder is established, the software will use Energy Plus as its simulation engine for analysis and output visual charts or data [8].

The meteorological data of Harbin, Beijing, Shanghai, and Guangzhou have been chosen to represent severe cold and cold zone, hot summer and cold winter zone, and hot summer and warm winter zone. The relationship between the various building forms and energy consumption in different climate zones is focused. Therefore, other parameters, such as HVAC system, envelope structure (see Table 1), indoor personnel activities (see Table 2) and operation schedule, are set as quantitative settings according to the Design Standard for Energy Efficiency of Public Buildings [9], or common practice summarized in the survey.

| Table 1. Layers of the exterior wall, roof, ground, internal floor of models. |
|-----------------------------------------------|-----------------|
| Layers (from outside to inside)               | U-values       |
| Exterior wall                                 |                 |
| Cement/plaster/mortar (20 mm)                 |                 |
| XPS Extruded Polystyrene (60 mm)              | 0.27 W/m²·K    |
| Concrete Block (240 mm)                       |                 |
| Cement/plaster/mortar (20 mm)                 |                 |
| Cement/plaster/mortar (40 mm)                 |                 |
| Roof                                          |                 |
| Asphalt (10 mm)                               | 0.19 W/m²·K    |
| Cement/plaster/mortar (20 mm)                 |                 |
| EPS Expanded Polystyrene (20 mm)              |                 |
Concrete (100 mm)  
Cement/plaster/mortar (20 mm)  
Foam (130 mm)  

Ground  
Cast concrete (100 mm)  
Floor Screed (30 mm)  

Internal floor  
Cement/plaster/mortar (20 mm)  
Cast concrete (100 mm)  

| Lighting power density (W/m²) | Equipment power density (W/m²) | Occupancy density (m²/p) | Personnel heat dissipation (W/p) | Fresh air flow rate (m³/h·p) | Heating temperature (°C) | Cooling temperature (°C) |
|-----------------------------|-------------------------------|--------------------------|-------------------------------|-----------------------------|-------------------------|-------------------------|
| 9                           | 5                             | 1.9                      | 108                           | 20                          | 26                      | 20                      |

Table 2. Typical design condition of occupant behaviour.

3. Simulation Results and Analysis

3.1. Building form and total energy consumption

The 8 models of different building forms are simulated separately in four major climate zones in China. The model of point-type with the smallest building shape coefficient is used as a reference to calculate the energy saving rate of other models and compare the relationship between each building form and energy consumption.

According to the simulation results shown in Fig. 2/3/4/5, the difference between the building form and total energy consumption in each climate zone is quite obvious. In severe cold and cold zone, more compact forms, such as point and slab building types, have lower energy consumption, while block-type and comb-type with more varied shapes have relatively higher energy consumption. The relationship between building form and total energy consumption is weak in the hot summer and cold winter zone, while the difference is more obvious in the hot summer and warm winter zone. The total energy consumption of the slab-type was the lowest in the severe cold and cold zone and the hot summer and cold winter zone, while the energy consumption of the block-type with two inner courtyards was the lowest in the hot summer and warm winter zone.

![Figure 2. Total energy consumption and energy saving rate of models in severe cold zone](image1)

![Figure 3. Total energy consumption and energy saving rate of models in cold zone](image2)
3.2. Building form and heating energy consumption

Figure 6 shows the average total energy consumption and the proportion of energy consumption of each building form in four major climate zones. The energy consumption in the severe cold zone is relatively high, mainly based on heating energy consumption, accounting for about 74.1% of the total energy consumption, and the proportion of heating energy consumption in the other climate zones decreases in turn. Therefore, the parameters in building form that have a great influence on heating energy consumption have different contribution rates in different climate zones.

Figure 7 shows the relationship between building form and heating energy consumption in severe cold zone and the energy saving rate. Building shape coefficient has a significant influence on severe cold and cold zone. The smaller the building shape coefficient is, the lower the building energy consumption will be. However, hot summer and warm winter zone do not conform to this rule. Therefore, for the severe cold and cold zone where heating energy consumption is the main energy consumption, controlling the shape factor and reducing the heat dissipation area to avoid heat loss are the main ways to reduce heating energy consumption.

3.3. Building form and cooling energy consumption

The simulation results of the itemized energy consumption data show that while the energy consumption of heating and lighting varies significantly with different building forms, the relationship between cooling energy consumption and building form in each climate zone is less obvious. Figure 8 shows the cooling energy consumption and energy saving rate of different building forms in hot summer and warm winter zone. The north-south oriented models (2-1, 3-1, 3-2, 4-3) reduces the cooling energy consumption effectively, because it avoids too much unfavorable solar radiation caused by east-west direction. In addition, by changing the form of the building, the self-shading of the building is formed, which also plays a positive role in reducing the cooling energy consumption.
3.4. Building form and lighting energy consumption

Various building forms will affect the organization of the internal functional space, and the depth of building will also change accordingly, which will have an impact on natural lighting conditions. Model 1-2 is the building form with the highest energy consumption in all climate zones except the severe cold zone. Figure 9 compares the relationship between building forms and lighting energy consumption in each climate zone. It can be seen that Model 1-2 leads to higher lighting energy consumption in each climate zone. For the severe cold zone where heating energy consumption is the main energy consumption, lighting energy consumption accounts for a relatively small proportion and has a relatively weak impact on the total energy consumption. However, for other climate zones, while the building depth increases, the lighting energy consumption will lead to a substantial rise in total energy consumption.

In addition, by comparing the two models of point-type building form, although the heating energy consumption of Model 1-2 is lower than Model 1-1 in severe cold zone, the total energy consumption is higher, because of the increase of lighting energy consumption due to the excessive depth. Compared with other building forms, models 2-1, 3-2, and 4-3 increase the lighting area facing south, and by embedding in the inner courtyard or outer courtyard, the building depth is reduced and the natural lighting conditions are improved, thereby reducing the lighting energy consumption.

4. Conclusion

Based on the typical forms of academic library buildings, which are point, slab, block and comb, this paper analyses the influences on the energy consumption in four major climate zones with the use of simulation software Design Builder and the investigation of relationship between building forms and heating, cooling and lighting energy consumption in different climate zones considering the different energy consumption characteristics of each climate zone.

It was found that the slab-type consumes less energy in all climate zones, whereas in hot summer and cold winter zone and hot summer and warm winter zone the block-type and E-shaped comb-type consume less energy. In severe cold and cold zone, although the energy consumption of heating can be effectively reduced by decrease the shape coefficient of building, excessive depth of building will lead to a significant increase in lighting energy consumption. Therefore, comprehensive consideration should be taken to select a compact building form and maintain a suitable depth of building. In hot summer and cold winter zone, the influence of building form on energy consumption is relatively inconspicuous, and the choice of building form in the early stage of building design is reasonably flexible. In hot summer and warm winter zone, it is more suitable for block-type and comb-type with more varied forms.

The study provides references for architects in the early stage of architectural design. Although the control of thermal performance of the building envelopes and active mechanical equipment are still important parts for building energy conservation. If the basic relationship between the building form and each climate zone can be improved and properly selected from the early stages of architectural design, it is possible to optimize the energy consumption of equipment, create an energy-saving effect.
with low cost and high efficiency, and maximize indoor environmental quality while minimizing the negative impact on the natural environment.

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