A Passive Building Energy-Efficiency Evaluation Method Considering Human Thermal Adaptation with Seasonal Climate Change

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Abstract. Under the premise of satisfying the human thermal comfort in the whole year, accurately evaluating the building energy-efficiency (BEE) through passive design can provide direct feedback and guidance for the passive design process. The scientific relationship between dynamic indoor thermal comfort benchmarks, outdoor climate change and passive building energy-efficiency design (PBEED) is a prerequisite for calculating BEE with passive design method. However, the current energy-efficiency effect evaluation method cannot reflect the dynamic change characteristics of the thermal comfort benchmark linked with the continuous dynamic change of the climate throughout the year. Firstly, BEE evaluation method in China was introduced, and energy conservation ratio calculating method was illustrated. Then, analyse and conclude 4 disadvantages of BEE evaluation method. Secondly, a new calculating method of PBEED evaluation considering human thermal adaptation with seasonal climate change was invented, including calculating model, some new concepts appeared in the model and calculating process of PBEED evaluation index. Finally, obtaining method of the PBEED evaluation index was proposed, including temperatures outdoors and indoors, dynamic thermal comfort zone. The results of this study will expand the application field of adaptive thermal comfort in building energy conservation, and will provide scientific support for accurately evaluating the passive building energy-efficiency design.

1. Introduction

There always exists a disparity between human thermal comfort and outdoor climate, and the original function of building is to weaken this disparity to provide a relatively comfortable living space. However, the comfortable indoor thermal environment can not only produced by buildings, but also rely on the heating/cooling installations like HVAC system very often, which will result in a larger amount of building energy consumption. It is, therefore, that building should not only provide a more comfortable living space, but also help to consume less energy in turn. These two factors need to be taken into account in the process of design for building energy efficiency (BEE).
In China, economic development and a desire for improved living standards have spurred rapid construction and development during the recent three decades. During the early 1980s, new construction floor area totaled 700-800 million m² per year. By the early 1990s, the yearly total was 1000 million m² [1], and the total floor area had exceeded 40 billion m² by 2006 [2]. This rapid rate of construction has implications for energy consumption [1], the share of which in total energy consumption in China rose from 10% in 1978 to 30% in 2006 [3], and was projected to increase to about 35% in 2020 [4, 5]. How to improve the BEE has been getting more and more attention from architects and engineers. It is indicated that the amount of energy consumption of a building depends on three factors [6]: (1) Thermal insulation performance of building envelope, including exterior wall, exterior windows and doors, roof, etc.; (2) Comfort demand of occupants, mainly refers to the indoor thermal environment including the parameters of temperature, air movement and humidity; and (3) Operating efficiency of heating/cooling system, including the selection of equipment, the operation and management. Among these, the former two determine the total of building energy consumption, and the third one determines the amount of energy use.

It has led to a number of studies conducted worldwide: on the designs and construction of building envelopes [7-11], adaptive comfort models dealing with the dynamic control of the set point temperature or implementing a wider/varying range of indoor design temperature for different time of the day and different outdoor conditions [12-14], the control and management of heating, ventilation and air conditioning (HVAC) installations and lighting systems [15, 16], energy-efficient measures for the renovation of existing buildings [17-20]. A significant proportion of the increase in energy use was due to the spread of the HVAC installations in response to the growing demand for better thermal comfort within the built environment [14]. If the energy use in HVAC installations decreases, the whole building energy consumption will be cut down efficiently. This proportion in China almost takes about 15% of overall energy consumption of the whole year [21]. The huge energy consumption not only consumes lots of valuable fossil energy use, but also seriously pollutes atmospheric environment and increases the CO₂ emissions.

The application of adaptive thermal comfort in building energy conservation also stays in the use of design or control building indoor thermal environment, which will save energy from HVAC system. The energy consumption of HVAC is fundamentally affected by performance of passive building energy-efficiency design (PBEED), in addition to the influence of the set temperature. Accurately calculating the energy conservation generated by PBEED section has become an important prerequisite, which can evaluate the advantages and disadvantages of architectural design. However, there still lack of a scientific method to evaluate it, especially considering the human seasonal adaptive thermal comfort requirements. The aim of the study is to develop a method to achieve it.

2. BEE evaluation methods in China and disadvantages

2.1. BEE evaluation methods in China

In China, design standards for BEE can not only guide building energy-efficiency design, but also can be a method to evaluate building energy-efficiency. Energy efficiency efforts began in the early 1980s in China, and the first standard was developed in 1986 for residential buildings in the very cold and cold zones. According to the national “Thermal design code for civil building” GB 50176-93 [22], China is divided into five major climatic zones, namely severe cold, cold, hot summer and cold winter, hot summer and warm winter, and mild (Figure 1). This simple climate classification is concerned mainly with conduction heat gain/loss and the corresponding thermal insulation issues [23]. The zoning criteria are based mainly on the average temperatures in the coldest and hottest months of the year. The numbers of days that daily average temperature is below 5 °C or above 25 °C are counted as the complementary indices for determining the zones [8, 23]. Therefore, standards for different climate zones should be developed as well. With the development of China's economy and social needs, the number of public buildings has been increasing at a high speed as well as the residential buildings, but the energy consumption per m² was several times than that of residential buildings. Hence the design standard for this category was enacted subsequently. Until 2010, building energy efficiency standards and regulations in China have been issued or updated.
In Chinese standards, building energy-efficiency evaluation is based on energy conservation ratio (ECR). In the energy-efficiency design standards of different periods, different ECR indicators are specified. Taking standard JGJ 26-2010[24] for example, the target of ECR is 65%, which is calculated as follows:

Based on the field investigation of energy consumption for heating in a number of typical buildings in northern China during 1980 to 1981, the value of energy consumption per m² (kg standard coal equivalent (SCE) per m²) can be obtained and was defined as the chosen benchmark equal to 100%; If SCE is reduced by 30% on the basis of the above, it will be considered to reach the target making in the standard JGJ 26-1986 (30% ECR); If SCE is reduced by 30% on the basis of 30% ECR, it will reach the target of 50%; If SCE is reduced by 30% on the basis of 50% ECR, it will finally reach the target of 65%, that means the design for BEE was evaluated with the standard JGJ 26-2010.

2.2. Disadvantages of BEE evaluation method
To achieve the energy conservation ratio, the standard JGJ 26-2010[24] includes indices of building heat loss and coal consumption for heating along with sections on thermally efficient building and heating design. The building’s shape coefficient and heat-transfer coefficients for each part of the envelope are listed in the standard providing for building designers to follow. Taking the building with less than or equal to three floors in cold zone B of China for example, the building’s shape coefficient (ratio of exterior surface to floor area) is less than or equal to 0.52, and the ratio of window to wall area (RWWA) is less than 0.30 for north windows, 0.35 for east and west windows, and 0.50 for south windows; The thermal performance parameters of the envelope are listed in table 1. If the design for energy efficiency follows the values that correspond to those thermal performance parameters of the envelope, it will be evaluated to be up to standard. Otherwise, if the shape coefficient and/or RWWA are not within the values specified above, the designer need to calculate the building heat-loss index using equations presented in standard, and change heat-transfer coefficients for each part of the building envelop until the heat-loss index is less or equal to the values listed in standard.

| Component                      | Heat-transfer coefficients (K-value)[W/(m²·K)] |
|--------------------------------|-----------------------------------------------|
| Roof                          | 0.25                                          |
| Exterior wall                  | 0.30                                          |
| Overhead or projecting floor-slab | 0.30                                         |
| Part                               | Value |
|------------------------------------|-------|
| Floor board over basement without heating | 0.35  |
| Lower part of balcony door          | 1.2   |
| Staircase without heating           |       |
| Partition                           | 1.2   |
| House door                          | 1.5   |
| RWWA \(\leq 0.2\)                  | 2.0   |
| RWWA \(0.2 < \leq 0.3\)            | 1.8   |
| RWWA \(0.3 < \leq 0.4\)            | 1.6   |
| RWWA \(0.4 < \leq 0.45\)           | 1.5   |
| Window                              |       |
| Heat -resistance of thermal insulation material \((R\text{-value})(m^2 \cdot K)/W\) |       |
| Ground floor                        |       |
| Perimeter                           | 1.40  |
| Non-perimeter                       | 1.50  |

That the building design follows the standard above means it is evaluated to meet the ECR index. However, there still exist some disadvantages of BEE evaluation method, which can be concluded as follows:

(1) The ECR index specified within the formulating of standard is inaccurate, and it cannot scientifically reflect the level of energy-efficiency via building envelope. The energy consumption for heating of a group of typical residential buildings in north China was collected during 1980-1981, which forms the basis of ECR in different standards. The problem is that this basis had not contain the data from other parts of China, and that will give rise to an imprecise result in calculating ECR in other climate zones. Besides, the index reached by 60% energy savings via building design and 40% via the heating system [4]. This distribution of energy savings can not inspire the building designers to design better buildings in thermal performance which could accordingly reduce the energy use in heating system.

(2) The comfort temperature range indoors is fixed between 18 °C in winter and 26 °C in summer, and it does not distinguish between climate zones and building types, which proved unreasonable in a large number of studies. The comfort temperature range is dynamic in different climate zones and different seasons, so the ECR index was calculated using the fixed comfort temperature range will be inaccurate.

(3) Design standards for different climate zones or for different building categories vary from each other, and the energy efficiency indices are not the same either. This will bring about that the design of building envelope for energy efficiency cannot be judged with a same norm in comparing two buildings in different climate zones or between two categories.

(4) Due to the strict quantitative indices for the thermal performance of building envelope pointed out in the design standard, a qualified energy-efficient building will be designed if it only follows these indices. This ignores and limits architects’ talent on designing more beautiful buildings with diverse appearances, which causes numerous buildings in different climate zones arising with almost no differences.

Therefore, we need a scientific and unique method to calculate the contribution rate of building envelope to building energy efficiency, and using it to evaluate the passive building energy-efficiency considering human thermal adaptation with seasonal climate change.

3. Development of PBEED evaluation method

3.1. Calculating model of PBEED evaluation

In this study, the method to calculate the PBEED contribution rate needs an index to represent the energy consumption, and then air temperature has been selected. Air temperature is the main index to describe the thermal environment of both outdoor and indoor, and it decides the amount of heating/cooling load of HVAC system which largely dominates in building energy consumption [25]. Therefore, the calculation principle of the method is described as the form as equation (1):
PBEED contribution rate = \[
\frac{\text{Energy consumption cut down by building envelope}}{\text{Energy consumption benchmark}} \times 100\% \tag{1}
\]

In the above expression, energy consumption cut down by building envelope is equal to basic energy consumption minus building energy consumption. The calculation principle can be vividly expressed in figure 2 to present the author's intention.

![Figure 2. Calculation model of PBEED evaluation.](image)

In order to explain the process definitely, some concepts involved in this invention are defined as follows:

**Outdoor temperature curve:** a curve generated by the data of daily mean outdoor temperature of the place the building located in, defining as the function $f_{out}(x)$.

**Indoor temperature curve:** a curve generated by the data of daily mean indoor temperature of naturally running building which are regulated by the opening and closing of windows by the occupants, defining as the function $f_{in}(x)$. Here, the data is obtained by calculation.

**Thermal comfort zone:** a range of indoor temperature that 90% people feel comfortable, defining the upper limit as the function $f_{\text{comf-upper}}(x)$ and lower limit as $f_{\text{comf-lower}}(x)$. In this paper, the zone considers human thermal adaptation with seasonal climate change.

**Energy consumption benchmark:** energy consumed by eliminating the disparity between human thermal comfort and outdoor climate, defining as $S$. This disparity mainly refers to the difference between comfort temperature and outdoor temperature, and the value is expressed by the enclosing area between $f_{out}(x)$ and $f_{\text{comf-upper}}(x)/f_{\text{comf-lower}}(x)$.

**Building energy consumption:** energy consumed by eliminating the disparity between human thermal comfort and indoor climate, defining as $S'$. This disparity mainly refers to the difference between comfort temperature and indoor temperature, and the value is expressed by the enclosing area between $f_{in}(x)$ and $f_{\text{comf-upper}}(x)/f_{\text{comf-lower}}(x)$.

**Energy consumption cut down by building envelope:** energy generated by weakening the energy consumption benchmark via building envelope, defining as $\Delta S$. It mainly refers to the difference between outdoor and indoor temperature, and the value is expressed by the enclosing area between $f_{out}(x)$ and $f_{in}(x)$, and $\Delta S=S-S'$.

### 3.2. Calculating process of PBEED evaluation index

According to the calculation principle above, the method our team has been proposed [26] was used as follows:

The area of energy consumption benchmark $S$ was calculated using equation (2):
\[ S = \int_{a}^{b} f_{\text{out}}(x) \, dx \]  

where \( a \) and \( b \) are the calculating time from the first day to last day of a year, equal to 1 and 365, respectively. \( \int_{a}^{b} f(x) \, dx \) can be calculated via definite integral as equation (3):

\[ \int_{a}^{b} f(x) - x \, dx \approx \sum_{D=1}^{l} y_{D} \Delta x = \frac{b - a}{l} \sum_{D=1}^{l} y_{D} \]  

where \( l \) is the number of calculating days equal to 365; \( y_{D} \) the difference value between daily mean temperature and upper limit/lower limit of comfort zone in day \( D \) \((1 \leq D \leq 365)\), °C. Therefore, energy consumption benchmark \( S \) can be calculated using equation (4) and (5):

When \( t_{D,\text{out}} > t_{\text{comf-upper}} \),

\[ S = \frac{b - a}{l} \sum_{D=1}^{l} y_{D,\text{out}} = \frac{365}{l} \sum_{D=1}^{l} t_{D,\text{out}} - t_{\text{comf-upper}} \]  

When \( t_{D,\text{out}} < t_{\text{comf-lower}} \),

\[ S = \frac{b - a}{l} \sum_{D=1}^{l} y_{D,\text{out}} = \frac{365}{l} \sum_{D=1}^{l} \left| t_{D,\text{out}} - t_{\text{comf-lower}} \right| \]  

where \( y_{D,\text{out}} \) is the difference value between daily mean outdoor temperature and upper limit/lower limit of comfort zone in day \( D \) \((1 \leq D \leq 365)\), °C; \( t_{D,\text{out}} \) daily mean outdoor temperature °C. In the same way, building energy consumption \( S' \) can be calculated using equation (6) and (7):

When \( t_{D,\text{in}} > t_{\text{comf-upper}} \),

\[ S' = \frac{b - a}{l} \sum_{D=1}^{l} y_{D,\text{in}} = \frac{365}{l} \sum_{D=1}^{l} t_{D,\text{in}} - t_{\text{comf-upper}} \]  

When \( t_{D,\text{in}} < t_{\text{comf-lower}} \),

\[ S' = \frac{b - a}{l} \sum_{D=1}^{l} y_{D,\text{in}} = \frac{365}{l} \sum_{D=1}^{l} \left| t_{D,\text{in}} - t_{\text{comf-lower}} \right| \]  

Where \( y_{D,\text{in}} \) is the difference value between daily mean outdoor temperature and upper limit/lower limit of comfort zone in day \( D \) \((1 \leq D \leq 365)\), °C; \( t_{D,\text{in}} \) daily mean outdoor temperature °C. Then, energy consumption cut down by building envelope \( \Delta S \) can be calculated using equation (8):

\[ \Delta S = S - S' \]  

According to the calculation principle proposed in this paper, contribution rate \( J \) can be calculated by equation (9):

\[ J = \frac{\Delta S}{S} \times 100\% = \frac{S - S'}{S} \times 100\% \]  

3.3. Obtaining method of the PBEED evaluation index

3.3.1. Temperatures outdoors and indoors. In the principle of PBEED evaluation method, the outdoor climate data can be collected from the local meteorological data or typical meteorological year (TMY) data; the indoor temperature can be obtained using the simulation software of building energy consumption. For indoor temperature, software of Design Builder was most usually used, which needs the building information input, such as the building model, design parameters, the heat-transfer coefficients of each part, the window and door area, building running mode, and so on.
3.3.2. Dynamic thermal comfort zone. The dynamic thermal comfort zone that considers human thermal adaptation with seasonal climate change can be obtained from a long-term thermal comfort investigation. The investigation includes the indoor and outdoor thermal environment parameters test and subjective questionnaire on human thermal comfort. Indoor climate (air temperature, relative humidity, globe temperature and air velocity) and outdoor air temperature and relative humidity were measured using lab grade instruments, and the accuracy of the above instruments meet the requirements of ISO 7726-2002. The instruments were positioned 1.1 m above the floor and close to the occupants, and data readings were recorded simultaneously during the interview.

Based on ASHRAE55-2013 [27], the prevailing mean outdoor air temperature was calculated for each surveyed day, and the daily mean neutral temperature of all subjects were calculated using Griffiths method [28] for the data collected in the current study, that is, using the equation of $t_n = t_{op} - \frac{TSV}{G}$ to calculate neutral temperature, where G is Griffiths Constant, which Nicol and Humphreys proposed to take 0.5 [29]. The seasonal adaptive thermal comfort models were subsequently established. de Dear [30] proposed a method to obtain the comfort zone in which 90% occupants express satisfaction. Adopting this method and other research methods [31, 32], the seasonal linear regression formula is $TSV = a \cdot t_{op} - b$, let $TSV = \pm 0.5$, based on which the acceptable temperature range that satisfied 90% occupants in each surveyed day was obtained, then arithmetic mean of the temperature ranges in each season was calculated, the width of acceptable zone for 90% in comfort in each season is obtained. Put all parameters above into excel, outdoor temperature curve, indoor temperature curve and dynamic thermal comfort zone can be generated (like Figure 3. shows). Using equations (2)-(9), energy consumption benchmark S, building energy consumption S’ and energy consumption cut down by building envelope $\Delta S$ can be calculated, and then the PBEED evaluation index J will be obtained.

![Figure 3. Calculating example of PBEED evaluation index for a building located in Xi’an, China.](image)

4. Conclusion
A method to calculate the contribution rate of passive building energy-efficiency design considering human thermal adaptation with seasonal climate change was invented.

(1) On the basis of analysing BEE calculation method in the current standards in China, 4 disadvantages were concluded about calculating the evaluation index of BEE. Such a method begins
with the introduction of the relationship between climate, building and thermal comfort, and based on three factors impacting on energy consumption of a building, this study indicates that a well-designed thermal insulation performance of building envelope is the key and basic of improving BEE.

(2) The calculating model of PBEED evaluation was presented, and some related concepts, such as outdoor temperature curve, indoor temperature curve, thermal comfort zone, energy consumption benchmark, building energy consumption and energy consumption cut down by building envelope were defined. Based on these, a calculating method for PBEED evaluation index was developed, mainly involving two processes: calculating outdoor and indoor temperature, and dynamic thermal comfort zone. Approach of definite integral was adopted to express the energy consumption in the new method, which relies on calculating the enclosing areas between outdoor temperature curve, indoor temperature curve and upper limit/lower limit of comfort zone. The PBEED evaluation index can be calculated finally.

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