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The energy saving index and the performance evaluation of thermochromic windows in passive buildings

Hong Ye [a,*], Linshuang Long [a], Haitao Zhang [a], Yanfeng Gao [b]

[a] Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei, Anhui 230027, PR China
[b] School of Materials Science and Engineering, Shanghai University, Shanghai 200072, PR China

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ABSTRACT

The concepts of the energy saving equivalent (*ESE*) and energy saving index (*ESI*) are presented in this paper to evaluate the performance of new materials and components in passive buildings. The *ESE* represents the hypothetical energy that should be input to maintain a passive room at the same thermal state as that when a particular material or component is adopted. The *ESI* is the ratio of a particular material or component's energy saving equivalent to the corresponding value of the ideal material or component that can maintain the room at an ideal thermal state in passive mode. The former can be used to estimate the effect of the adoption of a certain building component or material on the building's thermal state from an energy standpoint, while the latter can be used to characterize the performance of the actual building component or material from a common standpoint and be used to evaluate the performance of components or materials in different climatic regions or under different operating situations. In this study, the *ESI* was used to evaluate the performance of a thermochromic window, represented by a single vanadium dioxide (VO_2) glazing, in passive residential buildings in three climatic regions of China (cold zone, hot summer and cold winter zone, and hot summer and warm winter zone).

1. Introduction

China's total building energy consumption increased 1.5 times between 1996 and 2008. The energy consumption ratio of buildings to that of all of whole society was 23% in 2007 and 2008, and is still increasing [1]. Passive buildings, which can make full use of natural resources such as solar and wind energy, have been studied by many researchers to minimize operating energy consumption [2]. The thermal comfort of a passive building is achieved by passive energy saving techniques instead of active heating, ventilation and air conditioning (HVAC) systems. Widely studied passive energy saving techniques include the use of passive building components or materials (represented by cool colored coatings [3], phase change materials (PCMs) [4], etc.) and the adoption of certain energy efficient methods (e.g., reasonable fenestration [5], etc.).

An appropriate index is essential to evaluating the application performance of different passive techniques or identical techniques under different operating situations. In a passive building, the main purpose of adopting passive techniques is to improve the thermal comfort degree. Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment [6]. However, it is a highly subjective index that is influenced by numerous and complex factors [7]. Post-occupancy evaluation research and a survey of occupants have been undertaken by E. Mlecnik et al. to obtain recommendations for raising the end-user satisfaction level of near-zero-energy houses [8]. On the basis of Fanger's predicted mean vote (PMV) formula [9], the predicted percentage of dissatisfied (PMV-PPD) model has been adopted by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) to characterize indoor degrees of thermal comfort. On the basis of PMV-PPD, ASHRAE recommends the operative temperature as another evaluation index. The operative temperature can be influenced by the humidity, air speed, metabolic rate and clothing insulation [6].

In addition to the aforementioned subjective indices, certain objective indices are also used for evaluation. To evaluate the performance of passive solar houses, the hours within a comfort range of 18–28 °C are counted as an index along with a survey given to the inhabitants [10]. Ghiaus has presented the concept of free-running temperature to characterize the load curve of a building [11]. Using the free-running temperature, Christian Inard et al. have estimated the potential for free cooling by ventilation [12]. While Zhang et al. have adopted the integrated discomfort degree for indoor temperature [13] as a parameter with which to propose a

* Corresponding author. Tel./fax: +86 551 63607281.
E-mail address: hye@ustc.edu.cn (H. Ye).

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new approach for determining the ideal thermophysical properties of building envelope materials, ideal natural ventilation rates, and minimal additional space heating or cooling energy consumption [14].

It has been noted that the actual operating energy consumption should be a direct index for evaluating a building material or component's energy saving performance in an active operating mode [1]. However, the application of energy saving techniques to a passive building does not involve the active input of energy. As a result, current evaluation indices are usually on the basis of thermal state parameters (e.g., indoor air temperature, visible light illuminancy, indoor air humidity, etc.). To evaluate performance based directly on energy consumption, we present here the concepts of the energy saving equivalent (*ESE*), which can connect the thermal state parameter with hypothetical energy consumption, and the energy saving index (*ESI*), which can be used to evaluate the performance of building components or materials on a common basis.

The application performance of single vanadium dioxide (VO_2) glazing in passive buildings was estimated as an example of the new evaluation indices.

2. The concepts of *ESE* and *ESI*

2.1. Definition

The original thermal state of a passive room over a particular time period can be described as S_1. After the use of a building component or material (e.g., insulation material, PCM, etc.), the thermal state during the same period becomes S_2. The parameter used to characterize the thermal state is set as the indoor air temperature in this paper. In the scenario illustrated in Fig. 1, the black solid line represents the original indoor temperature state, S_1, and the red (in web version) dotted line represents the indoor temperature state after the use of a building component or material, S_2. If the indoor temperature state S_1 is forced to transfer into S_2 without the addition of the component or material, a cooling quantity (described as Q_c, the light-colored area in Fig. 1) and heating quantity (described as Q_h, the dark-colored area in Fig. 1) will be delivered into the room. Consequently, the use of the building component or material and the delivery of Q_c and Q_h have the same effect on the indoor temperature: they change the indoor temperature state from S_1 into S_2. From the perspective of changing the indoor temperature state, the use of the building component or material is equivalent to the effect of the Q_c and Q_h input, and means that Q_c and Q_h can be used to represent the effect of the building component or material applied to the passive room.

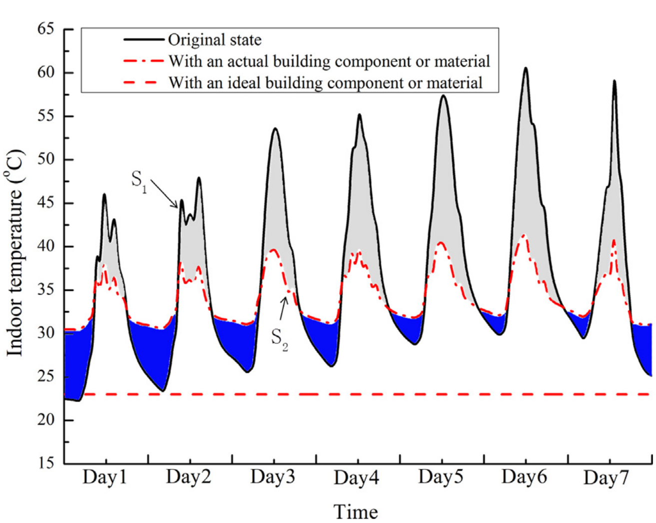

Fig. 1. Schematic representation of the energy saving equivalent.

According to Fig. 1, the effect of the component or material on reducing the indoor temperature is equivalent to Q_c and that on increasing the temperature is equivalent to Q_h. In the summer, the former is a positive effect and the latter is a negative effect. To comprehensively evaluate the effect of the component or material on changing the indoor temperature state, the negative effect must be deducted from the positive effect. Considering the difference in the coefficient of performance (*COP*), it is inappropriate to simply subtract Q_c from Q_h. In general, the cooling and heating quantities should be transferred into electric power. In the summer, the cooling quantity, which represents the cooling effect, can be taken as the energy "saved" by the component or material. Setting the cooling facility's coefficient of performance as COP_c, the cooling quantity can be transferred into electric power with Q_c/COP_c. To remove the negative heating effect caused by the use of the component or material, i.e., the heat quantity Q_h, the same cooling quantity should be delivered into the room and can be viewed as the energy "wasted" by the component or material. When converted into electric power, its value is Q_h/COP_c. As a result, the net gain (in electric power) from the component or material in the summer is:

$$ESE_{summer} = \frac{Q_c}{COP_c} - \frac{Q_h}{COP_c} \tag{1}$$

where ESE_{summer} is the equivalent energy "saved" by the component or material in the summer, referred to as the energy saving equivalent (*ESE*).

Similarly, the net gain (in electric power) from the component or material in the winter is:

$$ESE_{winter} = \frac{Q_h}{COP_h} - \frac{Q_c}{COP_h} \tag{2}$$

where COP_h is the heating facility's coefficient of performance.

The *ESE* for an entire year is obtained by adding ESE_{summer} and ESE_{winter}:

$$ESE_{annual} = ESE_{summer} + ESE_{winter} \tag{3}$$

On the basis of *ESE*, the energy saving index (*ESI*) can be defined as:

$$ESI = \frac{ESE}{ESE_{max}} \tag{4}$$

where *ESE* is the energy saving equivalent of the actual building component or material to be investigated and ESE_{max} is the *ESE* of an ideal building component or material. The ideal building component or material is defined as a hypothetical building component or material that can maintain the indoor temperature of a passive room at a constant comfortable level. The performance of the ideal component or material is represented by the red medium dashed line in Fig. 1. The indoor temperature at the constant comfortable level is set here as 23 °C, which mostly satisfies the demand for thermal comfort in both the summer and winter (Table A.5 in Ref. [15]).

According to Eq. (4), the *ESI* is a value less than unity. A positive *ESI* value means more energy is "saved" than "wasted". In other words, with the use of the component or material in a passive room may "save" energy, making the component or material "energy-saving". However, a negative *ESI* value means more energy is "wasted" than "saved", which means the component or material is