Ideal radiation parameters of energy-saving coatings for exterior wall

Hongxin Yao1, Yang Yi2, Xiyao Wang3 and Hong Ye1, 4

1 Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230027, People’s Republic of China
2 Unit 32381, Beijing 100071, People’s Republic of China
3 China Aerodynamics Research and Development Center, Mianyang 621000, People’s Republic of China
4 E-mail: hye@ustc.edu.cn

Abstract. Optimizing the solar absorptivity (α) and thermal emissivity (ε) of coatings for the exterior wall is an effective way to reduce building energy consumption (BEC). Guangzhou, Hefei and Beijing are chosen as the representative cities of the hot, hot-summer and cold-winter, and cold regions respectively, and the effects of α and ε of the exterior surface of the wall on the BECs of the residential buildings are studied. It is found that the BEC is much more sensitive to α than to ε, especially in summer, which means that solar irradiation is the main factor affecting the BEC. The optimal combination for Guangzhou, Hefei, and Beijing are (α=0 & ε=1), (α=0 & ε=0), and (α=1 & ε=0) respectively. The energy-saving performances of the six existing exterior wall coatings are evaluated, and the results show that the energy-saving performances of the coatings still need to be improved. Taking the most energy-efficient one in the six coatings as an example, the energy-saving potentials of coatings for Guangzhou, Hefei and Beijing are approximately 11%, 2% and 4% respectively.

1. Introduction
Building energy consumption (BEC) corresponds to 30~40% of the primary energy used in developed countries [1], and the implementation of low-energy buildings is an effective way to achieve building energy conservation [2]. Several countries have passed laws and regulations to promote low-energy buildings. For example, Energy Independence and Security Act [3], Directive on the energy performance of buildings [4] and Regulations on Energy Conservation in Civil Buildings [5], enacted by the US, EU and China respectively, explicitly stipulate that new buildings should further reduce BEC.

In recent years, more and more research work has been done on low-energy buildings. Eshraghi [6] designed a low-energy building according to the climate conditions of Tehran, the capital of Iran. They used photovoltaic, photovoltaic and battery energy storage system to achieve self-sufficiency in energy. Visa [7] transformed a building located in a university in Romania, and reduced the BEC by the ways of upgrading the envelope structure and making full use of renewable energy. Ascione [8] noted that passive energy-saving technologies, such as optimizing envelope design parameters, were more important than active energy-saving technologies, such as upgrading HVAC systems [8]. Becchio [9] also believed that improving the performance of the envelope was the most important way to achieve a low-energy building.
Improving the performance of the envelope is the most effective way to reduce BEC. Long [10] analyzed the influence of the thermal conductivity and the specific heat capacity of the walls on BEC, and comprehensively analyzed the role of the walls at different directions in the process of influencing the indoor temperatures. Ye [11] analyzed the energy-saving performances and the corresponding theoretical limitations of the active/passive smart windows regulating the solar spectrum response properties or the long wave thermal emission window regulating thermal emission property, and suggested a route to a perfect window. The effects of the thermal properties of walls and the radiation parameters of windows on BEC have been comprehensively discussed, while the research on the effects of the radiation parameters of the exterior surface of the wall on the BEC of residential buildings has not been reported.

In this paper, a mid-floor room in a multi-story residential building is considered. In different climatic regions, we make corresponding variations to the residential building model in the thickness of the exterior wall and the number of layers of glass installed in windows. We analyze the effects of $\alpha$ and $\varepsilon$ of the exterior surface of the wall on BEC and then obtain the ideal radiation parameters of energy-saving coatings in these regions. In addition, to evaluate the energy-saving performances of the existing exterior wall coatings, we measure the $\alpha$ and $\varepsilon$ of six common exterior wall coatings on the market, and their BECs are compared.

2. Model and methods

A mid-floor room in a multi-story residential building is shown in Figure 1, and it has internal dimensions of 4 m $\times$ 3.3 m $\times$ 2.8 m (length $\times$ width $\times$ height). The room has only one exterior wall oriented to the south, and contains a 1.5 m $\times$ 1.5 m window in the center of the exterior wall. The insulation materials are used on the exterior wall’s outer surface to obtain energy saving benefit. One of the most widely used insulation materials is expanded polystyrene (EPS), and whose density, thermal conductivity and specific heat are 55 kg/m$^3$, 0.027 W/(m·K) and 1210 J/(kg·K), respectively. Depending on the climatic region, the exterior wall thickness is 240mm or 370mm, the EPS thickness is 0 mm, 30 mm or 70 mm, and the window is installed with a single-layer or double-layer glass. The inner wall, roof and floor thickness of the room are 100mm. The indoor temperatures of this room and the adjacent ones are assumed to be the same. Therefore, there is no heat transfer occurs via the interior walls. The heat transfer via the exterior wall and glazing is assumed to be one-dimensional. The properties of the walls, roof, floor and window are listed in Table 1 and Table 2. The reference material for the walls is brick, that for the roof and floor is reinforced concrete, and that for the window is 6mm thick ordinary SiO$_2$ glass. According to the design standards [12-14], the inner heat gain from the occupants and equipment is taken to be 4.3 W per unit floor area, and that from lighting is 3.5 W per unit floor area when the lights are on from 18:00 till 22:00 every day. The ventilation rate is set as 1.0 air change per hour (ACH) in the winter, and 10.0 ACH in the summer.

The heat transfer processes related to the room are associated with corresponding energy balance equations, which are explained in [10]. Those equations are solved by employing the numerical software.
BuildingEnergy. The software has been validated in [10, 11, 15-17]. To verify the reliability of our calculation results, the case of the ordinary glass in [17] is calculated, and the comparison results agree well, as shown in Figure 2.

### Table 1. Thermal properties of the room’s envelop.

|                  | Density [kg/m³] | Specific heat [J/(kg·K)] | Thermal conductivity [W/(m·K)] |
|------------------|-----------------|--------------------------|-------------------------------|
| Wall             | 1400            | 1050                     | 0.58                          |
| Roof & floor     | 2500            | 920                      | 1.74                          |
| Window           | 2500            | 840                      | 0.76                          |

### Table 2. Radiation parameters of the room’s envelop.

|                          | Thermal emissivity | Solar absorptivity | Solar transmittance |
|--------------------------|--------------------|---------------------|---------------------|
| Interior wall            | 0.96               | 0.21                | 0                   |
| Inner surface of exterior wall | 0.96              | 0.21                | 0                   |
| Roof & floor             | 0.96               | 0.21                | 0                   |
| Window                   | 0.84               | 0.159               | 0.771               |

Using the BuildingEnergy software, we calculate the energy consumptions of the rooms with different exterior surface radiation parameters of the exterior wall to conduct a general discussion. The $\alpha$ and $\varepsilon$ of the exterior surface of the exterior wall are set from 0 to 1 with an interval of 0.1. The climate data used to simulate the energy consumption in BuildingEnergy are the typical meteorological year data offered by the Chinese Architecture-specific Meteorological Data Sets for Thermal Environment Analysis [18].

### 3. Materials and methods

To evaluate the energy-saving performances of the existing exterior wall coatings, we measured the $\alpha$ and $\varepsilon$ of six common exterior wall coatings on the market, as shown in Figure 3. The Bruker Vertex 80 Fourier spectrometer and the DUV-3700 spectrophotometer are used to measure the infrared and solar reflectivities of these coatings respectively. Assuming that these coatings are opaque in both solar and infrared spectra, we obtain the average solar and infrared reflectivities of these coatings by the weighted average method with the spectral energy as the weight, and the average solar absorptivities and thermal emissivities of these coatings are calculated by Kirchhoff’s law, and these average spectral parameters are given in Table 3.

![Figure 3. Six common exterior wall coatings.](image)

![Figure 4. Changes in BEC with the external wall radiation parameters in Guangzhou.](image)

### Table 3. Average spectral parameters of the six exterior wall coatings.

| Coatings          | White  | Umber  | Light gray | Light green | Beige  | Sky blue |
|-------------------|--------|--------|------------|-------------|--------|----------|
| Solar absorptivity| 0.2583 | 0.5398 | 0.5783     | 0.3672      | 0.3164 | 0.3801   |
| Thermal emissivity| 0.9435 | 0.9439 | 0.9447     | 0.9414      | 0.9435 | 0.9441   |
| Symbol            | ▲      | ●      | ★          | △           | ○      | ☆        |
4. Results and discussion

4.1. Hot region

Guangzhou is chosen as the representative city in the hot region, and the location of this city is (23.06° N, 113.15° E). Summer in Guangzhou begins on May 13 and ends on October 17. The room temperature is controlled at 26°C by the air conditioner in summer, and there is no temperature control in spring, autumn and winter. The model of the air conditioner is Midea KFR-26GW/WDAA3@ [19] and its EER is 3.46. The exterior wall of the considered room is 240 mm thick, the EPS thickness is 0 mm, and the window is installed with a single-layer glass. The power consumptions per unit floor area of the rooms with different radiation parameters of the exterior surface of the exterior wall are calculated, and the results are shown in Figure 4. In summer, the BEC is low when \( \varepsilon \) is large and \( \alpha \) is small, and the BEC is much more sensitive to \( \alpha \) than to \( \varepsilon \), which means that solar irradiation is the main factor affecting the BEC in summer. Due to the comparable \( \varepsilon \) of the six coatings, their BECs increase with the increase of \( \alpha \). The white coating is the most suitable for building energy saving in Guangzhou in summer among the six coatings, and the ideal radiation parameters of energy-saving coatings in Guangzhou are \((\alpha=0 & \varepsilon=1)\). Compared with the white coating, the annual energy saving effect of the coating with the ideal radiation parameters in Guangzhou is 11.11%.

4.2. Hot-summer and cold-winter region

Hefei is chosen as the representative city in the hot-summer and cold-winter region, and the location of this city is (31.87° N, 117.23° E). Summer in Hefei begins on June 15 and ends on September 5, and winter begins on December 5 and ends on March 5 of the next year. The room temperature is controlled at 26°C and 18°C by the air conditioner and heating equipment in summer and winter respectively, and there is no temperature control in spring and autumn. The model of the air conditioner is KFR-26GW/WDAA3@, and its energy efficiency ratio (EER) is 3.46. The COP is 3.18. The exterior wall of the considered room is 240 mm thick, the EPS thickness is 30mm, and the window is installed with a single-layer glass. The power consumptions per unit floor area of the rooms with different radiation parameters of the exterior surface of the exterior wall are calculated, and the results are shown in Figure 5, and the annual BEC is the sum of the BECs in summer and winter.

In summer, the BEC is high when \( \varepsilon \) is small and \( \alpha \) is large, and the BEC is much more sensitive to \( \alpha \) than to \( \varepsilon \), which means that solar irradiation is the main factor affecting the BEC in summer. Due to the comparable \( \varepsilon \) of the six coatings, their BECs increase with the increase of \( \alpha \). The white coating is the most suitable for building energy saving in Hefei in summer among the six coatings. In winter, a small \( \varepsilon \) and a large \( \alpha \) correspond to a low BEC, and the BEC is much more sensitive to \( \alpha \) than to \( \varepsilon \), which means that solar irradiation is the main factor affecting the BEC in winter. Due to the comparable \( \varepsilon \) of the six coatings, their BECs decrease with the increase of \( \alpha \). The light grey coating is the most suitable for building energy saving in Hefei in winter among the six coatings. For an entire year, owing to the
opposite demands of the building energy efficiency on $\alpha$ and $\epsilon$ in summer and winter, the annual BEC is the lowest when the radiation parameters of the exterior surface of the exterior wall are ($\alpha=0 \& \epsilon=0$). The light grey coating is the most suitable for building energy saving in Hefei over an entire year among the six coatings, and the ideal radiation parameters of energy-saving coatings in Hefei are ($\alpha=0 \& \epsilon=0$). Compared with the light grey coating, the annual energy saving effect of the coating with the ideal radiation parameters in Hefei is 2.01%.

4.3. Cold region

Beijing is chosen as the representative city in the cold region, and the location of this city is (39.56° N, 116.20° E). Summer in Beijing begins on June 12 and ends on September 1, and winter begins on November 1 and ends on March 15 of the next year. The room temperature is controlled at 26°C and 18°C by the air conditioner and heating equipment in summer and winter respectively, and there is no temperature control in spring and autumn. The model of the air conditioner is Midea KFR-26GW/WDAA3@, and its $EER$ is 3.46. All the residential buildings in Beijing adopt central heating, and the $COP$ of the central heating obtained by conversion of the electricity price [20] and the heating price [21] is 3.36. The exterior wall of the considered room is 370 mm thick, the EPS thickness is 70mm, and the window is installed with a double-layer glass. The power consumptions per unit floor area of the rooms with different radiation parameters of the exterior surface of the exterior wall are calculated, and the results are shown in Figure 6.

In summer, the BEC is high when $\epsilon$ is small and $\alpha$ is large, and the BEC is much more sensitive to $\alpha$ than to $\epsilon$, which means that solar irradiation is the main factor affecting the BEC in summer. Due to the comparable $\epsilon$ of the six coatings, their BECs increase with the increase of $\alpha$. The white coating is the most suitable for building energy saving in Beijing in summer among the six coatings. In winter, a small $\epsilon$ and a large $\alpha$ correspond to a low BEC, and the BEC is much more sensitive to $\alpha$ than to $\epsilon$, which means that solar irradiation is the main factor affecting the BEC in winter. Due to the comparable $\epsilon$ of the six coatings, their BECs decrease with the increase of $\alpha$. The light grey coating is the most suitable for building energy saving in Beijing in winter among the six coatings. For an entire year, owing to the opposite demands of the building energy efficiency on $\alpha$ and $\epsilon$ in summer and winter, the annual BEC is the lowest when the radiation parameters of the exterior surface of the exterior wall are ($\alpha=1 \& \epsilon=0$). The light grey coating is the most suitable for building energy saving in Beijing over an entire year among the six coatings, and the ideal radiation parameters of energy-saving coatings in Beijing are ($\alpha=1 \& \epsilon=0$). Compared with the light grey coating, the annual energy saving effect of the coating with the ideal radiation parameters in Beijing is 4.2%.

5. Conclusions

The effects of $\alpha$ and $\epsilon$ of the exterior surface of the wall on the BEC are discussed in different climatic regions. It is found that the BEC is much more sensitive to $\alpha$ than to $\epsilon$, especially in summer, which means that solar irradiation is the main factor affecting the BEC. There is an optimal combination of $\alpha$ and $\epsilon$ with the lowest annual BEC, and the optimal combination for Guangzhou is ($\alpha=0 \& \epsilon=1$), and that
for Hefei is ($\alpha=0 \text{ & } \epsilon=0$), and the corresponding combination for Beijing is ($\alpha=1 \text{ & } \epsilon=0$). The energy-saving performances of the existing exterior wall coatings still need to be improved. The energy-saving potentials of energy-saving coatings for the exterior wall for Guangzhou, Hefei and Beijing are approximately 11%, 2% and 4% respectively.

References
[1] Long L and Ye H 2017 Dual-intelligent windows regulating both solar and long-wave radiations dynamically Solar Energy Materials & Solar Cells 169 145-150
[2] Marszal A J, Heiselberg P, Bourrelle J, et al. 2011 Zero energy building—A review of definitions and calculation methodologies Energy Buildings 43(4) 971-979
[3] U.S. Government Printing Office. Energy Independence and Security Act of 2007
[4] World Public Library. Directive on the energy performance of buildings. 2010
[5] State Council of the People's Republic of China. Regulations on Energy Conservation in Civil Buildings. 2008
[6] Eshraghi J, Narjabadifam N, Mirkhani N, et al. 2014 A comprehensive feasibility study of applying solar energy to design a zero energy building for a typical home in Tehran Energy Buildings 72 329-339
[7] Visa I, Moldovan M D, Comsit M, et al. 2014 Improving the renewable energy mix in a building toward the nearly zero energy status Energy Buildings 68 72-78
[8] Ascione F, Bianco N, de Rossi F, et al. 2016 Concept, design and energy performance of a net-zero-energy building in Mediterranean climate Procedia Engineering 169 26-37
[9] Becchio C, Corgnati S P, Monetti V, et al. 2013 From high performing buildings to nearly zero energy buildings: potential of an existing office building CLIMAMED VII. Mediterranean Congress of Climatization. Istanbul 2013
[10] Long L, Ye H and Liu M 2016 A new insight into opaque envelopes in a passive solar house: Properties and roles Applied Energy 183 685-699
[11] Ye H, Meng X, Long L, et al. 2013 The route to a perfect window Renewable Energy 55 448-455
[12] JGJ 134–2010. Design standard for energy efficiency of residential buildings in hot summer and cold winter zone
[13] JGJ 75–2003. Design standard for energy efficiency of residential buildings in hot summer and warm winter zone
[14] JGJ 26–2010. Design standard for energy efficiency of residential buildings in severe cold and cold zones
[15] Ye H, Long L, Zhang H, et al. 2014 The performance evaluation of shape-stabilized phase change materials in building applications using energy saving index Applied Energy 113 1118-1126
[16] Long L, Ye H, Gao Y and Zou R 2014 Performance demonstration and evaluation of the synergetic application of vanadium dioxide glazing and phase change material in passive buildings Applied Energy 136 89-97
[17] Ye H and Long L 2014 Smart or not? A theoretical discussion on the smart regulation capacity of vanadium dioxide glazing Solar Energy Materials and Solar Cells 120 669-674
[18] Song F, Zhu Q, Wu R, Jiang Y, Xiong A, Wang B, Zhu Y and Li Q 2007 Meteorological data set for building thermal environment analysis of China In: Proceedings of the 10th international building performance simulation association conference and exhibition Beijing, China; p. 9e16
[19] Midea, 2020. https://www.midea.cn/10000/1000000000100511267271.html
[20] State Grid, 2020. http://www.bj.sgcc.com.cn/
[21] Bendibao, 2020. http://bj.bendibao.com/news/2019117/265861.shtm