SCIENCE CHINA
Technological Sciences

July 2012 Vol.55 No.7: 1999–2005
doi: 10.1007/s11431-012-4854-1

Simulation and improvement of energy consumption on intelligent glasses in typical cities of China

XU XiaoJie, WU Xi*, ZHAO Chao, WANG JiangXiang & GE XiaoTong

School of Physical Science and Technology, Soochow University, Suzhou 215006, China

Received August 24, 2011; accepted March 15, 2012; published online May 28, 2012

Five windows such as white glass, Low-E glasses and intelligent glasses are employed for simulation of heating and cooling energy consumptions in five typical cities of China by the software TRNSYS 16. The result shows that it is the most energy saving for the doubled glass when the VO_2 films are deposited on the inside surface of the outer pane. And it is 84.7% of energy saving compared with white glass. But the heating energy consumption is the highest. This is because the transition temperature of real intelligent glass is too high and the solar heat gain coefficient is very small when the glass is in the cold state. On this basis, the property of intelligent glass is improved from the theoretical level. The result shows that it can be the most effective way of energy saving when emissivity is 0, solar transmittance is 100% in the cold state; visible light transmittance is 100%, infrared and ultraviolet light transmission rate is 0 in the hot state. Because of the technology limitation, it is hard to lower the transition temperature to below 20℃. The transition temperature of the film should be lower and the emissivity higher as far as possible.

intelligent glass,VO_2 film, solar heat gain coefficient, total heat transfer coefficient

Citation: Xu X J, Wu X, Zhao C, et al. Simulation and improvement of energy consumption on intelligent glasses in typical cities of China. Sci China Tech Sci, 2012, 55: 1999–2005, doi: 10.1007/s11431-012-4854-1

1 Introduction

Intelligent glass can save the building energy by adjusting the solar radiation into the room because the optical properties of nano-films deposited on the glass change with the factors such as the ambient temperature and sunshine intensity. The changes of film optical properties are called discoloration, which has four types: electrochromic, thermochromic, gasochromic and photochromic. Due to the performance changes without consuming the extra energy or gas, the thermochromic glass is more suitable for widespread use in the building than other intelligent glasses.

The optical properties of thermochromic materials are not the same above (hot state) or below (cold state) the transition temperature. Currently, the most representative thermochromic materials are the thermo-optical polymers, chiral additive liquid crystals and inorganic thermochromic VO_2 films. Similar to the electrochromic LCD glass, the former two materials are transparent at low temperatures and muddy at high temperatures. Thermochromic glasses produced by these two materials have the advantages of simple preparation and low cost. However, the muddy color at high temperatures affects the visual appearance. The changes of optical properties of inorganic thermochromic VO_2 films occur mainly in the infrared region and rarely in the visible region at phase change. Therefore, VO_2 thin films have become an important direction to develop the thermochromic intelligent glass [1].

The disadvantages of VO_2 films developed in the early times are that the films have a higher transition temperature

---

*Corresponding author (email: wuxi@suda.edu.cn)

(68°C), a single color (khaki) and a lower transmittance of visible light. In order to improve the film properties, the high valence metal or nonmetal doped VO_2 film has been applied by a variety of methods including sol-gel, sputtering and chemical vapor deposition (CVD) [2–6]. In 2006, Vernardou et al. investigated $V_{0.98}W_{0.02}O_2$ thermochromic films using the direct liquid injection metal-organic (DLI-MO) CVD, reducing the transition temperature to 35°C [7]. In 2009, Batista et al. manufactured tungsten doped VO_2 films by sputtering. The transition temperature was reduced from 63°C to 28°C [8]. In 2007, Binions et al. made gold nanoparticle doped VO_2 thin films by the method of hybrid aerosol-assisted and atmospheric pressure CVD. The film color altered from yellow brown to green blue [9]. In 2009, Mlyuka et al. fabricated magnesium doped VO_2 films by DC reactive magnetron sputtering. It demonstrated that the transition temperature was decreased by about 3°C/at% of Mg. The transmittance of visible light and of solar radiation was enhanced by about 10% when the Mg content was about 7 at% [10]. In 2010, Carlos et al. also prepared molybdenum doped VO_2 films by sputtering. The optical analyses showed that the maximum optical transmittance in the visible ranges was from 35% to 45% and IR modulation capacity was decreased from 36% to 25% when the cold state changed into the hot state with increasing Mo content from 3% to 11%. At the same time, the transition temperature was decreased by about 3°C/at% of Mo and the lowest temperatures was 32°C [11].

Although lots of researches have been done on preparation and improvement of VO_2 thin films, there is little energy efficiency assessment of VO_2 intelligent glass applied to building. In 2009, Saeli et al. carried out an annual energy consumption simulation in a number of cities in Europe and North Africa with nano-Au particles doped VO_2 thin films. The results showed that the full year energy consumption for the VO_2 intelligent glass decreased by 2%–43% compared with plain float glass [12–14]. However, because the model assumption is based on solar radiation intensity reaching a particular value as the phase transition condition instead of the thin film temperature, the calculated results have certain limitations.

In order to investigate the application feasibility of the existing intelligent glass, white glass, Low-E glass and VO_2 glass mentioned in ref. [12] were employed in energy consumptions calculation in cooling and heating periods of five typical Chinese cities by the software of TRNSYS 16.

2 Simulation model and glass data

According to the Chinese energy efficiency standards, Haikou, Dali, Shanghai, Shenyang and Xi’an were selected as the representative cities for five climate zones of hot summer and warm winter, mild, hot summer and cold winter, cold and severe cold. The size of the chosen room is 6 m×5 m×3 m (length×width×height). The south wall is exposed to the external environment. The remaining three walls are not affected by external conditions. As shown in Figure 1, two different glazing possibilities (shaded area) were considered in the south wall. One where the window was 3.75 m^2 located in the middle of the south wall (covering 25% of this surface) was considered to represent a general office. The other comprised the whole of the southern face (covering 100% of the surface)–a glazing wall, representing a modern commercial building. The materials of the external wall are shown in Table 1.

The glasses used in this model are double glazed with a 12 mm air cavity. The thickness of each glazing is 4 mm. Figure 2 shows the diagrams of the five glasses used in the simulation. The Low-E and VO_2 thin films were respectively deposited on 4 mm thick white glazing. The gray and navy blue parts respectively corresponded to the location of the Low-E and VO_2 thin films on the glasses. The optical parameters of a single white glazing and a single Low-E glazing were selected from the database of the software Window 5 and the optical parameters of VO_2 thin film were obtained from ref. [12]. All the optical parameters are summarized in Table 2. The transition temperature of the VO_2 thin film is 38.5°C. The transmittance τ and reflectivity ρ in the hot state and the cold state are shown in Figure 3.

The internal conditions were chosen to be air-conditioned at 19°C–26°C to maintain a comfortable working/living environment. The power of cooling and heating was respectively 120 and 90 W m^{-2}. The office occupant density was 0.1 people m^{-2}. The casual heat gain (persons + equipment) was taken to be 24 W m^{-2} in total and the ventilation rate used was 0.025 m^3 s^{-1}. Building occupancy was set as occupied from 08:00 till 18:00, five days a week, as is normal for an office.

The load calculation method of the software TRNSYS is room heat balance method, which is prescribed in room energy consumption standards in many countries and is one of the methods recommended by the international standards.

3 Results and discussion

The annual energy consumption of heating and cooling of

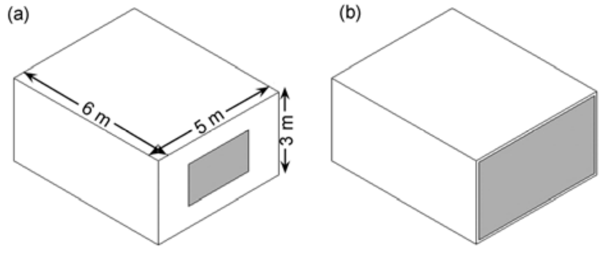

Figure 1 The two room models: (a) Ordinary window (25%); (b) glazing wall (100%).

Table 1 Parameters of the materials used for the external wall

Materials (From outside to inside)	Thickness (mm)	Density (kg m^{-3})	Specific heat (kJ kg^{-1} K^{-1})	Thermal conductivity (W m^{-1} K^{-1})
Vitrified microsphere	20	100	0.84	0.037
Polystyrene board	30	20	1.38	0.047
Aerated concrete	240	700	1.05	0.25
Cement slurry	20	1602	0.84	0.93

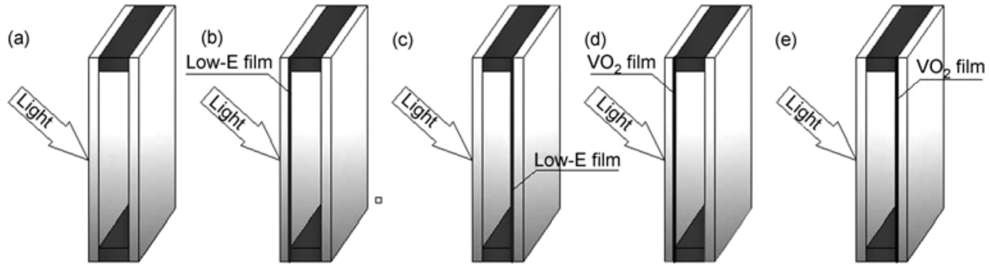

Figure 2 Schematic diagram of the window model. (a) White glass; (b) Low-E 1; (c) Low-E 2; (d) Intelligent 1;(e) Intelligent 2.

Table 2 Optical data of glasses

Glass type	Transition temperature (°C)	Cold solar transmittance	Hot solar transmittance	Cold state emissivity	Hot state emissivity
White glass	–	0.899	0.899	0.837	0.837
Single Low-E glass	–	0.606	0.606	0.083	0.083
Single VO$_2$ glass	38.5	0.426	0.350	0.827	0.789

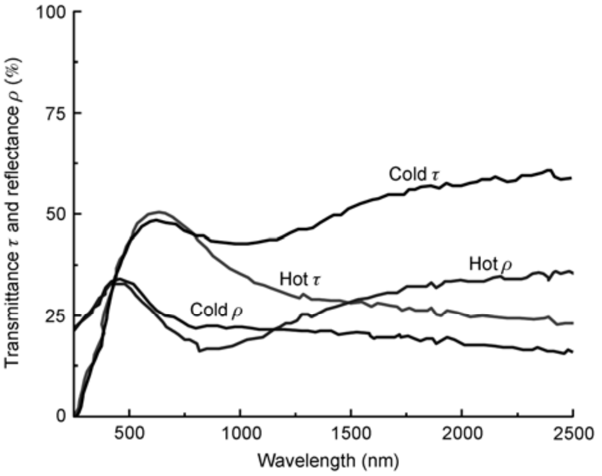

Figure 3 Transmittance and reflectance spectra for the gold nanoparticle doped thin films.

the building for the 25% window model and the 100% glazing wall is shown in Figures 4–7. It can be seen from the figures that every coated glass has a certain energy saving effect compared with white glass when the air conditioning is cooling. The cooling energy saving effect of Intelligent 1 is the most significant among them. Obviously, in the mild zone Dali, Intelligent 1 can decrease the energy consumption of 84.7%, 2.1%, 79.6% and 54.2% respectively, compared with white glass, Low-E 1, Low-E 2 and Intelligent 2 for the 25% window model. Compared with the white glass, Low-E 1, Low-E 2 and Intelligent 2, the cooling consumptions of Intelligent 1 are decreased by 83.7%, 72.9%, 83.6% and 70.4% respectively for the 100% glazing wall.

There is no need to heat for Haikou in the whole year because it is located in the zone of hot summer and warm winter. In the remaining four cities, the heating energy consumptions of two kinds of intelligent glasses are higher than the other three ones and reach a maximum for Intelligent 1. For two window models, the heating energy consumption of Intelligent 1 is increased by 1.12 to 17.57 times compared with the other four glasses. Especially for the 25% window in Dali, only 7 kW h is consumed annually. However, the energy consumption increases to 123 kW h for Intelligent 1.

To the intelligent glasses, the reason of energy saving in cooling period and high-energy consumption in heating period can be analyzed from the aspect of the window heat transfer. In 2001, ASHRAE basic manual developed the relations of the heat transfer from outside to inside through the window

$$q = U \cdot (T_{\mathrm{out}} - T_{\mathrm{in}}) + SHGC \cdot G, \qquad (1)$$

where q is the heat flux; U is total heat transfer coefficient; T_{out} and T_{in} are the outdoor and indoor temperatures respectively; $SHGC$ is the solar heat gain coefficient; G is solar radiation intensity. It can be seen from eq. (1), in a certain place, the main factors affecting window heat transfer are

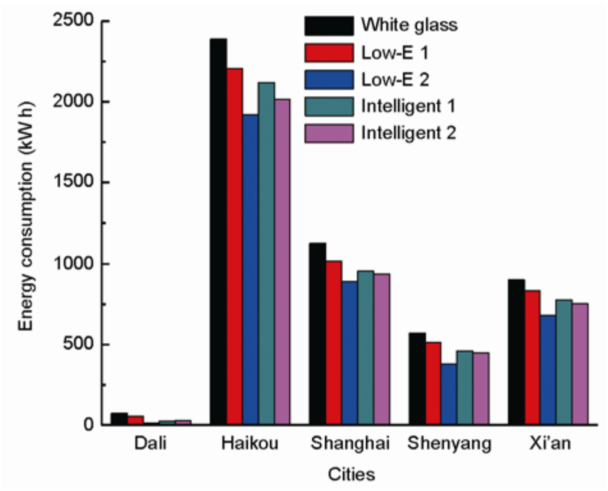

Figure 4 Annual cooling energy consumption of cities for the 25% window.

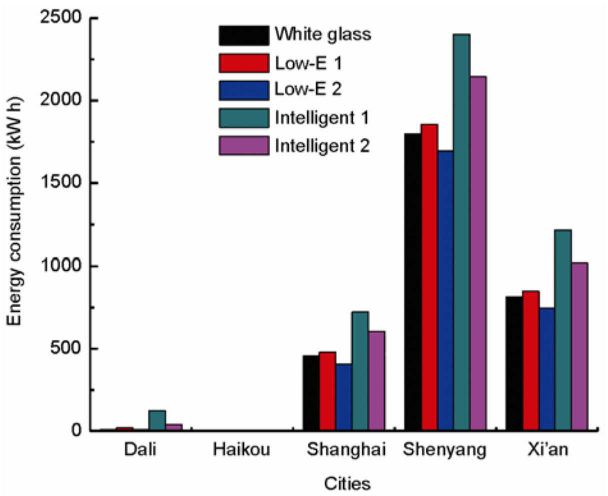

Figure 5 Annual heating energy consumption of cities for the 25% window.

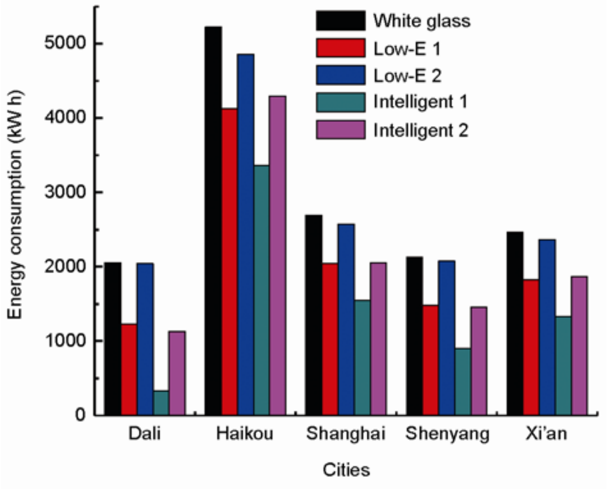

Figure 6 Annual cooling energy consumption of cities for the 100% glazing wall.

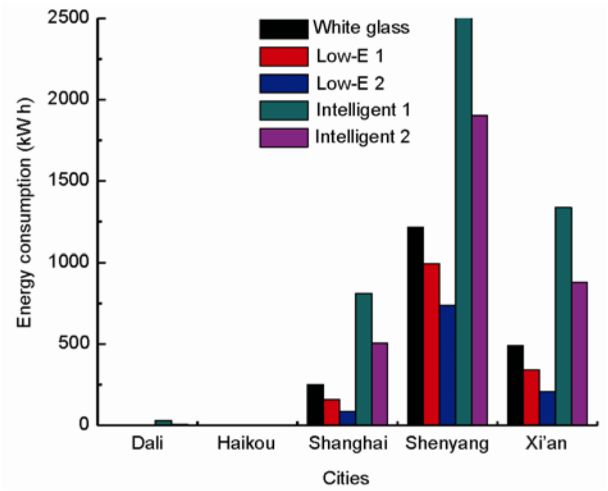

Figure 7 Annual heating energy consumption of cities for the 100% glazing wall.

the solar heat transfer coefficient *SHGC* and the total heat transfer coefficient *U* value.

The solar heat gain coefficient *SHGC* is the ratio of the incoming solar radiation through the window to the solar radiation reaching the outer surface of the window. It can be expressed as [15]

$$SHGC = \tau + N \cdot \alpha, \tag{2}$$

where τ is the transmittance of the glass; N is the proportion of the absorption solar radiation transferring into the room; α is the absorbance of the glass.

The total heat transfer coefficient U is defined as the heat transfer through a unit area of the window. It could be deduced as follows:

$$\frac{1}{U} = \frac{1}{\alpha_e} + \frac{1}{\alpha_m} + \frac{1}{\alpha_i}. \tag{3}$$

where α_e is the convective and radiant heat transfer coefficient between the external environment and outer surface of the window; $1/\alpha_m$ is the internal thermal resistance of the multi-layer glass; α_i is the convective and radiant heat transfer coefficient between the inner surface of the window and the indoor environment.

As shown in Table 3, The *SHGC* and *U* values in the same condition of the five windows were obtained by the software Window 5. The *U* values of two intelligent glasses are similar to that of white glass. However, the *SHGC* of two intelligent glasses is less than that of white glass whenever in the hot or cold state. Thus, the intelligent glasses are energy saving in summer and high-energy consumed in winter compared with white glass. Moreover, it was found that two intelligent glasses never enter their hot states due to the high transition temperatures. For the 100% glazing wall, the temperature changes of the VO_2 films deposited on two intelligent glasses in Shanghai are shown in Figures 8 and 9.

Table 3 *SHGC* and *U* values of the five windows

Parameters	White glass	Low-E 1	Low-E 2	Intelligent 1 (cold)	Intelligent 1 (hot)	Intelligent 2 (cold)	Intelligent 2 (hot)
SHGC	0.827	0.581	0.654	0.476	0.416	0.595	0.575
U value (W m^{-2})	2.9	1.75	1.75	2.89	2.85	2.89	2.85

As can be seen from the figures, the temperatures of the VO_2 thin films on Intelligent 2 did not change very largely because they were mainly influenced by the indoor temperature. However, Intelligent 1 reflected a better characteristic of "intelligently adjustable light" because its temperature changed largely.

The *U* value of Intelligent 1 is larger but the *SHGC* is smaller than that of the Low-E glasses. Therefore, in the cooling period, the solar radiation entering the room is more for Intelligent 1. When the outdoor temperature is higher than the indoor temperature, the cooling load increases along with the increase of *U* value. However, because of the change of the solar radiation intensity and the thermogenesis of indoor objects, the indoor temperature may reach 26°C and the air conditioning starts to cool even though the outside is not too hot. Therefore, generally speaking, Intelligent 1 is more energy saving than Low-E glasses in the cooling period. However, in the heating period, the heat load of the air conditioning for Intelligent 1 will be increased because of more reflection of the solar radiation. What is more, because the indoor temperature is higher than the outside temperature in the heating period, the high *U* value of Intelligent 1 makes the heat loss of the room increase, which is caused by the temperature difference between indoor and outdoor. The conclusion is that more energy will be consumed in heating period for Intelligent 1.

4 The ideal intelligent glass

From the above analysis, the disadvantages for Intelligent 1 can be concluded as follows. First, it consumes the most energy in heating period among the five glasses. Second, the transition temperature of Intelligent 1 is too high to represent the characteristic of adjusting optical properties along with the external environment change. Finally, Intelligent 1 has a larger *U* value than Low-E glass. Therefore, Intelligent 1 consumes more energy in winter because the heat transfer caused by the temperature difference between indoor and outdoor will be enhanced.

In view of the above defects, the ideal intelligent glass should have the following characteristics:

(1) In order to maximize the solar radiation entering indoor to reduce the heating energy consumption of the air conditioning, the transmittance of the VO_2 thin film deposited on the ideal intelligent glass should be 100% in the cold state. However, the visible transmittance of VO_2 thin film should be 100% in the hot state. The transmittance and reflectance of the ultraviolet and infrared regions should be respectively 0 and 100%. In this way, the solar radiation into the room will be minimized based on meeting the requirement of visible light in cooling period.

(2) The transition temperature of VO_2 film should be proper to switch the glass to the hot state in cooling period and to the cold state in heating period. So four transition temperatures, 5°C, 10°C, 15°C and 20°C, are chosen for the simulation in this paper.

(3) The *U* value of the intelligent should be decreased. Known from ref. [16], the smaller the emissivity of the thin film is, the smaller the *U* value is. To discuss the best emissivity of the ideal VO_2 thin film, the emissivity of the thin film ε is assumed to be 0, 0.5 and 1 respectively.

Because the city of Shanghai is located in the zone of cold winter with hot summer, it better embodies the performances for the ideal intelligent glass. For the 100% glazing wall in Shanghai, the comparison of the annual cooling and heating energy consumptions is shown in Figures 10 and 11 for the ideal intelligent glass and Intelligent 1.

As can be seen from Figures 10 and 11, the cooling and heating energy consumptions of the ideal intelligent glass are related to the transition temperature and the emissivity of VO_2 thin films. Less cooling energy and more heating energy will be consumed if the transition temperature is lower or the VO_2 thin film emissivity is higher. When the transition temperature and emissivity are respectively 5°C and 1, it has the least cooling energy consumption which is 23.5% of energy saving compared with Intelligent 1. When the emissivity is 0 and the transition temperature is 15 or 20°C, the heating energy consumption is the lowest saving 97.2% energy compared with Intelligent 1.

Figure 12 shows the annual energy consumption in the above situation. It illustrates that the annual energy consumption reduces first and increases again along with the temperature elevation, in other words, there is a best transition temperature. When the transition temperature is the same and is lower than 11°C, the annual energy consumption reduces along with the decrease of the emissivity. In addition, it decreases along with the increase of the emissivity when the transition temperature is higher than 20°C. The situation is more complex when the transition temperature is between 11°C and 20°C. It can be seen that the ideal intelligent glass with the emissivity of 0 and the transition temperature of 10°C is the most energy saving. But it is very difficult to realize such condition with the current technology. There is no report that VO_2 film with a transition temperature lower than 20°C has been prepared. Thus, in the preparation of VO_2 thin film, the transition temperature should be reduced, close to 20°C and the emissivity be

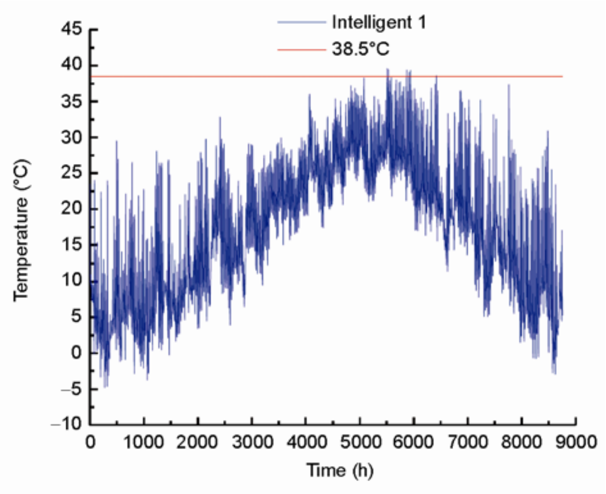

Figure 8 Annual temperature changes of the VO_2 films deposited on Intelligent 1 in Shanghai.

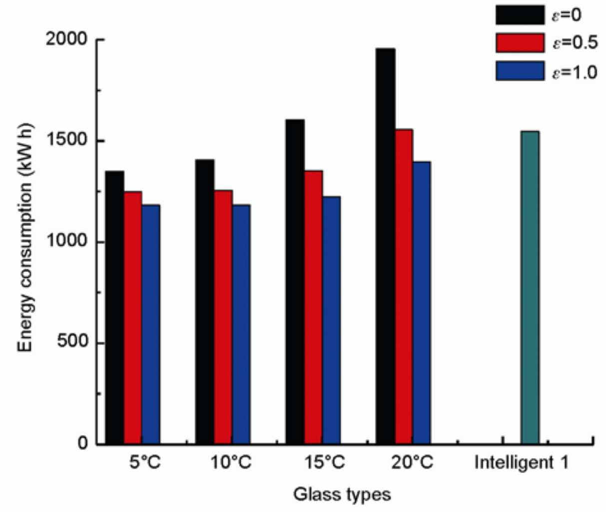

Figure 10 Annual cooling energy consumption in Shanghai for the 100% glazing wall.

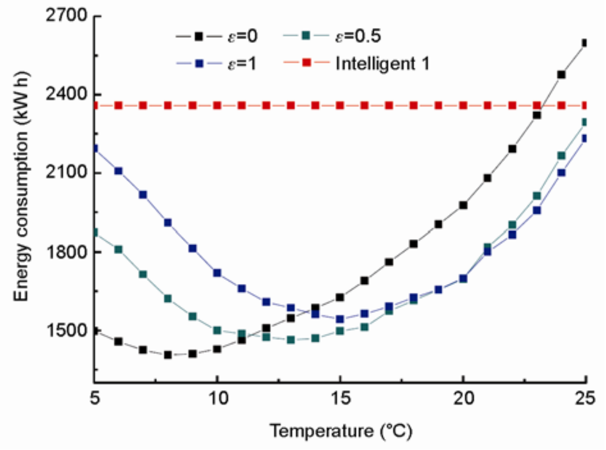

Figure 12 Annual energy consumption in Shanghai for the 100% glazing wall.

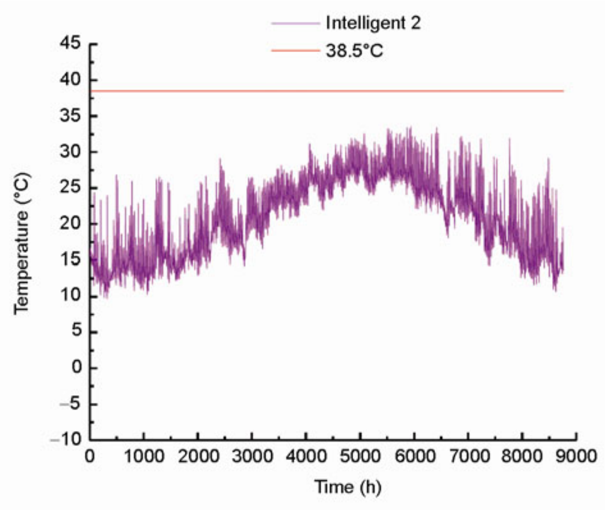

Figure 9 Annual temperature changes of the VO_2 films deposited on Intelligent 2 in Shanghai.

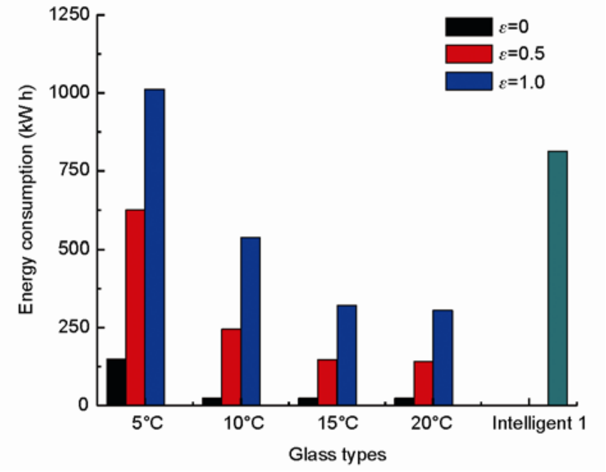

Figure 11 Annual heating energy consumption in Shanghai for the 100% glazing wall.

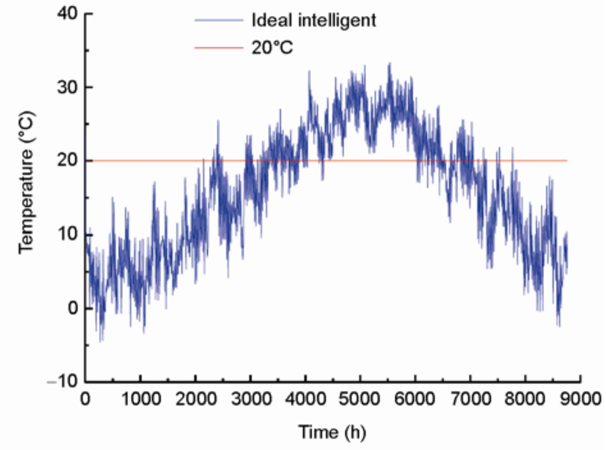

Figure 13 Annual temperature changes in Shanghai when T_c=20°C and ε=1.

as high as possible.

The changes of the ideal intelligent glass temperature all the year round when the transition temperature is 20°C and the emissivity is 1 in Shanghai are shown in Figure 13. It can be seen that the glass is almost switched to the hot state in summer and to the cold state in winter. The characteristic of "intelligently adjustable light" of the ideal intelligent glass is good.

5 Conclusions

(1) The energy saving effect of Intelligent 1 is very good when the air conditioning is cooling and is better than that of Low-E glass. However, its energy consumption is the highest among the five windows when the air conditioning is heating. Therefore, Intelligent 1 is only applicable to the area of hot summer with warm winter without heating all the year round in China. The energy saving effect of Intelligent 2 is not significant when the air conditioning is cooling, and the heating energy consumption is higher than that of white glass.

(2) For the ideal intelligent glass, less cooling energy and more heating energy can be achieved if the transition temperature is lower or the VO_2 thin film emissivity is higher.

(3) Taking annual energy consumption as a judgment standard, the VO_2 thin film transition temperature should be reduced to 20°C as far as possible. At the same time, its emissivity should be as high as possible.

1 He Y F, Xu G, Zhu J, et al. Research progress on VO_2 based thermochromic smart glass (in Chinese). Nanomater Struct, 2008, 45(7): 387–391

2 Barreca D, Depero L E, Franzato E, et al. Vanadyl precursors used to modify the properties of vanadium oxide thin films obtained by chemical vapor deposition. J Electrochem Soc, 1999, 146(2): 551–558

3 Parkin I P, Binions R, Piccirillo C, et al. Thermochromic coatings for intelligent architectural glazing. J Nano Res, 2008, 2: 1–20

4 Vernardou D, Pemble M E, Sheel D W. Vanadium oxides prepared by liquid injection MOCVD using vanadyl acetylacetonate. Surf Coat Technol, 2004, 188-189 (1-3): 250–254

5 Takahashi I, Hibino M, Kudo T. Thermochromic properties of double-doped VO_2 thin films prepared by a wet coating method using polyvanadate-based sols containing W and Mo or W and Ti. Jpn J Appl Phys, 2001, 40(3): 1391–1395

6 Burkhardt W, Christmann T, Meyer B K, et al. W- and F-doped VO_2 films studied by photoelectron spectrometry. Thin Solid Films, 1999, 345(2): 229–235

7 Vernardou D, Pemble M E, Sheel D W. Tungsten-doped vanadium oxides prepared by direct liquid injection MOCVD. Chem Vap Deposit,2007, 13(4): 158–162

8 Batista C, Ribeiro R M, Teixeira V. Synthesis and characterization of VO_2-based thermochromic thin films for energy-efficient windows. Nanoscale Res Lett, 2011, 6: 301–307

9 Binions R, Piccirillo C, Palgrave R G, et al. Hybrid aerosol assisted and atmospheric pressure CVD of gold-doped vanadium dioxide. Chem Vap Deposit, 2008, 14: 33–39

10 Mlyuka N R, Niklasson G A, Granqvist C G. Mg doping of thermochromic VO_2 films enhances the optical transmittance and decreases the metal-insulator transition temperature. Appl Phys Lett, 2009, 95(17): 171909

11 Carlos B, Teixeira V, Ribeiro R M. Synthesis and characterization of $V_{1-x}Mo_xO_2$ thermochromic coatings with reduced transition temperatures. J Nanosci Nanotechnol, 2010, 10(2): 1393–1397

12 Saeli M, Piccirillo C, Parkin I P, et al. Energy modelling studies of thermochromic glazing. Energy Buildings, 2010, 42(10): 1666–1673

13 Saeli M, Piccirillo C, Parkin I P, et al. Nano-composite thermochromic thin films and their application in energy-efficient glazing. Sol Energy Mater Sol Cells, 2010, 94: 141–151

14 Saeli M, Piccirillo C, Parkin I P, et al. Optimisation of thermochromic thin films on glass; Design of intelligent windows. Sci Technol, 2010, 75: 79–90

15 Xie Y. Measurement study and apparatus development on solar heat gain coefficient of window (in Chinese). Master Degree Thesis. Tianjin: Tianjin University, 2006. 1–73

16 Li H P, Hu B. Calculation and analysis of *U* value for Low-E glass units (in Chinese). Glass & Enamel, 2010, 38(1): 7–13