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Inexspensive all-season passive thin metal film for energy savings in cities

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ABSTRACT

Active thin film electrochromic or thermochromic coatings have been used in smart windows. However, the current cost of active thin film windows is approximately 10 times that of passive film windows. This paper proposes an inexpensive passive thin metal film for all-season energy savings. The proposed passive thin metal film allows heat to flow preferentially in one direction. Thin metal films attached to glass indoor can absorb solar heat and the solar can radiate the heat to a room and to the glass respectively until thermal equilibrium. Because of the heated metal film against the room, as long as the temperature of the film is higher than that of the room, there is no heat flux from the room to the thin metal film which is called perfect thermal insulation. The 960m^2 film was installed in an actual hotel in Japan over 10 years and contributed to reducing the energy cost of air conditioning from 54 million yen to 43 million yen, demonstrating an annual energy savings of 11 million yen (US$0.1 million). This paper briefly describes how the proposed economical passive thin metal film will provide all-season energy savings.

Introduction

According to IMARC Group, the global smart window market was worth US$960 million in 2021 (IMARC & IMARC, 2023). Smart windows are classified into electrochromic, thermochromic and hybrid. Thin film electrochromic coatings change color and darken with an applied voltage where the magnitude of the applied voltage determines the degree of coloring and bleaching (Martin, 2005). Thermochromic materials change color reversibly with changes in temperature. But, the durability of vanadium dioxide (VO_2) was limited in commercialization potential due to its instability in the operational environment (Vu et al., 2022). However, amorphous V2O5 was proposed, which may solve the instability problem (Vu et al., 2022).

According to Global Industry Analysts (CISION, 2022), global smart windows market will reach US$6.8 billion by 2026. Table 1 summarizes the current smart window cost per square. Their products are almost based on thin film electrochromic coatings.

In 1976, Mattox investigated the application of thin films to solar energy utilization for energy conservation purposes and discussed individual technology costs (Mattox, 1976). Reflecting and antireflection coatings are used to control incident solar radiation or to retain thermal energy.

Correa et al. proposed copper based thin films to improve glazing for energy-savings in buildings (Correa & Almanza, 2004). They simulated that the total energy saving was approximately 20 % of the total energy demand for Mexicali in Mexico over 35 °C in summer and below 6 °C in winter. However, they did not experiment their technology in actual sites.

Al-Kuhaili et al. investigated spectrally selective energy-saving coatings based on reactively sputtered bismuth oxide thin films (Al-Kuhaili et al., 2020). A transparent heat mirror is an energy-saving coating that transmits light and reflects infrared heat for the heat insulation of commercial residential and automotive glass windows to reduce cooling demands in warm climates. However, they did not indicate how much energy savings were achieved with their technology.

Feng et al. conducted the rapid development of energy-saving smart windows (Feng et al., 2022). However, they did not show how much energy savings at real sites can be achieved with individual technologies. There was no discussion regarding cost.

Chen et al. investigated the solar spectrum selective absorption film with simulation (Chen et al., 2021). They used the experimental site during all four seasons, but did not indicate how much energy savings could be achieved from a cost perspective with the proposed film. In other words, they have not compared the energy-saving effects of the film with and without the film.

Lin et al. proposed passive strategies combining daytime radiative

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Table 1
Smart windows cost per square.

Sales company	Smart window cost per square	Regular glass cost per square + passive film
modernize.com	\$50–\$150	\$10–\$15
homeadvisor.com	\$25–\$150	
zwellhome.com	\$50–\$100	
upgradedhome.com	\$35–\$150	

coolers and thermochromic smart windows (Lin et al., 2021). They built the models for calculating the expected energy-saving effects. However, they did not test their strategies in actual sites.

Tachikawa et al. reviewed advanced passive thermal control materials and devices for space applications (Tachikawa et al., 2022). However, they did not mention the durability or cost of passive thin films. To improve the durability of thin films, stress reduction plays an important role in extending their service life (Abadias et al., n.d.).

This paper proposes a new inexpensive passive thin metal film which allows heat to flow preferentially in one direction. Passive means that the three determinants of absorbance, reflectance, and emissivity of the thin metal film are fixed. Japan has four seasons: spring, summer, fall and winter. We have found the optimal set of three determinants to save energy throughout each of the four seasons. We tested and measured the difference on energy-saving effects between without and with the proposed thin metal film in the actual site.

To the best of our knowledge, there is no inexpensive passive thin film alone that provides energy-saving effects in all four seasons. No one has challenged to save energy in all seasons with passive thin films alone. In other words, the proposed inexpensive thin metal film can transform conventional ordinary glass windows and double-glazed windows into smart windows without the use of electricity or active coatings.

We must understand the important fact that developing a new thin metal film costs US\$0.5 million. In order to reduce the developing cost, we have collected the possible similar thin metal films from the world. More than 300 thin metal films with different determinant sets were collected and tested and experimented to measure and find the optimal determinant set for all-season energy savings.

The proposed thin metal film can achieve perfect thermal insulation in the winter daytimes not by the vacuum technology but by controlling heat flux like thermal diode. Thin metal films can absorb solar heat and the solar can radiate the heat to a room and to the glass respectively until thermal equilibrium. Because of the heated metal film against the room, as long as the temperature of the film is higher than that of the room, there is no heat flux from the room to the thin metal film which is called perfect thermal insulation. The proposed thin metal film is a solar beneficiary with low sun in winter and high sun in summer. In other words, the proposed metal thin film is more energy efficient in winter than in summer. Remember that with the proposed inexpensive thin metal film, energy savings of approximately 20 % can be achieved for all seasons.

Thin metal film can turn a conventional room into an air heat storage chamber due to its perfect thermal insulation in winter and near-perfect thermal insulation in summer. The contribution of this paper is that inexpensive passive thin metal films alone have been used to achieve seasonal energy savings in real-world sites. This paper will demonstrate how much energy savings in a hotel were achieved by the proposed thin metal film.

10-year UV exposure test of the proposed films manufactured in the US and Japan was conducted, but the life time of the proposed films is from 15 to 20 years. UV absorbers are included in the film's adhesive, and the life of the film is determined by the life of the absorber in the adhesive.

This paper describes a method to measure the difference in energy cost of air conditioning without and with the proposed film for one year each, and demonstrates the energy cost effectiveness of the proposed film using an actual hotel as an example.

Methods

Two kinds of heat transfer should be considered in this application: heat conduction and heat radiation. Heat conduction transfer requires direct contact, the vacuum prevents heat conduction transfer, and thermal radiation penetrates the vacuum. The temperature of transferred heat conduction depends on materials, thickness and area in the sun. Or it is depending on heat capacity.

They were tested and experimented to measure and find the optimal determinant set for all-season energy savings.

50-600 μm thin metal films were made by cost-effective vapor deposition with ATO, ITO, and tungsten 1 to 3 g/m^2. The proposed thin metal film has the following set of three determinants: absorption: 30.2 %, reflectance: 10.4 %, and emissivity: 0.886 for energy savings in all four seasons.

Fig. 1 shows the material layer ATO which plays a key role in behaving like thermal diode.

As shown in Fig. 2, the thin metal film is attached to the inside of the window. The thin metal film absorbance plays a key role in achieving perfect or near-perfect thermal insulation.

The higher film absorbance, the higher temperature of the metal film can be achieved. The higher solar radiation, the higher temperature of the metal film can be achieved.

However, for safety, we have to take care of avoiding glass thermal shock. In order to avoid the glass thermal shock, through our numerous experiments, we found that the film glass absorbance should be lower than 60 %.

Consider the winter case. Fig. 2 shows the heat flux of the film when the outdoor temperature is 0 °C and the room temperature is 20 °C. When the radiated film temperature is 20.9 °C which is higher than indoor temperature of 20 °C and the solar radiation energy is 555 W/m^2, the transmittance energy of 330 W/m^2 is transferred to indoor with film heat dissipation of 10 W/m^2 and the reflection energy of 58 W/m^2.There is no heat flux from indoor to the film as long as the temperature of film is higher than that of indoor.

The experimental design was to demonstrate annual energy savings costs by comparing two energy costs, one without and one with the proposed energy-saving film, for one year each. To demonstrate the energy-saving cost effectiveness of the proposed film, we actually measured the monthly electricity bill for air conditioning over a two-year period. In order to make fair comparisons, annual outdoor temperatures were observed for two years.

The proposed and similar thin metal films have been installed in

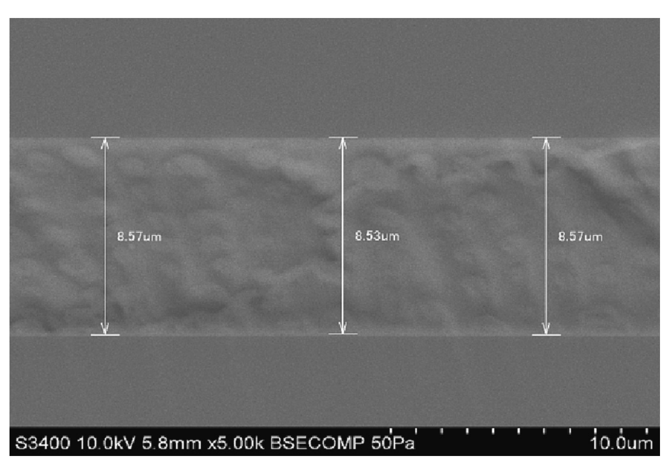

Fig. 1. Material layer ATO used in one of the thin metal films.

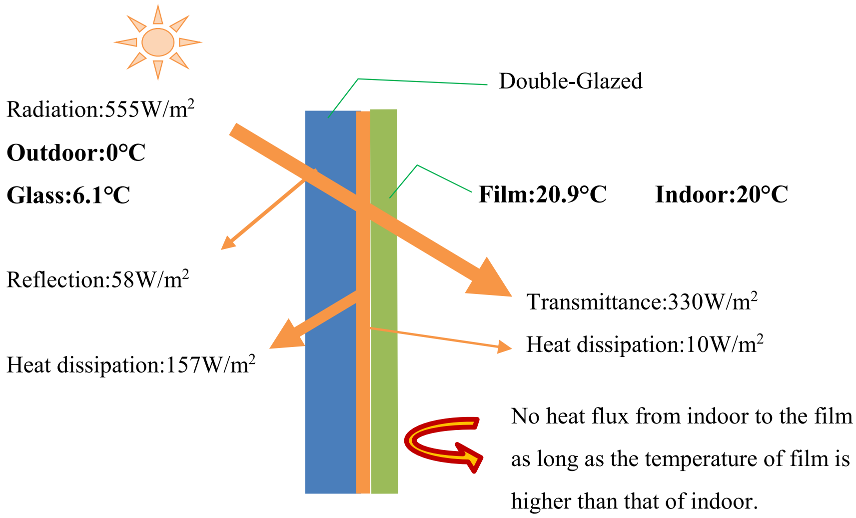

Fig. 2. Heat flux of Film (wind speed ≒ 0 m/s).

more than 30 hotels and hospitals in Japan, contributing to energy savings. However, hotels and hospitals do not want to disclose energy costs for air conditioning in Japan.

This paper presents a case study of a hotel for which authors have received consent. The 960 m^2 film was installed over a 10-year period on the glass windows of the actual hotel in Niigata, Japan, helping to reduce energy costs for air conditioning. This is an annual two-year long-term measurement project without and with the use of the proposed energy-saving film.

Energy costs for air conditioning are proportional to energy savings. In other words, energy savings are proportional to energy costs. The results of this experiment are not estimates, but actual measured energy costs for air conditioning over two years.

Results

Measurements of annual outdoor air temperatures in Niigata for two years showed no difference. Within the period measured, there was no change in electric utility rates. However, there was a significant difference in air conditioning costs and monthly electricity bills without and with the proposed film.

Fig. 3 shows the result of annual energy saving with/without thin metal film of 960 m^2 installed in the hotel in Niigata. The proposed film with 960 m^2 was actually installed on double glazing in the hotel and contributed to demonstrate reducing the high energy cost of 54 million yen to 43 million yen, and the annual energy savings of 11 million yen for all four seasons in Niigata. In other words, we compared the cost of one year with and without the proposed film, respectively. This two-year long-term period energy-saving measurement is the first attempt in the world using the proposed thin metal film alone.

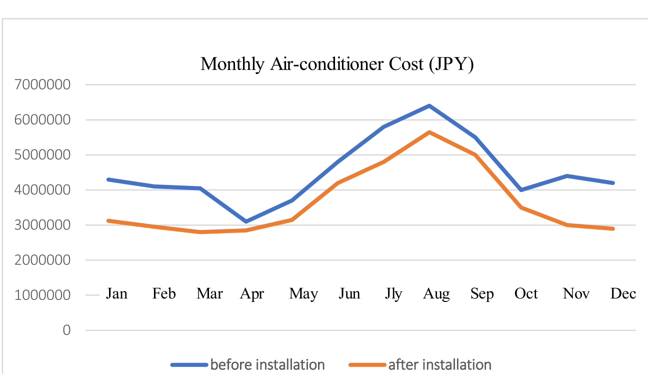

Fig. 3. Annual energy saving with/without thin metal film.

Fig. 3 shows that energy savings were achieved in all months and seasons, including spring, summer, fall, and winter which indicates that the proposed claim is consistent.

Energy saving in winter is larger than that in summer. Taking advantage of a solar beneficiary with low sun in winter and high sun in summer. The proposed metal thin film is more energy efficient in winter than in summer. This is because as long as the temperature of the heated film is higher than that of the room, there is no heat flux from the room to the thin metal film which is called perfect thermal insulation in winter. The proposed heated thin metal film allows heat to flow preferentially in one direction for energy savings.

In summer, the near-perfect thermal insulation can be achieved with the proposed thin metal film.

The vertical axis indicates Japanese Yen.

With the proposed inexpensive thin metal film, energy savings of approximately 20 % can be achieved for all seasons. If this method is applied to urban areas, significant energy savings can be achieved. As mentioned earlier, the colder the area, the greater the energy savings. In order to further improve energy-saving performance over the proposed passive thin metal film, we are experimenting with various optimal sets of energy savings for all-season, cold region-specific, and hot region-specific applications.

Based on long-term measurements over a two-year period, the 20 % energy saving cost can be achieved with the proposed inexpensive passive thin metal film.

Conclusion

After numerous experiments to find the optimal set of three determinants, we found the following set of determinants of the inexpensive passive thin metal film: absorbance: 30.2 %, reflectance: 10.4 %, and emissivity: 0.886 for all-season energy savings. We tested and measured the energy savings of all four seasons with/without thin metal film of 960 m^2 at the actual site. The result with the proposed passive thin metal film of 960 m^2 demonstrates that the annual energy savings are equivalent to approximately 11 million yen (US$0.1 million) in the hotel. In other words, 20 % energy savings can be achieved with the proposed inexpensive passive thin metal film. We continue to investigate and improve the energy-saving performance of various passive thin metal films.

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Declaration of competing interest

The authors have no conflict of interest.

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