Large-Scale Annual Modeling of Low-Emissivity Films for Energy-Saving Buildings

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Abstract: We present large-scale building simulations with a low-emissivity film. This film annually reduces heat gain and loss by 257.6 MJ per installation wall area. It is estimated to reduce 1.14 billion metric tons of global CO_2 emission.

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Saving energy to heat and cool buildings is important for sustainability, since about 35% of building energy consumption is directly related to the operation of heating, ventilation and air-conditioning (HVAC) systems. To this end, previous works demonstrated roof materials with low emissivity in the near-infrared (NIR) wavelength range [1]. However, building wall materials are much more important for energy-saving purposes, as walls constitute the main components for urban building envelopes.

In this work, we extrapolate the experimentally demonstrated low-emissivity film [2] which has high reflectance (90%) in infrared wavelength range and selective reflectance in the visible light wavelength range for desired colors. The as-fabricated low-emissivity films in assorted colours are displayed in Fig. 1 (a). The total mid-infrared (MIR) reflectance was measured with a Fourier transform infrared (FTIR) spectrometer, as shown in Fig. 1 (b). They are all highly reflective for MIR light, showing about 90% reflectance except for several narrow sharp peaks. The IR transmittance is nearly 0 due to the IR-opaque Al, thus the MIR emissivity is calculated to be about 0.1, which is ideal for low-emissivity materials. Therefore, our work focuses on engineering the MIR radiative heat exchange, which is more dominant with outdoor ambient surroundings than with the sky, and more pronounced in dense urban areas. Traditional building materials usually show high thermal emissivity, leading to intense radiative heat exchange. Therefore, a design that minimizes radiative heat transfer through the building wall envelope will be beneficial for both cooling and heating energy saving throughout the year.

We developed a thermal model to quantify the reduction of heat gain and loss through a wall by applying coloured low-emissivity films. In this model, we considered a post-1980 midrise apartment building's exterior walls, defined by the U.S. Department of Energy (DOE). The model building has four stories, a rectangular shape and a size as illustrated by Fig. 1 (c). We utilized EnergyPlus to conduct the evaluation of HVAC energy saving performance where we comprehensively consider the heat exchange of the whole building coupled with complicated HVAC systems and output the final HVAC energy use of the building. The HVAC energy use (cooling, heating, fans and water systems) was calculated for the building with conventional wall materials and with walls that have the surface property of our coloured low-emissivity material. The energy use difference was exactly the HVAC energy saving. By applying our coloured low-emissivity materials on walls, up to 124.46 GJ energy can be saved. The corresponding CO_2 emission reduction, as calculated by relevant factors 1 kW·h electricity $= 0.709$ kg CO_2, amounts to 1.14 billion metric tons of global CO_2 emission reduction. We evaluated the annual HVAC energy saving brought about by coloured low-emissivity film installation for such a prototype midrise apartment across the United States using EnergyPlus, and the energy saving map is plotted in Fig. 1 (d).

To demonstrate that the radiative heat component dominates heat transmission throughout a wall, we developed a model [3] to calculate the all-year energy saving when the low-emissivity film is installed on wall envelope exterior surface, interior surface, and double-sided surfaces, respectively. For all three cases, the indoor temperature set-point was set as $T_{\text{indoor}} = 22°\text{C}$, as the internal environment boundary condition. The outdoor temperature set-point was set as hourly weather data in the typical meteorological year (TMY3) [4], as the external environment boundary condition. The temperature of the interior and exterior sides of the wall can be obtained by solving the steady-state heat balance of outside and inside surfaces of the wall. With the extracted average radiative (subscript 'rad,in') and convective (subscript 'conv,in') energy transfer component with and without the film installation for the cases with (superscript 'w') or without (superscript 'wo') the low-e film, we then get the annual cooling and heating energy saving, defined as the reduction of interior heat transmitted to the wall as $P_{\text{save, cool}} = P^{\text{wo}}_{\text{rad,in}} + P^{\text{wo}}_{\text{conv,in}} - P^{\text{w}}_{\text{rad,in}} - P^{\text{w}}_{\text{conv,in}}$, $P_{\text{save, heat}} = -P^{\text{wo}}_{\text{rad,in}} - P^{\text{wo}}_{\text{conv,in}} + P^{\text{w}}_{\text{rad,in}} + P^{\text{w}}_{\text{conv,in}}$, respectively.

Based on this model, as illustrated in Fig. 1 (e), for all locations, our coloured low-emissivity films can bring about a reduction of heat gain/loss from dozens to hundreds of MJ per installation wall area. This effect is especially strong for cities in the southern and middle U.S. Taking Miami as an example, the double-sided installation can achieve heat transmission reduction of 257.6 MJ m^{-2}. To further assess the heat transmission reduction effect, we calculated for 16 cities the equivalent insulation layer thickness that would achieve the same reduction of heat gain or loss as our low-emissivity films, assuming the films are installed on both sides of non-insulated wall surfaces. The green columns in Fig. 1 (f) exhibit the annual reduction of heat gain and loss per unit wall area, and the orange columns show that the double-side installation of extremely thin coloured low-emissivity films (40 μm) on non-insulated walls is equivalent to adding around 6 mm insulation material (0.049 W m^{-1} K^{-1}), which is more than 70 times as thick as our films. This high equivalent insulation layer thickness indicates that coloured low-emissivity films decrease insulation thickness and provide design flexibility for new buildings.

In conclusion, we presented a low-emissivity film with excellent energy-saving performance across the U.S. Our work provides new insights for innovative energy saving building envelope materials that can help achieve global carbon neutrality and sustainability.

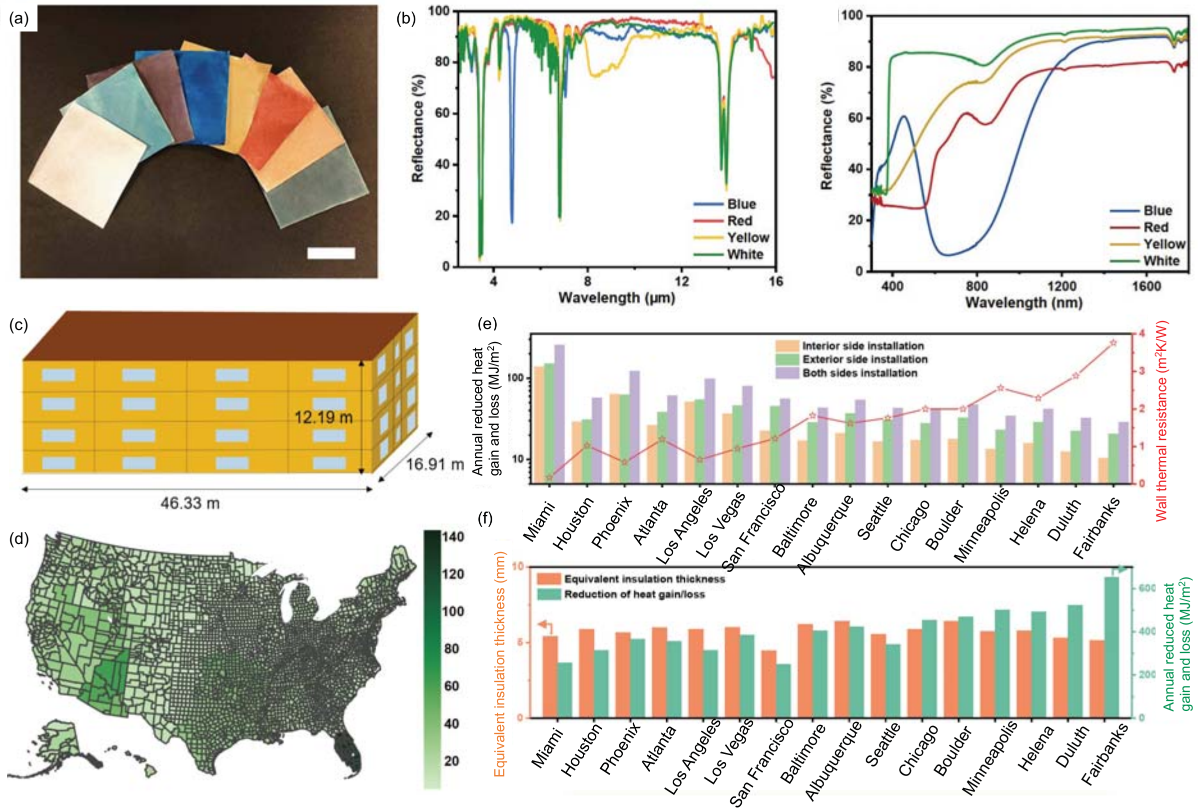

Fig. 1. (a) Photograph of coloured low-emissivity films in various colours. Scale bar, 5 cm. (b) Measured total reflectance spectra in the MIR wavelength range (left) and in the visible and NIR wavelength range (right) for white, blue, yellow and red samples. (c) Sketch of the modeled midrise apartment building. (d) HVAC energy saving map across the U.S. with coloured low-emissivity film installation on walls of a building in (c). (e) Calculated annual reduction amount per installation wall area of heat gain and loss for installation on wall interior surface, exterior surface and both sides for 16 representative cities in various climate zones. (f) Calculated equivalent insulation thickness for double-side installation of coloured low-emissivity materials on non-insulated walls and its annual reduction amount of heat gain and loss per installation wall area.

References

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