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Energy efficient surfaces on building sandwich panels—A dynamic simulation model

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ABSTRACT

The choice of building envelope is critical for the energy performance of buildings. The major part of the energy used by a building during its lifetime is used for maintaining a suitable interior thermal climate under varying exterior conditions. Although exterior heat radiation properties (i.e. total solar reflectivity and long wave thermal emissivity) have been well accepted to have a large impact on the need for active cooling in warmer climate, the effect of a reduced thermal emissivity on interior surfaces on the building thermal energy flux is rarely studied. This paper addresses the sensitivity of the thermal energy flux through a sandwich panel, by systematically varying the surface thermal emissivity (both interior and exterior) and total solar reflectance of exterior surface, for three geographical locations: southern, middle and northern Europe. A model is introduced for calculating the effect of both interior and exterior optical properties of a horizontal roof panel in terms of net energy flux per unit area. The results indicate potential energy saving by the smart choice of optical properties of interior and exterior surfaces.

1. Introduction

The energy required to maintain a desired indoor climate in buildings is usually larger by roughly an order of magnitude compared to the energy needed to provide the building materials [1]. A smart choice of material and sustainable design can trench the energy demand and contribute to less heating or cooling usage.

Among building materials, the sandwich panel has earned its reputation due to short construction time and cheaper labor cost. It can be used in a wide range of applications; new constructions, extensions and refurbishments.

Sandwich panels usually consist of two coil coated steel sheet profiles, which are tightly pressed and glued to an insulation core. They can be manufactured even without trans-sectional supports to avoid thermal bridges.

Coil-coated steel is profiled and utilized in sandwich panel as the shield. Since the shield is also interface between indoor and outdoor environment, it is considered for both climatic exposure and aesthetic aspects. Continuous development of paint, used in coil-coating has nowadays made it possible to improve both durability and energy performance of such materials. For the panel's exterior, coatings with high solar reflectance can contribute to lower surface temperatures and consequently reduce the thermal stresses and mechanical strains. The lower temperatures prolong the panel's life time and minimize buckling and other mechanical problems.

Coil-coating technology, with new paint formulations, has also improved radically. The use of reflective pigments has made it possible to adjust the optical properties of both interior and exterior sides of the panel independently for short and long wave radiation within wide ranges. In the aesthetic realm, pigments with high reflective properties in the near infrared region has now given a handful of choices to the architects to pick even darker colors with improved total solar reflectance and also an aid to the manufacturers to overcome thermal elongation problems and to provide panels with darker colors.

While the importance of total solar reflectance and optical properties of the exterior coatings has been well recognized [2–9], fewer studies probe the effect of optical properties of the interior side. Development in paint formulation has made it possible to produce coating with higher reflectance in the long wave radiation spectra. Thermal emissivities ranging from 0.25 to 0.7 have been measured for coil-coated materials with metallic paint coatings compared to values above 0.9 using non-metallic paint. This kind of coatings has been found mainly useful for interior coatings where it is expected to act like a thermal barrier against the radiation energy potentially emitted or absorbed by the panel surface when the radiation temperature differs significantly from the panel surface temperature. For instance, Daoud et al. [10] have shown that low emissive inte-

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rior coatings can contribute to the energy savings in an indoor ice rink.

This paper depicts a simple comprehendible approach to demonstrate the effects of optical properties for both interior and exterior coatings in one model and illustrate the potential energy saving towards more efficient and sustainable choice of materials.

2. Hourly dynamic model

2.1. Assumption and equations

To simplify and focus on optical properties of exterior and interior surfaces a unit area of a horizontal panel is considered with constant properties and without surface condensation or dust gathering. Thermal circuit analogy of the model is illustrated in Fig. 1. It includes two surface thermal nodes on the out and inside of the panel, *so* and *si*, respectively and n thermal nodes disseminated uniformly across the panel to account for its thermal mass. The insulation inside the sandwich panel is uniform and therefore the thermal mass and conductivity of the panel can be assumed uniformly discrete into n number of cells, each containing one of the n non-surface nodes. Therefore Δl is $1/n$ times the panel's thickness in m where n is the number of the cells. ρ and c_p are the density in kg m^{-3} and specific heat in J kg^{-1} K^{-1}, respectively.

Each cell consists of two ΔR_{cond} which equals to $R_{cond}/2n$, where R_{cond} is the conductive thermal resistance of the panel in m^2 KW^{-1}. For simplicity, in Eq. (1) the thin skins of steel, contact resistance between steel and insulation and thermal bridge of fasteners are neglected. Ditto the mathematical model, Eq. (1), consists of $n+2$ equations, forming a system of non-linear differential-algebraic equations that solves for the $n+2$ unknown temperature of the nodes, where for each node a energy balance equation is given.

$$\begin{cases} \text{Node } so: & G(1-TSR) - \dfrac{T_{so}-T_{amb}}{R_{conv,out}} - \sigma\varepsilon_{ext}(T_{so}^4 - T_{sky}^4) = \dfrac{T_{so}-T_1}{\Delta R_{cond}} \\ \text{Node } 1: & \dfrac{T_{so}-T_1}{\Delta R_{cond}} - \dfrac{T_1-T_2}{2\Delta R_{cond}} = \rho c_p \Delta l \dfrac{\partial T_1}{\partial t} \\ \text{Node } k: & \dfrac{T_{k-1}+T_{k+1}-2T_k}{2\Delta R_{cond}} = \rho c_p \Delta l \dfrac{\partial T_k}{\partial t}, \quad k = 2, \ldots, n-1 \\ \text{Node } n: & \dfrac{T_{n-1}-T_n}{2\Delta R_{cond}} - \dfrac{T_n - T_{si}}{\Delta R_{cond}} = \rho c_p \Delta l \dfrac{\partial T_n}{\partial t} \\ \text{Node } si: & \dfrac{T_n - T_{si}}{\Delta R_{cond}} = \dfrac{T_{si}-T_{in}}{R_{conv,in}} - \sigma\varepsilon_{int}(T_{si}^4 - T_{ri}^4) \end{cases} \quad (1)$$

where T_{amb}, T_{in}, T_{sky}, T_{so}, T_{si} and T_{ri} are ambient temperature, indoor air temperature (adjacent to interior surface), sky temperature, exterior surface temperature, interior surface temperature and interior radiation temperature (from interior surroundings as seen by the interior surface), respectively. T_1, T_n, T_k are the temperatures at the first, last and intermediate cells, respectively. All temperatures are in Kelvin. G is the incident solar irradiance on the exterior surface in W m^{-2} and σ is the Stefan–Boltzman constant. *TSR*, ε_{ext} and ε_{int} are total solar reflectance, effective infrared emissivity of the exterior and interior, respectively. $R_{conv,out}$ and $R_{conv,in}$ are convective thermal resistance of the exterior and interior surface in m^2 KW^{-1}, respectively.

The building energy simulation tools IDA SE and IDA ICE have been used in advanced modeling mode to build up the model as well as the hourly dynamic simulations. IDA ICE is an equation-based modeling tool which uses variable time-step differential-algebraic equation (DAE) solver [11]. Discrete thermal mass model (cell) is based on finite difference mathematical model of multi-layer component available in IDA ICE. Exterior heat transfer coefficient is calculated according to [14] based on local wind speed, direction of the wind and surface slope.

The interior vertical convective heat transfer coefficient is assumed to be 5.0 W m^{-2} K for upward heat flux and 0.7 W m^{-2} K for downward heat flux [12]. These values indicate that radiative heat dissipation is more dominant over convective in downward heat flux from the ceiling to the floor.

Interior radiation temperature, T_{ri}, is used here as a single value parameter only to represent the radiation temperature seen by the interior surface in the model. The concept of mean radiation temperature is generally used to avoid the complexity of geometric factors in radiation heat transfer. The radiation temperature can be calculated from the surrounding surface temperatures with the weight of the respective angle factors to the interior surface (see Eq. (2)) [13]. Most building materials (other than bare metals or metallic paint coated materials) have high emittance values, close to unity. Then the radiant temperature is:

$$T_r = (T_1^4 F_{p-1} + T_2^4 F_{p-2} + \cdots + T_N^4 F_{p-N})^{1/4} \quad (2)$$

where T_r is the radiation temperature (K), T_N is the surface temperature of surface N in K and F_{p-N} is the angle factor between the interior surface and the surface N.

By setting the interior radiative temperature, T_{ri}, some degrees higher than the indoor air temperature, T_{in}, the current model makes a simple representative of e.g. an active floor heating. A T_{ri} lower than T_{in} may be found e.g. in an indoor ice hockey arena. In a detailed model of a realistic building case, interior radiation temperature T_{ri} may be defined as one of the dynamic boundary conditions dependent on the detailed heating and cooling mechanism and schedules used. Here, however, it is used as a parameter to map the sensitivity of the total heat flux to the interior surface emissivity.

The interior emissivity (ε_{int}) is the effective emissivity between the interior surface and the surrounding that can be calculated from Eq. (3), where ε_{eff}, ε_s, and ε_r are effective emissvity, surrounding

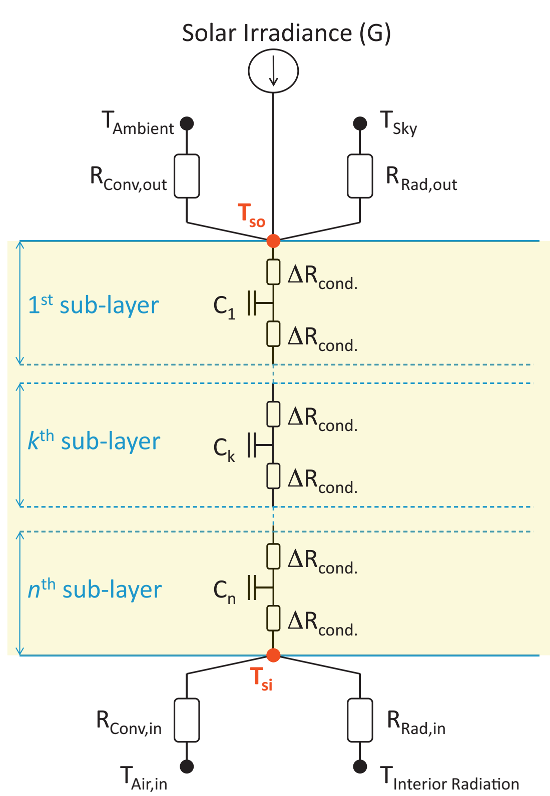

Fig. 1. Thermal circuit analogy for horizontal roof.