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CLIMATE-ADAPTIVE BUILDING SKINS FOR BUILDING ENERGY CONSERVATION AND UHI MITIGATION: TRANSIENT BUILDING ENERGY SIMULATION WITH THERMOCHROMIC COATINGS

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Abstract
The Intergovernmental Panel on Climate Change (IPCC) predicted for the end of the 21st century the 1.5°C to 2.0°C increase in global mean surface temperatures due to climate change. At the urban level, the impact of climate change is amplified by the urban heat island (UHI) phenomenon that is negatively influenced by the high-density built environment, low-albedo, and high thermal mass surfaces among other factors. The space cooling appliance ownership among occupants in residential buildings has been increasing to counter the indoor thermal discomfort occurring during the hot weather season as a result of the rising outdoor temperature. The excessive usage of conventional energy-intensive space cooling systems contributes directly to the urban heat island and indirectly to climate change. Several studies on innovative cool building envelope material characterized by high solar reflectance and high thermal emissivity have identified thermochromic materials as an efficient climate-adaptive solution especially for heating and cooling intensive climates. These advanced materials, able to change their color (i.e. absorbent capability) according to the temperature variations (i.e. from darker/high absorbance to lighter/low absorbance with an increase in temperature and vice-versa with a decrease in temperature), have the potential to be implemented in the building envelope as a passive strategy for improving building energy-saving and indoor thermal comfort, as well as mitigating urban heat island and climate change. Predicting the thermal-energy performance and mitigation potential of these materials is essential to provide key stakeholders with the required information to evaluate their applications in different building typology and climate contexts. The present study presents a transient building energy simulation approach to assess the potential of thermochromic coating for roof applications in conserving energy and reducing the UHI contribution specific to building type and climate. A representative residential building of the tropical Darwin city in Australia and a representative thermochromic material have been considered for the study. Three thermal comfort setpoint scenarios have been adopted for a business-as-usual (BAU) building case and thermochromic (TC) case to assess the energy-saving potential and the UHI contribution across scenarios and cases.
The preliminary analysis has shown for the TC case the highest energy savings in the natural ventilation setpoint (NV) scenario (i.e. 7%) followed by the adaptive setpoint (AS) scenario (i.e. 6%) and the static setpoint (SS) scenario (i.e. 5%) when compared to their respective scenarios in BAU case. The thermochromic coating applied in the roof and assumed in this study has shown uniform contribution across all three scenarios in reducing the UHI by containing the increment of the roof outside face temperature. The study recognised that the present-day transient building energy simulation tools do not account for the benefits and the penalties of climate-adaptive materials on the UHI phenomenon.

1.1 INTRODUCTION
The world is facing the early impacts of climate change (CC), and the increase in anthropogenic activities found to be the primary cause for the rise in global greenhouse gas (GHG) and CC [1]. The UNEP has identified the building sector as the most potential sector for effectively reducing GHG emissions in its Buildings and Climate Change report [2]. In 2018, more than 81% of the world's electricity was generated from fossil fuels [3]. According to the International Energy Agency [4], the buildings and buildings construction sectors have been alone responsible for over one-third of global energy, constituting nearly 40% of total direct and indirect CO_2 emissions. While building energy use seems to be a contributor to CC, the building energy performance seems to be vulnerable to CC. A study assessing the CC impact on building energy expenditure [5] has predicted increased building energy use

for most nations. Around 25% rise in energy demand has been predicted [6] for the countries located in the tropics and southern regions of the USA, Europe, and China. Another study conducted in the USA predicted an increase in cooling degree days and decreased heating degree days for the chosen IPCC global warming scenario [7]. Similarly, the studies conducted in Germany [8], Australia [9], Finland [10], Taiwan [11] also predicted a rise in future cooling energy demand in buildings. Along with CC, the building's energy performance is resulted to be vulnerable to the Urban Heat Island (UHI). The UHI phenomena refer to the increase in ambient temperatures of the cities compared to their abutting suburban and rural areas [12]. According to Zhou et al. [13], the UHI intensity increases with the city size logarithm and the fractal dimension. The new cities have been populating worldwide along with the growth of existing cities due to rapid urbanisation. The UHI phenomena has been largely documented [14] and in combination with the global warming it is expected to raise the ambient temperatures causing the higher demand for cooling in buildings. A study [15] observed a 13% increase in the cooling load of urban buildings compared to similar buildings in rural areas. The reduction in cooling demand can be achieved by referring to passive strategies such as controlling solar gains through glazing, reducing internal heat gains, and using thermal mass and night ventilation [16]. However, the CC impact study conducted in Taiwan [11] inferred that the conventional passive strategies such as natural ventilation and high thermal mass in silos could not reduce the need for space cooling requirements in the future. It has been observed that passive strategies such as natural ventilation and night flushing are not effective in regions affected by UHI. Thus, reducing low-albedo surfaces and increasing thermal mass in building envelopes could help reducing the UHI and demand for cooling in buildings.

The present-day building envelope materials could be grouped into three generations [17]. The first-generation includes the low-albedo heat-absorbing materials that contribute to UHI and cause the need for space conditioning [15]. Cool and fluorescent building materials could be considered as second and third-generation materials. Cool materials are featured with high solar reflectance (SR) and high thermal emittance (ε) and are usually available in the form of membranes [18], tiles, and coats in the market [19]. The study conducted by Synnefa et al. [20], has observed a decrement in building cooling load by 18-93% with the use of cool materials. The study also reported a reduction in maximum temperatures by 1.2°C to 3.3°C for naturally ventilated buildings. In another study [21] conducted in central California, homes reported annual space conditioning energy savings of 10.7 kWh/m^2 with a cool roof which is 15% in savings compared to the conventional case roof. Fluorescent materials are also characterised by high solar reflectance and thermal emissivity like cool materials and are available in non-white and light colours [22]. Various pigments are used to formulate fluorescent materials with the desired colours that can stay cool even when exposed to the sun. Few studies [23], [24], & [25] investigating these materials also observed an increase in heating energy requirement in winters for the climatic locations comprising significant heating along with cooling.

Thermochromic (TC) materials possess high solar reflectance and thermal emissivity similarly to fluorescent material but only when the underlying surfaces exceed the threshold temperature [26]. Thermochromism can be achieved either by Leuco dyes or non-dye-based materials [27]. TC coatings developed by Karlessi et al. [28], have demonstrated lower temperatures compared to cool and standard coatings in hot outdoor conditions. Similarly, reversibly thermochromic cement-based materials prepared by Ma et al. [29], have also shown the potential of warming the buildings in winter while reducing the over-heating of buildings in summer. The cementitious plaster with phase change materials and thermochromic paint developed by Soudian et al. [30] has shown a high solar absorption rate in building surfaces in colder temperatures than a regular cement plaster. Many characterisation studies have been performed to date for TC materials. Very few studies have predicted or measured the building energy performance of TC materials. The study conducted by Hu et al. [31] didn't detail out the approach of using Energy Management System (EMS) of EnergyPlus (EP) to simulate the TC performance on building roof. Zheng et al. [32] has also used EP to simulate the energy savings of prepared thermochromic coatings for his study. However, he has assumed the colourless phase of TC coatings for the months with a monthly mean ambient temperature greater than 25°C for the simulation. This assumption could undermine the heat gain for the months when ambient temperatures are less than 25°C. In his study, Berardi et al. [33] has considered scenarios with six different transition temperatures and five visible absorptance values for assessment of the potential energy savings of TC and cool coatings considering inter-building effects. A simulation study with a similar methodology was also published by Granaderio et al. [34] and Yuxuan et al. [35], with step transition in absorptance values for TC coatings. Usually, the shift in SR and ε properties of TC materials occur gradually. Therefore, adopting a single value for the band of temperatures could have a chance to either overestimate or underestimate the potential of TC coatings. The overestimation and underestimation commonly happen when most of the time, the surface temperatures fall at either end of the band. Therefore, the transient building energy simulation with TC coatings/materials is required to accurately predict the building energy performance for chosen climatic conditions. This study evaluates the energy performance of a TC coating on a residential building through a transient simulation approach. The present study analyses the following:

- cooling, heating, and total energy savings through TC coatings in a residential building operated in static, adaptive thermal comfort, and natural ventilation scenarios;
- TC coated roof contribution against conventional roof contribution to UHI;
- performance of TC case between the static, adaptive thermal comfort, and natural ventilation scenarios.

1.2 METHODOLOGY

A representative building model has been used to evaluate the energy performance of TC coating on a residential building in Darwin (Australia) with a transient simulation approach. The case based on the application of TC coating to the building roof and scenarios based on adaptive thermal comfort setpoint have been considered for the study. A representative TC coating from the literature review has been chosen, and a mathematical model representing the change in thermal and optical properties as a function of surface temperature has been scripted. The script has been integrated with EP to perform transient building energy simulation with TC coatings.

Darwin is the capital city of the Northern Territory (Australia). According to typical meteorological year (TMY) weather data, the city accounts for 6426.8 cooling degree days at 10°C (CDD10) and 2.5 heating degree days at 18°C (HDD18). The region falls under an extreme hot-humid climate. The geometry of the representative residential building is illustrated in Figure 1 and has been selected from a previous study [36].

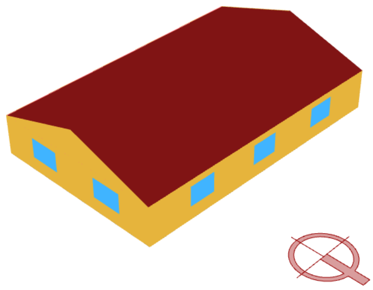


Figure 1. Representative residential building of Darwin (Australia) modeled in this study.

The Rhinocerous (Rhino) 3D modelling tool has been used to model the geometry. The Ladybug plugin of Grasshopper has been chosen to transform the Rhino model into EP model and suffice other required simulation inputs. The envelope, electro-mechanical equipment, lighting, occupancy, and ventilation has been referred from the same study [36]. The study considered the building inputs outlined in Table 1 for the business-as-usual (BAU) case. The thermochromic coating (TC) case is assumed to have the same inputs as the BAU case but differs by the TC coating applied on the roof. The occupancy, lighting, space conditioning, and equipment schedules details have been referred to from the handbook for estimating NABERS ratings [37] and remain the same for both cases. Three adaptive thermal comfort setpoints have been considered for this study. The static setpoint (SS) scenario operates building space conditioning with a cooling setpoint (CSP) at 25°C and a heating setpoint (HSP) at 20°C. A new adaptive thermal comfort model for homes in Australia [38] has been referred to calculate CSP and HSP for adaptive comfort (AS) and natural ventilation (NV) scenarios. The upper category I limit and lower category I limit of equations (1) and (2) are referred to as CSP and HSP, respectively, for AS scenarios. At the same time, the upper category II limit and lower category II limit of equations (3) and (4) are referred to as CSP and HSP, respectively, for the NV scenario.

$$\text{Upper category I limit (°C)} = 0.26\ x\ T_{pma(out)} + 19.4 \quad (1)$$
$$\text{Lower category I limit (°C)} = 0.26\ \text{x}\ \text{T}_{\text{pma(out)}} + 12.4 \quad (2)$$
$$\text{Upper category II limit (°C)} = 0.26\ x\ T_{pma(out)} + 20.4 \quad (3)$$
$$\text{Lower category II limit (°C)} = 0.26\ \text{x}\ \text{T}_{\text{pma(out)}} + 11.4 \quad (4)$$

where, $T_{pma(out)}$ is the prevailing mean outdoor air temperature.

Table 1. Model inputs for BAU and TC case.

Envelope	**Properties**
18° Sloped Roof	U = 0.435 W/m^{2}K; Solar absorptance = 0.7; Thermal absorptance = 0.9
Ceiling	U = 2.0 W/m^{2}K
External Walls	U = 0.342 W/m2K; Solar absorptance = 0.7; Thermal absorptance = 0.9

Floor	U = 0.835 W/m²K
Window	U = 5.60; SHGC = 8.50; VLT = 0.88
Total built-up area	260 m² (= 20m x 13m)
Window-to-wall ratio	18%
Infiltration rate	0.7 ACH ~ 0.16 m³/s
Ventilation rate	7 ACH ~ 1.6 m³/s
Occupancy	4 occupants ~ 0.0153 people/m²
Equipment loads	4.15 W/m²
Lighting load	3 W/m²

A TC coating developed by Karlessi T. et al. [28] has been used to generate the TC case-building model. The study provides the SR and ε values of the TC coating developed for coloured and colourless phased along with surface temperatures. This study assumed linear regression of SR and ε properties from coloured phase to colourless phase. The optical and thermal performance of the TC coating, assumed as the function of surface temperature, has been illustrated in Figure 2. In addition, the mathematical model of the TC coating has been derived as shown in equations (5) and (6). This model has been scripted and integrated with EP for transient building energy simulation.

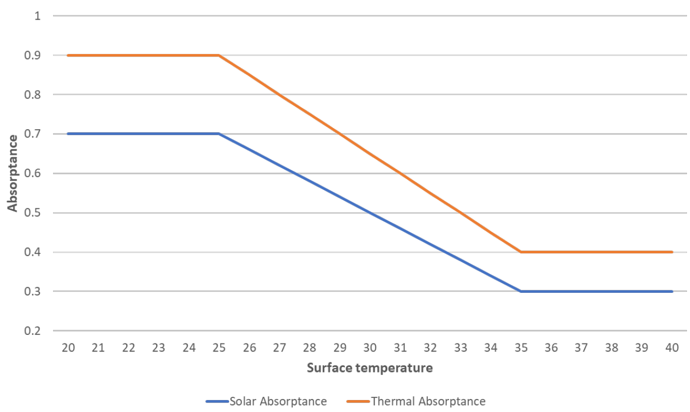


Figure 2. Optical (solar absorptance) and thermal (thermal absorptance) performance of the TC coating as the function of surface temperature.

$$SA = \begin{cases} 0.7 \; when \; ST < 25 \\ 0.3 \; when \; ST > 35 \\ 1.7 - (0.04 \times ST) \; when \; 25 \geq ST \leq 35 \end{cases} \quad (5)$$

$$TA = \begin{cases} 0.9 \; when \; ST < 25 \\ 0.4 \; when \; ST > 35 \\ 2.15 - (0.05 \times ST) \; when \; 25 \geq ST \leq 35 \end{cases} \quad (6)$$

where, ST is the surface temperature, SA the solar absorptance, and TA the thermal absorptance. Knowing SA and TA, it is possible to obtain SR and ε as per equation (7) and (8), respectively:

$$SR = 1 - SA \quad (7)$$

$$\varepsilon = TA \quad (8)$$

1.3 ANALYSIS

The analysis section has been divided into two sub-sections. The first section evaluates the energy savings with TC coating in SS, NV, and AS setpoint scenarios. The second section compares the outdoor surface temperature of the roof with and without TC coating for three setpoint scenarios to evaluate the UHI contribution.

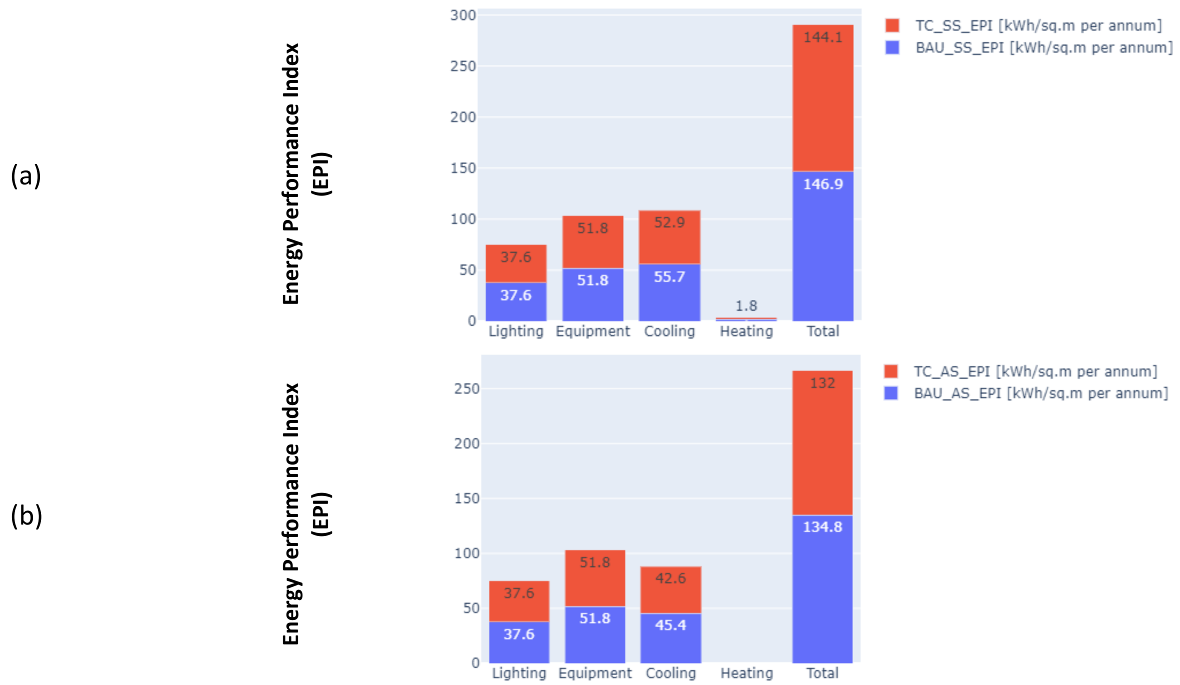
Cases	Setpoint Scenario		
	Static (SS)	Adaptive comfort (AS)	Natural Ventilation (NV)
Business-as-usual (BAU)	BAU_SS	BAU_AS	BAU_NV
Thermochromic Coating (TC)	TC_SS	TC_AS	TC_NV

- Energy savings
- UHI contribution

Figure 3. Analysis approach of this study.

Energy savings in each scenario

Figure 4 shows the energy performance index (EPI), equivalent to the energy used per unit area measured as kWh/m^2/year, for each set point scenario comparing the results for both cases BAU and TC. In the SS scenario, around 5% of cooling energy savings and 1.8 kWh/m^2/year increase in heating energy use could be observed in the TC case over BAU case (Figure 4(a)). On the other hand, cooling energy savings of about 6% and 7% could be observed in TC cases for both AS and NV scenarios without an increase in heating energy requirement. Figures 4(b) and 4(c) illustrate the deviation of cooling energy use between TC and BAU cases for AS and NV scenarios, respectively.



(c)

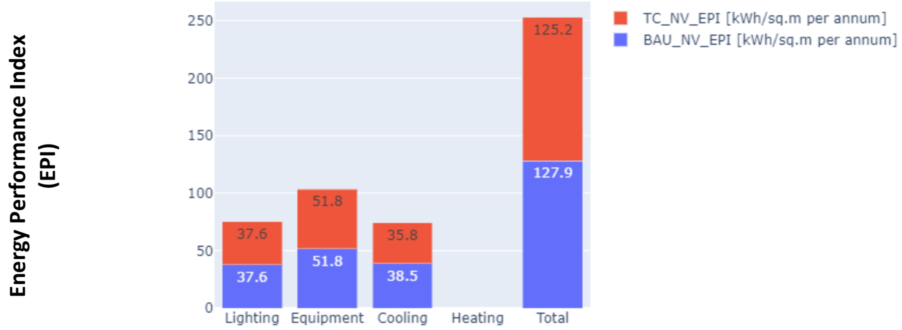


Figure 4. (a) Appliance-wise and total energy use (EPI) difference between BAU and TC case in SS scenario; (b) Appliance-wise and total energy use (EPI) difference between BAU and TC case in AS scenario; (C) Appliance-wise and total energy use (EPI) difference between BAU and TC case in NV scenario.

UHI contribution in each scenario

In the SS scenario, the roof outside surface temperature (ROST) exceeded 50°C in the BAU case when outdoor dry bulb temperature (DBT) crossed 25°C (Figure 5(a)). While in the TC case of SS scenario, the ROST hardly exceeded 50°C even when DBT crossed 25°C. Given that the variation in the set point do not influence the ROST, a similar result could also be observed in AS and NV scenarios (Figure 5(b) and 5(c), respectively).

(a)

(b)

(c)

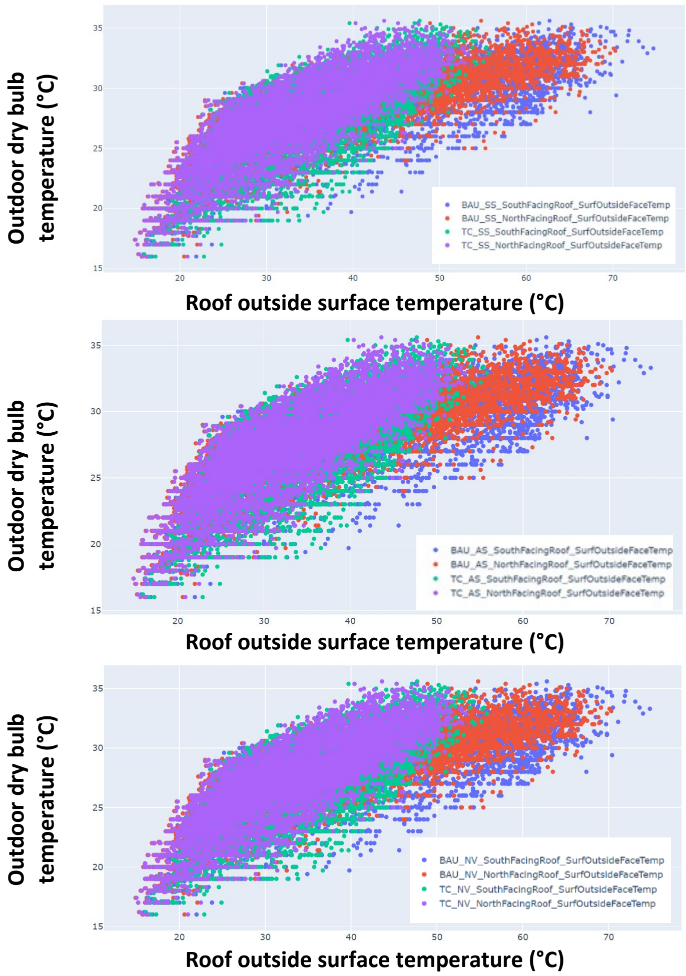


Figure 5. (a) Roof outside surface temperature of BAU and TC case concerning dry bulb temperature in SS scenario; (b) Roof outside surface temperature of BAU and TC case concerning dry bulb temperature in AS scenario; (C) Roof outside surface temperature of BAU and TC case concerning dry bulb temperature in NV scenario.

1.4 CONCLUSION

The world is facing the early impacts of climate change. Building energy use has been recognised as one of the contributors to climate change, at the same time the building sector is recognized to be a vulnerable sector to climate change. Additionally, the urban heat island phenomenon has been recognised as a catalyst for climate change to increase the cooling energy needs in the built environment and promote greenhouse gas emissions with fossil fuel-based energy use. The potential of advanced passive strategies such as thermochromic coatings/materials in reducing the space conditioning needs and contributing to the mitigation of the UHI in the built environment has also been recognised. However, the transient building energy simulation with thermochromic coatings is required to accurately predict the energy savings and the contribution to UHI for a building type located in a certain climatic zone and operated in varied conditions. Thus, the present paper illustrates the used approach by undertaking a representative residential case from the tropical city of Darwin, Australia. The study identifies higher energy savings for the thermochromic case in natural ventilation (NV) setpoint scenario (i.e. 7%), followed by adaptive comfort (AS) (i.e. 6%), and static (SS) (i.e. 5%) scenarios when compared to their respective business-as-usual (BAU) case. The thermochromic coating assumed in this study has shown uniform contribution across all three scenarios in reducing the urban heat island impact by reducing the increment in roof outside surface temperature (ROST) with respect to the BAU scenario. However, this study recognises that the present-day transient building energy simulation tools do not account for the benefits and the penalty of the UHI caused by self and surrounding built environment. An urban building energy and climate simulation study conducted by Huang et al. [39] has also agreed that existing building energy models are limited in accounting for micro-scale variations of the urban microclimate which impacts the building energy use intensity in high-density cities. The simulation tools of today refer static weather data provided by user. The study infers that accurate energy and urban heat island savings could be predicted if the micro-climate assessment models are integrated along with transient building energy simulation tools.

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