Energy Research and Development Division

FINAL PROJECT REPORT

Solar-Reflective “Cool” Walls: Benefits, Technologies, and Implementation

Appendix G: Effect of Wall Albedo on the Environment Inside an Unconditioned Building (Task 3.4 Report)

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Appendix G: Effect of wall albedo on the environment inside an unconditioned building (Task 3.4 report)

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Abstract

Interior air temperature (IAT), mean radiant temperature (MRT) and thermal comfort were analyzed for homogeneous neighborhoods of multi-family residences with cool walls in a coastal California climate zone. The thermal environment for an occupant of a building with neither heating nor air conditioning was simulated. The typical IAT and MRT reduction inside a building with cool walls (albedo of 0.60) versus a conventional wall (albedo of 0.25) is around 0.2 to 0.5 ˚C in most cases. Smaller IAT and MRT reductions occur during the day and larger IAT and MRT reductions occur at night. Since thermal sensation in buildings without air conditioning is generally cold at night and warm during the day this corresponds to a slight worsening of thermal comfort at night and an improvement of thermal comfort during the day. But since homes without cooling are more common than homes without heating, in practice the comfort worsening from cool walls during nighttime would not materialize and cool walls would then only improve the thermal comfort during the day.

1 Introduction and scope

High albedo (“cool”) walls are exterior building walls with surface (usually paint) properties that increase reflection of solar radiation. Albedo is the fraction of incident sunlight reflected, or “solar reflectance”, of a material. Raising a wall’s albedo decreases its solar heat gain, which can reduce heat conducted inward through the wall on a hot day, or increase heat conducted outward on a cold day. Cool wall effects on the outdoor thermal environment of pedestrians were examined in the Task 3.1 report: *Pedestrian mean radiant temperature and thermal comfort*. The current study examines cool wall effects on the indoor thermal environment.

The human temperature sensation is approximated through thermal comfort models. Thermal comfort depends on clothing and activity as well as environmental factors including mean radiant temperature (MRT), air temperature, and humidity. Mean radiant temperature (MRT) is defined as the uniform surface temperature of an imaginary enclosure in which the human body will exchange the same amount of radiant heat energy as in the actual non-uniform enclosure (ASHRAE Standard 55, 2010). For details on MRT see the Task 3.1 report: *Pedestrian mean radiant temperature and thermal comfort*.

In air-conditioned buildings the effect of cool walls on the indoor thermal environment is minimal as the heating, ventilation, and air conditioning (HVAC) plant removes or adds heat as needed to maintain the air temperature within the chosen setpoints. Cool walls primarily affect the indoor thermal environment through the indoor MRT (hereafter, simply "MRT"), which in turn depends on the interior wall temperature. Since wall heat storage dampens the amplitude of the interior wall temperature fluctuations compared to the exterior wall temperature fluctuations, the effect of cool walls on the MRT is small.

In buildings without air conditioning, cool walls are expected to affect the interior thermal environment more significantly. Cool walls reduce the absorption of sunlight which reduces the exterior wall temperature and the heat flux into the building. In the cooling season cool walls are expected to lead to a more comfortable (cooler) interior thermal environment, while in the heating season cool walls are expected to lead to a less comfortable (cooler) interior thermal environment.

The building outdoor and indoor thermal environment are simulated using a building-to-canopy model called TUF-IOBES (Temperature of Urban Facets – Indoor Outdoor Building Energy Simulator). TUF-IOBES simulates heat transfer in a small neighborhood of identical buildings to obtain indoor and outdoor air temperatures; interior and exterior temperatures of walls and ceiling; and radiative, convective, and conductive heat fluxes. To understand thermal impacts of cool walls on building occupants, calculations are performed for a sitting person. Calculations are performed hourly for a typical meteorological year (TMY) for a multi-family residence in CZ8 (Fullerton).

This report is structured as follows. Section 2 contains the methodology for the indoor air temperature, MRT, and thermal comfort calculation. Results are presented in Section 3 separately for MRT, indoor air temperature, and thermal comfort. Section 4 includes a discussion and concludes the report.

2 Indoor thermal environment and thermal comfort calculation

2.1 Urban and building configuration

TUF-IOBES simulates heat transfer for a 5 × 5 array of identical multi-family buildings with dimensions 27.2 by 27.2 m by 7.8 m and inter-building spacing of 31.1 m (Figure 1). Intermediate building floors and internal mass are not considered in TUF-IOBES. That is, the buildings are empty and do not store heat in the interior space. Building occupants are exposed to thermal radiation from the inside surface of exterior walls, roofs, and floor. Thermal comfort parameters are compared between simulations with wall albedo of 0.25 and wall albedo of 0.60.

The lack of internal walls and heat storage affects reductions in MRT and IAT. To simplify the discussion we define $\Delta T_{\mathrm{air}} = T_{\mathrm{air}}^{\mathrm{C25N25}} - T_{\mathrm{air}}^{\mathrm{C60N60}}$ (and a similar argument holds for ΔMRT). Lack of internal heat storage results in smaller reductions in IAT and MRT during the day when raising wall albedo, but larger reductions at night (larger ΔT_{air}). During the day, internal heat storage would result in some of the additional heat conducted through conventional walls to be stored in internal mass, rather than heating the room air, decreasing ΔT_{air}. At night, the additional stored heat in buildings with conventional walls would be convected back to the (now colder) room air, increasing ΔT_{air}. Internal walls also reduce ΔMRT, as some of the view factor from the human towards exterior walls would be replaced by view factor towards the internal wall. Since temperature differences of internal walls between C25N25 and C60N60 are smaller than temperature differences of external walls between C25N25 and C60N60 adding internal walls would reduce ΔMRT.

The lack of internal mass causes the IAT reduction curves to strongly resemble the MRT reduction curves. Since the only mass inside the building is that of the air, IAT will tend to closely follow the average wall temperature.

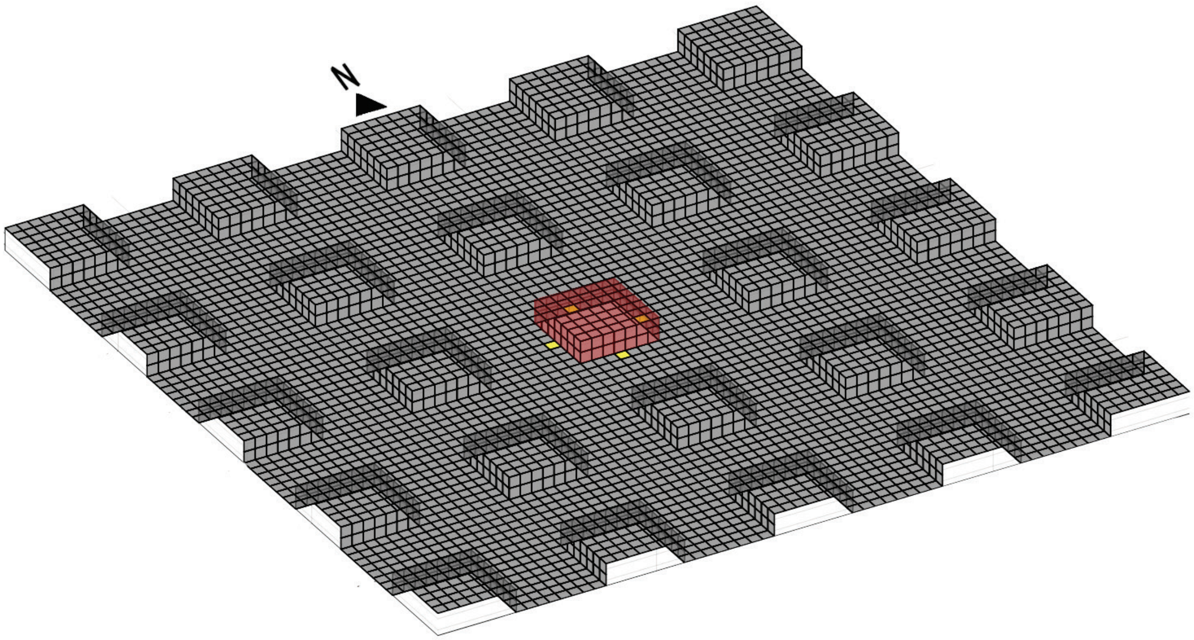

Figure 1. Calculation domain with a 5 × 5 array of multi-family residences. Results in this report refer to the central building unit highlighted in red.

Finally, while the simulations cover a building that is neither heated nor cooled, in practice buildings that are not cooled, but heated are more common. According to the 2015 Residential Energy Consumption Survey (RECS) (EIA 2015), 85% of homes in the Pacific census division (CA, OR, WA, AK, HI) use space heating (RECS Table HC6.8), while only 66% of these homes use space cooling (RECS Table HC7.8).

2.2 Air temperature

The interior air temperature (IAT) is calculated through a heat transfer model that considers heat conduction through the wall, roof, and floor; conduction and solar transmission through windows; interior heat sources, including lighting, equipment, and people; and longwave and shortwave radiative exchange between interior surfaces. The TUF-IOBES model simulates each building as a single room. Details of TUF-IOBES can be found in the Task 2.2 report: *Effect of neighboring cool walls on HVAC loads.*

2.3 Mean radiant temperature

The view factor from a person to a surface is the fraction of radiation leaving the person that strikes the surface. Since empty buildings are simulated, the human was exposed to thermal radiation from the ceiling (immediately below the roof), the insides surfaces of exterior walls, and the floor. Radiation from daylight transmitted through windows and artificial lighting is neglected in the calculation of MRT of the building occupant, but radiation from daylight transmitted through windows and artificial lighting does influence the interior surface temperatures. The ASHRAE handbook prescribes the following equation to determine MRT from plane radiant temperature (PRT) in different directions relative to the sitting person. The equation assumes view factors from the human to the internal building surfaces that are typical and do not necessarily correspond to the simulated building dimensions.

$$\mathrm{MRT} = \frac{0.18\left(\mathrm{PRT}^{\mathrm{up}} + \mathrm{PRT}^{\mathrm{down}}\right) + 0.22\left(\mathrm{PRT}^{\mathrm{right}} + \mathrm{PRT}^{\mathrm{left}}\right) + 0.30\left(\mathrm{PRT}^{\mathrm{front}} + \mathrm{PRT}^{\mathrm{back}}\right)}{2(0.18 + 0.22 + 0.30)}$$

2.4 Thermal comfort

The ASHRAE comfort model based on Fanger's theory (Fanger, 1970) is used to compute thermal comfort considering IAT, humidity, metabolic activity, and clothing. Human comfort models attempt to emulate the typical human perception of environmental conditions through thermal comfort indices. Thermal comfort is expressed as "Predicted Mean Vote" (PMV) and "Percentage of People Dissatisfied" (PPD). PMV can take on values of -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), and 3 (hot). PPD ranges from 0% to 100%.

An example of the "neutral" comfort zone is given in Figure 2. To interpret this figure, note that

- 1 Clo (0.155 $m^2 \cdot K/W$) is the thermal resistance of clothing (e.g., a business suit) needed to maintain a person in comfort sitting at rest in a room at 21°C (70 °F) with humidity less than 50%;
- 1 met (58.2 W of heat per m^2 of body surface area) is the heat generation by an average person seated at rest;
- operative temperature is a measure of human thermal comfort; and
- since air speed in buildings is small, operative temperature can be assumed to equal the average of indoor air temperature and indoor mean radiant temperature (ASHRAE 2009).

We assume that the person generates 1 met year-round; wears trousers and a T-shirt in summer, providing 0.57 Clo = 0.088 $m^2 \cdot K/W$; and wears trousers and a long-sleeve shirt the rest of the year, providing 0.61 Clo = 0.095 $m^2 \cdot K/W$.

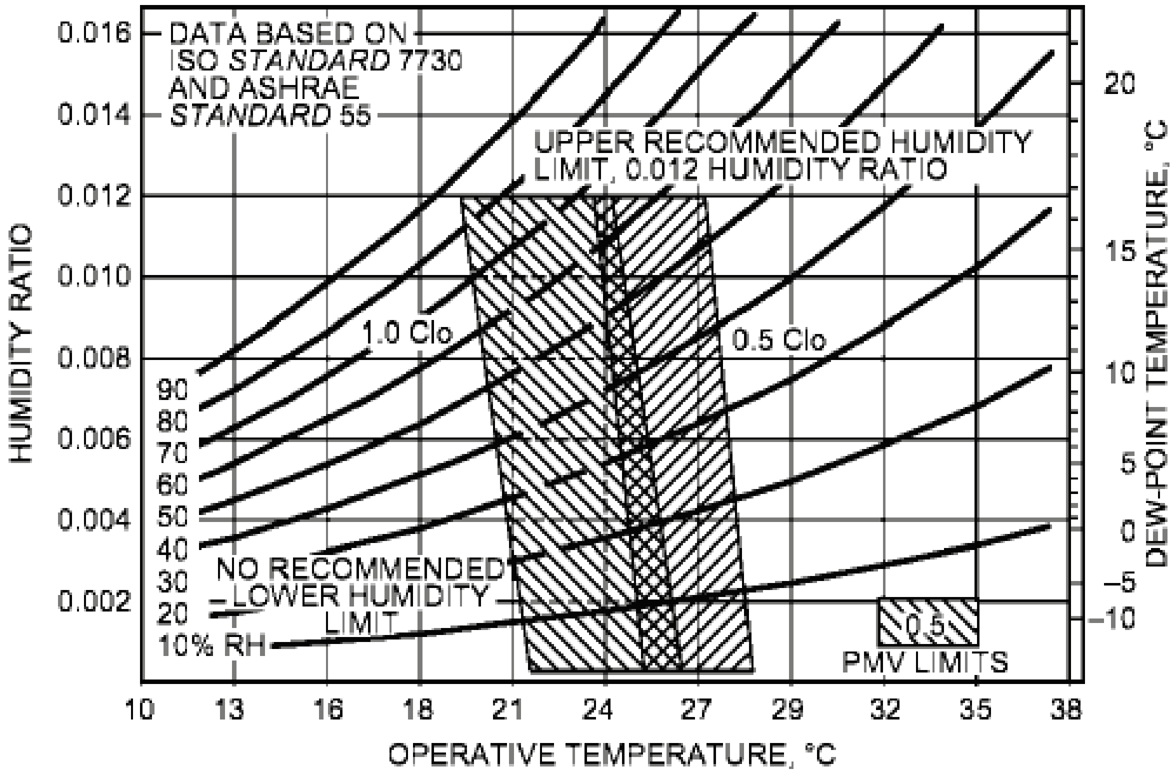

Figure 2. ASHRAE Comfort Zones: Acceptable ranges of operative temperature and humidity with air speed less than 0.2 m/s for people wearing 1.0 and 0.5 Clo clothing during primarily sedentary activity (< 1.1 met metabolic rate). Source: ASHRAE (2009).

3 Results

3.1 Interior Air Temperature (IAT)

IAT for wall albedos of 0.25 and 0.60 are compared for the multi-family residence in Fullerton, CA (California building climate zone [BCZ] 8) for the year (Figure 3) and by season (Figure 4). IATs peak around 15:00 – 16:00 local standard time (LST). The reduction in IAT with cool walls is between 0.2 °C midday and 0.5 °C at night. IATs follow the expected seasonal cycle. The reduction in IAT with cool walls is consistent across the seasons. While four-wall average solar irradiation in summer is 35% larger than in winter, the increase in four-wall solar irradiation transmitted through windows when changing wall albedo to 0.60 from 0.25 is only 0.04 kWh m^{-2} day^{-1} in summer and 0.03 kWh m^{-2} day^{-1} in winter. Cool walls raise window transmitted solar radiation only by 4% compared to conventional walls. The small effect of wall albedo on transmitted solar radiation is due to small wall-to-wall view factors.

Compared to a conventional wall, during daytime cool walls absorb a smaller fraction of incident solar radiation. This lowers the temperature of the wall's outer surface, reducing heat flux through the wall and the air temperature in the occupied space. The daytime decrease in heat storage in cool walls causes lower wall temperatures and IAT to persist through the night.

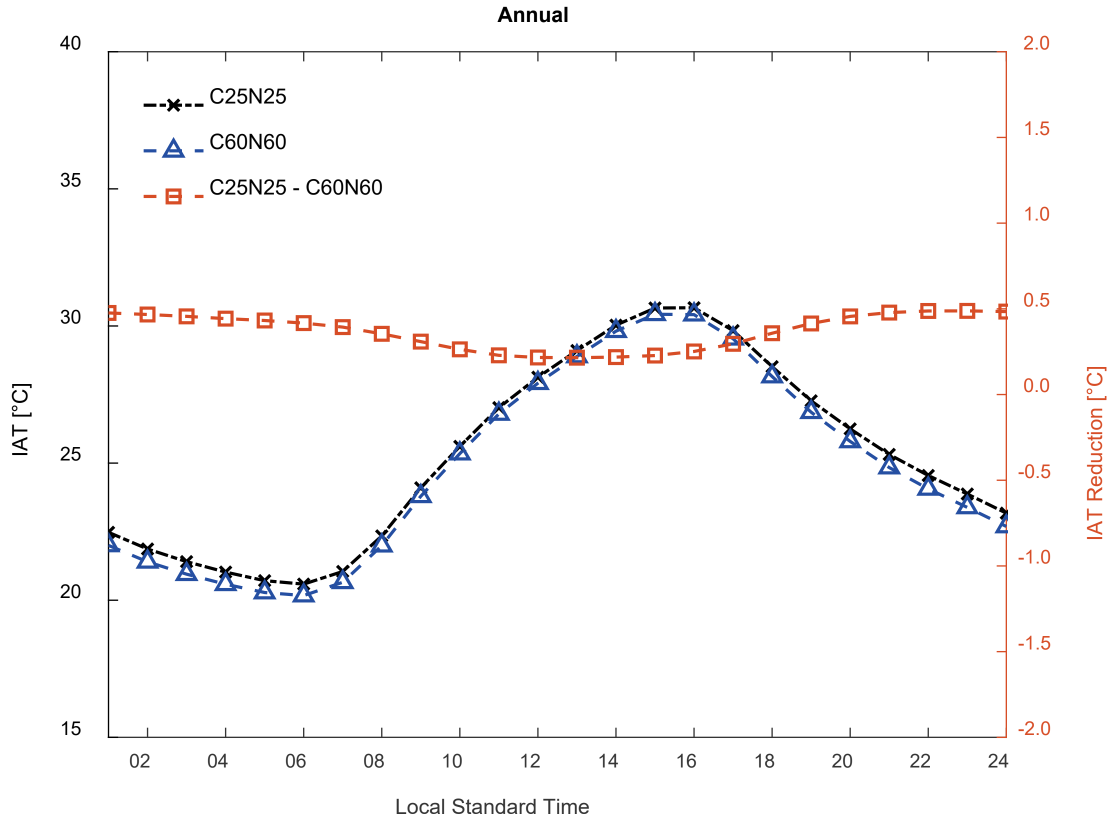

Figure 3. Average (over the year) daily cycle of interior air temperatures (IATs) for the multi-family residence in Fullerton (BCZ 8) with wall albedos equal to 0.25 (conventional wall, denoted as C25N25) and 0.60 (cool wall, denoted as C60N60). The right axis shows the IAT reduction due to cool walls.

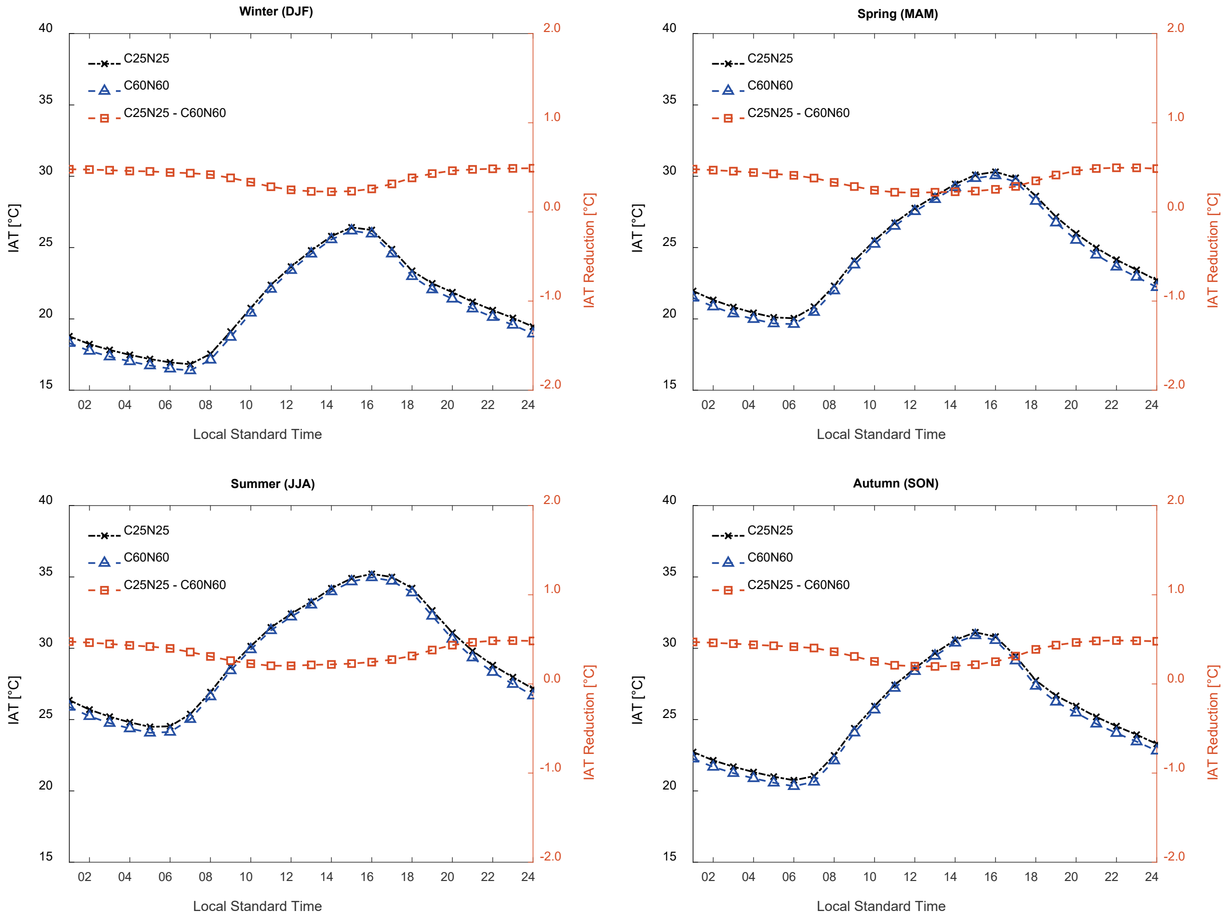

Figure 4. Seasonal analogs of Figure 3 (winter = Dec/Jan/Feb, spring = Mar/Apr/May, summer = Jun/Jul/Aug, and autumn = Sep/Oct/Nov).

3.2 Mean Radiant Temperature (MRT)

Figure 5 shows the annual average interior MRT and average rise in MRT upon switching to a cool wall (albedo 0.60) from a conventional wall (albedo 0.25). Seasonal results are presented in Figure 6. Increasing wall albedo reduces daytime MRT for the same reasons as wall albedo reduced IAT.

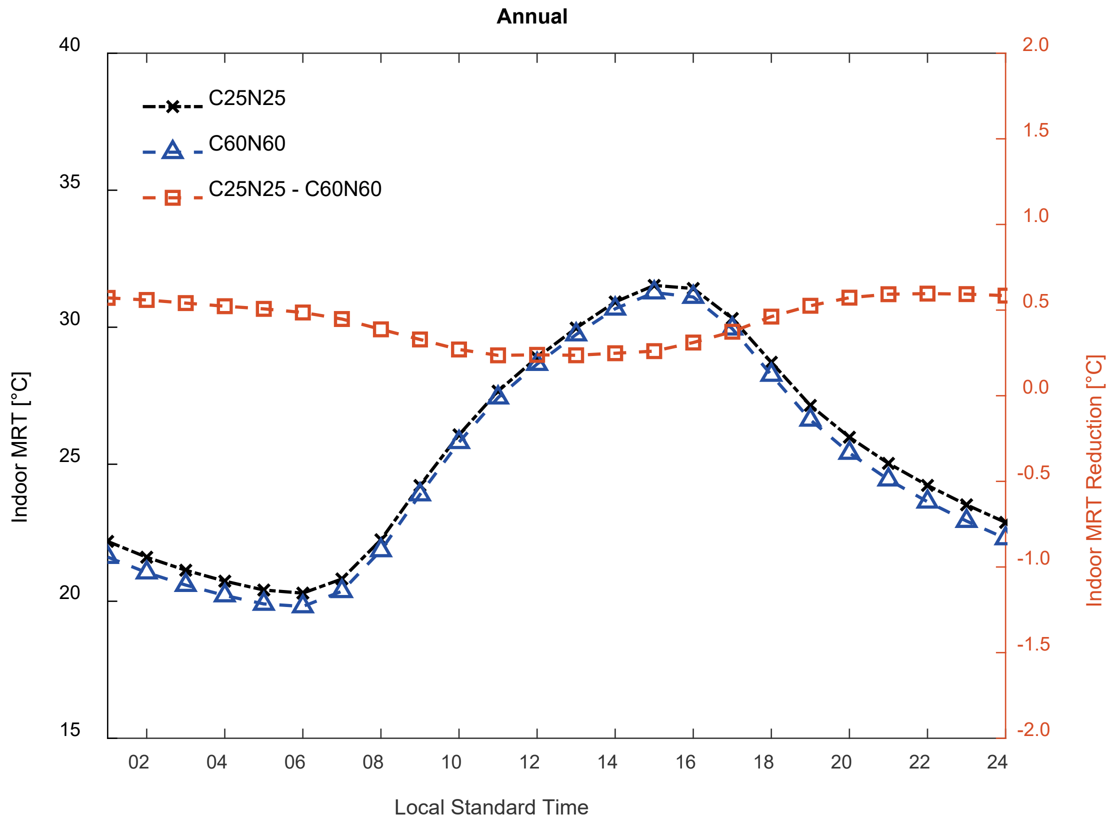

Figure 5. Average (over the year) daily cycle of mean radiant temperatures (MRTs) for the multi-family residence in Fullerton, CA (BCZ 8) with wall albedos equal to 0.25 (conventional wall denoted as C25N25) and 0.60 (cool wall denoted as C60N60). The right axis shows the MRT reduction due to raising wall albedo.

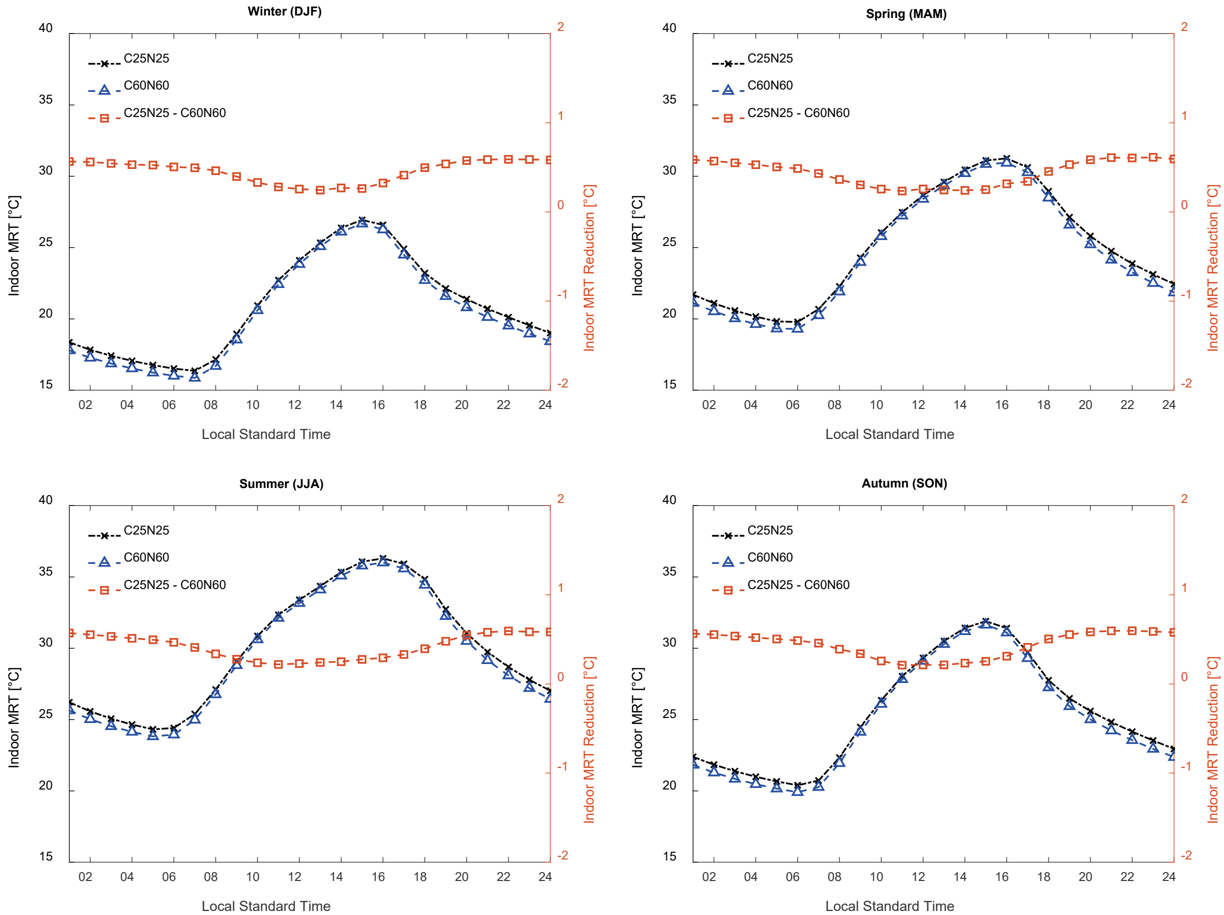

Figure 6. Seasonal analogs of (winter = Dec/Jan/Feb, spring = Mar/Apr/May, summer = Jun/Jul/Aug, and autumn = Sep/Oct/Nov).

3.3 Thermal comfort

The thermal comfort trends during the day follow the MRT and IAT trends. Since daylight and artificial light are neglected in the thermal comfort calculation, the exposition focuses on changes in thermal comfort when raising wall albedo. Figure 7 shows PMV averaged over the year. On average, the building occupant tends to be slightly cool to cool during the night and slightly warm to warm during the day. The diurnal comfort trends are expected to remain valid if daylight and artificial light were considered, because (a) daylight would further warm the occupant in daytime and (b) at night, artificial lighting impacts would be small and not reverse the cool sensation. Increasing wall albedo reduces PMV by 0.07 during midday and up to 0.17 at night. Figure 8 shows the results by season which exhibit similar trends as those for the year.

Figure 9 shows PPD averaged over the year. Figure 10 shows the results by season which exhibit similar trends as those for the entire year.

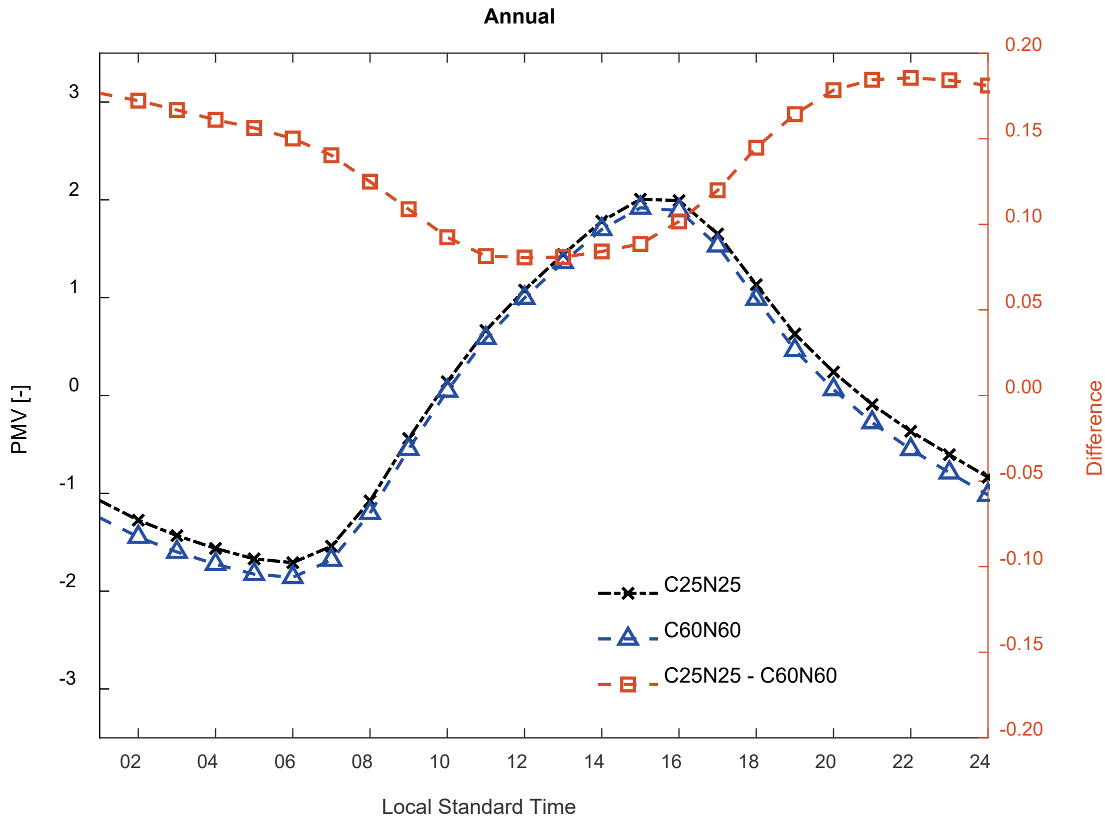

Figure 7. Average (over the year) daily cycle of predicted mean vote (PMV) for the multi-family residence in Fullerton, CA (BCZ8) with wall albedos equal to 0.25 (conventional wall denoted as C25N25) and 0.60 (cool wall denoted as C60N60). The right axis shows the PMV reduction due to raising wall albedo.

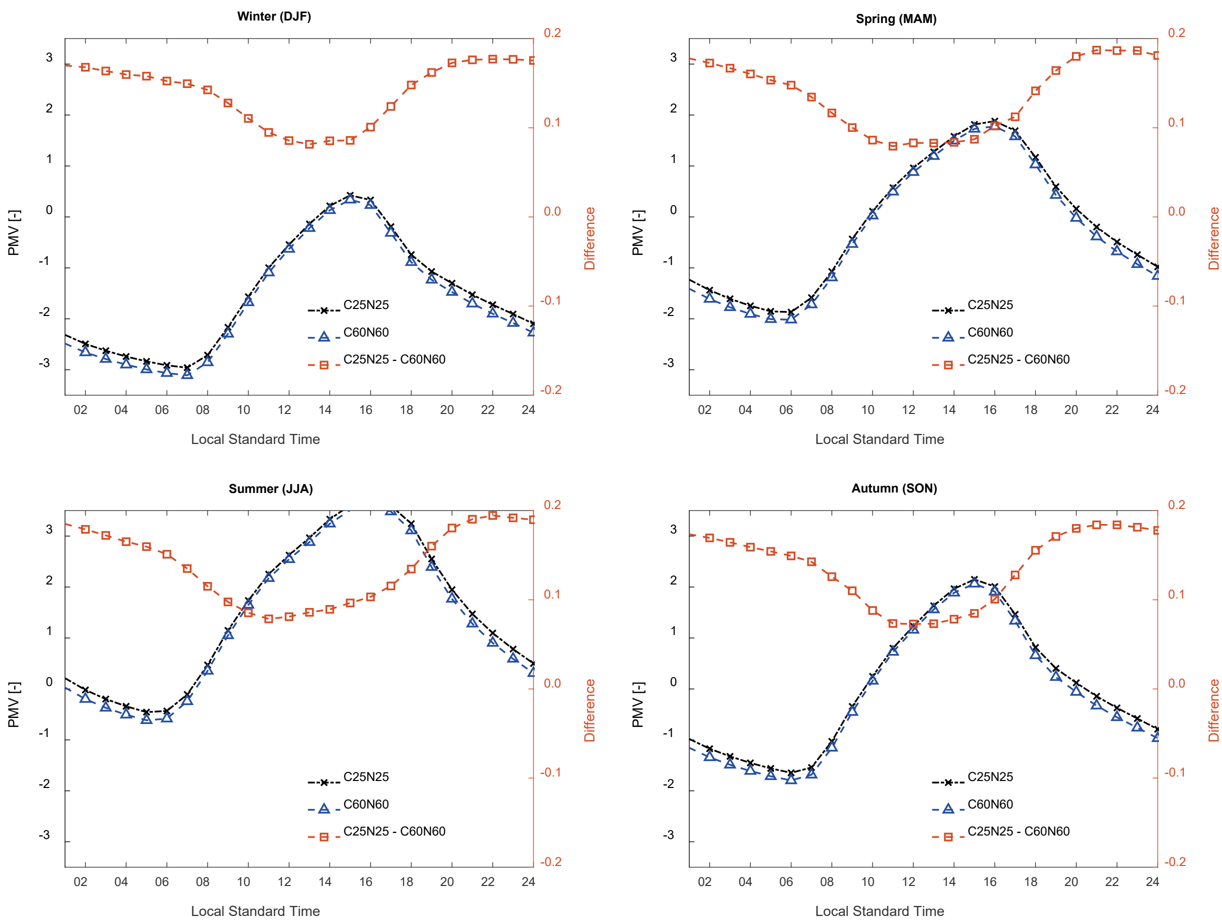

Figure 8. Seasonal analogs of Figure 7 (winter = Dec/Jan/Feb, spring = Mar/Apr/May, summer = Jun/Jul/Aug, and autumn = Sep/Oct/Nov).

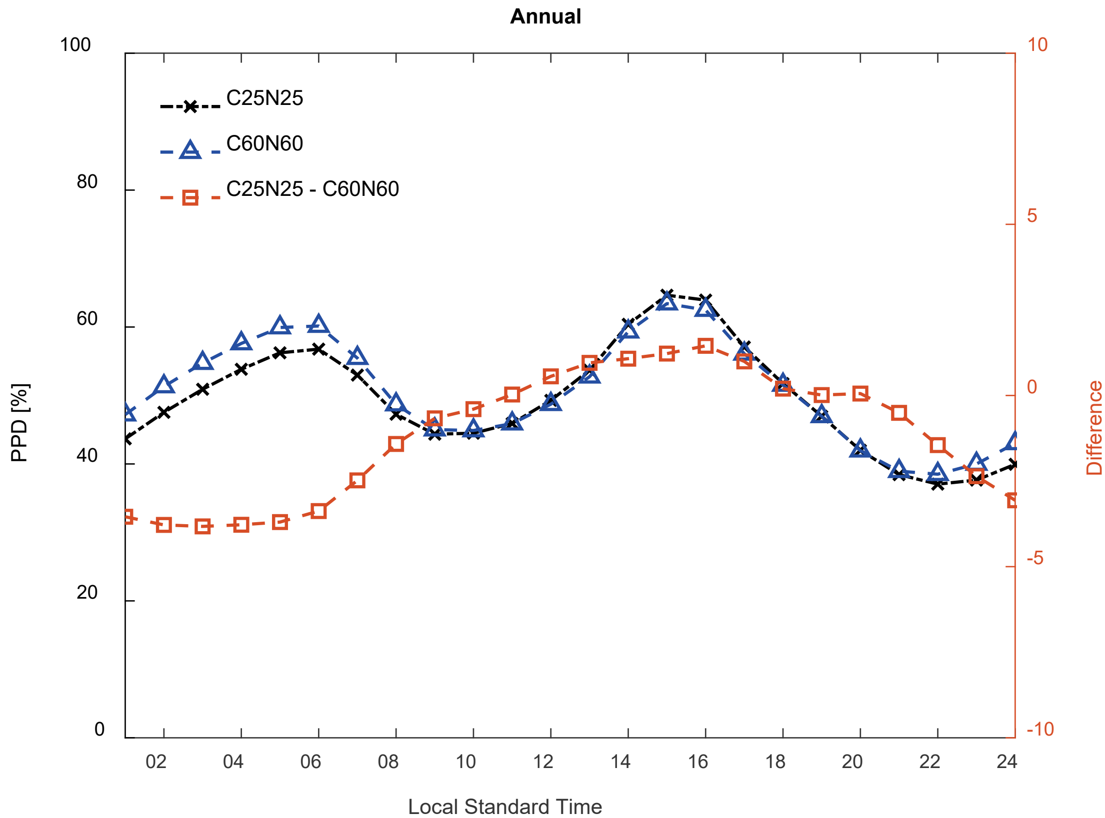

Figure 9. Average (over the year) daily cycle of percentage of persons dissatisfied (PPD) for the multi-family residence in Fullerton (CZ8) with wall albedos equal to 0.25 (conventional wall denoted as C25N25) and 0.60 (cool wall denoted as C60N60). The right axis shows the PPD reduction due to raising wall albedo.

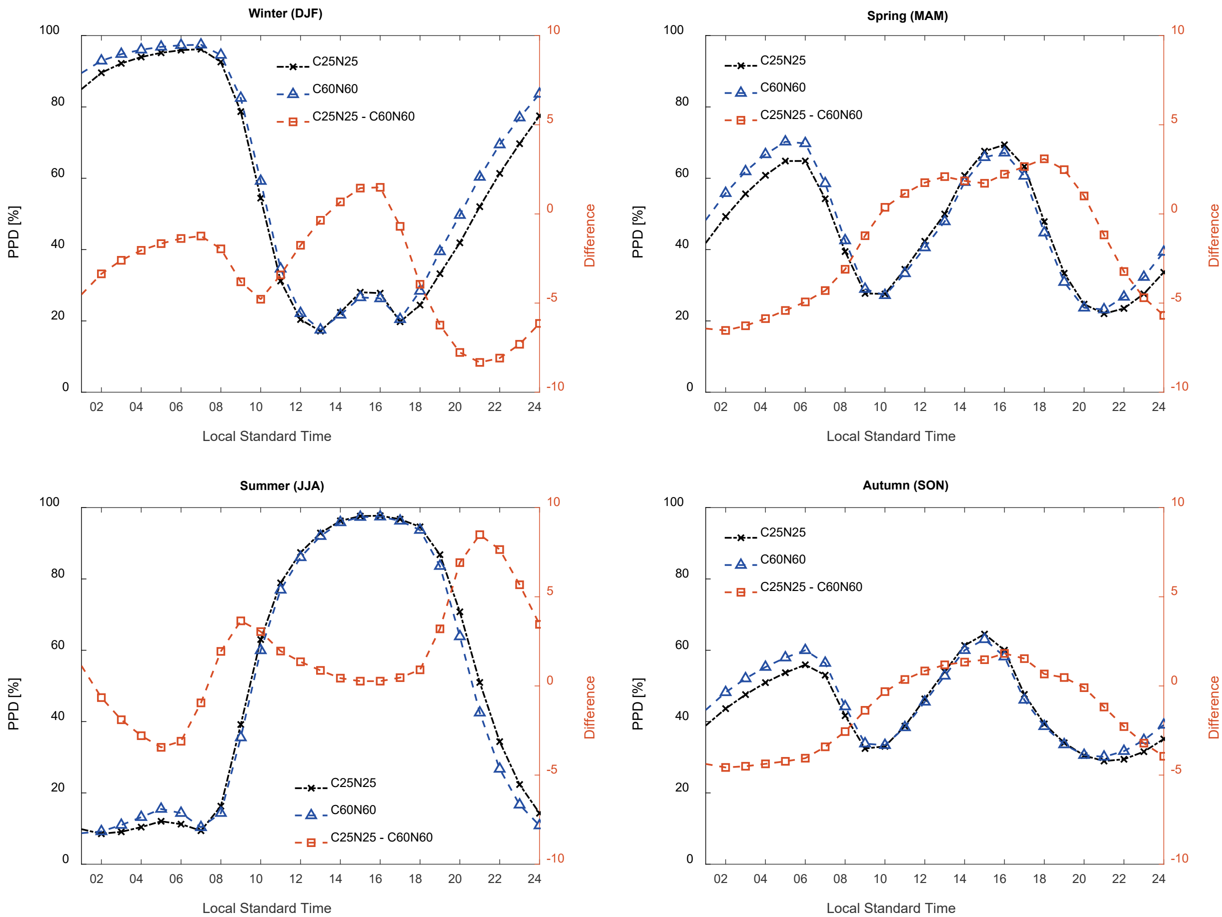

Figure 10. Seasonal analogs of Figure 9 (winter = Dec/Jan/Feb, spring = Mar/Apr/May, summer = Jun/Jul/Aug, and autumn = Sep/Oct/Nov).

4 Discussion and conclusions

Interior air temperature (IAT), mean radiant temperature (MRT) and thermal comfort were analyzed for homogeneous neighborhoods of multi-family residences with cool walls. Typical meteorological year weather data is input to a neighborhood heat transfer model (TUF-IOBES) in a coastal California climate zone to understand impacts on an occupant of a building with neither heating nor air conditioning. The typical IAT and MRT reduction inside a building with cool walls (albedo of 0.60) versus a conventional wall (albedo of 0.25) is around 0.2 to 0.5 ˚C in most cases. Smaller IAT and MRT reductions occur during the day and larger IAT and MRT reductions occur at night. The lack of internal building heat storage enhances this diurnal trend by causing smaller reductions in IAT and MRT during the day, but larger reductions at night.

Since thermal sensation in buildings without air conditioning is generally slightly cold to cold at night and slightly warm to warm during the day this corresponds to a slight worsening of thermal comfort at night and an improvement of thermal comfort during the day. But since homes without cooling are more common than homes without heating, in practice the PPD increase from cool walls during nighttime would not materialize and cool walls would then only decrease the PPD during the day.

The variable hourly trends in the PPD reduction curves in Figure 9 are a result of the fact that PPD increases for both a too-hot and a too-cold thermal environment. Raising albedo results in a cooler building day and night. During the night, the thermal sensation of an occupant is predominantly cold. Therefore, raising wall albedo increases PPD at night. During the afternoon, the occupant thermal sensation is predominantly warm. Raising wall albedo then decreases PPD. For the rest of the day (morning and evening) too warm or too cold sensations are about equally present. Raising wall albedo increases PPD on cool days while decreasing PPD on warm days, but averaged over the year the PPD remains the same.

References

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