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Revisiting radiant cooling systems from a resiliency perspective: A preliminary study

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Abstract. Radiant heating and cooling systems have been proven to be an energy-efficient and resource-effective heating and cooling solution for buildings. One of the key features of radiant systems is the possibility of activating and controlling the thermal mass. This feature allows spreading the heat removal from indoor spaces over a longer period, compared to more conventional systems e.g., air-conditioning. This feature of radiant systems could be particularly beneficial under heat wave and power outage events. The present study investigated the performance of Thermally Active Building Systems (TABS) and Packaged Terminal Air Conditioners (PTAC) in terms of controlling indoor temperatures under future typical weather files, and under future heat wave and power outage events. The simulations were carried out for Copenhagen, Denmark. For future typical meteorological years, TABS performed better with heavyweight construction, but PTAC had little influence from the construction type. During heat waves, both systems were able to maintain a generally comfortable temperature range but with a slightly overall higher temperature. When a heat wave and power outage occurred at the same time, the cases with heavyweight construction had lower temperatures regardless of the cooling system. With TABS and heavyweight construction, the room temperature was maintained within the comfort range of 26°C for 16 hours after the heat wave and power outage started. After the power outage was over, TABS with heavyweight construction was able to reduce the room temperature to the comfort condition of 26°C faster than PTAC by 18 – 71 hours. Results obtained from this initial set of simulations suggest TABS could be a better solution than PTAC in terms of its resiliency to heat waves and power outages although both systems could have different advantages depending on the operation, building type and building use.

Keywords. Heat wave, power outage, resiliency, Thermally Active Building System (TABS), Packaged Terminal Air Conditioner (PTAC).
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1. Introduction

There are several passive and active cooling systems that are widely used in buildings. The cooling performance (in this context, keeping indoor temperatures within desired or required comfort limits) of these systems vary depending on several factors such as physical principles, operation, control and geography.

One of the critical selection criteria for these cooling systems is their resiliency i.e., resiliency against heat waves and power outages. International Energy Agency (IEA), Energy in Buildings and Communities Programme (EBC) Annex 80 – Resilient Cooling of Buildings [1] is working on defining resiliency and its key concepts in terms of building cooling [2] [3], developing qualitative and quantitative key performance indicators [4], and evaluating different cooling systems based on these indicators. One of the critical tasks of the Annex is to develop future typical meteorological year weather files and future heat wave weather files [5].

Radiant cooling systems have been proven to be an energy-efficient and resource-effective cooling solution for buildings [6]. One of the key features of radiant systems is the possibility of activating and controlling the behavior of the thermal mass. This feature allows spreading the heat removal from indoor spaces over a longer period, compared to more conventional systems e.g., air-conditioning. This feature of radiant systems is particularly important under heat wave and power outage events.

Table 1 – Physical properties of building materials. [8]

Construction	Material	Thickness [mm]	Density [kg/m³]	Conductivity [W/(m·K)]	Thermal Capacity [Wh/(kg·K)]	Emissivity [-]
Floor/ceiling	Screed	45	2000	1.4	0.28	0.94
	Acoustical insulation	20	50	0.04	0.42	
	Concrete	180	2400	2.1	0.28	
Outside wall (light)	Aluminium	2	2600	200	0.28	0.3
	Insulation	100	30	0.04	0.28	
	Aluminium	2	2600	200	0.28	
Outside wall (heavy)	Plaster	8	1000	0.7	0.28	0.82
	Insulation	80	40	0.04	0.42	
	Sand lime brick	240	1200	0.56	0.28	
	Plaster	15	1200	0.35	0.28	
Internal wall (light)	Plasterboard	25	900	0.21	0.28	0.82
	Insulation	60	20	0.04	0.28	
	Plasterboard	25	900	0.21	0.28	
Internal wall (heavy)	Plaster	15	1200	0.35	0.28	0.82
	Sand lime brick	115	1800	0.99	0.28	0.93
Window	Wooden frame, 30% Glass	Frame thermal transmittance: 2.1 W/(m²·K) Glass thermal transmittance: 1.1 W/(m²·K) Window thermal transmittance: 1.4 W/(m²·K) g-value: 0.58				

Radiant cooling systems and air-conditioning systems are commonly used in buildings and they are also a part of the studied cooling systems in IEA EBC Annex 80. Therefore, the present study compared the performance of Thermally Active Building Systems (TABS) and Packaged Terminal Air Conditioners (PTAC) in terms of controlling indoor temperatures under future typical weather files, and under future heat wave and power outage events.

2. Methodology

2.1 Building Model

Simulations were conducted with TRNSYS version 18 [7]. The model was based on the simulation model used by Olesen and Dossi [8] and Kolarik et al. [9] The model consists of east and west facing office rooms (floor area of 19.8 m^2 each) with a corridor (floor area of 8.6 m^2) in between them. The east and west walls were external walls, and all other surfaces were adjacent to another zone with the same temperature. Both heavyweight and lightweight constructions were modelled. Fig. 1 shows the section view of the building model and the physical properties of the building materials are listed in Table 1.

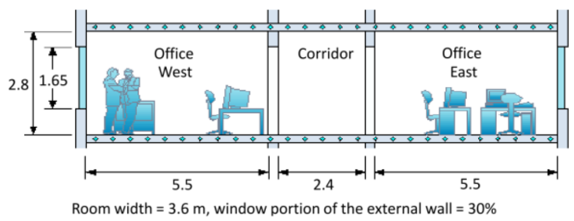

Fig. 1 – Section view of building model (units: m) [10].

Each room was assumed to be a two-person office, and the room was occupied on weekdays from 8:00 to 17:00 with a lunch break between 12:00 and 13:00. The sensible load during occupancy was 550 W (27.8 W/m^2), corresponding to two occupants, two computers, a printer and lights. The sensible load during the lunch break was reduced to 350 W (17.7 W/m^2). Moisture production of 0.1 kg/h was given during occupancy. The infiltration was set to 0.3 h^{-1}. A shading factor of 0.5 was given to the windows when there was direct solar radiation during occupancy.

The corridor had a constant air volume (CAV) system supplying air with an air change rate of 0.5 h^{-1} at a constant temperature of 19 °C. The CAV was operating on weekdays from 6:00 to 18:00. The infiltration was set to 0.3 h^{-1}.

2.2 Cooling systems

Two types of systems were modelled for comparison: a thermally activated building system (TABS) and a packaged terminal air conditioner (PTAC). All the values and settings presented in this section were taken from [8] and [9], unless otherwise stated.

The TABS piping was embedded in the center of the concrete slab, i.e., 90 mm from both sides of the slab. The pipes had an outside diameter of 20 mm, and a spacing of 150 mm. The supply water pump to the TABS was operating for 24 hours every day. The pump flow rate was fixed at 350 kg/h with an on/off control with a deadband of 23 – 24 °C. The deadband was increased by 1 K to prevent overcooling. The supply water temperature was modulated based on the outdoor temperature with equation (1) [8]. An air-cooled chiller was selected as the cooling source for the chilled water. A simulation with ideal supply water conditions calculated by equation (1) was conducted to obtain the maximum system load, and the chiller was sized with a capacity 15% higher than the maximum load as a buffer.

$$T_{water\ supply} = 0.35 \cdot (18 - T_{outdoor}) + 18 \qquad (1)$$

Where:

$T_{outdoor}$: Outdoor air temperature (°C)

An air-to-air heat recovery unit with a constant flow of 2 L/(s·m^2) to each office zone was used for ventilation for the TABS cases. This ventilation rate is based on two-people in the office rooms of a non low-polluting building [11]. The ventilation system was turned on between 7:00 and 18:00 on weekdays. The sensible and latent efficiency of the heat recovery unit was set to 0.85.

For the PTAC cases, the default component provided by TRNSYS was used [12]. The outdoor air was fixed to 2 L/(s·m^2) per zone and was mixed with recirculated air, supplying a total of 7.2 L/(s·m^2) to each zone. The supply air flow rate was calculated internally within the component based on ASHRAE Standard 90.1 [13]. The deadband for the supply air temperature control was set to 24.5 ± 1.5 °C, corresponding to Category II of EN 16798-1 [11]. A simulation with ideal cooling was conducted to obtain the maximum room cooling load, and the PTAC was sized with a capacity 15% higher than the maximum load as a buffer.

2.3 Weather files and simulation cases

Weather files created by the IEA EBC Annex 80 Weather data task force were used for the simulations. The weather data is based on the European Coordinated Regional Downscaling Experiment (EURO-CORDEX) [14]. The methodology for creating the weather data is reported by Machard et al. [15]. Weather files were created in EPW format for each representative climatic zone and city.

Weather files were generated for three periods i.e., contemporary (2001 – 2020), medium-term future (2041 – 2060), and long-term future (2081 – 2100). For each period, a typical meteorological year (TMY) file was created. In addition, heat wave year (HWY) files were created for each period. Multiple heat waves with different characteristics were created. The heat waves were characterized by its intensity (maximum temperature), duration (length of heat wave), and severity (combined evaluation of temperature and duration, i.e., degree days).

Table 2 lists the simulated weather files. The weather file for Copenhagen, Denmark was used for the analysis. The selection of the cases follow the simulation guideline developed by IEA EBC Annex 80 [16]. Typical meteorological years for three different periods were used. For the heat wave years, the most severe heat wave years for the contemporary, medium-term future, and long-term future were each selected. All simulations were conducted between 1. May and 30. September with a simulation time step of 15 min. Load calculations for sizing the TABS and PTAC were conducted with the typical meteorological year 2001 – 2020.

For the heat wave cases, simulations were conducted both with and without a power outage. According to the simulation guideline developed in the Annex, simulations are to be conducted with power outage throughout the entire duration of the heat wave (worst case scenario) [16]. During the power outage, TABS (and the ventilation system) and PTAC were both turned off. The internal heat gain during the heat wave was limited to equipment load (i.e., 12 W/m^2).

Table 2 – Simulated weather files.

Type	Year / Category	Power outage
TMY: Typical Meteorological Year	2001 – 2020	No
	2041 – 2060	No
	2081 – 2100	No
HWY: Heat wave year, Most severe	Contemporary	Both with and without power outage
	Medium-term future	
	Long-term future	

3. Results and Discussion

3.1 Indoor temperatures without power outage

Fig. 2 shows the distribution of operative temperature in the west office during occupied hours. The west office was selected as higher temperatures were observed and therefore was more critical than the east office. The cases without power outage was selected. For TMY files, the results were evaluated from 1. June, and for HWY files, results were evaluated from 1 week before to 1 month after the heat wave. The temperature range shaded in green represents the default indoor operative temperature values for office spaces according to Category II of EN 16798-1 [11] in the cooling season.

The simulation result of the typical meteorological year cases show that both TABS and PTAC can maintain the indoor operative temperature within a comfortable range in most cases. TABS had a tendency of a larger range of room operative temperature in lightweight construction. For TABS, a lightweight construction results in less precooling during unoccupied hours, which causes more room

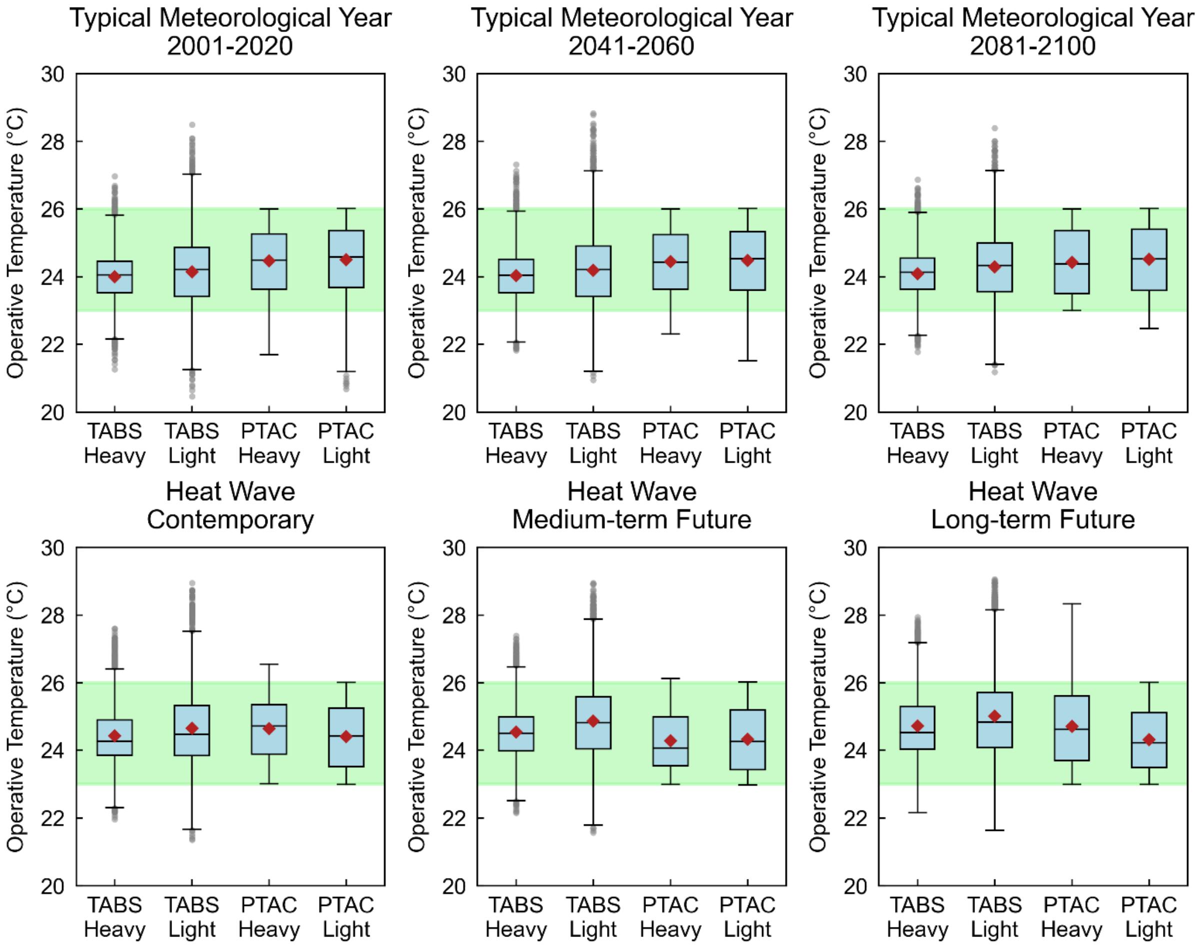

Fig. 2 – Distribution of operative temperature in the west office during occupied hours.

temperature fluctuation during occupied hours. For both systems and building types, the time period of the TMY files had minimal effects on the simulation outcome.

It can be seen that under the heat wave conditions, overall room temperatures increased, which was an expected result. The differences in the room temperatures due to the different heat removal mechanisms of the two systems can be seen by comparing the TABS Heavy and the PTAC Heavy cases. In the long-term future weather case, higher room temperatures compared to other cases are observed for the PTAC Heavy cases. The PTAC system is struggling to remove the heat from the room as there is also heat accumulated in the building thermal mass. TABS on the other hand is cooling the building structure (i.e., thermal mass) and also cooling the room through cooled surfaces and it is more effective in keeping the room temperatures within the desired range.

Overall, PTAC with lightweight building construction had the most of the occupied hours within a comfortable range. TABS with heavyweight construction was also able to have most of the hours within the same range, but temperatures were occasionally outside of those ranges. However, it must be noted that the most common operating principle of TABS allows the fluctuation of the indoor temperature and does not aim to control at a fixed temperature throughout the day.

3.2 Indoor conditions with power outage

Fig. 3 shows the operative temperature of the west office under contemporary heat wave conditions with power outage. The red line indicates the 26 °C comfort limit [16].

During the heat wave and power outage, the cases with heavyweight construction maintained a temperature generally lower than the lightweight construction cases; however, this difference between the heavyweight and lightweight cases became smaller as the heat wave continued. TABS with heavyweight construction had the lowest room temperatures, and was able to maintain a room temperature below 26 °C for the longest time after the heat wave and power outage. At the final day of the heat wave (20 days), the temperature of the TABS and PTAC heavyweight cases had similar temperatures. After the heat wave and power outage, the four scenarios showed a different trend in their temperature recovery. TABS with lightweight construction was the fastest to reach 26 °C, and PTAC with heavyweight construction was the slowest.

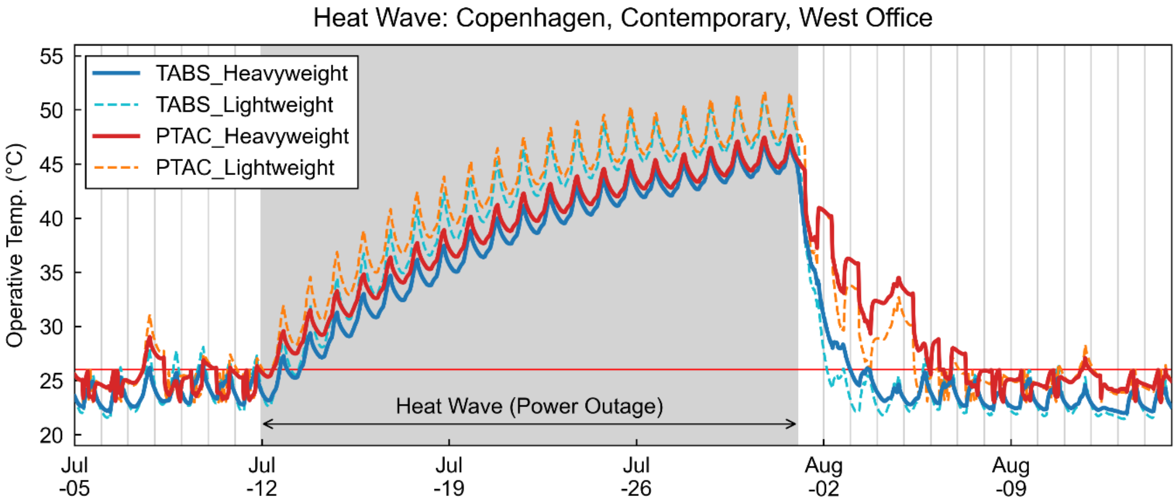

Fig. 3 – Operative temperature of west office under contemporary heat wave conditions with power outage.

Figs. 4 and 5 show a closer look at the operative temperature of the west office for 3 and 7 days from the beginning of the heat wave and power outage. Horizontal lines were drawn at 26, 27, 28 °C as a reference for different comfort limits. TABS with heavyweight construction was able to maintain a temperature below 26 °C for 16 hours after power outage, and for 40 hours when the comfort limit was set to 28 °C. PTAC with heavyweight construction was able to maintain a temperature below 26 °C for 10 hours, but the temperature increased to nearly 30 °C in the evening.

The difference in the daily peak temperature between the heavyweight and lightweight cases increased gradually to about 5 K for both TABS and PTAC. On the first day of the heat wave and power outage, TABS heavyweight case had a peak temperature 1.9 K lower than the lightweight case, and the difference increased to 4.8 K on the seventh day. For PTAC, the corresponding temperature differences were 2.4 K and 4.9 K, respectively. When comparing the same heavyweight construction cases, TABS had a peak temperature lower than PTAC by 2.3 K on the first day, and the difference decreased to 1.4 K on the seventh day. In the comparison of lightweight cases, the corresponding peak temperature differences were 2.8 K and 1.5 K, respectively. As the systems were not operating during the power outage, the difference by the cooling systems became smaller each day.

Figs. 6 and 7 show a closer look at the operative temperature of the west office for 3 and 7 days after the end of the heat wave and power outage. For TABS, the lightweight construction was able to lower the room temperature to 26 °C after 27 hours and after 48 hours for the heavyweight construction. For PTAC, the room temperature reached 26 °C in 66 hours for the lightweight construction and 119 hours for the heavyweight construction. Table 3 summarizes the hours each system maintained below a certain baseline temperature and the hours it took to recover to the baseline after the heat wave.

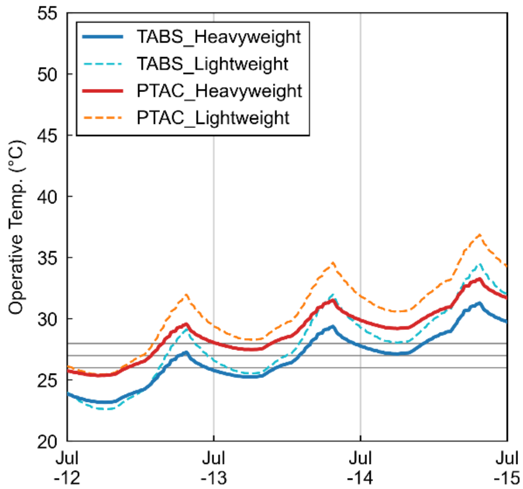

Fig. 4 – Operative temperature of west office for the first 3 days of the heat wave (contemporary, with power outage).

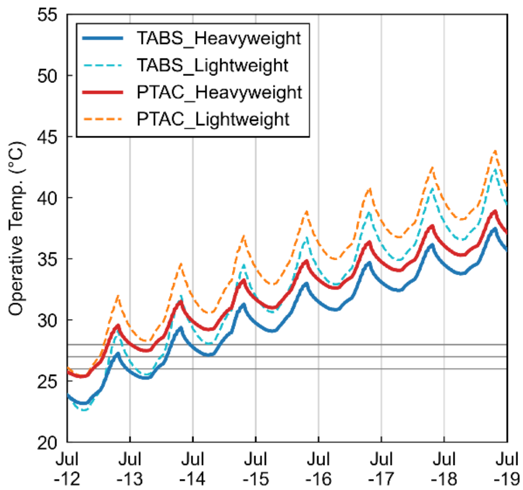

Fig. 4 – Operative temperature of west office for the first 7 days of the heat wave (contemporary, with power outage).

Table 3 – Hours below baseline (at the beginning of heat wave) and hours until baseline (after heat wave).

Baseline (°C)	TABS Heavy	TABS Light	PTAC Heavy	PTAC Light
Hours maintained below baseline temperature				
26	16	15	10	0
27	19	16	14	12
28	40	18	16	14
Hours until baseline temperature is reached				
26	48	27	119	66
27	45	25	117	61
28	38	24	108	59

4. Overall Discussion

In this study, a series of simulations were conducted for a simple comparison of TABS with consistent operation and PTAC with intermittent operation. The systems simulated in this study were sized with the typical meteorological year file of 2001 – 2020, but did not result in a substantial difference in the operative temperature of the cases with future weather files. This suggests that sizing a system based on future weather files may not provide a clear advantage, though it should be noted that the capacity of the cooling plants was 15% higher than the maximum load as a buffer. It should also be noted that in reality the sizing of the chiller for a TABS and for a PTAC system would be different.

Though the present results suggest that TABS with heavyweight construction is a better solution than PTAC under heat wave and power outage conditions, further studies should be performed, especially for the control strategies and the heat source. Different control strategies of TABS (e.g., varying the supply water temperature or operation during night time only) and PTAC (e.g., precooling) would likely result in a different outcome. As this was a preliminary study, relatively simple control strategies were used for both systems. Future studies will investigate optimized control strategies.

Both of the studied systems intend to condition the entire indoor space. The combination of these ambient control systems with a personalized environmental conditioning system (PECS) to offset the comfort conditions could also be an alternative solution and could help occupants get back to the buildings sooner

In the studied boundary conditions, the selection of the heat source is likely to have a large impact to the simulation results. Another possibility would be to consider the use of renewable energy, such as geothermal heat. While systems that rely on outdoor air temperature will be directly affected by the

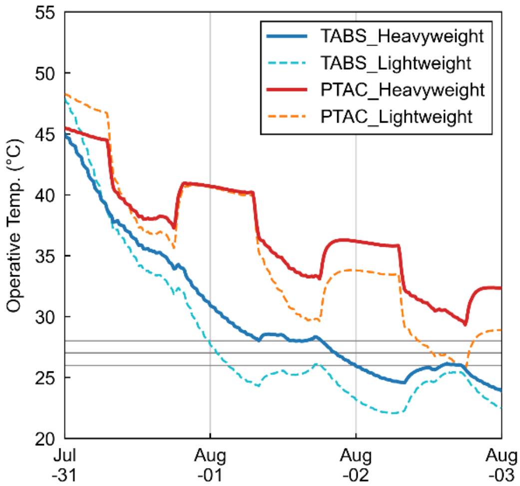

Fig. 6 – Operative temperature of west office 3 days after the heat wave (contemporary, with power outage).

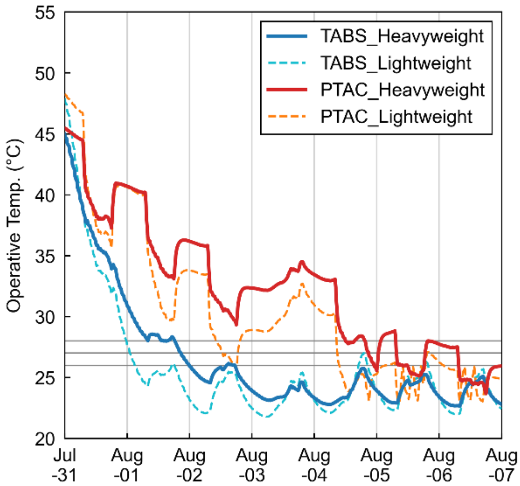

Fig. 7 – Operative temperature of west office 7 days after the heat wave (contemporary, with power outage).

temperature rise during the heat wave, the ground temperature is likely to be less influenced. However, the effect of the increasing yearly average temperature of the site (and thus the ground) must be considered.

5. Conclusion

Simulations were conducted to re-evaluate radiant cooling systems from the resiliency perspective. Thermally Active Building Systems (TABS) with consecutive operation and packaged terminal air conditioners (PTAC) with intermittent operation were compared. Future weather files of typical meteorological years (TMY) and heat wave years (HWY) were used.

For future typical meteorological years, both TABS and PTAC were able to provide an indoor temperature within a comfortable range. TABS performed better with heavyweight construction, but PTAC had little influence from the construction type. During heat waves (but with power available), both systems were able to maintain a generally comfortable temperature range but with a slightly overall higher temperature.

On the first day of the power outage with heavyweight construction cases, TABS was able to maintain a peak temperature 2.3 K lower than with PTAC. This difference became gradually smaller, and became 1.4 K after one week. With lightweight construction, TABS kept the peak temperature lower than that of PTAC by 2.8 K on the first day of the power outage, and 1.5 K lower after one week.

When a heat wave and power outage occurred at the same time, the cases with heavyweight construction had lower temperatures regardless of the cooling system. With TABS and heavyweight construction, the room temperature was maintained within the comfort range of 26°C for 16 hours after the heat wave and power outage started. After the power outage was over, TABS with heavyweight construction was able to lower the room temperature to the comfort condition of 26°C faster than PTAC by 18 – 71 hours. Results obtained from this initial set of simulations suggest TABS could be a better solution than PTAC in terms of its resiliency to heat waves and power outages although both systems could have different advantages depending on the operation, building type and building use.

6. Acknowledgement

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7. Data Access Statement

The datasets generated during and/or analyzed during the current study are not available because of a non-disclosure agreement but the authors will make every reasonable effort to publish them in near future.

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