A qualitative evaluation of the resiliency of Personalized Environmental Control Systems (PECS)

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ABSTRACT

A Personalized Environmental Control System (PECS) aims to condition the immediate surrounding of occupants. This approach is fundamentally different from typical HVAC systems, which aim to create uniform indoor environments, regardless of the occupant preferences. PECS has several advantages including allowing occupants to adjust their immediate surroundings according to their preferences, which could improve their satisfaction with the indoor environment, and may lead to higher productivity. PECS can also lead to noticeable energy savings, if implemented effectively in buildings and if coupled to building HVAC systems. PECS can also be an effective solution in combating pollutant and disease transmission in indoor spaces. An emerging type of personalized devices is wearable heating and cooling devices, which can be used in both indoor and outdoor settings. An international project "IEA EBC Annex 80 – Resilient Cooling of Buildings" is developing qualitative and quantitative key performance indicators (KPIs) for evaluating the resiliency of different cooling solutions under heat wave and power outage events. The present study evaluates the resiliency of PECS in terms of thermal comfort and indoor air quality, using and expanding the principles and KPIs developed by IEA EBC Annex 80. The results serve as the first step towards the quantification and guidance on the applicability and potential of PECS under future heatwaves, power outages, and indoor and outdoor air pollution.

KEYWORDS

Resiliency, Thermal Comfort, Indoor Air quality, Heatwave, Cooling

1 INTRODUCTION

A Personalized Environmental Control System (PECS) conditions the local environment of occupants through heating, cooling, ventilation, lighting and acoustic functions. The benefits of PECS have been reviewed and organized by Rawal et al. (2020). Individual control of the local environment is expected to increase occupant satisfaction with the indoor environment and productivity. If coupled with the building heating, ventilation, and air conditioning (HVAC) systems, PECS has the potential to reduce energy use. In addition, ventilation functions can more efficiently provide occupants with fresh air, protecting them from pollutants.

International Energy Agency (IEA), Energy in Buildings and Communities Programme (EBC) Annex 80 – Resilient Cooling of Buildings (IEA-EBC, 2022a) is developing an evaluation framework for building cooling solutions in terms of their resiliency towards heatwaves and power outages. Qualitative and quantitative key performance indicators (KPIs) are being developed for this purpose (Zhang et al., 2021). To enable simulation studies of different cooling strategies, future weather files (both typical meteorological years and years with heatwaves) have been developed within the annex (Machard et al., 2020). The present study evaluates the resiliency of PECS using the developed qualitative KPIs and weather files, and expands the evaluation scheme to address the resiliency of PECS in terms of indoor air quality.

2 METHODOLOGY

The present study is organized in two steps. In the first part, resiliency characteristics of PECS are presented and analysed individually in terms of the thermal environment and indoor air quality. Previous simulation studies of Annex 80 and findings from literature were used. PECS was then evaluated in terms of the thermal environment using the KPIs developed in the annex and the scope was further expanded to indoor air quality.

Annex 80 proposed to characterize the resiliency of cooling strategies by four criteria, i.e., absorptive capacity, adaptive capacity, restorative capacity, and recovery speed (Zhang et al., 2021). Absorptive capacity is the ability to absorb the impact of disruptive events. Adaptive capacity is the ability to adjust to disruptions, especially in cases where the absorptive capacity is exceeded. Restorative capacity represents the ability to return to the normal operation after a disruptive event, or even to a better state than before the disruption. Recovery speed is the speed of the restorative process. The recovery speed is ranked in three categories, i.e., high, moderate, and low. Each level corresponds to a recovery speed of one hour or less, several hours, and one or more days, respectively. The absorptive, adaptive, and restorative capacities are also ranked in high, moderate, and low levels. Cooling strategies categorized as “high” can maintain or increase its capacity during disruptive events. “Moderate” level strategies can maintain its capacity for the majority of the time during disruptive events. “Low” level strategies will experience a decrease in its capacity during a disruptive event. (Zhang et al., 2021)

The resilience characteristics described above have been developed primarily for the evaluation of thermal performance of cooling strategies in the event of heatwaves and power outages. However, the developed criteria may be adapted to other disruptive events and indoor environmental quality variables. In the present study, the resiliency of PECS was also evaluated in terms of indoor air quality in the event of outdoor air pollution and spread of pathogens between building occupants.

3 RESULTS AND DISCUSSIONS

3.1 Thermal Comfort

In principle, the use of PECS enables the relaxation of the ambient temperature setpoint. For example in ISO 17772-1:2017, it allows a correction of the indoor operative temperature in the presence of increased air velocity with personal control (when the operative temperature is above 25 °C). The air speed at occupant level of 0.6, 0.9, and 2.2 m/s corresponds to an offset of 1.2, 1.8, and 2.2°C, respectively (ISO, 2017). EN 16798-2 provides example criteria for PECS, of which the requirement for temperature control during the summer is to allow temperature adjustment within a range of 22 – 27°C, in equivalent temperature (CEN, 2019b). A literature review conducted by Veselý and Zeiler reported that thermal comfort can be maintained up to ambient temperature of 30°C and relative humidity of 70% with the use of PECS (Veselý & Zeiler, 2014). Some studies report that thermal comfort can be achieved even at higher temperatures, e.g. 32°C (He et al., 2017; Huang et al., 2013). In addition to the energy savings potential with relaxed setpoint temperatures, this characteristic of PECS is also beneficial from a resiliency point of view. Maintaining comfort conditions at higher temperatures allows buildings to be habitable for a longer time during disruptive events, such as heat waves and power outages.

Figure 1 shows the operative temperature of a two-person office for the first 7 days of a concurrent occurrence of a heat wave and a power outage, and 7 days after the disruptive event.

The dataset for the analysis was based on those reported in a previous simulation study (Kazanci, Shinoda, & Olesen, 2022). The building model was based on those developed by Olesen and Dossi, and the boundary conditions were based on those specified in the Dynamic Simulation Guideline of the IEA EBC Annex 80 (Olesen & Dossi, 2004; Zhang, Kazanci, Attia, et al., 2021). A heat wave weather file developed within Annex 80 for Copenhagen was used (Machard et al., 2020). The simulated office had either heavyweight or lightweight construction, and the cooling system was either a packaged terminal air conditioning unit (PTAC) or a thermally activated building system (TABS). For TABS, both a 24-hour and intermittent operation was simulated. The simulation assumed the worst case scenario in which a power outage occurred during the whole duration of a heat wave.

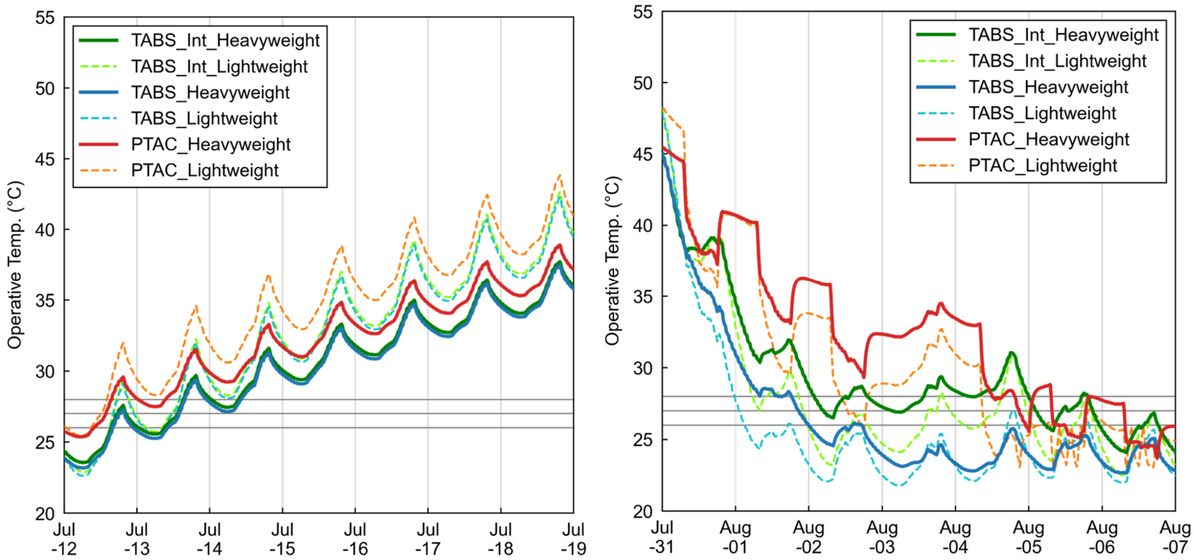


Figure 1: Operative temperature in an office for the first 7 days of the heat wave and power outage (left) and 7 days after the heat wave (right)

Table 1 compares the number of hours a building could maintain its indoor temperature below a certain baseline temperature at the beginning of a major disruptive event (concurrent heat wave and power outage), and the number of hours it takes until the indoor temperature recovers to the baseline temperature after the event. The values are based on the dataset shown in Figure 1. The number of hours in the table varies (i.e., given in a range of hours) depending on the thermal mass of the building, the cooling system (PTAC or TABS), and the system operation. Operative temperature of 26, 27, and 28°C corresponds to the upper limit of Categories II, III, and IV of EN 16798-1 (CEN, 2019a), respectively, and 30°C corresponds to the upper limit in which PECS can provide thermal comfort according to the review by Veselý and Zeiler (2014).

Table 1: Hours below baseline temperature at the beginning of heatwave/power outage and hours until baseline after heatwave/power outage

Baseline Temperature (°C)	Hours maintained below baseline temperature (h)	Hours until baseline temperature is reached (h)
26	0 – 16	27 – 126
27	12 – 19	25 – 117
28	14 – 40	24 – 108
29	15 – 42	23 – 106
30	17 – 64	21 – 64

Under an extreme event in which a heat wave and power outage occurs concurrently, buildings can still maintain a certain temperature range depending on the thermal mass and cooling operation at previous time steps. In the presence of a backup battery or reduced electricity supply in which only PECS operation is possible (and not sufficient for the ambient system to operate), it would be possible for comfort conditions to be met for the first 17 – 64 hours of the disruptive event. PECS would act as a backup conditioning system in this case. When such use is intended, the required power use of the PECS should be sufficiently low. After the power outage ended and the ambient system started to operate, it took 1 – 5 days for the indoor temperature to reach the upper limit of category IV (28°C) in the simulated scenario. However, if thermal comfort could be met with an indoor temperature of 30°C with the use of PECS, the building could be occupied within 1 – 2.5 days. The lower ends of the recovery time are cases with thermally active building systems, and the higher ends are cases with packaged terminal air conditioning units. It should be noted that while comfort conditions may be met for occupants with (stationary) PECS within the extended comfort range, occupants in other areas without PECS would experience overheating. Wearable devices may be a viable option for such occupants to compensate for the high ambient temperature.

In summary, if PECS can be used during a heatwave and power outage, occupants can stay longer in the building, and if it can be used after the disruptive events, the building can be occupied again earlier. In both cases, thermal comfort will not be compromised thanks to the increased comfort range due to the use of PECS.

3.2 Indoor Air Quality (IAQ)

PECS is not limited to conditioning the thermal environment but can also condition the air quality if equipped with an air terminal device (ATD) that provides personalized ventilation, i.e. air directed towards the occupant's breathing zone. According to Lipczynska et al. (Lipczynska et al., 2015) personalized ventilation can be almost ten times more efficient in delivering clean air at workstations than total volume ventilation strategies such as mixing ventilation. Nevertheless, in order to reach high personal exposure effectiveness, the air jet coming from the ATD should be free of pollutants, i.e. reduce entrainment of polluted room air (Assaad et al., 2017; Melikov, 2016; Melikov et al., 2002).

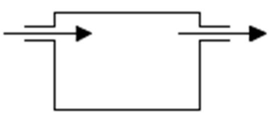
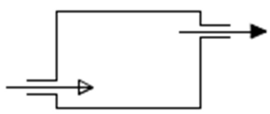
Several types of ATDs can be found in literature, ranging from workspace to workstation and wearables. Workstation designs include movable panels, vertical or horizontal desk grills (Melikov et al., 2002) to different duct type ATDs (Assaad et al., 2017; Khalifa et al., 2009) such as the co-flow nozzle presented by Khalifa et al. (Khalifa et al., 2009). Wearable air terminal devices are usually headset oriented (Dyson, n.d.; Melikov, 2016) while workspace devices consist of ceiling, workstation or floor mounted diffusers that direct the flow towards the occupant's zone (Alotaibi et al., 2018; Melikov, 2016; Yang et al., 2007). The advantage of an ATD that is close to the occupant, i.e. workstation or wearable, is that it can easily be oriented towards the mouth and nose, i.e. breathing zone, even at low air flow rates (2.4 to 7.5 L/s). However, to ensure high personal exposure effectiveness, an air speed of 0.3 m/s to 0.5 m/s close to the person's face is required to penetrate the thermal plume of the person without being too high to cause discomfort due to eye irritation or draft (Khalifa et al., 2009; Melikov et al., 2002). An optimized ATD intermittent airflow may however lead to satisfactory personal exposure effectiveness levels by reducing entrainment of surrounding air (Assaad et al., 2017).

PECS research is focused on reducing inhaled contaminants by supplying fresh outdoor air or cleaned indoor air directly to the breathing zone (Assaad et al., 2017; Melikov, 2004; Melikov et al., 2002). This is effective in reducing exposure to indoor pollutants (human respiration, computers, office furnishing, bacteria/virus), which has positive effects in case of cross-contamination (Cermak et al., 2006; Lipczynska et al., 2015; Li et al., 2013). Although dependent on the ATD (Cermak et al., 2006; Melikov, 2004), when combined with total volume ventilation strategies (mixing or displacement ventilation) personalized ventilation will generally be able to improve the inhaled air quality. However, additional considerations are required regarding displacement ventilation and the direction of the flow coming from the ATD to avoid exposure of the co-occupant (Cermak et al., 2006; Li et al., 2013). Therefore, it is proven that personalized ventilation coupled to fresh outdoor air can be a resilient ventilation method when the pollutant source is located in the space (the indoor environment) – such as a virus in the context of the COVID-19 pandemic.

There are limited studies on how and if personalized ventilation could be used when the outdoor air is polluted. According to Power and Worsley, urban air pollution (industrial emissions, car exhaust, high levels of bacteria and allergens) is a major environmental concern (Power & Worsley, 2018) while extreme events such as wildfires (forest fires), volcanic eruptions, and sandstorms generate high amounts of particulate matter and organic aerosols (Liu et al., 2017) which pollute the outdoor air. Under these scenarios, filtration - which is effective in lowering particulate matter from wildfires - and air cleaning may be the only effective solutions at reducing pollution in the indoor air (Barn et al., 2008; Carlsten et al., 2020; Fisk & Chan, 2017).

Air cleaning and filtration systems are already combined with total volume ventilation systems, either centralized (e.g. on the main outdoor supply) or as standalone units (Bogatu et al., 2021). One such example was presented by Kazanci et al. where the PECS ventilation system was equipped with a high efficiency particulate filter (HEPA) and an ultraviolet germicidal irradiation component (Kazanci et al., 2022). Aside for the fact that the cost of implementing filtration-based standalone units in case of wildfires exceeds the economic benefits of reduced hospital admissions (Fisk & Chan, 2017), typical energy intensive ventilation systems may not be available during blackouts, which could also occur during heatwaves. The idea behind personalized ventilation is that air quality is increased even for small airflows leading to similar or added benefits to perfect mixing for a lower energy use (Olesen et al., 2011; Schiavon et al., 2010; Schiavon & Melikov, 2009). Table 2 shows that personalized ventilation exceeds the ventilation effectiveness ($\mathcal{E}v$) range of mixing ventilation and displacement ventilation (maximum 3.5 compared to 1.0-1.4), however dependent on the air terminal device (ATD). Furthermore, portable air cleaners may reach high enough clean air delivery rates but they are dependent on their placement and air movement inside the space. Thus, the advantage of personalized ventilation coupled with filtration and air cleaning devices is that the clean air is supplied directly into the breathing zone of the person. Being less energy intensive, these systems could potentially operate even during blackouts if coupled to a battery. Such solutions are already emerging, as researchers and manufacturers point to wearable headsets coupled with air filtration, however in the context of indoor and urban air pollution (Melikov, 2016).

Table 2. Ventilation effectiveness ($\mathcal{E}v$) ranges for different combinations of supply-return air positions (Adapted from (Olesen et al., 2011))

Mixing ventilation	Mixing ventilation	Displacement ventilation	Personalized ventilation
			
$\mathcal{E}v$ [-] 0.4 - 1.0	$\mathcal{E}v$ [-] 0.9 – 1.0	$\mathcal{E}v$ [-] 0.2 - 1.4	$\mathcal{E}v$ [-] 1.2 - 3.5

3.3 Overall Qualitative Assessment of PECS

The resilient capabilities of PECS in terms of thermal comfort and indoor air quality have been discussed in the previous sections. Table 3 summarizes the assessment of PECS in terms of its resilience to heatwaves, power outages, and outdoor air pollution. The columns correspond to the four criteria described in section 2, and the assessments for the heatwave and power outage were taken directly from Zhang et al. (2021). The assessment for air pollution was added in the present study. Although the same four criteria as the heatwave and power outage cases were adopted for the evaluation of air pollution, the time span of the recovery speed was adjusted, i.e., instantaneous (high), several hours (moderate), and one day (low). PECS with heating, cooling, and ventilation (either clean/fresh air from outdoors or cleaned indoor air) functions were assumed for the assessment.

PECS presents no absorptive capacities no matter the type of extreme event even if equipped with heating, cooling, ventilation, light, and acoustic functions. This is because PECS does not have a buffer, e.g., heat storage, to absorb the impact. As presented in Zhang et al. (2021) in terms of cooling, adaptive capacity is low or not present during power outages if the PECS is not coupled with a backup power source, e.g. battery. The restorative capacity and recovery speed would however be both high if PECS is operational. During heat waves, except for the absorptive capacity, all other KPIs would be high as long as the PECS is able to offset the impact of the event (see section 3.1).

In the event of outdoor air pollution or when the source of pollution is in the indoor space (e.g., a pandemic), PECS has high adaptive and restorative capacities, as well as recovery speed. By supplying air individually to each occupant breathing space, PECS can minimize cross-contamination. This applies however only if the air supplied by the PECS is clean and free of pollutants and, in case the outdoor air is polluted, its efficiency is dependent on the air cleaners integrated. While PECS does not have an absorptive capability where it can dampen the effect of pollution, it is able to provide fresh air more efficiently to the breathing zone of the occupants. Clean air is provided when operating the PECS and delivered as soon as the users turn on the device. This allows the system to maintain better air quality for the occupants (adaptive capacity) and to make the building habitable earlier than a ventilation system for the whole room such as a mixing ventilation system (restorative capacity and recovery speed).

Nevertheless, PECS does not restore the air quality conditions to the entire building volume as prior to the event. If fitted with an air cleaner, the maintenance of PECS, i.e. regular cleaning, may be required to ensure its resilient attributes are preserved.

Table 3: Assessment of PECS in terms of resilience (Excerpted and modified based on Zhang et al., 2021)

Extreme event	Absorptive capacity	Adaptive capacity	Restorative capacity	Recovery speed
Heatwave	N/A	High	High	High
Power outage	N/A	N/A or low	High	High
Air pollution	N/A	High	High	High

3.4 Future Research Needs

As shown by the qualitative assessment, PECS has the potential to be a highly resilient system in the event of heatwaves, power outages, indoor pollution (e.g., viruses), and outdoor air pollution. Despite its known benefits such as improved occupant satisfaction and comfort, there is a limited number of PECS currently available in the market (Zhang et al., 2021). Open issues in further promoting PECS are interdisciplinary, involving both technical issues and policy-related issues (e.g., regulations/standards for the combined use of PECS and the ambient system, responsibility over installation and maintenance). Such issues will be addressed in the new IEA EBC Annex 87 – Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems (IEA-EBC, 2022b).

One of the future research needs for PECS is the evaluation method of PECS. As PECS could come in various shapes and functions, standardized quantitative KPIs and evaluation framework are necessary. Measurement with a breathing thermal manikin is an effective method, but not available for many interested parties. Computer Fluid Dynamics (CFD) simulations are commonly conducted for evaluating the air distribution characteristics and performance of ATDs. However, other simulation methods are lacking, as many building energy simulation studies assume a relaxed setpoint but do not simulate the interaction between PECS and the ambient system. Human subject experiments are difficult to conduct in extreme conditions (e.g., high/low temperatures or pollutant levels) as a reference condition without PECS would expose subjects to highly uncomfortable or even health-affecting conditions. Another research need is the interaction of indoor environmental quality (IEQ) factors, as many PECS are equipped with multiple functions that would influence them. The interaction of IEQ factors are yet to be implemented in comfort standards (Khovalyg et al., 2020) and is an open topic for research. Indicators for short term resiliency, as was explored in this study, would be necessary as well.

4 CONCLUSIONS

Previous studies have shown that PECS is a promising solution in many different aspects (Rawal et al., 2020). Preliminary assessments in this study showed that PECS has the potential to be a resilient solution to maintain thermal comfort and indoor air quality in the case of extreme events such as heatwaves, power outages, and outdoor and indoor air pollution (e.g. wildfires, sandstorms, volcanic eruptions, pandemics). Qualitative KPIs developed within IEA EBC Annex 80 were used and expanded to evaluate the resiliency characteristics of PECS. This study was therefore a first step towards identifying the resilient characteristics of PECS and their quantification.

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