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Evaluating the Practical Energy Saving Potential of a Personal Cooling System in the Tropics

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Abstract

Over twenty years of research have demonstrated personal cooling systems (PCS) as a promising approach to reducing the energy consumed to cool the built environment. However, existing PCS relied on the central system and fixed ductwork to deliver cooled air, restricting its application in practice. In this study, we designed a decentralized PCS that is energy-efficient, portable, and easy to use. An integrative design framework was used to optimize the performance of the thermoelectric cooler and other system components. Based on actual testing data, we developed a co-simulation framework to quantify the energy-saving potential. The results reveal the significant synergetic effect between the proposed PCS and natural ventilation in tropical climates. Noticeably, a considerable 45.8% cooling energy reduction compared with traditional cooling was achieved.

Key Innovations

- A portable and energy-efficient personal cooling device for practical use.
- An integrative design framework to optimize the system performance.
- Considerable energy-saving potential based on actual experiments and co-simulation.
- Significant synergy between PCS and natural ventilation revealed by energy simulation.

Practical Implications

Different components of a portable PCS should be designed in an integrative manner to ensure thermoelectric-based cooling efficiency. Combining natural ventilation could reduce both air conditioning and personal cooling energy consumption.

Introduction

Buildings account for over 30% of global greenhouse gas emissions (IEA, 2022), underscoring its vital position in decarbonization. Air conditioning is an energy-intensive end use, which could contribute 50-60% in hot climates and is expected to further increase in the face of global warming. Therefore, there is a pressing need for a less consuming approach to cooling the buildings.

Personal cooling has emerged as an effective strategy for reducing cooling energy consumption. By only conditioning the small ambient environment around occupants, it provided higher flexibility in background temperature control (Song et al., 2022). Given moderate outdoor conditions, this also expanded the time window for natural ventilation, enabling mixed-mode ventilation even in hot and humid climates (Peng et al., 2022). Despite its potential, previous studies were confined to simulation and experimental setups, with existing systems being complex, bulky, and inflexible. Consequently, with limited demonstrations of its benefits in practice, adopting personal cooling in real-world buildings is challenging.

Personal cooling systems

Research from the past twenty years has demonstrated the benefits of PCS. For instance, Heidarinejad et al. (2018) analyzed the energy impact of using PCS in major US cities, revealing up to 21% reduction in cooling-related CO_2 emissions. While extending the background setpoint significantly reduces the cooling energy consumption, PCS could also improve the energy efficiency of other end uses such as fans. Using simulations, it was shown that personalized ventilation could cut energy consumption in Singapore by up to 51% compared to conventional mixing ventilation (Schiavon et al., 2010).

Regarding thermal comfort, subject tests were conducted to demonstrate the effectiveness of PCS in maintaining occupant comfort under various background conditions. For example, over 90% of subjects found the environment acceptable with individually controlled cooled air supply from a desk-mounted round movable panel (Chen et al., 2012), and a pair of head-oriented nozzles effectively reduced the facial skin temperature and thereby improved the overall thermal sensation of the occupants coming from a warm ambient environment of 30°C (Jin and Duanmu, 2016). Moreover, personalized ventilation achieved up to eighty percent reduction in pollutant

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levels in inhaled air (Niu et al., 2007). The capability of regulating the micro-environment also offered a psychological delight that enhances the occupants' thermal sensations (Parkinson and De Dear, 2015).

There are many different forms of PCS, such as cooled chair (Pasut et al., 2013), desktop diffusers (Amai et al., 2007), and radiant panel (Ismail and Ouahrani, 2023), which respectively deliver cooling through conductive, convective, and radiative heat transfer. Among these alternatives, cooling and ventilation are usually more desirable with the elevated air movement speed and fresh air directly supplied to the breathing zone. However, most previous studies deployed PCS in lab environments, often connected to central air handlers through intricate ductwork, which is inflexible and impractical for installation in actual environments. Underfloor air distribution (UFAD) provided a partial solution by concealing the ducts (Shen et al., 2013). Yet, it remained constrained by its reliance on centralized air supply and limited adaptability. These challenges underscore the need for a truly decentralized personal cooling system that offers greater flexibility and ease of implementation in diverse situations.

Thermoelectric cooling

The key to decentralized personal cooling is a portable local cooling device. For example, Ling et al. (2021) designed a self-contained small-scale air conditioner (AC) integrating a mini heat pump with phase change material (PCM). Although smaller than a traditional AC, the device, with the refrigeration cycle and the large volume of PCM, is not fully portable and induces noises. Thermoelectric cooling (TEC), on the other hand, is a well-established technique that provides local cooling using a compact module with no moving parts, which has been applied in many fields such as domestic refrigeration and electronic cooling (Zhao and Tan, 2014).

Recent studies investigated the use of TEC for personal cooling, primarily in two forms: desk diffusers (Kazanci et al., 2022) and wearable undergarments (Rahimi et al., 2024; Wei et al., 2023). A common challenge across these applications is managing the exhaust heat and maintaining a stable temperature on the TEC hot side. Directly ejecting the heat into the ambient environment through forced convection would increase the background cooling load. Moreover, increased hot side temperature significantly deteriorates TEC efficiency and cooling capacity, which is often overlooked when claiming the Coefficient of Performance (COP). Kazanci et al. (2022) used circulated water to absorb the heat, which, however, compromises the portability and faces limitations in operating duration as the water temperature quickly escalates. Therefore, a better heat dissipation solution is needed to ensure TEC efficiency, and its energy performance should be more robustly quantified in practical settings.

Research overview

To summarize, thermoelectric cooling is a promising approach to realizing the potential of personal cooling, but an integrative device that can function in a plug-and-play manner is absent. The challenge lies in dissipating the exhaust heat without interfering with the ambient environment and coordinating the system components to efficiently deliver cooled air. To guarantee the system performance in practice, energy efficiency needs to be comprehensively evaluated.

To address these challenges, we developed a desktop personal cooling device that regulates the boundary conditions of TEC with a supply air fan and a PCM module. An integrative design framework was employed to optimize the system parameters. The system performance was carefully examined through simulations and experiments. Further, we used co-simulation to estimate the energy-saving potential of the proposed system. The system design and evaluation were conducted in a typical hot and humid climate as a worst-case scenario to ensure its robustness. The contributions of this study are twofold:

- Designed a desktop TEC-based personal cooling system that is energy-efficient, portable, and easy to use.
- Quantified the energy performance of the proposed PCS and estimated its energy-saving potential.

Design of the personal cooling device

The proposed personal cooling device consists of three main modules: thermoelectric cooler, cold-side air handling, and hot-side heat dissipation. In operation, TEC uses the Peltier effect to move heat from the cold side to the hot side, thereby reducing the cold side surface temperature. The cooling power is then transferred to the air blown through the fins. Meanwhile, the heat dissipation module absorbs the exhaust heat and maintains the hot-side temperature.

While TEC is the primary actuator of the system, its performance is highly sensitive to the cold- and hot-side temperatures and ambient conditions. Therefore, all three modules are critical to ensure the system delivers cooled air effectively and efficiently. As illustrated in Figure 1, an integrative design framework was adopted to identify the optimal specifications of each component in the system. The three stages of the framework consecutively optimized the design of the three modules. The entire framework is subject to several global constraints such as the dimensions and operating conditions, and the results of each stage serve as the boundary conditions for the next stages.

Cold-side condensation prevention

Parallel fin heat sinks are commonly used to transfer the thermal energy from thermoelectric modules

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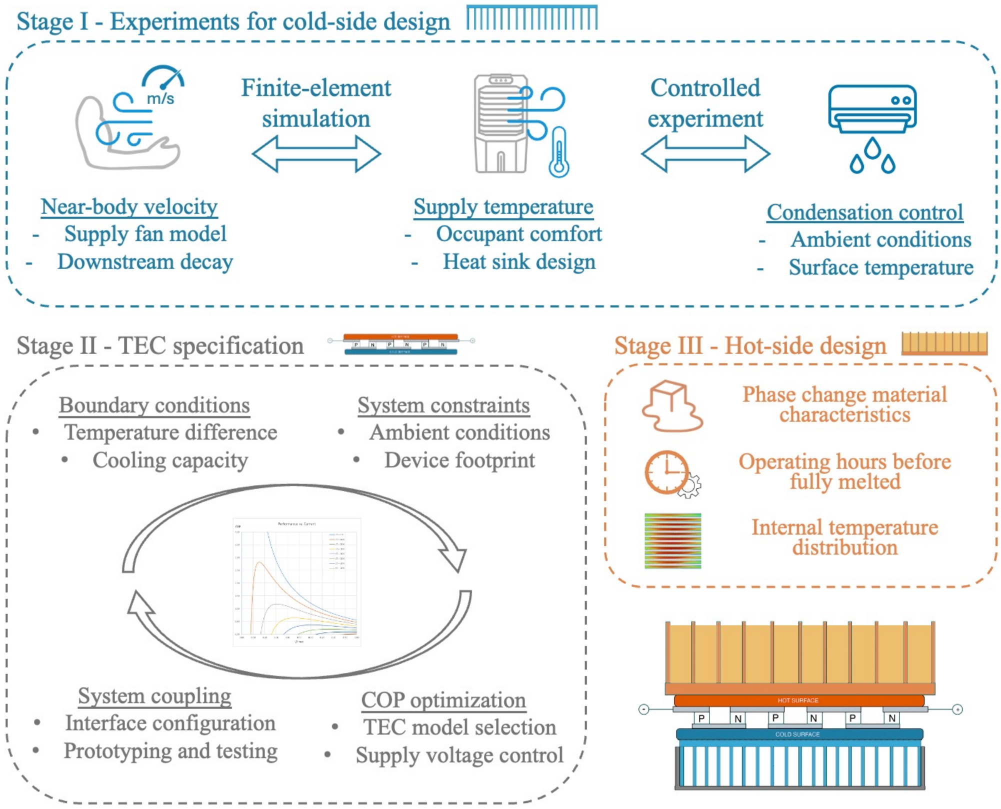


Figure 1: Design framework of the personal cooling device.

to air. However, the practical considerations for the system to be plug-and-play and energy-efficient led to conflicting factors in design. For example, a lower surface temperature required to effectively cool the air could also cause condensation, which should be avoided. Hence, the cold-side heat sink was designed to balance practicality and energy efficiency.

Condensation on cooled surfaces is a typical challenge in hot and humid climates. Traditional active dehumidifiers are either too bulky to be integrated or cannot last. Although many passive condensation prevention technologies have been developed for radiant cooling applications (Xing et al., 2021), they are not applicable in this case as air must be in contact with the surface for convective heat transfer. Therefore, our design prevents condensation by precisely controlling the cold side surface temperature.

Surface condensation is a multi-physics process affected by ambient conditions, air velocity, and surface temperature, which should ideally be optimized together. However, multi-physics co-simulations are computationally expensive and difficult to validate. Therefore, a series of controlled experiments were conducted to determine the lower bound of surface temperature, which then served as an input when designing the heat sink geometry.

A sample heat sink was attached to a water-cooled plate, which provided a stable surface temperature using chilled water. The devices were placed in several semi-outdoor conditions ($T_{ambient}$, $RH_{ambient}$), and ambient air was blown through the heat sink with a constant velocity ($V_{surface}$). The surface temperature was gradually reduced until condensation first appeared on the surface ($T_{condensation}$). Table 1 displays the experimental setting and results of two representative conditions in semi-outdoor environments. It was observed that condensation happened 1 to $1.5°C$ lower than the dew point temperature. Considering that the surface temperature could be less uniform with TEC, the lower bound of TEC cold-side temperature was conservatively set to $1°C$ lower than the real-time dew point temperature.

Cold-side heat sink geometry

The system footprint, subject to the portability requirements and the necessary area of TEC, was first determined to limit the number of dimensions in optimal design. Considering the limited cooling power density of commercially available TEC modules, the number of TEC modules was involved in fixing the dimensions of the contact surface. Based on the preliminary iterative tests, the maximum cooling power roughly falls in the capacity range of three 50 x 50mm TEC modules[1]. Therefore, the heat sink base was set to 50 x 150mm.

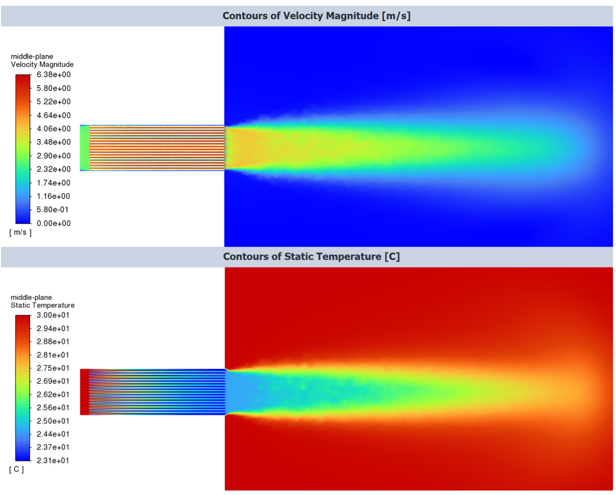
[1]The capacity refers to the cooling power at its highest efficiency according to the TEC data sheet.

Table 1: Results of condensation tests.

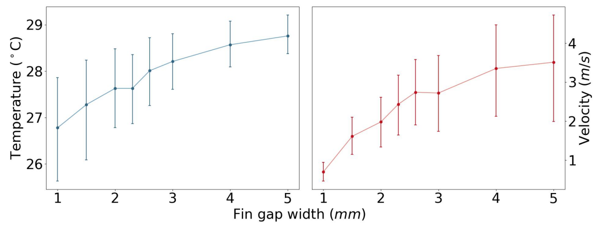
	$T_{ambient}$	$RH_{ambient}$	$T_{dewpoint}$	$V_{surface}$	$T_{condensation}$
1	$31.2°C$	74.8%	$26.2°C$	5.2 m/s	$24.6°C$
2	$28.4°C$	70.6%	$22.5°C$		$21.4°C$

On the other hand, the width and height of the fin block are associated with the supply air fan. Considering the energy efficiency, pressure rise, and power supply compatibility, an NMB 7530 12V blower fan was used. The fin block was of the same size as the fan outlet (42 x 23mm), and the remaining edge of 8mm was reserved for assembly. Thereby, the air gap between fins is the last design parameter, which was determined by balancing the cooling effect and the pressure loss.

With the predetermined surface temperature and fin length, the width of fins contemporarily affected the outlet air temperature and velocity. Narrower gaps enhance the cooling effect with a larger cooling surface area but also come with larger flow resistance. Therefore, parametric Finite-element simulations were conducted to investigate the impact on internal heat conduction, fin-to-air convection, and pressure loss across the fins. Figure 2a shows an example of coupled fin surface temperature distribution, air temperature field, and air velocity field.



(a) Temperature and velocity distributions of a heat sink with 2mm fin gaps.



(b) Air temperature and velocity at 300 mm from the heat sink outlet given different fin gap widths.

Figure 2: Simulation results for cold-side design.

The simulations assumed a worst-case ambient condition of $30°C$ temperature and 70% relative humidity. Correspondingly, the surface temperature was set as $23°C$. For each alternative gap width between 5 mm and 1 mm, the range and average of air temperature and velocity at 300 mm from the heat sink outlet were exported for analysis. 300 mm was selected empirically based on the distance between occupants and the desktop cooling device, which also accounts for the degradation after leaving the heat sink. As visualized in Figure 2b, the downstream air temperature and velocity decreased when the width was reduced. While the rate of temperature decrease was relatively stable, the velocity decayed faster when the width went below 2.5 mm. Considering the simulation results and the fabrication capability, the fin gap width was determined to be 2 mm.

TEC model and Hot-side integration

Based on the simulation results and validation experiments, the cooling capacity needed to cool the air can be estimated by:

$$Q_{cool} = C_p \rho (N d h) v_{out} (T_{amb} - T_{out}) \qquad (1)$$

where C_p and ρ are respectively the heat capacity and density of air, N is the number of fins, d and h are the width and height of each fan, v_{out} and T_{out} are the air velocity and temperature at the outlet, and T_{amb} is the ambient temperature. Considering the uncertainty caused by heat transfer efficiency, Q_{cool} was estimated to be 25-30 W.

To stay beyond the possible range of ambient temperature, the PCM melting temperature was predetermined to be $35°C$. Neglecting the heat resistance within the heat sink (much smaller compared with the convection and contact resistance), the temperature difference ΔT across TEC can be estimated to be $12°C$. Given these boundary conditions and the performance curve, TEC would reach the highest COP when the operating current is between 0.15 and 0.2 of the maximum current I_{max}. According to $Q_{cool,max}$ and the preference for taller thermoelectric pillars, three pieces of model HT064134 were used.

Lastly, the needed volume of PCM was estimated based on the PCM heat capacity, TEC exhaust heat generation rate, and operating hours. Balancing durability and portability, the volume was determined to be 1.5 liters that could last 3 hours under the nominal conditions. Besides, there are three considerations when designing the PCM container: 1) as PCM has a much lower heat conductivity than metal,

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the fin was twice thicker than the colder side to facilitate internal heat conduction; 2) the width of fin gaps was determined to balance heat conduction and volume efficiency; 3) considering the volume change of PCM melting, extra space was kept in the container. Finally, Figure 3 shows the dimensions of the integrated cold-side heat sink, TEC, and hot-side PCM container.

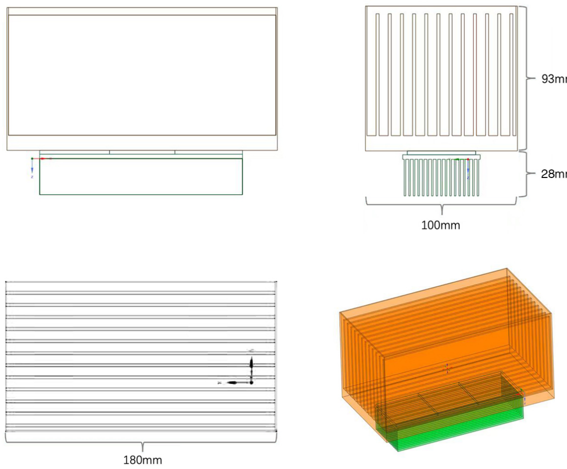
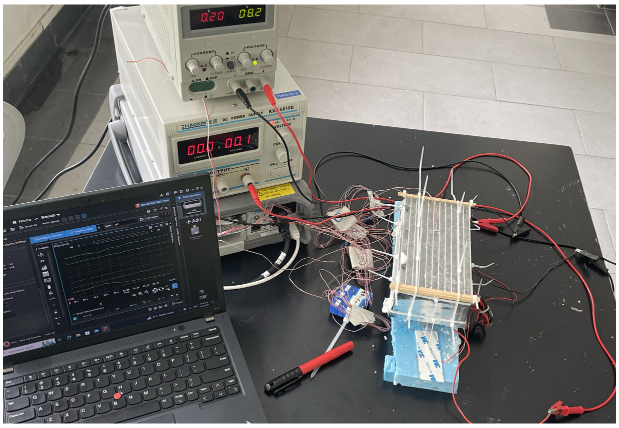
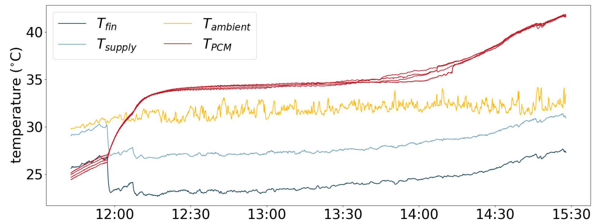


Figure 3: Three-dimensional views of the integrated main components.



(a) Experimental setup to test the energy performance of the final design.



(b) Temperature profiles from a typical scenario.

Figure 4: Experimental setup and results of the prototype tests.

Energy performance evaluation

Prototype and testing results

Figure 4a is the prototype and experimental setup to test the energy performance of the personal cooling device. Two constant current DC power supplies were used to actuate and measure the power of TEC and supply fan. Thermocouples and RTD sensors were installed to record the temperature at multiple locations through a Keysight 34970A data logger. Kanomax M1590 Anemometers were used to measure the downstream air temperature and velocity. The test was repeated in a semi-outdoor environment to emulate the worst-case operating conditions.

Figure 4b plots the resulting temperatures in a typical testing scenario. After the short initialization period to stabilize the measurements, the actuators were activated to start cooling. In this case, the TEC operating voltage and current were respectively 6 V and 0.9 A. It can be seen that the cooling surface and outlet air temperature immediately dropped to the design conditions, and the hot side temperature slowly increased to the melting temperature. The several well-aligned red lines are measured at different locations in the PCM container, indicating satisfactory internal conduction. The temperatures stayed stable for two hours until PCM fully melted, and then slowly increased to a new equilibrium. Calculating the effective cooling power based on Equation 1 during the two hours of stable operations, the TEC modules achieved a COP of 3.03. Including the supply fan consumption, the system COP was 2.33. Due to the integrative system design and operation, the cooler was significantly more efficient than the literature (Kazanci et al., 2022; Lou et al., 2020).

Based on past thermal comfort studies (Mihara et al., 2019; Peng et al., 2022), three operating modes were defined for the final prototype to promote thermal comfort with or without the TEC running. When the ambient temperature is mild, specifically below $27°C$, local thermal comfort can be provided by only turning on the supply fan and elevating the near-body air velocity. In contrast, when the ambient temperature exceeds $29°C$, the required air velocity to compensate for the temperature could be too high (at least 0.8 m/s). Therefore, TEC will be activated to deliver cooled air. When the temperature is between $27°C$ and $29°C$, the occupants are provided the freedom to decide whether to use TEC. Table 2 summarizes the three modes and the corresponding range of power, which combines the experimental results and the thermal comfort range based on the PMV model.

Energy simulation setup

The personal cooling device was integrated into an energy model to investigate its interaction with the central HVAC system and evaluate its energy-saving potential. The model was based on an actual office room located in Singapore. It has a floor area of

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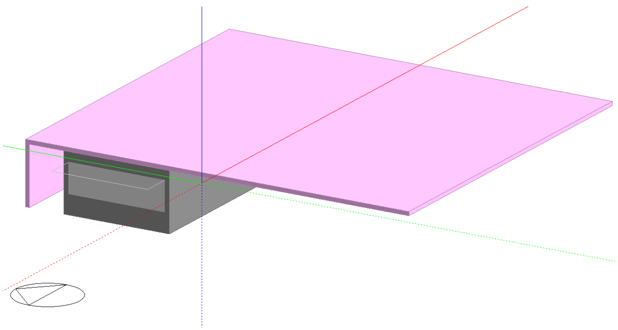
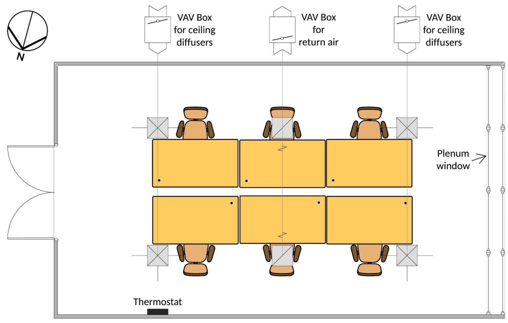
Table 2: Personal cooling device operating modes and corresponding power ranges.

Ambient temperature (°C)	Operating mode	Power (W)
T_{amb} <27	Personal ventilation	1.2-2.8
27≤ T_{amb} ≤29	Customized	1.2-7
29< T_{amb}	Personal cooling	3.5-10.4

49.5 m^2 and six seats. The office was equipped with a variable air volume (VAV) system, the energy usage of which, together with other end uses, was submetered and used to calibrate the model. As shown in Figure 5a, the room was well-shaded by the other part of the building, with a large west-facing plenum window. In the simulations, the room was conditioned from 7 am to 6 pm each weekday, when the occupants were assumed to follow a standard office schedule.



(a) 3D view of the energy model.



(b) Floor plan of the actual office.

Figure 5: Schematics of external geometry and floor plan of the energy model.

Associated with the threshold temperatures of the personal cooling operating modes, we compared four operating strategies as summarized in Table 3. The baseline followed a typical approach without personal conditioning, with a constant cooling setpoint of 24°C and no natural ventilation. The first hybrid cooling strategy raised the setpoint to 27°C and enabled the ventilation mode of the personal cooling device. For hybrid 2, we further raised the setpoint to 29°C, kept the windows closed, and let the occupants control the personal device based on the room temperature. Lastly, in mixed-mode operation, the setpoint stayed at 29°C, but natural ventilation was enabled with concurrent control[2]. Same as hybrid 2, the operating mode of personal devices was based on the resulting room temperature at each time step. When personal cooling was involved, each occupant was assigned two devices. Considering the variance in personal thermal preference, the median of the corresponding power range was assumed to be the average power of all twelve devices.

Table 3: Alternative operating strategies of the HVAC and the person cooling system in the energy simulation.

Mode	Cooling setpoint (°C)	Natural ventilation	Personal cooling mode
Baseline	24	No	Off
Hybrid 1	27	No	Personal ventilation
Hybrid 2	29	No	Customized
Mixed-mode	29	Yes	Customized

Energy saving results

Table 4 summarizes the simulation results of the four operating strategies based on weather data from a typical meteorological year. Although the number of cooling hours did not significantly change, raising the cooling setpoint and enabling personal ventilation reduced the cooling-related energy by 14.8%. As expected, increasing the setpoint to 29°C further cut the central air conditioning energy. Although the use of TEC almost doubled the personal conditioning (PC) energy, hybrid 2 still achieved a 27.2% saving. Surprisingly, introducing natural ventilation in the mixed-mode operation not only reduced the cooling energy and operating hours again but also slightly reduced the PC energy. Combined, the total cooling energy of mixed-mode was 45.8% lower than the baseline. Regarding the peak load, it is understandable that it was mainly associated with the cooling setpoint, decreasing from baseline to the two hybrid strategies, and about the same between hybrid 2 and mixed-mode.

To better understand the synergy between natural ventilation and personal cooling, Figure 6 compared the power curves and temperature profiles of the four strategies on a relatively cool day in January. For reference, the daily cooling energy consumption is included in the title of each subplot, and the outdoor temperature is presented in the last subplot. It can be seen that PC power took a very small ratio of the total power most of the time. While the light green area gradually increased among the first three plots, the light blue area significantly reduced. Regarding

[2]Mechanical cooling is allowed to operate when the windows are opened, to take advantage of the transition hours.

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Table 4: Results of integrated energy simulation.

Mode	AC energy[a] (kWh)	Peak load (kW)	Cooling hours	PC energy (kWh)	Saving percentage (%)
Baseline	1761.2	4.5	2871	NA	NA
Hybrid 1	1427.8	3.8	2860	73.6	14.8
Hybrid 2	1140.7	3.4	2666	141.6	27.2
Mixed-mode	820.6	3.3	1915	134.4	45.8

[a] The numbers have been converted to electricity energy assuming an overall COP of 5.

the comparison between hybrid 2 and mixed-mode, it is noticeable that the room temperature under mixed-mode almost followed the outdoor temperature below the setpoint, whereas hybrid 2 had to cool the room during the operating hours. This is because natural ventilation dealt with the internal and solar heat gain. Corresponding to the lower room temperature, PC also consumed less throughout the day.

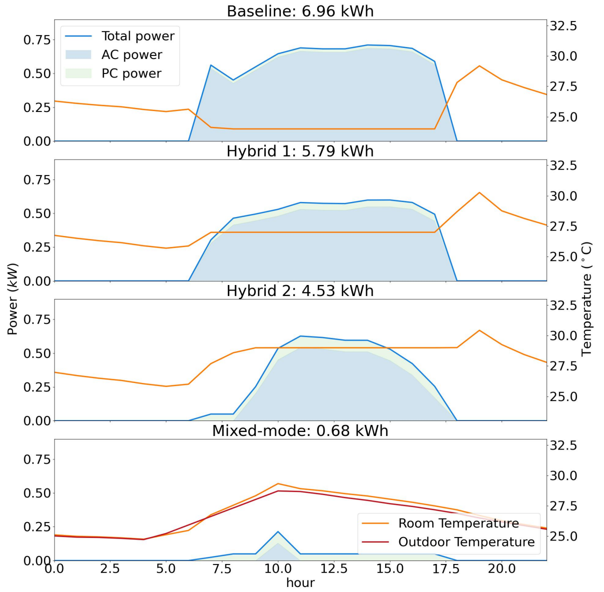

Figure 6: Load curves and temperature profiles of the four operating strategies on January 15th.

In contrast, Figure 7 exhibits the results from a relatively warm day in May (note the change of y-axis ranges). Different from the previous day, the outdoor temperature was mostly above the 29°C setpoint during the operating hours. Correspondingly, natural ventilation was only possible in the early morning and at the end of the day. Therefore, the difference between hybrid 2 and mixed-mode operations was much smaller. Interestingly, the difference between hybrid 1 and 2 was also minor. Although the raised cooling setpoint resulted in slightly lower consumption of the central AC, the PC consumption increased to compensate for the higher room temperature.

To summarize, the proposed personal cooling system provides thermal comfort at a higher ambient temperature. Given the average PC power below 10 W per person, the additional PC energy will be much

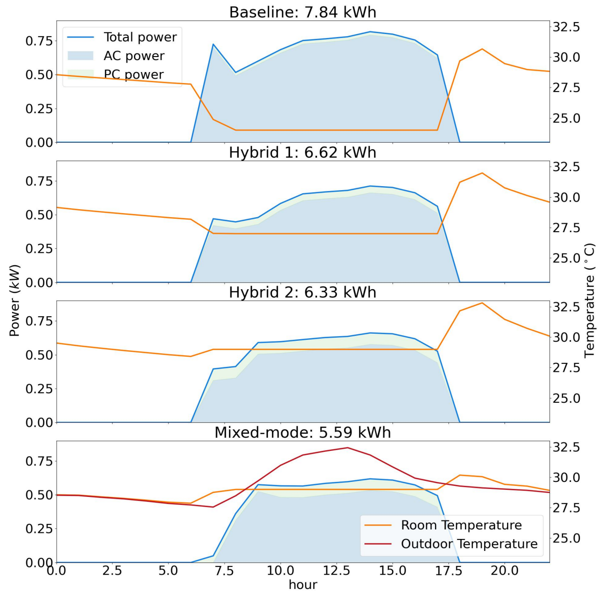

Figure 7: Load curves and temperature profiles of the four operating strategies on May 31st.

lower than the cooling energy reduction associated with the raised setpoints. The energy-saving potential is more significant under mild outdoor conditions, when the 2-degree increase of cooling setpoint led to a critical change of indoor-outdoor temperature difference (external heat gain). On the other hand, when the outdoor temperature is lower than 29°C, natural ventilation can be enabled, which could reduce both AC and PC power.

Note that the saving percentages are associated with the typical meteorological year in Singapore. Further investigation is needed to evaluate the potential in warmer or milder climates. The assumptions of a standard occupancy density and effective natural ventilation are also crucial for the system performance. More parametric experiments could be conducted to determine the range of desirable operating conditions.

Conclusion

Aiming to promote the application of personal cooling systems, we designed a portable and energy-efficient device based on thermoelectric coolers and phase change material. The system components were optimized based on an integrative design framework, and the energy performance was validated in actual experiments. The data collected from prototype tests were further combined with different HVAC operating strategies to estimate the annual energy-saving potential. Simulation results demonstrated an up to 45.8% reduction rate of cooling-related energy and highlighted the synergetic effect between personal cooling and natural ventilation.

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