



Low-energy miniature wearable air-conditioner with direct cold-air delivery: A novel water–electricity hybrid energy system[☆]

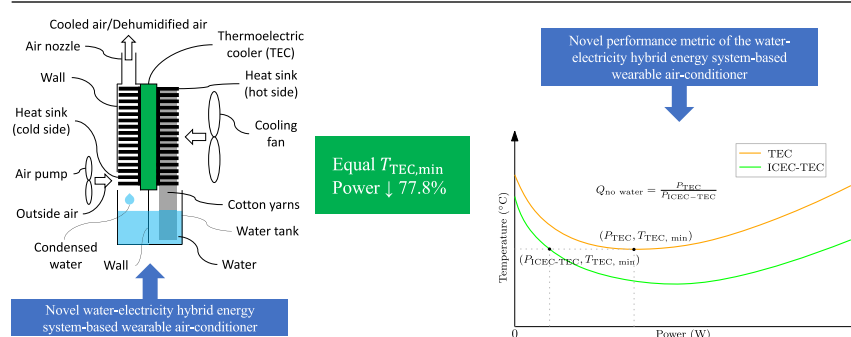
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HIGHLIGHTS

- 22.2% power consumption of same size TEC at equal minimum cooling temperature.
- Wearable air-conditioner that literally provides continuous cold air.
- Also dehumidifies air to improve thermal comfort in high humidity.
- Portable water as a novel renewable energy source for TEC heat rejection.
- Water-cycle function enabling the recycling of condensed water for closed-loop use.

GRAPHICAL ABSTRACT



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ABSTRACT

In indoor environments, cooling accounts for approximately 10% of global electricity consumption, largely due to the low efficiency of compressor-based air-conditioners. In outdoor environments, heat-related deaths have become a severe public health concern. Wearable coolers can reduce system-level energy use by cooling only the occupant rather than an entire room, but thermoelectric coolers (TECs)-based wearable coolers still suffer from low COP and high electrical demand. This study proposes a novel water–electricity hybrid energy system that leverages capillary-driven water evaporation to address the high electricity consumption of TECs. The resulting wearable air-conditioner achieves a 77.8% reduction in electrical power relative to a conventional TEC, while maintaining an equivalent maximum cooling temperature under a hot, moderate-humidity (32.4 °C, 49.6%) ambient condition, with reduced volume and weight. This significant cooling capability combined with low energy consumption allows the device to provide cooled air in a miniature form, a feature not currently available on the market. Under the same ambient condition, the device lowered the air temperature by 4.6 °C at an airflow rate of 1.966 L min^{−1}, while consuming only 5.862 W of power, which is affordable for Li-ion batteries. A novel performance metric is introduced to quantify the benefit of the hybrid energy system. This research significantly facilitates practical implementations of both wearable conductive coolers and air-conditioners, while also contributing substantially to energy conservation in both indoor and outdoor environments. To our knowledge, this work is the first demonstration of portable water as a renewable energy source (RES) to drive TEC heat rejection.

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Nomenclature

Abbreviations

ACG	air cooling garment
COP	coefficient of performance
DEC	direct evaporative cooler
ICEC-TEC	Indirect Capillary-Evaporative Cooler-Thermoelectric Cooler
ICEC	Indirect Capillary-Evaporative Cooler
ICG	ice cooling garment
IEC	indirect evaporative cooler
LCG	liquid cooling garment
PCS	personal cooling systems
PLA	polylactic acid
PPE	personal protective equipment
RES	renewable energy source
RH	relative humidity
TEC	thermoelectric cooler

Variables

$I_{\max}$	maximum current that can safely be supplied to a Peltier module (A)
$P_{\text{ICEC-TEC}}(T_{\text{TEC,min}})$	power consumed by the ICEC-TEC to reach the same minimum cooling temperature $T_{\text{TEC,min}}$ (W)
P	total electrical power input (W)
p_{amb}	ambient total pressure (kPa)
ϕ	relative humidity (fraction)
P_{ICEC}	power of the ICEC (W)
$P_{\text{ICEC-TEC}}$	power of the ICEC-TEC (W)
P_{TEC}	power of the TEC (W)

$P_{\text{TEC}}(T_{\text{TEC,min}})$	power consumed by the TEC when reaching its minimum cooling temperature $T_{\text{TEC,min}}$ (W)
P_{total}	total electrical input to the ICEC-TEC-based air-conditioner (W)
p_v	partial pressure of water vapor (kPa)
p_{ws}	saturation water-vapor pressure (kPa)
$\dot{Q}_{c,\max}$	maximum cooling power that a Peltier module can achieve (W)
$Q_{\text{no water}}$	quotient of the $P_{\text{TEC}}(T_{\text{TEC,min}})$ and the $P_{\text{ICEC-TEC}}(T_{\text{TEC,min}})$
RH_{amb}	ambient relative humidity (%)
RH_{out}	outlet relative humidity (%)
T	average surface temperature of the cooler (°C)
T_{amb}	ambient dry-bulb temperature (°C)
T_{db}	dry-bulb temperature (°C)
T_{ICEC}	surface temperature of the ICEC (°C)
$T_{\text{ICEC-TEC}}$	surface temperature of the ICEC-TEC (°C)
$\Delta T_{\max}$	maximum temperature difference that a Peltier module can create (°C)
T_{out}	outlet dry-bulb temperature (°C)
$\Delta T_{s,\text{amb}}$	surface-to-ambient temperature difference (°C)
T_{TEC}	surface temperature of the TEC (°C)
$T_{\text{TEC,min}}$	minimum cooling temperature achieved by the TEC (°C)
$U_{\max}$	maximum voltage that can be applied to a Peltier module (V)
$\dot{V}_{\text{out}}$	outlet-air volumetric flow rate ($\text{m}^3 \text{s}^{-1}$)
V_M	voltage applied to the DC motor (V)
V_P	voltage applied to the Peltier module (V)
w	humidity ratio (absolute humidity) ($\text{g kg}_{\text{da}}^{-1}$)
w_{amb}	ambient humidity ratio ($\text{g kg}_{\text{da}}^{-1}$)
w_{out}	outlet humidity ratio ($\text{g kg}_{\text{da}}^{-1}$)
Δw	change in humidity ratio ($\text{g kg}_{\text{da}}^{-1}$)

1. Introduction

1.1. Necessity of wearable coolers in both indoor and outdoor environments

In indoor environments, traditional compressor-based air-conditioners suffer from inherently low energy efficiency and the incapability to account for individual differences [1–3]. Since these air-conditioners have to cool the entire volume of indoor air, significant energy losses occur due to heat dissipation through walls, floors, and ceilings, further reducing efficiency, as illustrated in Fig. 1. According to the International Energy Agency, cooling accounted for approximately 10% of global electricity demand in 2023 [4]. In outdoor environments, meanwhile, heat-related deaths have increased significantly due to more frequent heat waves and rising temperatures, as reported by

the United States Environmental Protection Agency [5]. Additionally, personal protective equipment (PPE), extensively used in medical settings [6], particularly during the COVID-19 pandemic [7,8], has presented challenges in thermal comfort and regulation due to its high insulation properties [9–11].

Compared to traditional whole-space cooling systems [12,13], wearable coolers can improve personalized thermal comfort with potentially lower cooling energy demand by directly cooling the body surface rather than the entire surrounding air volume. However, wearable coolers are not intended to replace building ventilation systems, which remain essential for indoor air quality, fresh-air supply, and contaminant removal. This direct and localized approach also allows better adaptation to individual thermal preferences.

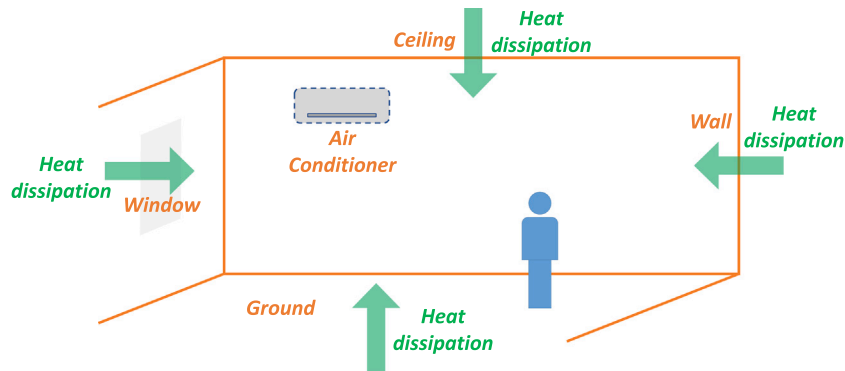


Fig. 1. Illustration of heat dissipation channels in traditional air-conditioners within indoor environments.

Personal cooling systems (PCS), designed to alleviate heat stress in hot environments [12–14], have emerged as promising, energy-efficient cooling technologies and have become a hot topic in recent years. By directly cooling the human body, PCS fundamentally circumvent the low energy efficiency inherent to traditional air-conditioners. However, many PCS implementations, such as liquid cooling garments (LCG) [15, 16] and ice cooling garments (ICG) [17], are too heavy to carry comfortably or require continuous power through tethered cords, making them impractical for outdoor use. Miniaturization of cooling devices remains a critical challenge. Moreover, air-cooling garments (ACG) [18], which do not reduce air temperature directly, exhibit limited cooling capability and may even exacerbate heat stress if the ambient air temperature exceeds skin temperature.

1.2. Weakness of conventional thermoelectric coolers

Existing wearable cooling technologies mainly include liquid cooling garments (LCGs), ice cooling garments (ICGs), air-cooling garments (ACGs), and thermoelectric-cooler (TEC)-based devices. LCGs and ICGs often provide strong cooling performance, but they are typically heavy or inconvenient for mobile use. ACGs are generally lighter, but they usually do not reduce the air temperature directly and therefore provide limited cooling under very hot conditions. TEC-based devices are compact and electrically driven, making them attractive for wearable use, but their practical performance is often limited by low coefficient of performance (COP), battery burden, warm exhaust, and insufficient real-world thermal comfort evaluation. Due to their compact size, thermoelectric coolers (TECs) have been widely adopted in wearable cooling applications in existing literature and commercial markets. Suen et al. [19] developed a TEC-based wearable air-conditioned mask weighing approximately 284 g, which remains relatively heavy for wearable devices. The Sony Reon Pocket [20], designed by Sony Corporation, is compact enough to be discreetly worn on the upper back. Nevertheless, the high power consumption of TEC-based wearable coolers severely restricts their usability [21–23]. Additionally, the inherent warm exhaust emitted by the Sony Reon Pocket causes considerable discomfort for users [24].

Lou et al. developed a TEC-based air-conditioned undergarment using tubes to deliver cold air [25]. They further advanced this concept of PCS by integrating cooling and dehumidifying systems specifically designed for PPE users, again utilizing TECs [26]. Despite enhancements such as novel fin structures improving heat transfer and airflow, these solutions still do not adequately address the inherent size and weight issues due to the low energy efficiency of TECs. Numerous studies report that TECs have significantly lower coefficients of performance (COP) compared to compressor-based air-conditioners [27], resulting in high electricity consumption and substantial burden on Li-ion batteries.

Consequently, current TEC-based wearable coolers typically rely on conductive cooling, which directly cools the skin surface but provides a limited cooling experience [28]. They fail to achieve a two-stage cooling strategy—first cooling a heat sink and subsequently using that cooled heat sink to cool the air, since such an approach would necessitate larger and heavier TECs and batteries, reducing overall device portability and usability. Additionally, excessively low conductive cooling temperatures carry a risk of frostbite, further constraining cooling performance [29].

1.3. Potential of latent heat of water evaporation for cooling

Water evaporation, driven by its high latent heat and the ubiquity of water, offers strong potential for compact cooling. In this work, we treat portable water as a renewable energy source (RES)-equivalent latent-heat carrier that enhances hot-side heat rejection in TECs. Approximately 50% of solar energy absorbed by the Earth's surface drives evaporation, corresponding to a global average energy flux of about 80 W m^{-2} [30–32]. Cavusoglu et al. [33] further showed that natural evaporation can achieve power densities up to 10 W m^{-2} , about three times that of contemporary wind power.

From a portable thermal management perspective, the latent heat associated with water evaporation provides a high energy density for heat absorption (approximately 2429.8 J g^{-1} at 30°C), which exceeds the typical energy density of Li-ion batteries ($360\text{--}954 \text{ J g}^{-1}$) and enables efficient cooling with minimal electrical input. In addition, water refilling (and similarly, liquid-fuel refueling) can be completed much faster than recharging Li-ion batteries, which is critical for uninterrupted thermal regulation in practical use. Although gasoline has a much higher chemical energy density (44000 J g^{-1}), it is neither renewable nor environmentally friendly. In contrast, water is abundant, safer, and easy to replenish in common settings such as homes, schools, and offices. These advantages make water evaporation an attractive and practical latent-heat carrier for wearable thermal management devices.

Evaporative cooling systems leveraging water evaporation, such as Direct Evaporative Coolers (DECs) and Indirect Evaporative Coolers (IECs), have emerged as energy-efficient alternatives to traditional air-conditioners. DECs pass airflow directly through water-saturated pads, cooling the air but increasing its relative humidity (RH). IECs, in contrast, use a two-stream configuration: primary air is cooled indirectly through a heat exchanger, while secondary air undergoes direct evaporation. However, both DECs and IECs are fundamentally constrained by the wet-bulb temperature of the ambient air. To overcome this limitation, this study integrates capillary-driven evaporation with a TEC, enabling cooling below the wet-bulb limit while simultaneously addressing the high electricity burden of conventional TEC-based wearable coolers.

1.4. Paper contributions

The contributions and novelties of this study are summarized as follows. The novelty of this work lies in the wearable miniaturization and specific integration concept of a water–electricity hybrid energy system for a wearable air-conditioner, in which capillary-driven water evaporation is employed to enhance TEC hot-side heat rejection in a compact configuration. Compared with prior TEC-based wearable cooling studies that rely solely on electrical energy, the proposed approach aims to achieve comparable cooling performance with substantially lower electrical power consumption under hot ambient conditions. Compared with currently used TEC-evaporative systems, the proposed approach further differs by using water as a portable RES-equivalent latent-heat carrier and by combining capillary-driven water supply with forced convection to accelerate evaporation and enhance TEC hot-side heat rejection. In addition, the proposed device realizes continuous direct cold-air delivery with an optional dehumidification mode in a lightweight prototype, whereas existing TEC-based PCS solutions typically offer only conductive cooling and suffer from warm exhaust discomfort. A new evaluation metric is also introduced to quantify the electrical-power-saving benefit of the hybrid system relative to a conventional TEC under the same cooling target.

2. Methodology

To overcome the well-known limitation that the performance of a TEC is governed by how rapidly heat can be removed from its hot side [34,35], in our preliminary work [36], we proposed a water–electricity hybrid energy system. In this system, latent heat from water evaporation is extracted through capillary-driven evaporation within a pin-fin heat sink, closely coupled to the hot side of a Peltier module. This approach enhances the effective heat dissipation capacity without requiring bulky pumps or fans, making it particularly suitable for wearable cooling applications. The following subsections detail the design and fabrication of the Indirect Capillary-Evaporative Cooler (ICEC), its integration with the TEC (ICEC–TEC), and the comparative experiment conducted to evaluate the cooling capabilities of the ICEC, TEC, and ICEC–TEC, and the introduction of a novel performance metric for assessing the efficiency of the hybrid energy system.

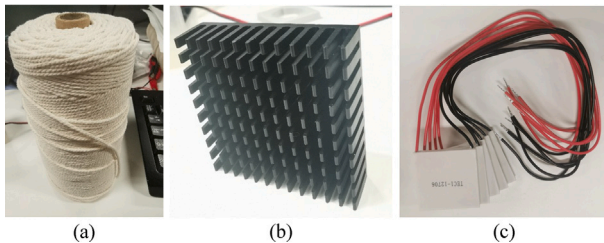


Fig. 2. Cotton yarns (a), aluminum pin-fin heat sink (b), and Peltier modules (c) used in this study.



Fig. 3. Illustration of water absorption by cotton yarns arranged within the heat sink and immersed in a water tank.

2.1. Indirect capillary-evaporative cooler (ICEC)

Traditional IEC systems typically require continuous water spraying onto wicked materials, necessitating reservoirs and pumps to recirculate water using gravity [37–39], resulting in bulky systems. For wearable coolers, miniaturization is essential. In this study, the capillary effect is utilized to replace traditional pumps and spray mechanisms. Zhao et al. [40] comparatively studied various IEC materials (fibers, ceramics, carbon, metals, and zeolite), concluding that thermal properties (thermal conductivity and water-retention) of capillary materials have limited influence on heat and mass transfer. Thus, basic and inexpensive cotton yarns were selected as the wicks for this study, despite the availability of high-performance capillary materials such as Coolmax fabric [41,42]. The cotton yarns have a diameter of 1.2 mm, as shown in Fig. 2(a).

An aluminum pin-fin heat sink was selected for the ICEC, as shown in Fig. 3, and its specifications are summarized in Table A.1. Fig. 3 shows the layout of the cotton yarns arranged inside the heat sink and an illustration of the cotton yarns absorbing water from a water tank. The cotton yarns were evenly cut into equal-length pieces and arranged inside every other column formed by the fins of the heat sink, tiled into three layers. The length of each cotton yarn piece was set to 70 mm. By immersing the cotton yarns in water, water could be transported from the bottom to the top of the yarns due to the capillary effect. The cotton yarns were arranged inside the heat sink so that they minimally affect both the device's volume and weight, as cotton is light. Since water delivery to the heat sink is wick-fed by capillarity (no sprays or jets), no free water is discharged during operation. An open water tank was used to simplify the experimental setup and allow direct observation. A product-oriented design will compress and clamp the wicks where they pass through the tank wall, using sealed pass-throughs to suppress leakage under normal body movements.

A 3D-printed fan (radius: 20 mm, width: 6 mm) driven by a DC motor was implemented to supply airflow to the heat sink, as shown in Fig. 4(b) and the specifications of the DC motor are summarized in Table A.1. The

cotton yarn arrangement ensures that airflow is delivered to every corner of the heat sink and the cotton yarns, allowing every fin of the heat sink to be simultaneously contacted by both the cotton yarns and the airflow. Instead of using a plate-fin heat sink, the pin-fin heat sink allows air to flow through the lateral sides of the intersections between the cotton yarns and the fins, enhancing the evaporation rate. As a result, both the water evaporation rate and the cooling effect are increased. Compared to conventional TEC-based wearable coolers, the ICEC leverages capillary-driven evaporation for conductive cooling.

A 3D design application, Shapr3D [43], was employed to design the ICEC framework. Fig. 5 shows the ICEC framework dimensions and structure, providing structural and dimensional references to support reproducibility of the device fabrication. The ICEC framework comprises a bottom water tank ($40 \text{ mm} \times 27.5 \text{ mm} \times 17 \text{ mm}$, 18.7 cm^3), a motor support structure ($43 \text{ mm} \times 19 \text{ mm} \times 43 \text{ mm}$) at the top, and four arms ($5 \text{ mm} \times 17.4 \text{ mm} \times 5 \text{ mm}$ each) fixing the heat sink. Wall thicknesses were set to 1.5 mm, except for the water tank's front wall (4.9 mm). A rectangular vent ($40 \text{ mm} \times 10 \text{ mm}$) between the water tank and the cooling fan was fabricated to facilitate airflow for evaporation. The diameter of the big cylinder in the motor support structure was set to 40 mm to keep consistent with the heat sink size.

In this study, all polymer parts were fabricated by fused-filament 3D printing (Flashforge Guider II) using transparent polylactic acid (PLA) filament. The specifications of the Flashforge Guider II 3D printer are detailed in Table A.1. Fig. 7(a) displays the 3D-printed ICEC framework, including the DC motor and fan. The assembled ICEC is shown in Fig. 7(b). Fig. 7(e, f) shows the DC motor and the 3D-printed fan, respectively.

2.2. TEC

A conventional TEC (Fig. 4(a)) was designed by simply removing the cotton yarns from the ICEC and arranging a Peltier module (Fig. 2(c)) in front of the heat sink, with its hot side tightly attached to the heat sink using a thin layer of thermal grease, as illustrated in Fig. 7(c). No separate analytical assumption for thermal contact resistance was introduced in this experimental study. Instead, the contacting components were tightly assembled with a thin thermal-grease layer, and the relevant thermal-grease specifications are listed in Table A.1. The Peltier module consists of 127 semiconductor couples within an area of $40 \text{ mm} \times 40 \text{ mm}$, with two ceramic electrical insulators on both sides. The specifications of the Peltier module are listed in Table A.1. The extremely low costs of the Peltier module, heat sink, and DC motor highlight the affordability and scalability of the proposed device design.

2.3. Water–electricity hybrid energy system-based ICEC–TEC

By applying the same thermal grease to tightly attach the hot side of the Peltier module to the heat sink surface of the ICEC, a novel water–electricity hybrid energy system-based cooler, the ICEC–TEC, is proposed, as illustrated in Fig. 4(c). Fig. 7(d) shows the fabricated ICEC–TEC.

2.4. ICEC–TEC-based novel air-conditioner

By applying the same thermal grease to tightly attach the surface of another heat sink to the cold side of the ICEC–TEC, enclosing the surface and left and right sides of the cold-side heat sink with walls, placing an air pump at the bottom of the cold-side heat sink to provide airflow, fabricating an air nozzle at the top of the cold-side heat sink to deliver cooled air for human use, enlarging the water tank of the ICEC–TEC to cover both heat sinks, and installing a wall directly beneath the Peltier module to divide the water tank into two sections and isolate the airflow between them, while leaving a small channel at the bottom to allow water communication, a novel ICEC–TEC-based air-conditioner is proposed, as illustrated in Fig. 4(d) (This novel air-conditioner is protected by Japanese Patent JP2024-123456 [44]). The design of the water tank covering the cold-side heat sink is intended to collect condensed water

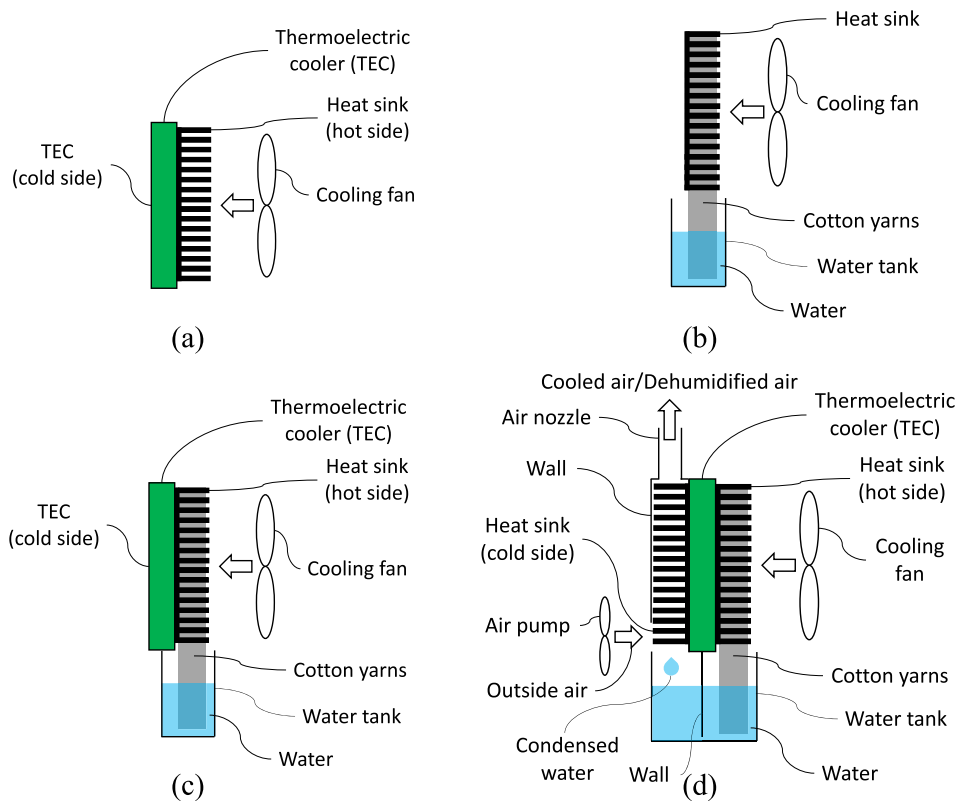


Fig. 4. Schematic of (a) the TEC, (b) ICEC, (c) ICEC-TEC, and (d) ICEC-TEC-based novel air-conditioner.

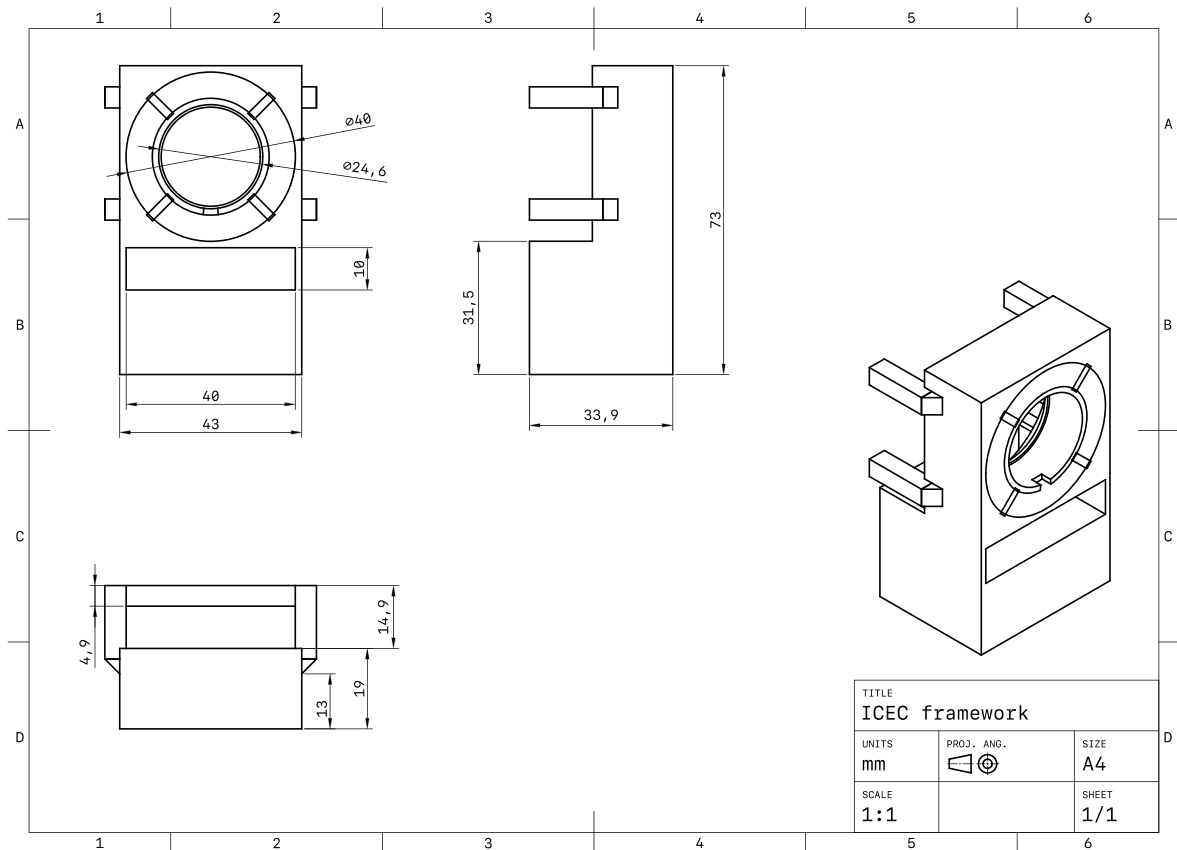
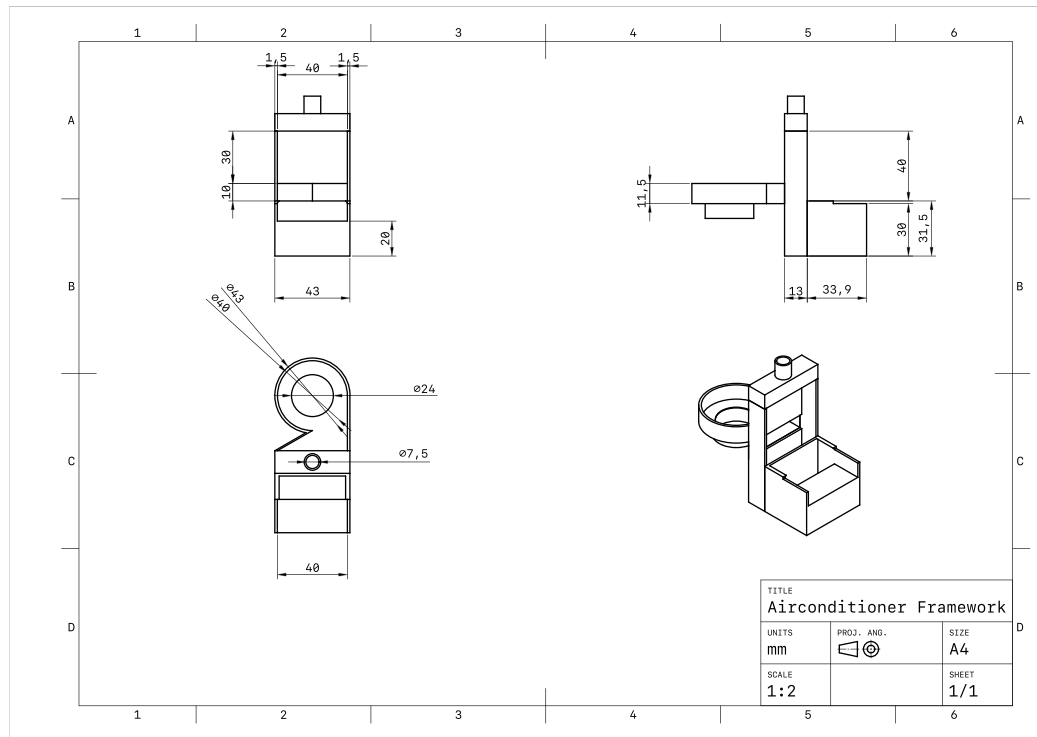
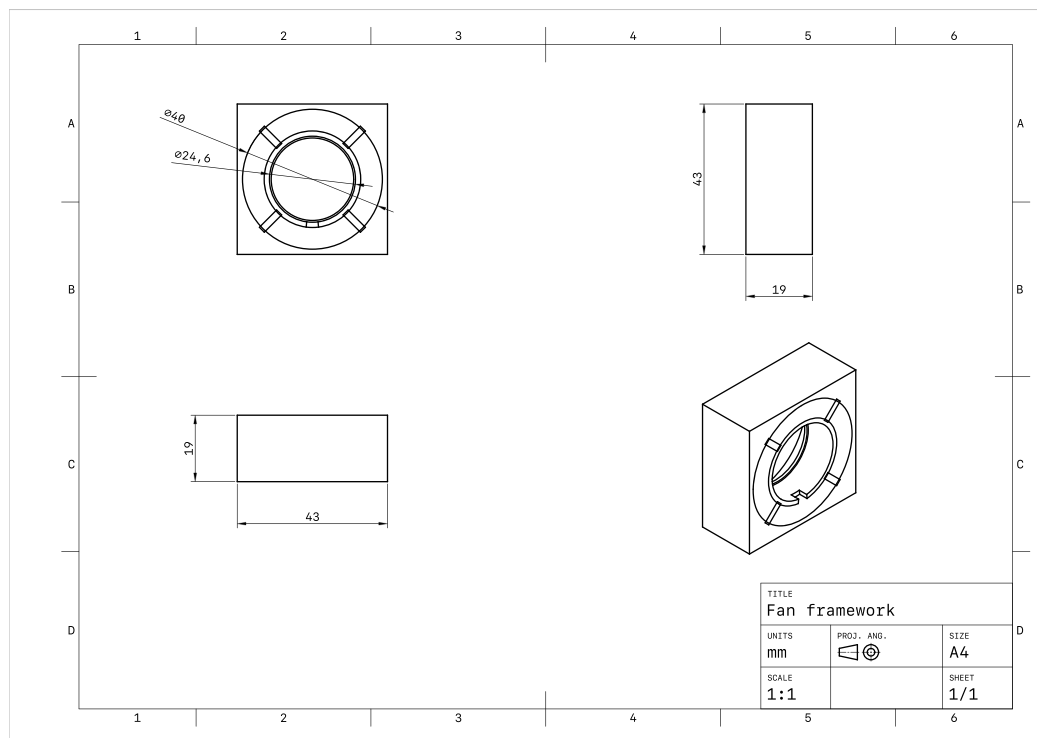


Fig. 5. Three-dimensional design of the ICEC framework (rendered in Shapr3D v5.831.0). The orthographic (three-view) drawing provides the dimensional reference to the actual device, and all linear dimensions are given in millimetres.



(a)



(b)

Fig. 6. Three-dimensional designs of the ICEC-TEC-based air-conditioner framework (a) and the fan framework (b) (rendered using Shapr3D v5.831.0). The orthographic (three-view) drawing provides the dimensional reference to the actual device, and all linear dimensions are given in millimetres.

produced through air dehumidification and supply it to the cotton yarns in the hot-side heat sink.

Fig. 6 shows the 3D designs and dimensions of the prototypes of the ICEC-TEC-based air-conditioner and fan frameworks, providing

structural and dimensional references to support reproducibility of the device fabrication. Except for the nozzle wall thickness (1 mm), all other wall thicknesses were set to 1.5 mm. To simplify prototyping and isolate baseline behavior, the small channel at the bottom of the partition wall

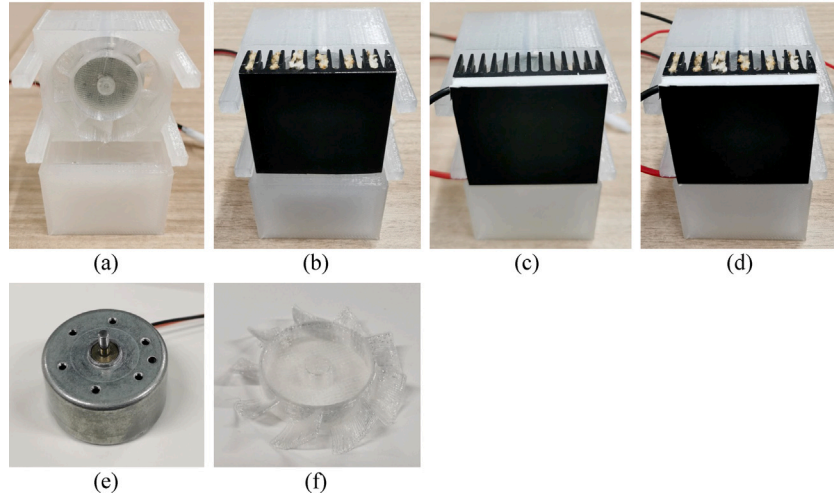


Fig. 7. Components of the cooling systems: (a) ICEC framework, (b) ICEC, (c) TEC, (d) ICEC-TEC, (e) DC motor, and (f) fan. The heat sink and Peltier module have a footprint of 40 mm × 40 mm, which provides a dimensional reference for the assembled devices.

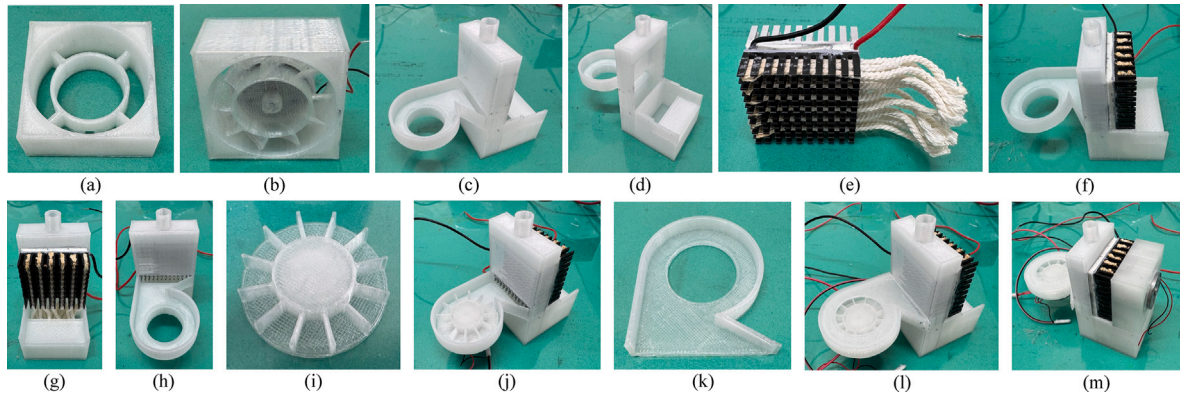


Fig. 8. Fabrication process of the ICEC-TEC-based air-conditioner: (a) motor support framework, (b) cooling fan, (c–d) ICEC-TEC-based air-conditioner framework (front and back views), (e) assembly of the Peltier module, cooling heat sink (silver), and heat dissipation heat sink (black) using the thermal grease, (f–h) insertion of the assembly into the framework, (i) air pump fan, (j) assembly of the air pump using the air pump fan and the same DC motor, (k) lid, (l) attachment of the lid to the air pump, and (m) completed ICEC-TEC-based air-conditioner. The heat sink and Peltier module have a footprint of 40 mm × 40 mm, which provides a dimensional reference for the assembled device.

between the two water tanks was intentionally omitted in this build. Consistent with this choice, the prototype used an open water tank and an unthrottled wick feed. Closed-loop condensate return was not implemented in the current study. Fig. 8 shows the fabrication process of the ICEC-TEC-based air-conditioner. Similar to the ICEC framework, a rectangular vent (40 mm × 10 mm) was fabricated between the hot-side heat sink and the cooling fan to facilitate airflow for evaporation in the hot-side heat sink.

The fully assembled ICEC-TEC-based air-conditioner weighs only 170.8 g (including the 3D-printed objects, two same DC motors, one Peltier module, two same heat sinks with different colors, and the hot-side water tank fully filled, while the cold-side water tank is initially empty), making it lightweight and suitable for wearable applications, especially compared with previously reported TEC-based devices. The volume of the hot-side water tank (40 mm × 30.9 mm × 17 mm) is 21.012 cm³, whereas the volume of the cold-side water tank (40 mm × 11.5 mm × 30 mm) is 13.8 cm³.

2.5. Novel performance metric of the ICEC-TEC

In this study, instead of solely relying on the COP to evaluate cooling devices, we exclusively propose a novel performance metric $Q_{no\ water}$, as

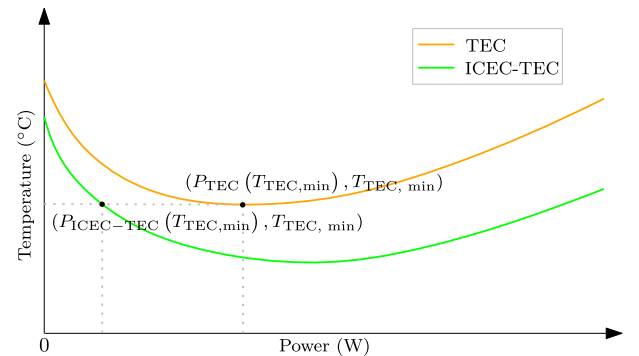


Fig. 9. Schematic illustration of the novel performance metric $Q_{no\ water}$ for evaluating the ICEC-TEC.

illustrated in Fig. 9 and Eq. (1). Importantly, Fig. 9 is a schematic illustration designed to conceptually explain this metric, rather than a plot of measurement data. In all cases, the reference TEC and the ICEC-TEC use the same 40 mm × 40 mm Peltier module and 40 mm × 40 mm heat sink,

so $Q_{\text{no water}}$ is defined for an identical cold-side footprint and directly comparable geometry. The meaning of $Q_{\text{no water}}$ is as follows: when the ICEC-TEC is in the dry state, functionally equivalent to a conventional TEC, namely, when the water tank is empty and no water evaporation is available to enhance cooling, the device solely relies on electrical input and the power required by the TEC to reach its minimum cooling temperature $T_{\text{TEC,min}}$ is recorded as $P_{\text{TEC}}(T_{\text{TEC,min}})$. When the cotton yarns in the ICEC-TEC are fully saturated with water, the power required by the ICEC-TEC to achieve the same cooling temperature $T_{\text{TEC,min}}$ is recorded as $P_{\text{ICEC-TEC}}(T_{\text{TEC,min}})$. Thus, $Q_{\text{no water}}$ is defined as the quotient of the $P_{\text{TEC}}(T_{\text{TEC,min}})$ and the $P_{\text{ICEC-TEC}}(T_{\text{TEC,min}})$, making it a dimensionless performance metric. Similar to the COP, a higher $Q_{\text{no water}}$ indicates greater efficiency of the ICEC-TEC. It should be noted that $Q_{\text{no water}}$ is defined here as a device-level comparative metric rather than a direct thermal comfort metric, and the equal cold-side temperature is used only as a common cooling target for controlled comparison under comparable geometry. Accordingly, $Q_{\text{no water}}$ is intended as a complementary power-saving metric rather than a substitute for COP or a direct ratio of the actual cooling power delivered to the user. In addition, $Q_{\text{no water}}$ is sensitive to ambient temperature and relative humidity through their influence on the hot-side evaporation rate, while its current definition is based on the comparative ICEC-TEC / TEC cooling experiments and therefore does not directly incorporate the airflow-rate setting of the

final air-conditioner.

$$Q_{\text{no water}} = \frac{P_{\text{TEC}}(T_{\text{TEC,min}})}{P_{\text{ICEC-TEC}}(T_{\text{TEC,min}})} \quad (1)$$

3. Experimental setup for cooling performance evaluation

To enable fair, directly comparable evaluation across ambient temperature T_{amb} and ambient relative humidity RH_{amb} , we conducted the same set of experiments on the ICEC, TEC, ICEC-TEC, and the ICEC-TEC-based air-conditioner under three different room-ambient scenarios following a controlled-variable method. Scenarios I and II vary T_{amb} from slightly hot to hot while maintaining nearly the same moderate RH_{amb} , whereas Scenarios II and III vary RH_{amb} from moderate to high while maintaining nearly the same hot T_{amb} . Each scenario was established using the room air-conditioner temperature setpoint and humidifiers. The target setpoints are summarized in Table 1. The experiments were conducted only after T_{amb} and RH_{amb} became steady. The actual ambient conditions reported are the inlet-air states measured at the ICEC-TEC-based air-conditioner inlet in a baseline configuration (air pump at 5.00 V, with the Peltier module and hot-side fan turned off). These values therefore represent the actual ambient conditions used for all subsequent tests, as shown in Table 3. Within each scenario, we first

Table 1

Temperature-power characteristics of the ICEC, TEC, and ICEC-TEC under the three ambient scenarios (bold font: lowest temperature and its corresponding power for each device in each ambient scenario).

Scenario (T_{amb} , RH_{amb})	ICEC			TEC			ICEC-TEC		
	V_{M} (V)	P_{ICEC} (W)	T_{ICEC} (°C)	V_{P} (V)	P_{TEC} (W)	T_{TEC} (°C)	V_{P} (V)	$P_{\text{ICEC-TEC}}$ (W)	$T_{\text{ICEC-TEC}}$ (°C)
I (28 °C, 50%)	0.00	0.000	26.1	0.00	0.000	30.1	0.00	0.000	27.3
	0.50	0.004	25.9	1.00	0.315	24.2	1.00	0.320	21.5
	1.00	0.009	25.8	2.00	0.919	18.6	2.00	0.931	16.1
	1.50	0.015	25.4	3.00	1.961	13.5	3.00	1.988	10.5
	2.00	0.026	25.5	4.00	3.442	9.5	4.00	3.482	7.5
	2.50	0.034	25.5	5.00	5.283	9.3	5.00	5.403	5.5
	3.00	0.048	25.3	6.00	7.474	8.9	6.00	7.756	3.5
	3.50	0.062	25.2	7.00	10.079	9.8	7.00	10.379	5.1
	4.00	0.079	25.1	8.00	12.899	10.4	8.00	13.469	5.3
	4.50	0.103	24.9	9.00	16.049	11.5	9.00	16.759	6.6
	5.00	0.129	24.7	10.00	19.329	13.6	10.00	20.379	7.7
II (32 °C, 50%)	5.50	0.159	24.6	11.00	22.809	16.4	11.00	24.349	8.8
	6.00	0.197	25.1	12.00	26.449	19.8	12.00	28.439	10.9
	0.00	0.000	32.7	0.00	0.000	33.8	0.00	0.000	31.4
	0.50	0.004	32.3	1.00	0.319	27.7	1.00	0.322	25.4
	1.00	0.009	32.1	2.00	0.907	22.7	2.00	0.919	20.6
	1.50	0.015	32.2	3.00	1.908	18.9	3.00	1.941	15.8
	2.00	0.026	32.4	4.00	3.333	15.8	4.00	3.376	12.4
	2.50	0.034	32.2	5.00	5.138	14.8	5.00	5.208	11.3
	3.00	0.048	31.9	6.00	7.305	13.6	6.00	7.448	9.3
	3.50	0.062	31.7	7.00	9.824	13.1	7.00	10.049	8.9
	4.00	0.079	31.9	8.00	12.599	14.2	8.00	12.949	9.8
III (32 °C, 70%)	4.50	0.103	32.1	9.00	15.639	15.4	9.00	16.179	10.1
	5.00	0.129	31.8	10.00	18.859	17.3	10.00	19.694	10.8
	5.50	0.159	31.9	11.00	22.339	19.5	11.00	23.464	12.2
	6.00	0.197	32.0	12.00	25.919	22.4	12.00	27.449	14.3
	0.00	0.000	31.7	0.00	0.000	34.0	0.00	0.000	31.0
	0.50	0.004	31.1	1.00	0.322	28.1	1.00	0.316	24.7
	1.00	0.009	30.4	2.00	0.917	22.6	2.00	0.918	20.3
	1.50	0.015	29.8	3.00	1.926	19.1	3.00	1.950	15.9
	2.00	0.026	30.0	4.00	3.378	15.9	4.00	3.392	12.8
	2.50	0.034	29.9	5.00	5.168	15.2	5.00	5.208	11.7
	3.00	0.048	30.2	6.00	7.381	13.4	6.00	7.490	9.7
	3.50	0.062	30.1	7.00	9.913	13.0	7.00	10.049	9.6
	4.00	0.079	30.0	8.00	12.649	14.5	8.00	12.924	10.2
	4.50	0.103	29.8	9.00	15.969	15.5	9.00	16.164	10.6
	5.00	0.129	30.3	10.00	19.279	17.7	10.00	19.664	11.7
	5.50	0.159	30.4	11.00	22.824	19.8	11.00	23.374	13.2
	6.00	0.197	30.2	12.00	26.489	22.5	12.00	27.334	15.6

Values shown in the Scenario column are the target ambient setpoints (T_{amb} , RH_{amb}). The actual measured ambient inlet conditions used for the tests are reported in Table 3.

characterized the temperature–power behavior of the ICEC, TEC, and ICEC–TEC, and then evaluated the outlet-air cooling and dehumidification performance of the ICEC–TEC-based air-conditioner using the same ambient inlet air, as illustrated in Sections 3.1 and 3.2.

3.1. Cooling performance comparison of the ICEC, TEC, and ICEC–TEC

Comparative experiments were conducted under the three ambient scenarios as shown in Table 1 to evaluate the cooling capabilities of the ICEC, TEC, and ICEC–TEC. The water tank was filled with water using a needle. Two high-precision DC stabilized power supplies were used separately to control the applied voltages of the motor and the Peltier module. The supply voltage and power were monitored on the panel displays of the power supplies, as shown in Fig. 11. The specifications of the DC power supplies are listed in Table A.1.

An infrared camera, Thermo GEAR G100EX, was used to measure the surface temperatures of the ICEC, TEC, and ICEC–TEC. The specifications of the Thermo GEAR G100EX are listed in Table A.1. The camera specifies an accuracy of $\pm 2^\circ\text{C}$ or $\pm 2\%$ (whichever is larger) and a thermal sensitivity of 0.04°C at 30°C (60 Hz), which is relatively high. The camera was placed directly opposite the surface of the heat sink or Peltier module, as shown in Fig. 10(a), to ensure that the heat sink or Peltier module appeared as a square in the thermal images. Since different materials have different thermal emissivities, the same matte black adhesive tapes were applied to the measured surfaces of the heat sink or Peltier module on the ICEC, TEC, and ICEC–TEC to reduce emissivity-related uncertainty in the infrared measurements and ensure fair relative comparison among the three devices, as shown in Fig. 7(b–d). Since the tapes were applied identically to all three devices, any effect of the tapes on elevating the measured temperature would result in a common, systematic overestimation. This means that the absolute temperature values may be slightly higher, but the relative comparisons among the ICEC, TEC, and ICEC–TEC remain valid. Therefore, the reported temperatures should be interpreted as upper-bound values, providing a conservative assessment of cooling performance. Although the nominal absolute accuracy of the infrared camera is limited, the same camera, viewing geometry, matte black tape treatment, and image-analysis procedure were consistently applied to all three devices. Therefore, the infrared measurements in this study are suitable and reasonable for controlled relative comparison among the ICEC, TEC, and ICEC–TEC.

Fig. 10(b) shows an example thermal image of the ICEC–TEC. In Fig. 10(b), the surface of the Peltier module was manually covered with a square frame (A) using the auxiliary software of the Thermo GEAR G100EX. The average temperature within the square frame area was then automatically calculated by the software.

For the ICEC, the motor voltage was set from 0.00 V to 6.00 V at intervals of 0.50 V. For the TEC and ICEC–TEC, the voltage of the Peltier module was set from 0.00 V to 12.00 V at intervals of 1.00 V. When the voltage of the Peltier module was 0.00 V, the motor voltage was also set to 0.00 V. When the Peltier module voltage was nonzero, the

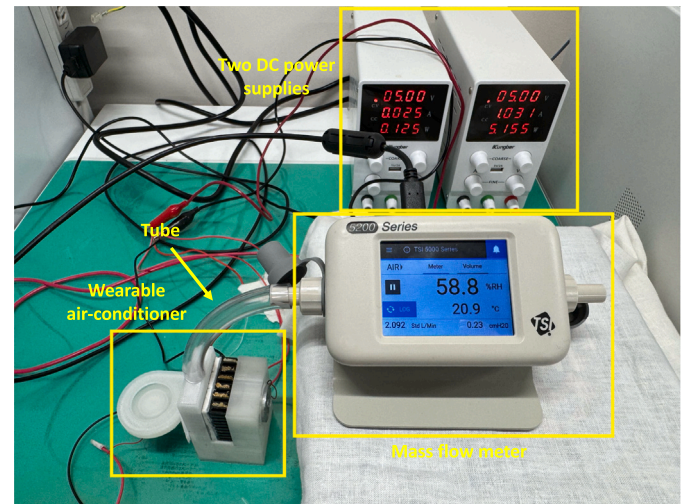


Fig. 11. Measurement of cooling air velocity, temperature, and RH using the TSI mass flow meter 5230-2.

motor voltage was fixed at 5.00 V (rated voltage) throughout the measurement to follow the controlled-variable method and isolate the effect of Peltier module power on the results. After adjusting the voltage, we waited 2 min for stabilization and recorded the temperature only after the IR trace visibly plateaued. This 2-min dwell corresponds to approximately 4–5 estimated thermal time constants for the assembly (aluminum heat sink and wetted cotton yarns), i.e., 98% approach to steady state.

3.2. Performance evaluation of the ICEC–TEC-based air-conditioner

To evaluate the air cooling and dehumidification functions of the ICEC–TEC-based air-conditioner, qualitative evaluation experiments were conducted. During the measurement, the Peltier module and the cooling fan shared a single DC power supply in a parallel connection (higher TEC power requires greater heat dissipation), while the air pump used a separate DC power supply. The control voltages for the air pump, cooling fan, and Peltier module are listed in Table 3. A mass flow meter (TSI Mass Flow Meter 5230-2) was connected to the air nozzle of the air-conditioner using the plastic tube provided with the mass flow meter to measure the outlet-air temperature (T_{out}), relative humidity (RH_{out}), and volumetric flow rate ($\dot{V}_{\text{out}}$), as shown in Fig. 11, with specifications listed in Table A.1. The inlet air was the room ambient (open system, no recirculation) and was recorded as the ambient condition. During the measurements, the devices were placed on a horizontal table with the air nozzle directed vertically upward, i.e., opposite to gravity. The air-flow pathway of the device is illustrated in Fig. 4(d). Measurements at the nozzle represent the supply air delivered to a user.

Firstly, the device was kept in a dry state, and only the air pump was turned on at a 5.00 V working voltage, while the Peltier module and fan remained off, to measure the T_{amb} and RH_{amb} . Secondly, water was filled into the water tank and the system was left until full saturation of the cotton yarns was achieved. Next, the Peltier module and cooling fan were fixed at a 5.00 V working voltage, and the air pump voltage was adjusted to 1.00 V (low-flow) and 5.00 V (high-flow) respectively. The measurements of the corresponding total power consumption of the Peltier module, cooling fan, and air pump (P_{total}), T_{out} , RH_{out} , and $\dot{V}_{\text{out}}$ were conducted 5 min after adjusting to new setpoints to ensure that a steady state had been reached.

4. Results and discussion

4.1. Cooling performance of the ICEC, TEC, and ICEC–TEC

$$T(P) = a \cdot \exp(-bP) + c \quad (2)$$

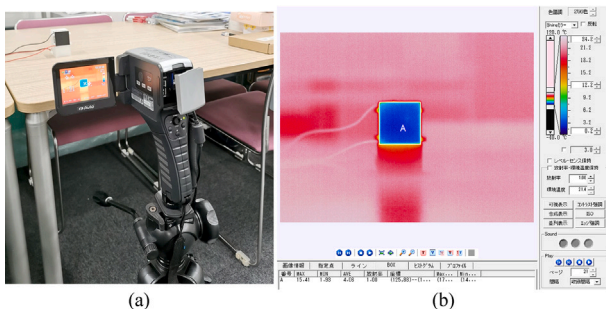


Fig. 10. Surface temperature measurement using the Thermo GEAR G100EX (a) and thermal image analysis on the software interface (b).

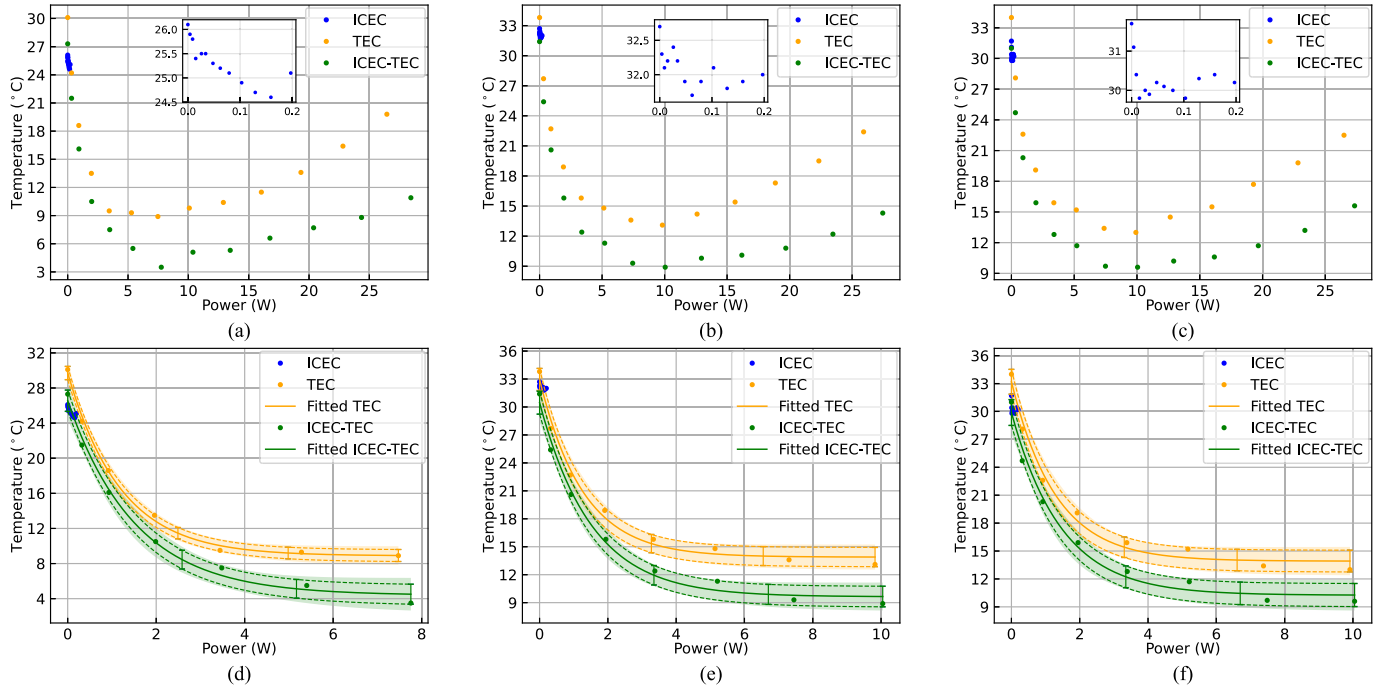


Fig. 12. Temperature–power characteristics of the ICEC, TEC, and ICEC–TEC under three ambient scenarios: (a–c) measured data and (d–f) exponentially fitted curves for scenarios I–III, respectively.

The measured total power and average surface temperatures of the ICEC, TEC, and ICEC–TEC are shown in Table 1. In Table 1, the power of the ICEC refers to the motor power, while the power of the TEC and ICEC–TEC refers to the combined power of the motor and the Peltier module. Fig. 12(a–c) shows the original data of the temperature–power characteristics of the ICEC, TEC, and ICEC–TEC. It is noticeable that for the TEC and ICEC–TEC, when the power of the Peltier module exceeds a certain value, the temperature stops decreasing and begins to rise due to the capacity limitation of the Peltier module. The standalone ICEC is included here mainly as a control case to isolate the cooling contribution of capillary-driven evaporation alone, rather than as the main target device of this study. Although the standalone ICEC provides only limited cooling capacity, it demonstrates that capillary-driven evaporation can reduce the heat-sink temperature below ambient with very low electrical input, thereby justifying its role as the hot-side heat dissipator in the proposed ICEC–TEC hybrid system. Accordingly, the purpose of including the ICEC curve in Fig. 12 is to clarify the physical mechanism of hybrid performance enhancement, while the main performance comparison of this study remains between the ICEC–TEC and the conventional TEC. In addition, the standalone TEC used the same commercially available conventional square aluminum heat sink (40 mm × 40 mm) as the basis of the hybrid device, rather than a heat sink specially tuned for evaporative operation. This provides a reasonable baseline by isolating the benefit of the proposed evaporative enhancement under the same compact geometry.

As can be observed from Table 1 and Fig. 12(a–c), the ICEC exhibits its highest surface temperature when the cooling fan is off ($V_M = 0$) in all three ambient scenarios. Once the cooling fan is activated ($V_M > 0$), the ICEC surface temperature drops rapidly with very small power input but then varies non-monotonically with increasing motor power, showing noticeable oscillations. This is due to the fact that the ICEC temperature drop is rather modest (no more than 1.9 °C), and part of the apparent point-to-point oscillation may be comparable to the infrared camera measurement uncertainty. In contrast, the TEC attains a larger maximum temperature drop under Scenarios I–III, respectively, but its

cooling performance reverses when the applied power exceeds its capacity. The hybrid ICEC–TEC leverages both evaporative and thermoelectric effects to achieve the greatest cooling, which far outperforms the maximum cooling capacity of the TEC, and reaches a maximum temperature drop under Scenarios I–III, respectively. Similar to the TEC, excessive power input beyond the optimal point leads to a reversal of cooling. In addition, the TEC exhibited an apparently higher surface temperature in the non-operating state than the room ambient, as the matte black adhesive tape absorbs ambient thermal radiation. Therefore, the reported surface temperature drops should be interpreted as conservative estimates, and the true cooling performance of all the devices will be higher than indicated by the measurements.

By observing the data patterns, nonlinear least squares fitting was applied to the temperature and power data of the TEC, and ICEC–TEC to fit the exponential function given by Eq. (2), using the Python SciPy package. In Eq. (2), a , b , and c are real-number parameters ($b > 0$) to be optimized, while P and T represent power and surface temperature, respectively. The exponential form Eq. (2) is chosen since it captures the asymptotic cooling behavior observed physically. As input power increases, (1) TEC performance is progressively constrained by Joule heating and back-conduction on the hot side, and (2) in the ICEC–TEC, the hot-side evaporative heat-rejection enhancement approaches a saturation limit set by the available evaporation rate and ambient conditions. Both effects yield diminishing returns consistent with an exponential-like approach to an asymptote. During the curve fitting process, only the periods in which the temperature monotonically decreased for the TEC and ICEC–TEC were used. The fitted temperature–power characteristic curves of the TEC, and ICEC–TEC are shown in Fig. 12(d–f). The regression in Fig. 12(d–f) visualizes statistical uncertainty in three complementary ways: shaded bands denoting the 95% confidence interval of the mean fit, dashed envelopes indicating the $\pm 1\sigma$ prediction bands, and sparse whisker error bars at representative power levels to show local prediction spread without clutter.

The TEC and ICEC–TEC perform effectively within their respective operating ranges, with the ICEC–TEC providing the deepest and most

energy-efficient cooling overall, whereas the ICEC achieves only a limited temperature drop. However, the ICEC is advantageous in that it can reduce its temperature below the ambient air temperature and thus serve as the heat dissipator for the TEC, enabling heat rejection that conventional air-cooling-type heat sinks cannot achieve since they can only asymptotically approach the ambient air temperature.

Moreover, the cotton yarns arranged inside the heat sink of the ICEC or ICEC-TEC do not take up extra space and contribute almost no additional weight due to their lightness compared to conventional aluminum heat sinks. Nonetheless, a water tank is required, but its volume is offset by the higher latent heat energy density than Li-ion batteries. Furthermore, water is soft, and the water tank can be fabricated from thin, flexible film materials to enhance user experience compared to traditional rigid devices. Moreover, since conventional TEC-based wearable coolers suffer from the inherent warm exhaust issue, as reported by numerous users of the state-of-the-art product, the SONY REON POCKET [45], the ICEC-TEC-based air-conditioner utilizes water evaporation to lower the exhaust temperature. As a result, the user experience could potentially be significantly enhanced.

4.2. $Q_{\text{no water}}$ of the ICEC-TEC

Next, the common logarithmic energy efficiency ratio between the ICEC-TEC and the TEC was calculated as $\log_{10}(P_{\text{TEC}}/P_{\text{ICEC-TEC}})$ at the same surface-to-ambient temperature difference $\Delta T_{\text{s,amb}}$ under the three ambient scenarios, as shown in Fig. 13(a–c). The ratios are evaluated over the overlapping $\Delta T_{\text{s,amb}}$ range shared by both devices using the exponentially fitted curves of the ICEC-TEC and TEC, i.e., from the minimum $\Delta T_{\text{s,amb}}$ up to the maximum $\Delta T_{\text{s,amb}}$ attainable by the TEC on its monotonic cooling branch.

As shown in Fig. 13(a–c), the logarithmic energy efficiency ratio between the ICEC-TEC and the TEC exhibits the same qualitative trend in all three ambient scenarios: the ICEC-TEC is consistently more energy efficient than the TEC over the full overlap range of $\Delta T_{\text{s,amb}}$. Specifically, the ratio is extremely high at the start (smallest $\Delta T_{\text{s,amb}}$), decreases monotonically to a minimum as $\Delta T_{\text{s,amb}}$ increases, and then increases again as the TEC approaches its capacity limit and the required TEC power rises steeply.

The corresponding key points (minimum $\Delta T_{\text{s,amb}}$, minimum $P_{\text{TEC}}/P_{\text{ICEC-TEC}}$, and maximum $\Delta T_{\text{s,amb}}$) and the fitted powers are summarized in Table 2. The very large $P_{\text{TEC}}/P_{\text{ICEC-TEC}}$ values at the minimum $\Delta T_{\text{s,amb}}$ arise because the ICEC provides natural evaporative heat rejection with essentially no electrical input; thus only a very small additional electrical power is needed by the ICEC-TEC to produce a modest sub-ambient temperature drop. Consequently, smaller $\Delta T_{\text{s,amb}}$ corresponds to a larger ratio.

By definition, the $Q_{\text{no water}}$ values of the ICEC-TEC (Section 2.5) correspond to $P_{\text{TEC}}/P_{\text{ICEC-TEC}}$ at the maximum $\Delta T_{\text{s,amb}}$ (the end point of the overlap range), which are 3.19, 4.49, and 4.13 for Scenarios I–III, respectively, as shown in bold font in Table 2, corresponding to electrical power reductions of 68.7%, 77.8%, and 75.8%, respectively. Overall, $Q_{\text{no water}}$ is significantly higher in the hotter Scenarios II and III than in Scenario I, indicating higher ICEC-TEC efficiency at elevated T_{amb} . This is consistent with the fact that higher T_{amb} increases the evaporation rate on the hot side, strengthening evaporative heat rejection. Since water is the dominant energy contributor in this hybrid energy system, the term “water–electricity hybrid energy system” is used instead of “electricity–water hybrid energy system.”

On the other hand, Scenario III shows a slightly lower $Q_{\text{no water}}$ than Scenario II. Since Scenarios II and III share nearly the same hot T_{amb} but

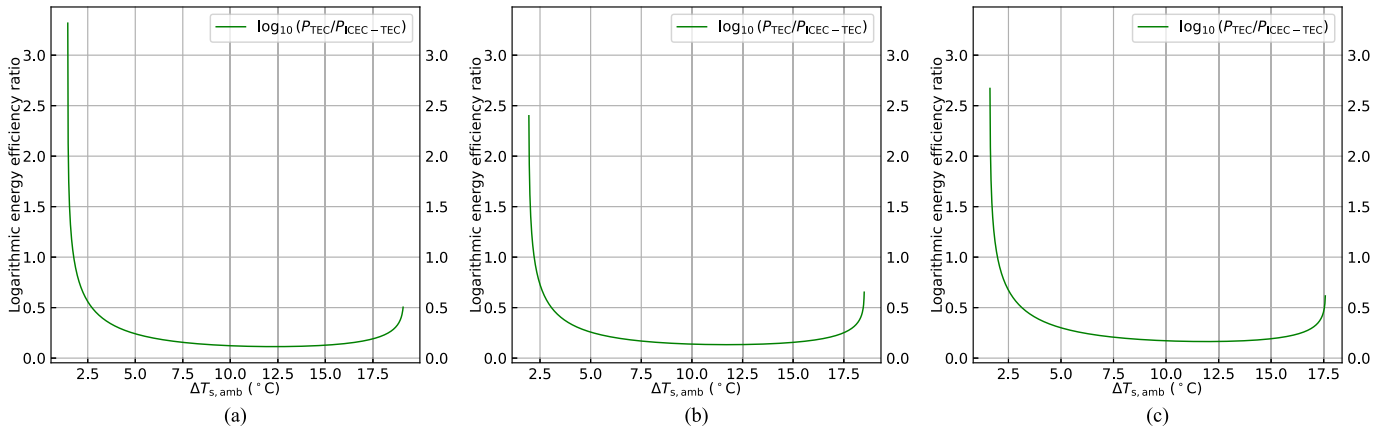


Fig. 13. Logarithmic energy efficiency ratio between the ICEC-TEC and the TEC under three ambient scenarios: (a) Scenario I, (b) Scenario II, and (c) Scenario III.

Table 2

Key values of the energy efficiency ratio between the ICEC-TEC and the TEC under the three ambient scenarios, with the corresponding fitted powers at the same $\Delta T_{\text{s,amb}}$ (bold font: $Q_{\text{no water}}$ of the ICEC-TEC in each ambient scenario).

Scenario (T_{amb} , RH_{amb})	Key point	$\Delta T_{\text{s,amb}}$ (°C)	P_{TEC} (W)	$P_{\text{ICEC-TEC}}$ (W)	$P_{\text{TEC}}/P_{\text{ICEC-TEC}}$	$\log_{10}(P_{\text{TEC}}/P_{\text{ICEC-TEC}})$
I (28 °C, 50%)	min $\Delta T_{\text{s,amb}}$	1.45	0.196063	0.000094	2075.03	3.32
	min $P_{\text{TEC}}/P_{\text{ICEC-TEC}}$	12.28	1.328977	1.022918	1.30	0.11
	max $\Delta T_{\text{s,amb}}$	19.09	7.730044	2.422070	3.19	0.50
II (32 °C, 50%)	min $\Delta T_{\text{s,amb}}$	1.95	0.179241	0.000713	251.23	2.40
	min $P_{\text{TEC}}/P_{\text{ICEC-TEC}}$	11.71	1.309910	0.964151	1.36	0.13
	max $\Delta T_{\text{s,amb}}$	18.51	10.870543	2.418685	4.49	0.65
III (32 °C, 70%)	min $\Delta T_{\text{s,amb}}$	1.62	0.243869	0.000521	468.32	2.67
	min $P_{\text{TEC}}/P_{\text{ICEC-TEC}}$	11.90	1.578979	1.082628	1.46	0.16
	max $\Delta T_{\text{s,amb}}$	17.58	10.109862	2.448383	4.13	0.62

Values shown in the Scenario column are the target ambient setpoints (T_{amb} , RH_{amb}). The actual measured ambient inlet conditions used for the tests are reported in Table 3.

differ in RH_{amb} , this difference indicates that elevated RH_{amb} reduces the hot-side evaporative enhancement, but only modestly within the present range. Notably, as shown in Table 1, even at high RH_{amb} (70.0%), the ICEC-TEC maintains a similar temperature–power characteristic to Scenario II. At the same working voltage (i.e., nearly the same power consumption), the surface temperatures of the ICEC-TEC in Scenarios II and III are close, and a discernible deviation appears as $P_{ICEC-TEC}$ increases, remaining within 1.3 °C. By contrast, RH_{amb} has a negligible influence on the TEC as expected, as no evaporative process is involved and the temperature–power characteristics in Scenarios II and III are nearly identical in Table 1.

Since both higher T_{amb} and higher RH_{amb} increase thermal discomfort, and elevated RH_{amb} also suppresses evaporative cooling, Scenario III simulates the most challenging ambient condition considered in this study. Even under Scenario III, the ICEC-TEC achieves $\Delta T_{s,amb} \approx 17.58$ °C at $P_{ICEC-TEC} \approx 2.45$ W, while the TEC requires $P_{TEC} \approx 10.11$ W to reach the same $\Delta T_{s,amb}$, corresponding to a 75.8% reduction in electrical power, indicating the capability of the ICEC-TEC for low-energy wearable conductive cooling. Practically, for equal run-time, the required battery capacity and mass can therefore be reduced by 75.8%. Assuming the same charger C -rate, charge time scales with capacity. For a fixed battery, the ICEC-TEC runtime extends by about 4.13 times that of the TEC at $T_{TEC,min}$, significantly alleviating the high discharge burden typical of conventional battery-only TECs.

Moreover, the magnitude of $Q_{no\ water}$ depends on the ambient environment. As T_{amb} increases while RH_{amb} remains moderate, the hot-side evaporative driving potential increases, which facilitates evaporation and further reduces the TEC power required to reach $T_{TEC,min}$, thereby increasing $Q_{no\ water}$. Conversely, at very high RH_{amb} (near saturation), the evaporative advantage will theoretically diminish and $Q_{no\ water}$ will tend toward 1. Therefore, the present results already indicate that the proposed hybrid system remains effective under a relevant hot and humid condition (32 °C, 70% RH), while its evaporative advantage is expected to deteriorate progressively as the ambient condition moves closer to saturation.

4.3. Air cooling and dehumidification functions of the ICEC-TEC-based air-conditioner

Table 3 summarizes the air cooling and dehumidification performance of the ICEC-TEC-based air-conditioner. First, the ambient reference values T_{amb} and RH_{amb} were obtained by operating only the air pump at 5.00 V and recording the resulting outlet readings, i.e., T_{out} and RH_{out} , while keeping the Peltier module and cooling fan off. Next, the air pump voltage was set to 1.00 V (low-flow). Under all three ambient scenarios, T_{out} decreased slightly relative to T_{amb} , while RH_{out} decreased markedly relative to RH_{amb} . Since RH is defined as the ratio of the actual water-vapor content to the saturation capacity at a given

temperature, cooling without condensation would increase RH as temperature decreases. Therefore, the simultaneous decreases in T_{out} and RH_{out} provide clear evidence of net moisture removal, confirming both air cooling and dehumidification in the low-flow condition across all three ambient scenarios.

Next, the air pump voltage was increased to 5.00 V (high-flow). Under all three ambient scenarios, the higher airflow further reduced T_{out} relative to the low-flow condition. In contrast, RH_{out} showed scenario-dependent behavior: in Scenarios I and II, RH_{out} became higher than RH_{amb} , whereas in Scenario III it remained lower than RH_{amb} . This increase in RH in Scenarios I and II does not necessarily indicate the absence of condensation, as RH is strongly temperature-dependent and cooling with modest condensation can still lead to a higher RH. Therefore, to rigorously assess whether dehumidification occurred in Scenarios I and II under the high-flow condition, the humidity ratio (absolute humidity) w ($g\ kg_{da}^{-1}$) is calculated using the following Eq. (3). We define $\Delta w = w_{amb} - w_{out}$, where $\Delta w > 0$ indicates net moisture removal:

$$p_v = \phi p_{ws}(T_{db}) \quad (3a)$$

$$w = 0.62198 \frac{p_v}{p_{amb} - p_v} \quad (3b)$$

$$p_{ws}(T_{db}) = 0.61078 \exp\left(\frac{17.2694 T_{db}}{T_{db} + 237.3}\right) [kPa] \quad (3c)$$

$$\Delta w = w_{amb} - w_{out} \quad (3d)$$

where ϕ is RH (fraction), T_{db} is the dry-bulb temperature (°C), p_{ws} is the saturation vapor pressure at T_{db} (kPa), p_v is the water-vapor partial pressure (kPa), $p_{amb} = 101.325$ kPa is the ambient pressure. The resulting Δw values are reported in Table 3.

In Table 3, Δw is positive for both low-flow and high-flow conditions in all three ambient scenarios, confirming net moisture removal. The larger Δw observed in the low-flow condition reflects the longer air residence time and greater opportunity for condensation on the cold-side surfaces. Since condensation releases latent heat, part of the cooling capacity is spent removing this heat of condensation, which can keep T_{out} in the low-flow condition higher than in the high-flow condition even though more moisture is removed. In the high-flow condition, the increased airflow velocity shortens the contact time and can promote re-evaporation of condensate on the cold-side surface, thereby reducing the net moisture removal per unit mass of dry air, even though the outlet air is cooled more.

Under the high-flow condition in Scenario II, the device achieved a larger 4.6 °C temperature drop at a total power of only 5.862 W compared with previously reported TEC-based wearable coolers, for example, the 284 g air-conditioned mask developed by Suen et al. [19], which consumed 7.03 W to achieve a 3.5 °C air temperature drop. It should be noted, however, that the present device is a prototype intended for

Table 3

Air cooling and dehumidification performance of the ICEC-TEC-based air-conditioner under different operating conditions and the three ambient scenarios.

Scenario (T_{amb} , RH_{amb})	Peltier module & Fan		Air pump		P_{total} (W)	T_{out} (°C)	RH_{out} (%)	$\dot{V}_{out}$ (L min ⁻¹)	Δw (g kg ⁻¹)
	Voltage (V)	Power (W)	Voltage (V)	Power (W)					
I (28 °C, 50%)	0.00	0.000	5.00	0.119	0.119	28.0	50.6	1.886	–
	5.00	5.798	1.00	0.008	5.806	27.8	40.2	0.167	2.608
	5.00	5.848	5.00	0.119	5.967	23.9	58.5	1.842	1.130
II (32 °C, 50%)	0.00	0.000	5.00	0.124	0.124	32.4	49.6	1.982	–
	5.00	5.723	1.00	0.010	5.733	30.9	42.8	0.171	3.206
	5.00	5.743	5.00	0.119	5.862	27.8	58.8	1.966	1.384
III (32 °C, 70%)	0.00	0.000	5.00	0.114	0.114	31.5	70.0	1.906	–
	5.00	5.713	1.00	0.008	5.721	31.2	48.1	0.165	6.803
	5.00	5.738	5.00	0.109	5.847	28.4	64.4	1.822	4.835

Values shown in the Scenario column are the target ambient setpoints (T_{amb} , RH_{amb}). The actual measured ambient inlet conditions used for the tests are given by the first row of each scenario (with the Peltier module and fan off).

localized spot cooling rather than whole-body personalized ventilation. Therefore, the measured flow rate of 1.966 L min^{-1} should be interpreted as suitable for local thermal relief in a limited region, such as near the face, neck, or inside PPE, rather than for conditioning a large personal zone. In this sense, the present application is closer to local cooling near a mask microenvironment, as in Suen et al. [19], than to conventional high-flow personalized ventilation systems. Unlike Suen et al.'s device, which primarily cools air inside a semi-sealed mask cavity, our device continuously delivers cold-air flow that can be directed to the face, neck, or other areas, providing a stronger and more versatile cooling sensation while weighing just 170.8 g (including water fully filled), further highlighting its portability and energy efficiency.

4.4. Potential water-cycle function of the ICEC-TEC-based air-conditioner

In high RH and enclosed environments, such as inside the PPE, where sweating causes extremely high RH and thermal discomfort for the users, our ICEC-TEC-based air-conditioner has the potential not only to dehumidify the air inside the PPE and increase thermal comfort but also to recycle and utilize the large amounts of condensed water to power the heat dissipation part of the air-conditioner through water evaporation. In this special situation, since much more condensed water can be acquired compared to ordinary non-enclosed usage scenarios, water may not need to be provided from the outer environment, the condensed water alone may be sufficient. This will significantly increase the practicality for application to the PPE.

Fig. 14 illustrates the two potential operation modes of the ICEC-TEC-based wearable air-conditioner. For Operation Mode I, the device is primarily used for air cooling in an open environment, making this mode suitable for daily life use. Depending on the ambient condition and airflow setting, minor condensate may occur and can be utilized. The device can be positioned at various body locations, including hand-held, chest, or back, according to the user's preference, as shown in Fig. 14(a). For Operation Mode II, the device is configured to provide both air cooling and deliberate dehumidification to cope with the enclosed high-temperature and high-RH environment inside the PPE. The cold-side conditioned air and the hot-side evaporative exhaust are structurally separated in the device. In Operation Mode II, the hot-side heat dissipation section is arranged outside the PPE, which helps reduce possible interference of the humid exhaust with the user's inhalation zone. If necessary, the hot-side exhaust can also be guided through tubes to locations farther away from the human body surface, providing an additional design option to further reduce possible interference. In this mode, the air pump and air outlet are arranged inside the PPE, while the heat dissipation section is arranged outside, as shown in Fig. 14(b, c). The air pump draws in high RH air from inside the PPE, dehumidifies and cools it, and then recirculates the conditioned air. The device uses

sealed condensate pathways to prevent spillage during normal movement when worn as PPE. Operation Mode II performance depends on the balance between condensate production at the cold side and evaporative use at the hot side: in very humid air and with a deliberately metered wick cross-section on the hot side, condensate production can meet or exceed evaporative demand, whereas oversupplying the wick increases evaporative water usage and can outpace condensate under drier conditions. In practice, the wick feed area is treated as a tunable design parameter to maintain adequate hot-side heat rejection while enabling near-balance in typical use. During operation, the device should be kept upright and prolonged inversion should be avoided. If inversion is unavoidable, the tank should be emptied after use to prevent slow capillary leakage through the wicks.

5. Conclusions and future work

5.1. Conclusions

In this study, we proposed the novel ICEC-TEC, in which the ICEC serves as the heat dissipator for the TEC, together with a water-electricity hybrid energy system that utilizes water as a portable RES-equivalent latent-heat carrier to enhance TEC hot-side heat rejection via the latent heat of water evaporation. This enables the ICEC-TEC to achieve higher cooling performance while consuming much less electricity than the same standalone TEC. Under the three ambient scenarios, the ICEC-TEC achieved $Q_{\text{no water}} = 3.19\text{--}4.49$, corresponding to electrical power reductions of 68.7%–77.8% at the same $\Delta T_{\text{s,amb}}$, and maintained good performance even under the high-RH Scenario III. As a result, the ICEC-TEC is promising for miniature wearable air-conditioners due to its higher overall energy density than solely Li-ion-battery-powered TECs by leveraging the latent heat of water evaporation. The high cooling performance of the ICEC-TEC-based air-conditioner enables continuous cold-air delivery in a miniature device. Under Scenario II it achieved a 4.6°C air-temperature drop at $\dot{V}_{\text{out}} = 1.966 \text{ L min}^{-1}$ while consuming only 5.862 W. Two operation modes of the ICEC-TEC-based air-conditioner were proposed and discussed. Operation Mode I corresponds to daily-life use, requiring battery charging and periodic water refilling. Operation Mode II corresponds to use within a high-RH enclosed PPE environment, requiring battery charging but potentially reducing or eliminating external water refilling by harvesting condensed sweat vapor.

5.2. Future work

In future work, it would be reasonable to use improved materials instead of cotton yarns to achieve a stronger capillary effect and a higher evaporation rate in the ICEC. In particular, it would be preferable to use a single material capable of both water absorption and high thermal

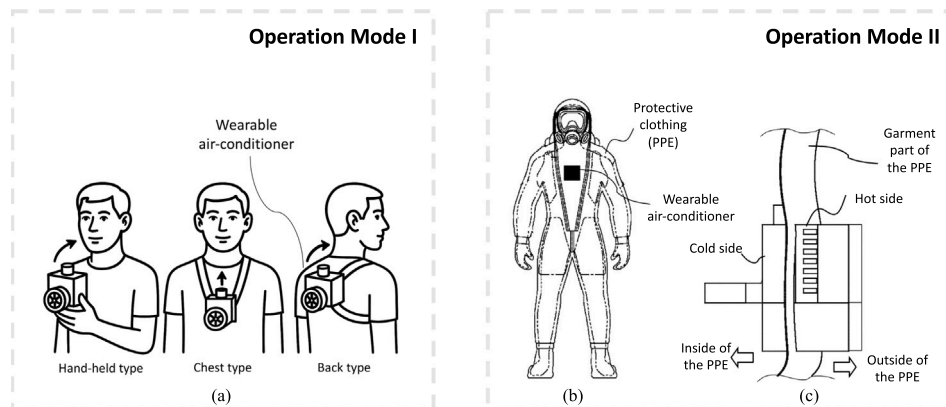


Fig. 14. Two operation modes of the ICEC-TEC-based wearable air-conditioner. (a) Operation Mode I: configuration for daily life use. (b-c) Operation Mode II: configuration for integration with PPE [44].

conductivity, instead of combining cotton yarns with an aluminum heat sink, to further improve efficiency. For example, surface-functionalized hydrophilic carbon nanotubes could be a promising candidate. While experimental analyses were conducted to assess the cooling performance of the proposed devices, detailed simulations and modeling, as well as further improvements in aspects such as the airflow pathway design, are required in future investigations to enhance the device beyond its basic prototype functionality. Furthermore, it is feasible to integrate the wearable real-time thermal comfort assessment framework, based on heart rate variability and body surface temperature analysis, as developed in our previous study [46], with the wearable air-conditioner proposed in this work to establish a closed-loop thermal comfort maintenance system. Further optimization by industry is expected to improve the airflow pathway, device structure, and practical product design beyond the present proof-of-concept prototype. In addition, human-subject experiments will be necessary to evaluate the thermal comfort effect of the device for localized cooling applications, such as use near the face or within PPE, and to optimize the airflow rate and air-delivery pathway for practical use. Future work should also directly measure the temperature and RH of the hot-side exhaust air and evaluate their possible influence on the user's local thermal comfort and inhalation zone, together with further optimization of the exhaust direction. Future work should also include uncertainty quantification to further strengthen the quantitative evaluation of the cooling performance.

CRedit authorship contribution statement

Ziyang Wang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ryuji Matsuhashi:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Ziyang Wang has patent #JP 7646260 – Portable air-conditioning device, performance-evaluation method for a portable air-conditioning device, and protective clothing; Priority application JP 2024-116582, issued to Ziyang Wang (individual inventor and assignee); no licensee. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Specifications of the experimental apparatuses

Table A.1

Specifications of the apparatuses used in the experiments.

	Features	Descriptions
3D printer	Brand	Flashforge Guider II
	Price	\$1113
	Nozzle diameter	0.4 mm
	Print speed	30–100 mm s ⁻¹
	Print volume	280 mm × 250 mm × 300 mm
	Layer thickness	0.1–0.4 mm
	Print precision	±0.2 mm

(continued on next page)

Table A.1 (continued)

	Features	Descriptions
DC motor	Brand	uxcell
	Price	\$4
	RPM	6000 rpm
	Rated voltage	5 V
Heat sink	Dimensions	24 mm × 24 mm × 12 mm
	Brand	Tuloka
	Price	\$1
	Type	Pin-fin
	Material	Aluminum
	Dimensions	40 mm × 40 mm × 11 mm
	Fin size	3.1 mm × 1.3 mm
Peltier module	Fin configuration	10 rows × 13 columns (130 fins total)
	Model number	TEC1-12706
	Price	\$2
	Dimensions	40 mm × 40 mm × 3.9 mm
	Power cord	200 mm
	Weight	160 g
	Thermocouple quantity	127 pieces
	$\dot{Q}_{c,max}$	58–65 W
	ΔT_{max}	65 K
	I_{max}	6 A
Infrared camera	U_{max}	15.4 V
	Brand	Thermo GEAR G100EX
	Price	\$6051
	Dimensions	212 mm (H) × 75 mm (W) × 138 mm (D)
	Weight	800 g
	Resolution	320 (H) × 240 (V)
	Temperature range	−40 °C – 1500 °C
	Thermal sensitivity	0.04 °C at 30 °C (60 Hz)
	Accuracy	±2 °C or ±2%
	Power	4.3 W
Mass flow meter	Brand	TSI Mass Flow Meter 5230-2
	Price	\$2205
	Range	0 to ±30 Std L min ⁻¹
	Accuracy	1.7% of reading
DC power supply	Calibration	Air, O ₂ , N ₂
	Brand	Jesverty SPS-3010V
	Price	\$56
	Output voltage range	0–32 V
Thermal grease	Resolution	0.01 V
	Display accuracy	± (0.5% of reading + 5 digits)
	Brand	BSFF BS-139
	Price	\$7
	Thermal conductivity	13.9 W m ⁻¹ K ⁻¹
	Type	Carbon-based thermal paste
	Net weight	11 g

Data availability

The authors do not have permission to share data.

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