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Pilot Study on a Low-Energy Wearable Air-Conditioner Based on A Novel Water-Electricity Hybrid Energy System#

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ABSTRACT

Wearable thermoelectric coolers (TECs), applicable in both indoor and outdoor environments, directly cool the human body surface and are considered to have much higher energy efficiency compared to compressor-based air-conditioners. However, the low coefficient of performance (COP) of TECs continues to be a significant burden on lithium-ion batteries, limiting the widespread use of TEC-based wearable coolers. In this study, we propose a novel water-electricity hybrid energy system by utilizing the water evaporation and capillary effect of water to solve the high electricity consumption issue of TECs. The novel water-electricity energy system-based cooler saves 81.8% of the electricity required to reach the lowest cooling temperature of a traditional TEC, by keeping the same size to the TEC. The excellent cooling capability enables the provision of cooling air, significantly increasing the practicality of the cooler compared with conductive models, and substantially contributing to energy conservation in both indoor and outdoor environments.

Keywords: wearable air-conditioner, thermal comfort, evaporative cooling, evaporation energy, thermoelectric cooling, energy conservation

NONMENCLATURE

Abbreviations	
COP	Coefficient of performance
ICEC	Indirect Capillary-Evaporative Cooler
TEC	Thermoelectric Cooler
ICEC-TEC	Combination of the ICEC and TEC
PPE	Personal protective equipment
RH	Relative humidity
Symbols	
a, *b*, *c*	Real number parameters
e	Natural logarithm
P	Power (W)
$Q_{\text{no water}}$	Novel performance metric of the ICEC-TEC-based air-conditioner
T	Temperature (°C)

1. INTRODUCTION

In the indoor environment, traditional compressor-based air-conditioners suffer from the inherent low energy efficiency issue and the incapability to account for individual differences [1,2], since an air-conditioner has to cool the entire air inside the room, and heat dissipation through the wall, the floor, and the ceiling further lower the efficiency, as illustrated in *Fig. 1*. As reported by the International Energy Agency, in 2018, cooling has accounted for 10% of global total energy consumption [3,4].

Compared to traditional compressor-based air-conditioners [5], conductive wearable thermoelectric coolers (TECs) boast a higher energy efficiency since they can cool the human body surface directly without cooling all the air inside the room, resulting in significantly higher energy efficiency and the capability to account for individual differences. However, the coefficient of performance (COP) of the TEC is significantly lower than that of the compressor-based air-conditioner [5], as reported by numerous studies.

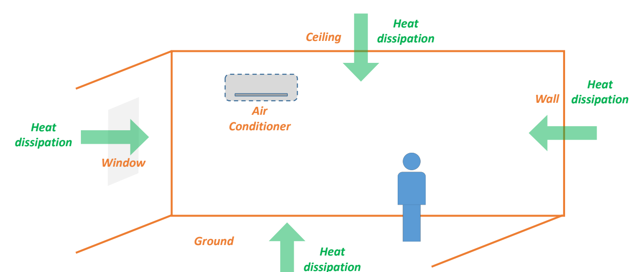

Fig. 1 Illustration of the heat dissipation channels of traditional compressor-based air-conditioners in the indoor environment.

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Table 1 Energy density comparison between Li-ion battery and the latent heat of water vaporization.

Energy source	Gravimetric density (J/g)	Volumetric density (J/mL)
Li-ion battery	360-954	900-2412
Latent heat of water vaporization (30℃)	2429.8	2429.8

2. WATER-ELECTRICITY HYBRID ENERGY SYSTEM

In this paper, a water-electricity hybrid energy system by utilizing water evaporation to enhance the heat dissipation capacity of the heat sink used in traditional TEC-based coolers to extensively increase the cooling capability is designed. *Table **1*** shows the gravimetric and volumetric energy density of Li-ion battery and the latent heat of water vaporization at 30℃. It can be observed that the latent heat of water is much higher than that of Li-ion batteries. By adopting cotton yarns inside an aluminum pin-fin-type heat sink (size: 40 mm × 40 mm × 11 mm) and arranging the bottom of the cotton yarns inside a water tank, capillary effect can be utilized to transport water from the bottom to the top of the cotton yarns to absorb and take away the heat from the heat sink by evaporation. The cotton yarns were evenly cut into equal-length pieces, arranged inside every other column formed by the fins of the heat sink, tiled into three layers, as shown in *Fig. **2***(d). The length of every cotton yarn piece was set to 70 mm. The diameter of the cotton yarns is 1.2 mm. By adding a motor-powered fan to the heat sink, the evaporation speed can be increased. *Fig. **2***(a-c) show the materials used to design the water-electricity hybrid energy system-based cooling device.

In order to test the cooling capability of the water-electricity hybrid energy system, a comparative experiment was carried out by introducing three devices as illustrated in the following Sections.

2.1 Design of the Indirect Capillary-Evaporative Cooler (ICEC)

The Indirect Capillary-Evaporative Cooler (ICEC), takes advantage of water evaporation and capillary effect, as illustrated in *Fig. **5***(b), is designed by fabricating a supporting framework and a fan using a 3D design software Shapr3D [6] and a 3D printer. The framework consists of a water tank (size: 40 mm × 27 mm × 20 mm), which is arranged at the bottom of the framework, a motor support structure (size: 43 mm × 19 mm × 43 mm), which occupies the upper part, and four arms (size of each: 5 mm × 14.5 mm × 5 mm) for fixing the heat sink, as shown in *Fig. **3*** and *Fig. **4***(a). *Fig. **4***(b) shows the fabricated ICEC, with a fan (radius: 20 mm, width: 6 mm) driven by a DC motor (rated voltage: 5V, 6000 RPM, size:

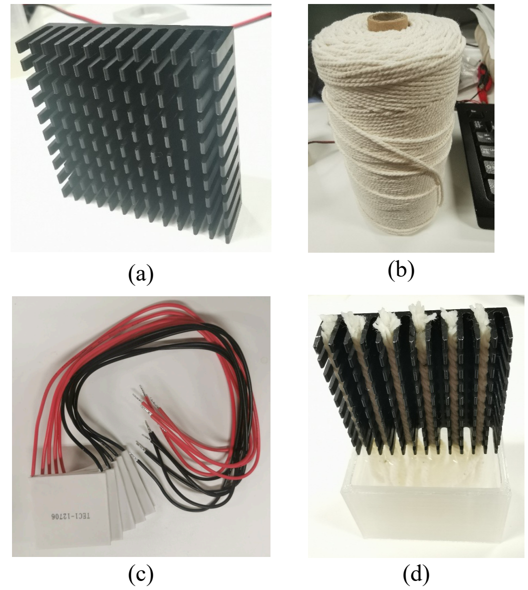

Fig. 2 The (a) aluminum pin-fin-type heat sink, (b) cotton yarns, (c) Peltier module (TEC), and (d) cotton yarns arrangement within the heat sink fins.

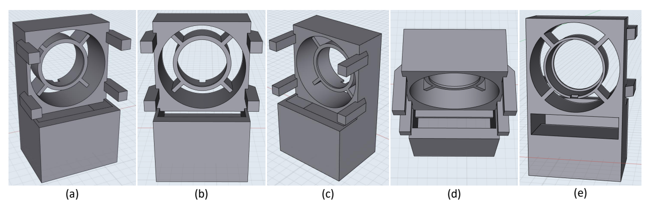

Fig. 3 Different viewing angles of the 3D design of the ICEC framework.

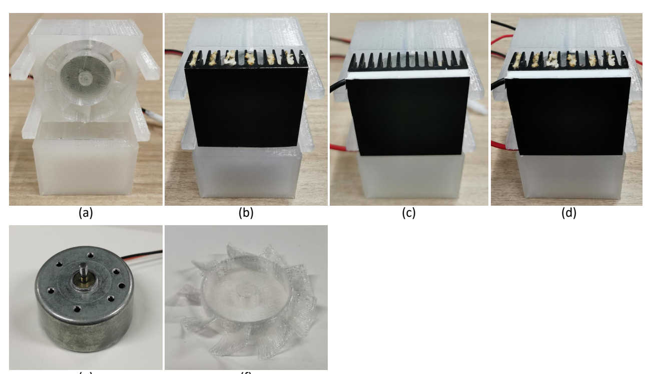

Fig. 4 The (a) 3D-printed framework, (b) ICEC, (c) TEC, (d) ICEC-TEC, (e) DC motor, (f) 3D-printed fan.

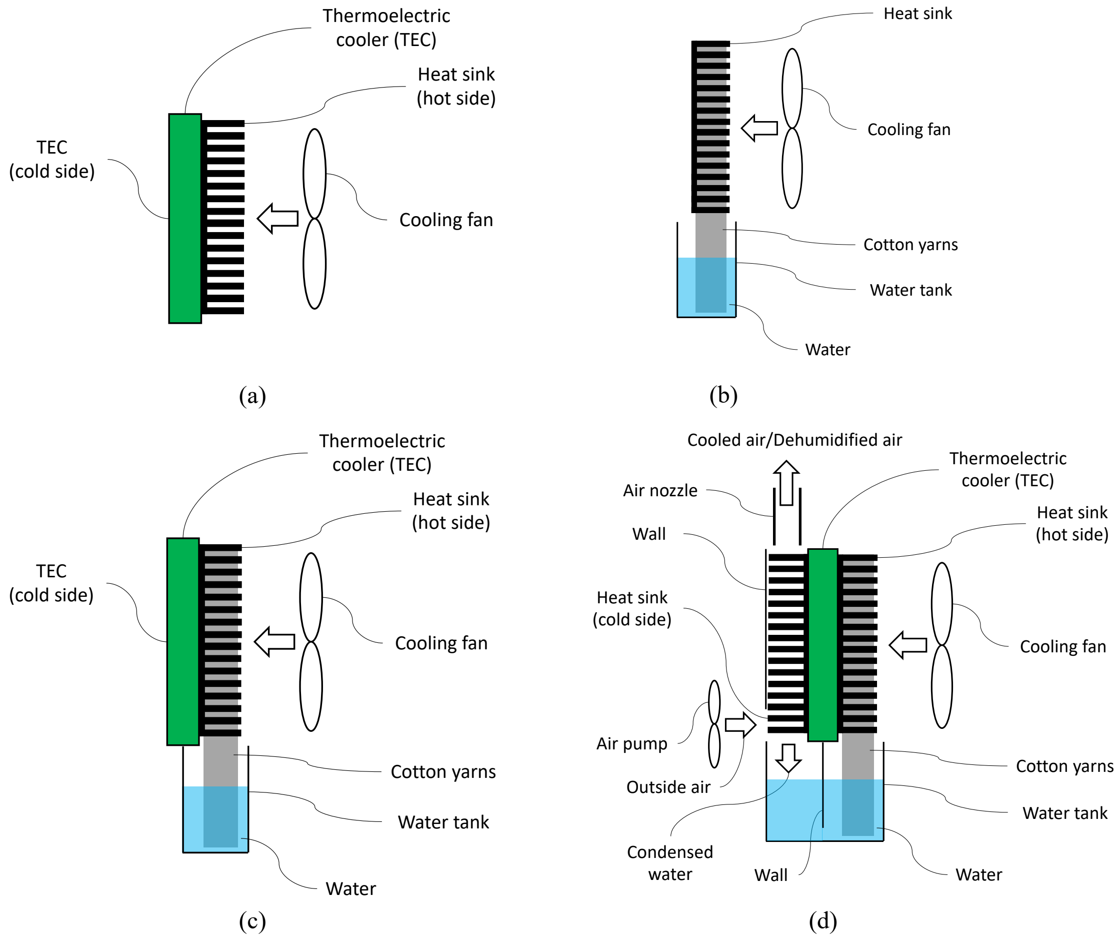

Fig. 5 Schematic of (a) the TEC, (b) ICEC, (c) ICEC-TEC, and (d) ICEC-TEC-based novel air-conditioner.

24 mm × 24 mm × 12 mm). *Fig.* ***4***(e-f) show the DC motor and the 3D-printed fan, respectively.

By arranging the cotton yarns within the heat sink can keep the volume and weight nearly unchanged compared with the original heat sink since the cotton yarns are arranged completely inside the heat sink and the weight of cotton yarns can be almost neglected.

2.2 Design of the TEC

A conventional TEC is designed by simply removing the cotton yarns in the ICEC and arranging a Peltier module (*Fig.* ***2***(c)) in front of the heat sink, with its hot side tightly stuck to the heat sink, as illustrated in *Fig.* ***4***(c). The Peltier module consists of 127 semiconductor couples in an area of 40 mm × 40 mm with two ceramic electrical insulators on both sides.

2.3 Design of the ICEC-TEC

The ICEC-TEC, by arranging the same Peltier module mentioned in Section *2.2* in front of the ICEC, with its hot side tightly stuck to the heat sink of the ICEC, to realize the water-electricity hybrid energy system-based novel cooler, is designed, as illustrated in *Fig.* ***5***(c) and *Fig.* ***4***(d).

2.4 Design of the ICEC-TEC-based air-conditioner

By arranging another heat sink tightly onto the cold side of the ICEC-TEC, enclosing the sides of the heat sink (cold side) with walls, placing an air pump at the bottom of the heat sink (cold side) to provide airflow, fabricating an air nozzle at the top of the heat sink (cold side), enlarging the water tank of the ICEC-TEC to cover both heat sinks, and setting a wall right beneath the TEC to isolate the air between both heat sinks while leaving a small channel at the bottom to allow water communication between both sides, a novel ICEC-TEC-based novel water-cycle air-conditioner is proposed, as illustrated in *Fig.* ***5***(d). The design of the water tank to also cover the heat sink (cold side) is intended to acquisite the water condensation from the heat sink (cold side) through air cooling and provide the acquisited water to the cotton yarns in the heat sink (hot side). *Fig.* ***7*** shows the fabricated prototype.

3. PERFORMANCE EVALUATION

3.1 Cooling performance comparison of the ICEC, TEC, and ICEC-TEC

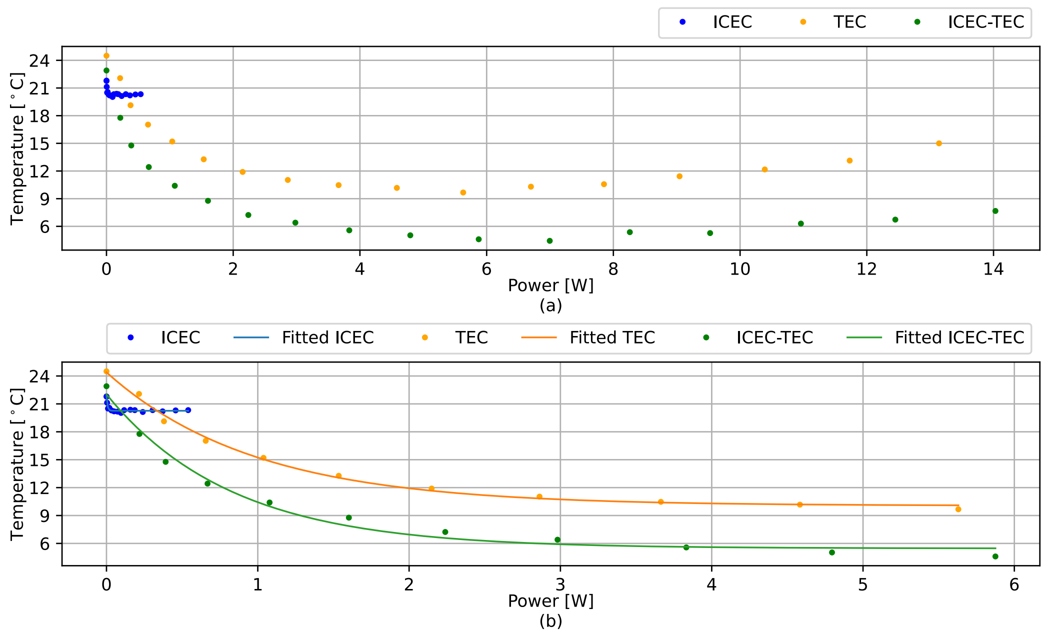

Fig. 6 Temperature-power characteristics of (a) the ICEC, TEC, and ICEC-TEC, and (b) the corresponding fitted characteristic curves using the exponential function.

A comparative experiment was conducted to test the cooling capability of the ICEC, TEC, and ICEC-TEC. The water tank was filled with water using a needle. Two DC stabilized power supplies were used separately to control the applied voltages of the motor and the Peltier module. The ambient air temperature was measured 24.5℃ during the experiment.

An infrared camera Thermo GEAR G100EX was used to measure the surface temperature of the ICEC, TEC, and ICEC-TEC. Since different materials have different thermal emissivity, to eliminate this concern in the measurement, black tapes were used to cover the surfaces of the heat sink or Peltier module in the ICEC, TEC, and ICEC-TEC, as shown in *Fig.* ***4***(b-d).

For the ICEC, the motor voltage was set to [0.00V, 8.00V] at intervals of 0.50V. For the TEC and ICEC-TEC, the voltage of the Peltier module was set to [0.00V, 8.00V] at intervals of 0.50V. When the voltage of the Peltier module was 0.00V, the motor voltage was set to 0.00V, too. When the Peltier module voltage was not 0.00V, the motor voltage was fixed to 5.00V (rated voltage) throughout the measurement. After adjusting the voltage for 2 min, the surface temperature measurement was performed to ensure the temperature became steady.

3.2 Performance evaluation of the air cooling and dehumidification functions of the ICEC-TEC-based air-conditioner

To evaluate the air cooling and dehumidification functions of the ICEC-TEC-based air-conditioner, a qualitative evaluation experiment consisting of three scenarios was conducted. During the measurement, the Peltier module and cooling fan shared a single DC power supply in a parallel connection, as higher cooling power of the Peltier module requires higher heat dissipation capability. However, the air pump used a separate DC power supply. The three scenarios of the controlling voltages of the air pump, cooling fan & Peltier module are shown in *Table* ***2***. A mass flow meter (TSI Mass Flow Meter 5230-2) was connected to the air nozzle of the air-conditioner to measure the air temperature, RH, and airflow rate.

4. RESULTS AND DISCUSSION

Fig. ***6***(a) shows the original data of the temperature-power characteristics. It is noticeable that for the TEC and ICEC-TEC when the power of the Peltier module exceeds a certain value, the temperature stops descending and goes up due to the capacity of the Peltier module. By observing the data patterns, non-linear least squares was applied to the temperature and power data of the ICEC, TEC, and ICEC-TEC to fit an exponential function in Eq. (1) using the Python Scipy package.

$$f(T) = a \cdot e^{-bP} + c \qquad (1)$$

In Eq. (1), the *e* is the natural logarithm; the *a*, *b*, *c* are real number parameters (*b*>0) to be optimized; the *P* and *T* are power and temperature, respectively. In the curve fitting process, only the temperature monotonically decreasing periods of the TEC and ICEC-TEC were used. The obtained temperature-power characteristic curves of the ICEC, TEC, and ICEC-TEC are shown in *Fig. **6***(b). The limitation of the ICEC is that it has an upper limit of cooling level (4.5°C) under the ambient air temperature of 24.5°C according to *Fig. **6***(b). When the motor power of the ICEC exceeds 0.05 W (approximately), the surface temperature of the ICEC no longer goes down further, and the maximum cooling temperature is 20.03°C.

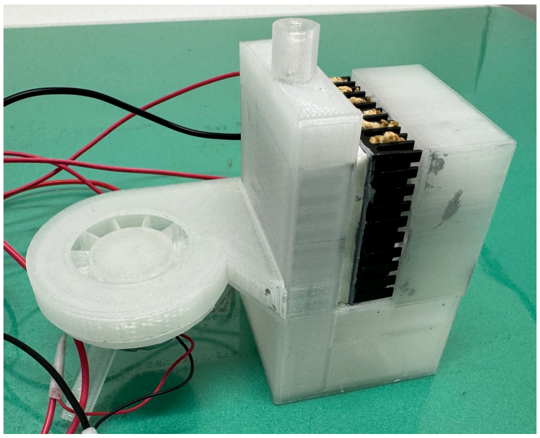

Fig. 7 The designed ICEC-TEC-based wearable air-conditioner by utilizing the proposed water-electricity hybrid energy system.

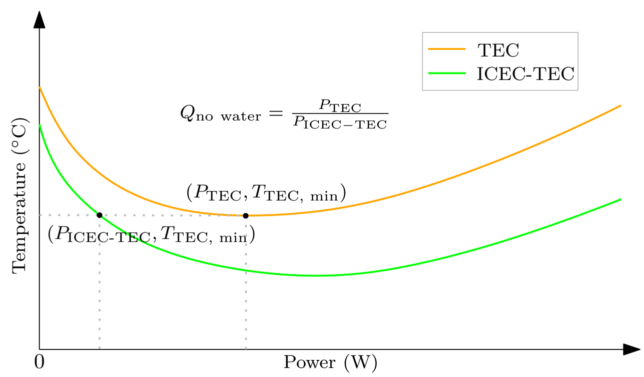

Fig. 8 Illustration of the novel performance metric $Q_{\text{no water}}$ of the ICEC-TEC.

Table 2 Air cooling and dehumidification performance of the ICEC-TEC-based air-conditioner.

		Voltage	Power
Scenario I	Air pump	0.205 V	0.016 W
	Fan & Peltier module	0 V	0 W
	Air temperature	25.0 C	
	RH	35.20%	
	Airflow rate	0.689 L/min	
		Voltage	Power
Scenario II	Air pump	0.205 V	0.016 W
	Fan & Peltier module	6 V	7.668 W
	Air temperature	23.7 C	
	RH	28.20%	
	Airflow rate	0.678 L/min	
		Voltage	Power
Scenario III	Air pump	6 V	0.2 W
	Fan & Peltier module	6 V	7.668 W
	Air temperature	21.3 C	
	RH	37.30%	
	Airflow rate	4.102 L/min	

4.1 Novel performance metric of the ICEC-TEC

The ICEC-TEC extensively outperforms the traditional TEC. In this study, instead of solely relying on the COP to evaluate the ICEC-TEC, we exclusively propose a novel performance metric for the ICEC-TEC, as denoted in *Fig. **8***. This metric is the quotient of the P_{TEC} at the largest cooling temperature of the TEC, and the corresponding $P_{ICEC\text{-}TEC}$ at the same temperature, denoted as $Q_{\text{no water}}$. Literally, the meaning of $Q_{\text{no water}}$ is that when the ICEC-TEC is at dry state and the water tank is empty, the device relies solely on the electricity and the TEC to function without the assistance of water evaporation. Similar with the COP, the higher the $Q_{\text{no water}}$, the more efficient the ICEC-TEC.

In this investigation, the $Q_{\text{no water}}$ for the ICEC-TEC is calculated to be 5.5, indicating the COP of the ICEC-TEC is 5.5 times higher than the TEC.

4.2 Qualitative evaluation of the air cooling and dehumidification functions of the ICEC-TEC-based air-conditioner

*Table **2*** shows the air cooling and dehumidification performance of the ICEC-TEC-based air-conditioner. In Scenario I, the fan & Peltier module were turned off, while the air pump was set to 0.205 V. The measured air temperature and RH were the same as the ambient air temperature and RH. In Scenario II, the air pump voltage was kept the same as in Scenario I, while the voltage of the fan & Peltier module was set to 6 V. In this situation, both the air temperature and RH decreased compared to Scenario I. In Scenario III, the voltage of the fan & Peltier module was kept the same as in Scenario II, while the air pump was set to 6 V. In this situation, the air temperature further decreased compared to Scenario II, while the RH even increased compared to Scenario I.

These phenomena indicate that during Scenario II, the slow air velocity allowed for both air cooling and dehumidification. During Scenario III, the increased air velocity caused the dehumidification to completely disappear, resulting in even higher RH compared to Scenario I.

5. CONCLUSIONS AND FUTURE WORK

In this paper, the ICEC-TEC, which utilizes the water evaporation and capillary effect has been proposed and demonstrated to consume much less electricity compared to the traditional TEC and is promising for real applications of low-energy wearable coolers.

The energy efficiency of the ICEC-TEC is always higher than that of the TEC. The superiority of the ICEC-TEC is that it can reach a larger temperature drop than the TEC while consuming less electricity. A novel performance metric $Q_{\text{no water}}$ for the ICEC-TEC has been proposed exclusively in this paper. The higher the $Q_{\text{no water}}$, the more efficient the ICEC-TEC. In this study, the $Q_{\text{no water}}$ of the ICEC-TEC reached 5.5, the ICEC-TEC can save 81.8% electricity energy compared with the TEC when maintaining the same maximum cooling temperature of the TEC.

The air cooling and dehumidification functions of the proposed ICEC-TEC-based air-conditioner has been verified.

In high RH and enclosed environments, such as inside the personal protective equipment (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.

The ICEC-TEC boasts a smaller volume and weight compared to traditional TECs while keeping the same cooling capacity due to the higher energy density of water evaporation. Since water is dominant in this hybrid energy source, the denomination "water-electricity" is used instead of "electricity-water." In addition, this is the first study to propose water as a novel portable renewable energy source.

In the future work, it is feasible to combine the wearable real-time thermal comfort assessment framework by analysis of body surface temperature in our previous study [2] and the novel wearable air-conditioner proposed in this paper to form a closed-loop thermal comfort maintenance system.

DECLARATION OF INTEREST STATEMENT

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Ziyang Wang has a Japanese patent #携帯型空調装置、携帯型空調装置の性能評価方法、防護服 (Patent Application Number: 2024-116582) pending to Ziyang Wang. 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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