Performance Assessment of Integrated Building Envelopes Using Thermoelectric Modules for Temperature Regulation

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ABSTRACT HEADING

A thermoelectric building envelope (TBE) is a new type of active building envelope that incorporates thermoelectric material in the building's enclosure. In TBE, the electrical energy and thermal energy can transfer between them through thermoelectric material. As a result, TBE can provide cooling or heating to indoor space if power is applied. TBE-based cooling or heating has high reliability and a low maintenance cost, low CO_2 emission, and no refrigerant use. TBE is conducive to the operation of net-zero energy and greenhouse gas emission buildings by using renewable energy. In this study, a multi-stage TBE prototype for space heating and cooling was designed, assembled, and tested. The performance of the TBE prototype was evaluated in two psychrometric chambers with controlled temperature and humidity in Herrick Laboratory at Purdue University. The performance was analyzed, including the surface and air temperatures, cooling capacity, and COP defined as the ratio of cooling capacity to the power input. The test result indicated that the COP of TBE in summer scenarios ranged from 0.46 to 2.4 with varied power inputs. The cooling capacity of one prototype can exceed 6.3 kW/cm^2. The findings discussed can guide the design and operation of TBE.

INTRODUCTION

To alleviate the energy crisis and environmental deterioration, people seek sustainable energy generation and energy-efficient technologies, as well as the application of clean and renewable energy. Therefore, thermoelectric technology becomes a promising strategy to alleviate energy and environmental issues due to its capacity of energy conversion between thermal energy and electrical energy. Thermoelectric modules (TEM) can work as a power generator to generate electricity under a given temperature gradient through a phenomenon named the Seebeck effect [1]. The same module can also work as a thermoelectric cooler/heat pump (TEC/TEH) by transferring thermal energy from one end to another with power input, according to the Peltier effect [2]. The overall performance of thermoelectric material is determined by the balance of Fourier's law, Peltier effect, Thomson effect, and Joule heat effect.

Recently, there has been an increasing interest in using thermoelectric technology in buildings. Existing studies have used TEMs in walls, roofs, ventilation, and hot water systems, demonstrating TEM's ability to adjust the room and water temperature and reduce heating, cooling, and air conditioning (HVAC) [3–8]. The highest cooling and heating COPs of TBE are mainly 0.5–1.21 and 0.6–3.92. However, the TBE system faces numerous challenges, including low TEM efficiency and high initial cost. The commercially available TEM does not have the optimal design for building applications requiring the TEM to maintain a significant temperature difference. Due to the insufficiency of the TBE design, TBE can not provide effective space cooling as the cold-side temperature increases with the rising hot-side temperature.

Therefore, the study aims to address the research challenges abovementioned by investigating the performance of a TBE prototype designed and assembled by the team. The TBE prototype was tested in seven summer conditions in cooling mode and monitored using a data acquisition system made by NI cDAQ and a programmable power supply. Moreover, the test investigated the impacts of current input on the temperature, cooling capacity, and COP.

METHODOLOGY

Prototype development and test setup

The overall dimension of the TBE prototype is 15 × 15 × 5.3 in^3. It contains three major parts: the building envelope module, the TEM, and heatsinks. The building envelope module consists of a half-inch thick rigid XPS board with two 5mm thick plywood boards covered on both sides in a sandwich configuration. The TEM is made by three high-performance commercially available single-stage TEMs, purchased from TE Technology, Inc. Those TEMs are connected both thermally and electrically in series. One HP-127-1.4-2.5 TEM is in the middle between two HP-199-1.4-0.8 TEMs. The configuration could help TBE build up a large temperature difference than single-stage TEM to provide stable and effective space cooling and heating. Two tall heatsinks and 12V DC fans are adopted to improve heat transfer on the surface. The specifications of TEMs, heatsink, and fan are summarized in Table 1. The TEMs and heatsinks are in the through-hole of insulation and plywood boards tightly, as shown in Figure 1 (a).

Table 1. Specifications of TEMs, heatsink, and fan

Device	Model No.	Operation conditions	Size [mm^3]
TEM	HP-199-1.4-0.8	I<11.3A, V<24.6V -40ºC<T<80ºC	40×40×40 element: 1.4×1.4×0.8
TEM	HP-127-1.4-2.5	I<3.7A, V<16.3V -40ºC<T<80ºC	40×40×40 mm^3 element: 1.4×1.4×2.5
Fan	F-4010H12BII-12	V=7~12V, I=0.18A (rated) P=0.7W (calculated)	40×40×10 mm^3
Heatsink	CS40-50B	Thermal R≈0.84K/W	40×40×50 mm^3

An experimental apparatus has been built between two psychrometric chambers in Herrick Labs at Purdue University to evaluate the performance of the TBE prototype. The apparatus comprises three parts: the TBE prototype, instruments and data acquisition system, and two chambers. As depicted in Figure 1, the developed TBE prototype is mounted in the interior wall between the two chambers. A DC power supply unit is used to power the three-stage TEMs. Twelve thermocouples are used for surface and air temperature measurement in the TBE prototype. Four are embedded in the interfaces between TEM and heatsinks. There are two thermocouples embedded in the interfaces between plywood and XPS boards. Two TCs are placed about 20 cm away from DC fans at both cold and hot sides to measure the actual inlet air temperature. The other four TCs are used to measure the air temperature near the base of the heatsink. All TCs are connected to a NI 9213 module and a cDAQ device for data acquisition. A LabVIEW project is developed to acquire and visualize the data and write temperature readings from cDAQ and power input readings from PSU to the file. A sample rate of 1 Hz is set for all channels and devices. The specifications of measurement instruments are listed in Table 2.

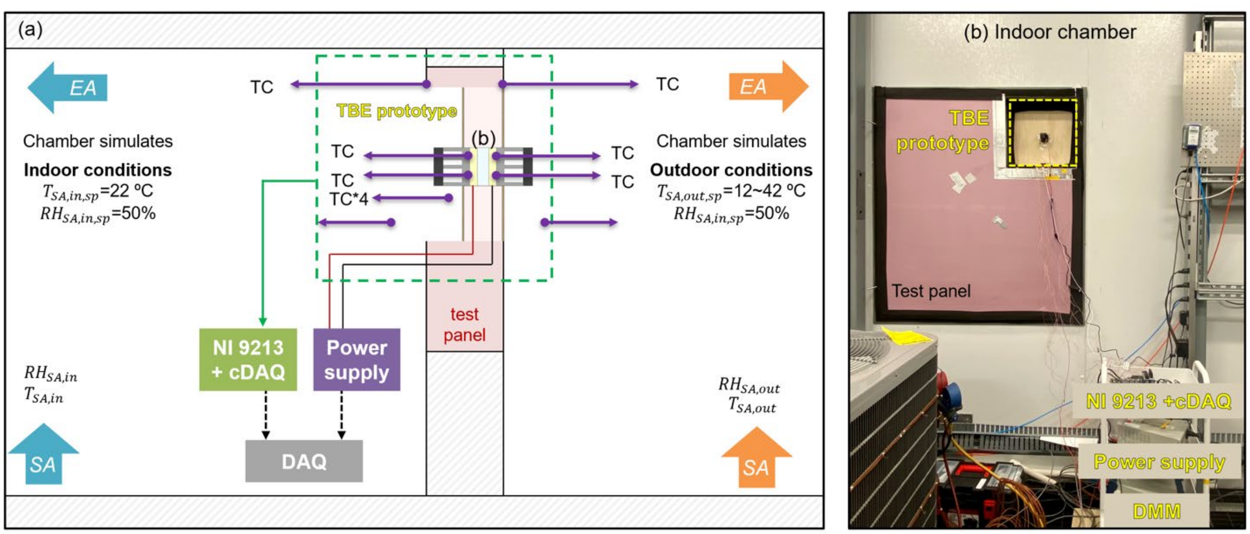

Figure 1 (a) Schematic diagram and (b) graphical view of the experimental setup for evaluating TBE prototype in psychrometric chambers.

Table 2. Specifications of measurement instruments

Measured variable	Instrument	Operation range	Resolution	Uncertainty
Surface temperature	36 AWG K-type thermocouples	-270–1260 °C	~ 41 μV/°C	±1.1 °C
Air temperature	30 AWG T-type thermocouples	-270–370 °C	~ 43 μV/°C	±0.5 °C
Current input	Siglent SPD1168X power supply unit	0–8A	1mA	I: ± (0. 3%×reading+10 mA)
Voltage input		0–16V	1mV	V: ± (0.03%× reading+10 mV)
Thermocouple module	NI 9213 16-channel TC input module	V: ±78 mV T: -40–70 °C RH: 10%–90%	<0.02°C 24 bits 75 S/s	-
Data acquisition module	NI 9178 cDAQ	T: -20–55 °C RH: 10%–90%	32 bits	-

Test scenarios

Seven tests were carried out for evaluating the performance of the multi-stage TBE prototype in different operating conditions, as listed in Table 3. The chamber used for simulating the indoor conditions has a constant supply air (SA) temperature around 22 °C. Meanwhile, the other chamber simulates the outdoor conditions in different weathers. The outdoor SA temperatures in cold-summer, mid-summer, and hot-summer were set as 27, 32, and 42 °C, respectively. Current input varied from 0.3–1.5A was applied to the TBE in mid-summer, while current input was 1.5 Amps in the cold and hot summer.

Table 3. Summary of operating conditions in 7 tests for TBE evaluation in summer

Test	Summer	Outdoor temperature	Indoor temperature	RH [%]	Current [A]
1	Cold (scenario 1)	27°C/300.15K			1.5
2					0.3
3					0.5
4	Mid (scenario 2)	32°C/305.15K	22/295.15K	50	0.7
5					1
6					1.5
7	Hot (scenario 3)	40°C/313.15K			1.5

Performance indicators

The thermoelectric behavior of a thermoelectric heat pump can be evaluated by the hot-side surface temperature (T_h), cold-side surface temperature (T_c), cooling capacity ($\dot{Q}_c$), and coefficient of performance (COP). For a simplified three-stage TBE model without considering the Thomson effect and heat loss, the heat equations of the i-th TEM are written as

$$\dot{Q}_{hi} = S_i I T_{hi} - K_i(T_{hi} - T_{ci}) + 0.5I^2R_i \quad (1)$$

$$\dot{Q}_{ci} = S_i I T_{ci} - K_i(T_{hi} - T_{ci}) - 0.5I^2R_i \quad (2)$$

where K is the thermal conductance and I is the current input, and R is the electrical resistance of the material. Since the three-stage TEM is symmetric, both TEM1 and TEM3 can work as the hot or cold side. Assuming the TEM1 provides cooling while TEM 3 provides heating to space. Because three TEMs are connected thermally in series, they share the same temperature and heat flux on the interfaces. Hence, we have, $\dot{Q}_{h1} = \dot{Q}_{c2}$, $\dot{Q}_{h2} = \dot{Q}_{c3}$, $T_{h1} = T_{c2}$, $T_{h2} = T_{c3}$. As T_{c1} and T_{h3} can be easily obtained by the measurement, the mathematical model finally becomes a system of linear equations with two unknowns T_{h1} and T_{h2}. After solving the linear system, the cooling capacity ($\dot{Q}_c = \dot{Q}_{c1}$) and the heating capacity ($\dot{Q}_h = \dot{Q}_{h3}$) of three-stage TEM can be calculated by substituting T_{h1} and T_{h2} to equation 1 and equation 2, respectively. The effective cooling capacity furtherly considered the overall heat loss through the TBE prototype.

The electrical power applied to the TEC is used for Joule heating and increases the electrochemical potential at the hot side. It is also the power difference of heat between the hot and cold sides, as calculated in equation 3.

$$P = \dot{Q}_h - \dot{Q}_c = SI(T_h - T_c) + I^2 R + \tau I \Delta T + Q_{loss} \quad (3)$$

The coefficient of performance (COP) is the ratio of useful heating or cooling power provided to work required with higher values resulting in lower operating costs. Ideally, the COP is expressed as equation 4 without considering the external power consumptions. In our cases, if the power consumption of the fan is included, then the corrected cooling COP of a thermoelectric heat pump needs to be modified as equation 5. The actual power consumption of the fan is determined from the pressure intersections of fan and heatsink under the same operating velocity.

$$COP = \frac{\dot{Q}}{P} = \frac{\dot{Q}}{\dot{Q}_h - \dot{Q}_c} \quad (4)$$

$$COP_{c,fan} = \frac{\dot{Q}_c}{\dot{Q}_h - \dot{Q}_c + W_{fan}} \quad (5)$$

RESULTS AND DISCUSSIONS

Figure 2 shows the temperature profiles of the TBE prototype with a current input of 1.5A in the mid-summer scenario. There is an intrinsic temperature difference of around 10 ºC between the indoor and outdoor air. It is shown in the solid red and blue curves that the surface temperature of TEM changes quickly with the current input, and the surface temperature difference is built in a very short time. Due to the large thermal mass of TEM, the hot-side surface temperature rises gradually, and the cold-side surface temperature drops. The time for the temperature to reach a steady-state is determined by the surface thermal resistance (i.e., the reciprocal of the product of the heat transfer coefficient and the area). The lower the thermal resistance, the better the heat dissipation performance, and the faster the temperature can reach a steady state. In the operation of TBE, a better heat dissipation rate is desired for a larger cooling/heating capacity.

As the hot-side temperature increases to 60 ºC, the cold-side surface temperature starts to increase due to heat conduction between the hot and cold surfaces. This phenomenon indicates that the choice of current input is very important in the actual operation. In a certain range, the higher the current, the higher the thermal energy per unit area of TBE. However, when the current is too high, the TBE will not provide effective cooling instead, which is due to a large amount of Joule heat and the heat conduction, which seriously degrades the cooling capacity.

When the current input is removed, the hot surface temperature drops, and the cold surface temperature rises because there are no thermoelectric effects at this moment but pure conduction. Later, both surface temperatures gradually reach the ambient temperature. At the steady-state, the TBE can reduce the indoor surface temperature from 25 ºC to 18 ºC. The green-shaded area indicates the measured indoor air temperature near the base of the heatsink. The air temperature drops about 1.8 ºC as the air flows through the heatsink.

The surface temperature, cooling capacity, and cooling COP in different summer scenarios are compared in Figure 3. As the outdoor temperature increases in summer, the indoor and outdoor surface temperatures increase simultaneously. As a result, the cooling capacity decreases. The effective cooling capacity, which considers the overall heat loss through the whole TBE prototype, drops more in the hot summer. The cooling COP without and with the fan consumption also decreases with the higher outdoor air temperature (Figure 3b). This result is intuitive, as the system cooling effect decreases in more severe weather. The cooling COP with current input of 1.5A is always lower than 0.52, which indicates that the operating current for TBE should not exceed 1.5A in our case. The optimal operating current should be explored.

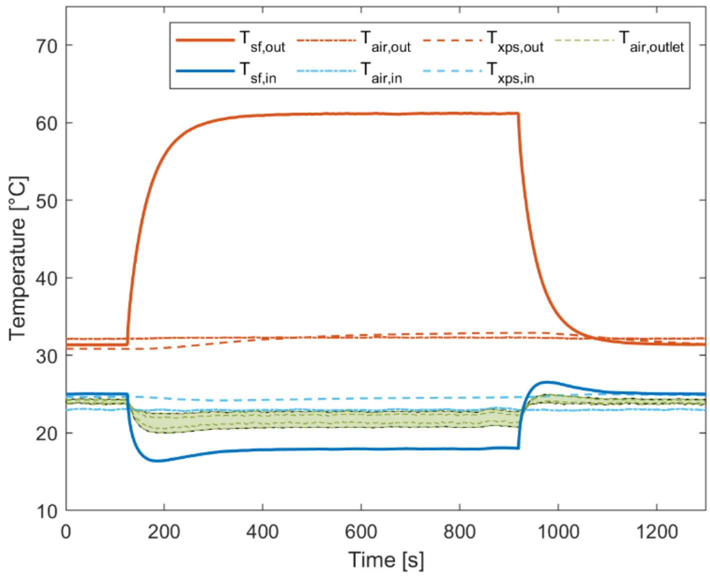

Figure 2 The test result of temperature profiles of TBE prototype with I=1.5A in mid-summer ($T_{outdoor}$=32 ºC, T_{indoor} =22ºC).

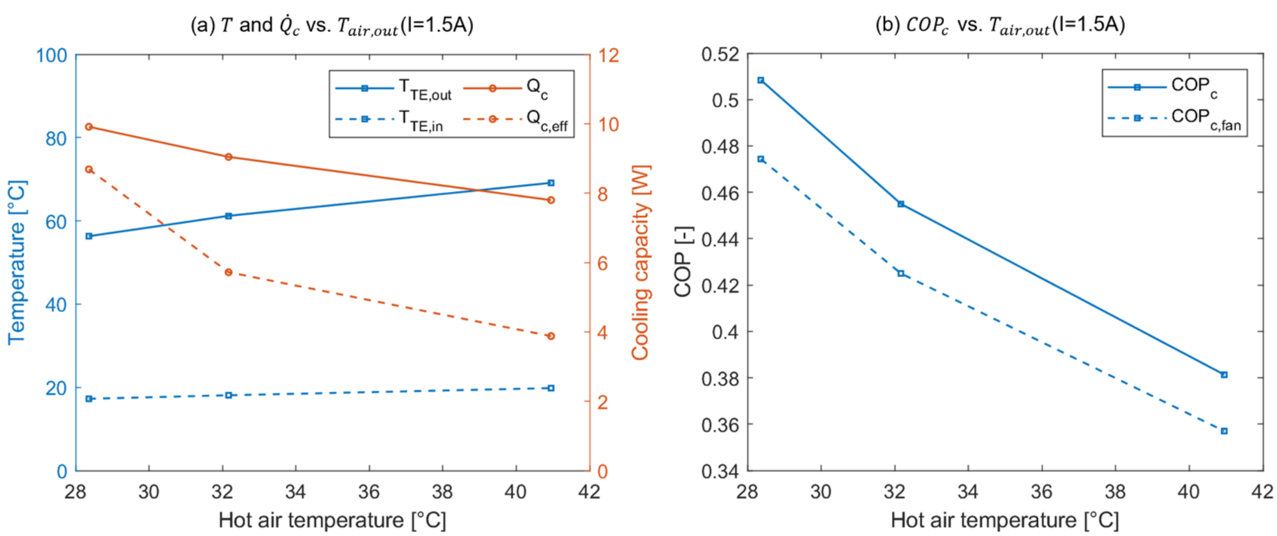

Figure 3 (a) Steady-state surface temperatures and cooling capacity, and (b) cooling COP of three-stage TBE with I=1.5A in three summer scenarios.

The test results studying the impact of current input on the TBE performance are elucidated in Figure 4. The current input changes from 0.3 A to 1.5A in the mid-summer (scenario 2). The outdoor surface temperature and cooling capacity increase while the indoor surface temperature decreases with a higher current input. In our cases, if the current exceeds 1.5A, the cold-surface temperature may rise and fail to provide cooling. Effective cooling largely depends on heat dissipation technology. The cooling COP calculated from the test results drops with higher current input. This is because the Joule heat and conduction play a more important role with a larger current input as compared with Peltier heat. Joule heat and conduction in the cooling mode can be considered as heat loss which degrades the cooling performance. Thus, TBE works better in the heating mode in winter since Joule heat improves the heating capacity. The cooling COP with the fan consumption first increases and then decreases with the increasing current input. There is a highest COP with fan, indicating the optimal operating current. The paper studied two types of COPs because multiple TEMs can share a single fan or other heat dissipation system in the real application, which significantly reduces the fan power shared by a single TEM and makes the dashed line converge to the solid line in Figure 4b.

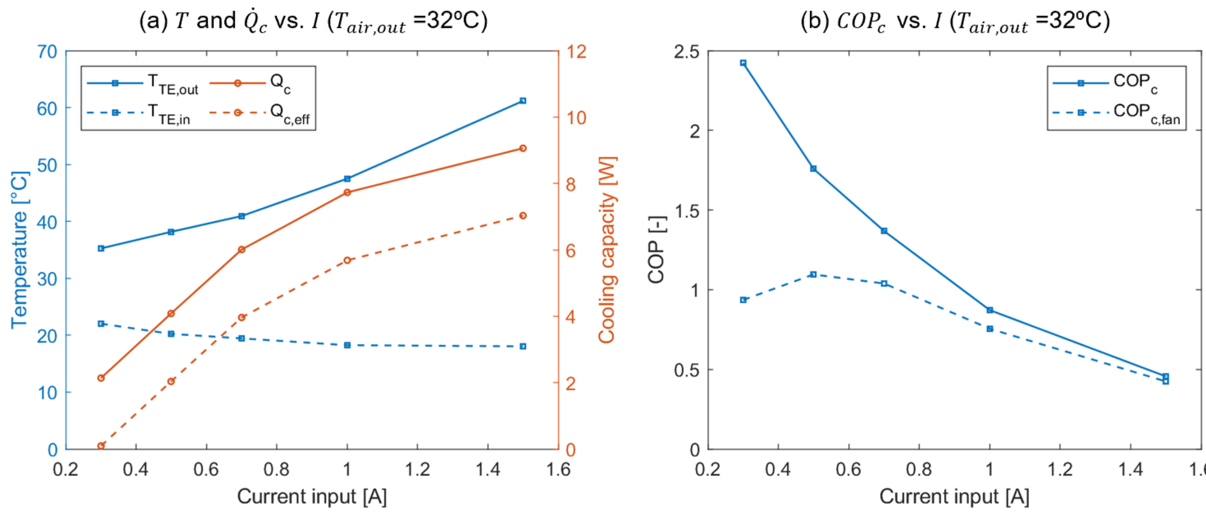

Figure 4 (a) Steady-state surface temperatures and cooling capacity, and (b) cooling COP of three-stage TBE with I=0.3–1.5A in mid-summer ($T_{outdoor}$=32 ºC, T_{indoor}=22ºC).

CONCLUSION

In this paper, a three-stage TBE prototype for space cooling was developed and evaluated under different scenarios and operating conditions. The TBE performance changes with different outdoor temperatures and current input. Experimentally, the cooling capacity varies from 2.1–9.1 W, and the cooling density varies from 1.4–6.3 kW/cm^2. The COP with and without considering fan power ranges from 0.35–1.08 and 0.46–2.4. The cooling capacity and COP depend on the current input, operating temperature, thermal resistance, etc. The better cooling performance can be observed when there is no temperature difference between the indoor and outdoor chambers. The COP with fan power included starts to decrease when the current exceeds 0.5A, and thus, the optimal current input can be selected for the highest COP and a reasonable thermal capacity. There is a balance between operating costs and initial investment costs. Furthermore, a higher cooling capacity and COP can always be obtained with an effective and energy-efficient heat dissipation technology. Hence, the combination of TBE technology with other building systems (i.e., other types of the active building envelope, water system, etc.) for an improved system performance might be another choice of applying thermoelectric in buildings.

Future work in this study will include developing a numerical model for the TBE system, the use of the numerical model for systematic parametric studies, optimization of design variables, etc.

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NOMENCLATURE

S = Seebeck coefficient

I = current

T = temperature

K = thermal conductance

R = electrical resistance

COP = coefficient of performance

Subscripts

h = hot-side

c = cold-side

i = the i-th layer

$loss$ = heat loss

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