A three-stage thermoelectric building envelope for cooling: design, prototyping, and experimental evaluation

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Abstract. 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. TBE can provide cooling or heating to indoor space if power is applied. TBE-based cooling or heating is quiet and reliable and has low maintenance cost, low or no CO_2 emission. TBE is conducive to the operation of net-zero energy and emission buildings by using renewable and low-grade energy. In this study, a multi-stage TBE prototype 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 test result concludes that the highest COP of TBE is 0.46–2.4 in summer scenarios for different power inputs. The findings discussed can guide the design and operation of TBE.

1. Introduction

To alleviate the energy crisis and environmental deterioration, people seek sustainable energy generation and energy-efficient technologies, and the application of clean and renewable energy. Therefore, thermoelectric technology becomes a promising strategy due to the mutual energy conversion between thermal energy and electrical energy. Thermoelectric modules (TEM) can work as a power generator to generate electricity due to a 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]. TBE system has many merits including reducing greenhouse gas emissions, low maintenance cost, simple and scalable system configuration, and control precision, which make it suitable for small enclosures with a high requirement of temperature accuracy. 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 results recover the impacts of current input on the temperature, cooling capacity, and COP.

2. Methodology

2.1. Prototype development and test setup

The overall dimension of the TBE prototype is 15in × 15in × 5.3in. 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 was made by three high-performance commercially available single-stage TEMs, purchased from TE Technology, Inc. Those TEMs were 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 can 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 were adopted to improve heat transfer on the surface. The TEMs and heatsinks are in the through-hole of insulation and plywood boards tightly (Figure 1).

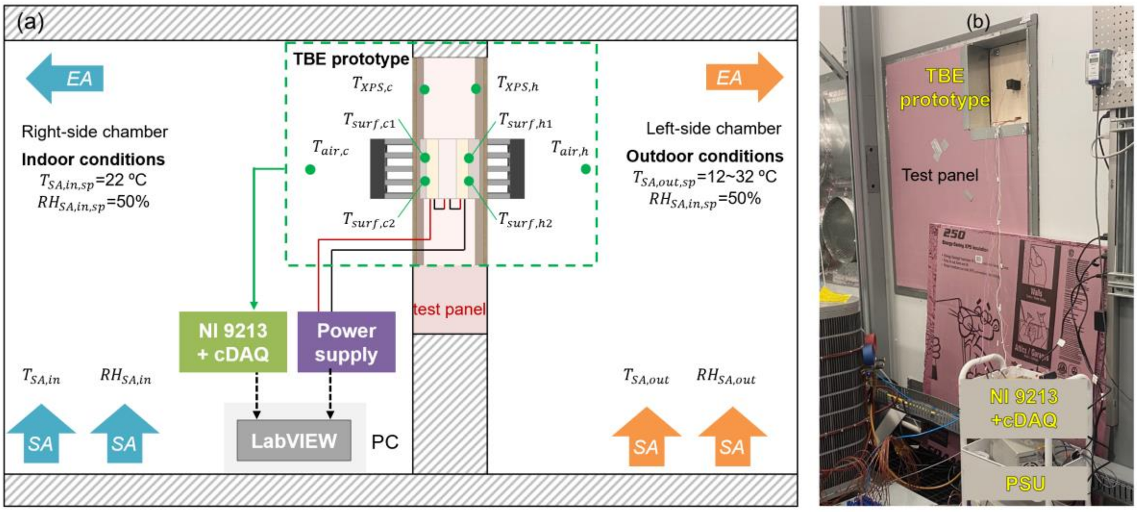

Figure 1. (a) Schematic diagram and (b) graphical view of the experimental setup for evaluating TBE prototype in psychrometric chambers.

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 was mounted in the interior wall between the two chambers. A DC, power supply unit, was used to power the three-stage TEMs. Twelve thermocouples were used for surface and air temperature measurement in the TBE prototype. Four were embedded in the interfaces between TEM and heatsinks. There are Two thermocouples embedded in the interfaces between plywood and XPS boards. Two were 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 were used to measure the air temperature near the base of the heatsink. All TCs were connected to a NI 9213 module and a cDAQ device for data acquisition. The temperature and humidity of the supply air for both chambers were collected by internet-shared variables. A LabVIEW project was 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 was set for all channels and devices.

2.2. 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 1. 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 for summer scenarios 1, 2, and 3 were set as 27, 32, and 42 °C, respectively. Current input varied from 0.3-1.5A was applied to the TBE in summer scenario 2, while current input was 1.5 Amps in scenarios 1 and 3.

Table 1. Summary of operating conditions in 18 tests conducted for TBE evaluation.

	Summer	$T_{outdoor}$ [°C]	T_{indoor} [°C]	RH [%]	Current [A]
Test 1	Senario 1	27	22	50	1.5
Test 2		32	22	50	0.3
Test 3		32	22	50	0.5
Test 4	Senario 2	32	22	50	0.7
Test 5		32	22	50	1
Test 6		32	22	50	1.5
Test 7	Senario 3	40	22	50	1.5

2.3. 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

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

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

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.

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

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.

$$COP = \frac{\dot{Q}}{P} = \frac{\dot{Q}}{\dot{Q}_h - \dot{Q}_c} \tag{4}$$

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

3. Results and Discussions

Figure 2 shows the temperature profiles of the TBE prototype with a current input of 1.5A in summer scenario 2. There is an intrinsic temperature difference of around 10 ºC between the indoor and outdoor air. It is shown in the plots 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 continuously, and the cold-side surface temperature drops. As the hot-side temperature increases to 60 ºC, the cold-side surface temperature also increases due to heat conduction. 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.

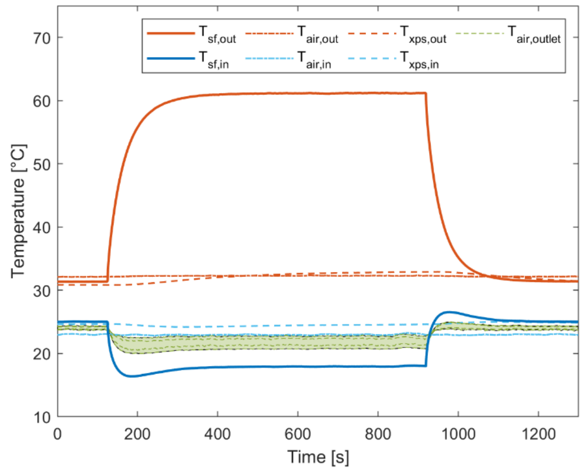

Figure 2. The test result of temperature profiles of three-stage TBE with I=1.5A in summer ($T_{outdoor}$=32 ºC, T_{indoor}=22ºC).

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 a hotter summer. The cooling COP without and with the fan consumption also decreases with the higher outdoor air temperature.

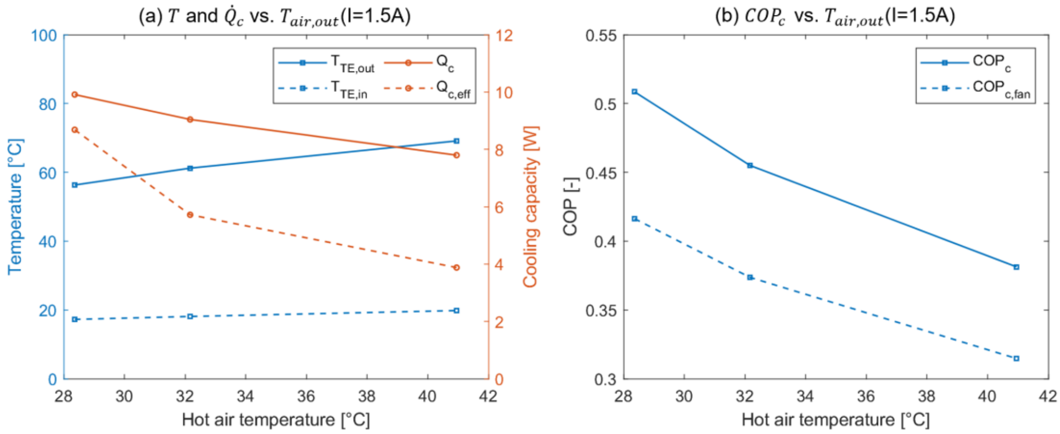

Figure 3. (a) Steady-state surface temperatures and cooling capacity, and (b) cooling COP of three-stage TBE with I=1.5A in three summer scenarios.

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 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 from 3.2 to 1.5 with higher current input. On the contrary, the heating capacity considering fan power first increases from 0.4 to 0.69 and then drops to 0.37 with higher current input.

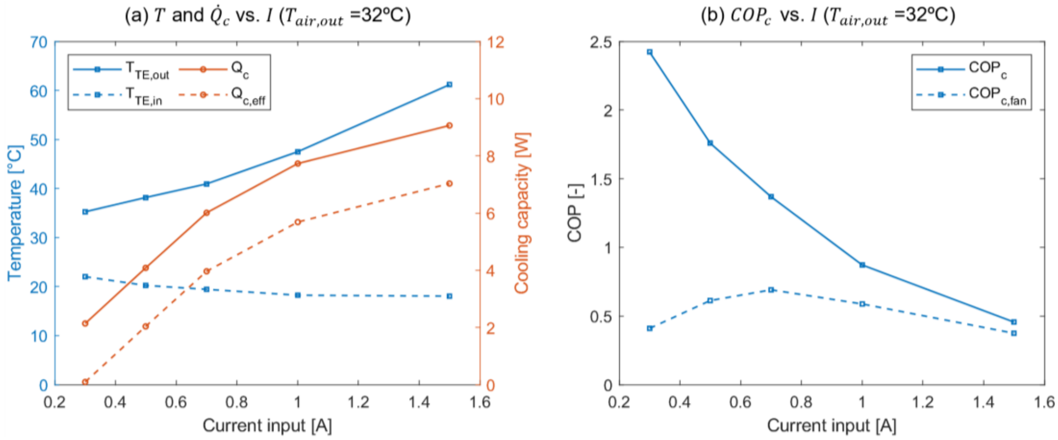

Figure 4. (a) Steady-state surface temperatures and cooling capacity, and (b) cooling COP of three-stage TBE with I=0.3–1.5A in summer scenarios 2 ($T_{outdoor}$=32 ºC, T_{indoor}=22ºC).

4. Conclusions

In this paper, a novel 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. The COP with and without considering fan power ranges from 0.37–0.69 and 0.46–2.4. A higher cooling capacity and COP can be obtained with a lower outdoor temperature and a higher current input, and a better heat dissipation technology. The COP with fan power included starts to decrease when the current exceeds 0.7A, and there is an optimal current input for the highest cooling capacity and cooling COP. To improve the COP of the system, more energy-efficient technology for heat dissipation is required.

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