2022

Performance Modeling and Analysis of a Thermoelectric Building Envelope for Space Heating

Xiaoli Liu

Ming Qu

Kazuaki Yazawa

Jorge Kohanoff

Piotr Chudzinski

See next page for additional authors

Authors

Xiaoli Liu, Ming Qu, Kazuaki Yazawa, Jorge Kohanoff, Piotr Chudzinski, Lorenzo Stella, Brian Norton, Niall Holmes, Ruchita Jani, Hongxi Yin, and Conrad Johnston

Performance Modeling and Analysis of a Thermoelectric Building Envelope for Space Heating

Xiaoli LIU[1], Ming QU[1]*, Kazuaki YAZAWA[2], Jorge KOHANOFF[3], Piotr CHUDZINSKI[4], Lorenzo STELLA[4], Brian NORTON[5], Niall HOLMES[5], Ruchita JANI[5], Hongxi YIN[6], Conrad JOHNSTON[7]

[1]Lyles School of Civil Engineering, Purdue University
West Lafayette, Indiana, USA
mqu@purdue.edu

[2]Birck Nanotechnology Center, Purdue University
West Lafayette, Indiana USA
kyazawa@purdue.edu

[3]Instituto de Fusion Nuclear "Guillermo Velarde", Universidad Politecnica de Madrid
Madrid, Spain
j.kohanoff@upm.es

[4]School of Mathematics and Physics, Queen's University Belfast
Belfast, United Kingdom
l.stella@qub.ac.uk

[5]School of Civil and Structural Engineering, Technological University Dublin,
Dublin, Ireland
brian.norton@tyndall.ie

[6]Sam Fox School of Design and Visual Arts, Washington University in St Louis, St Louis, Missouri, USA
hongxi.yin@wustl.edu

[7]Pacific Northwestern National Laboratory, Richland, WA 99354, USA
conrad.s.johnston@googlemail.com

* Corresponding Author

ABSTRACT

To provide energy-efficient space heating and cooling, a thermoelectric building envelope (TBE) embeds thermoelectric devices in building walls. The thermoelectric device in the building envelope can provide active heating and cooling without requiring refrigerant use and energy transport among subsystems. Thus, the TBE system is energy and environmentally friendly. A few studies experimentally investigated the TBE under limited operating conditions, and only simplified models for the commercial thermoelectric module (TEM) were developed to quantify its performance. A holistic approach to optimum system performance is needed for the optimal system design and operation. The study developed a holistic TBE-building system model in Modelica for system simulation and performance analysis. A theoretical model for a single TEM was first established based on energy conversion and thermoelectric principles. Subsequently, a TBE prototype model combining the TEM model was constructed. The prototype model employing a feedback controller was used in a whole building system simulation for a residential house. The system model computed the overall building energy efficiency and dynamic indoor conditions under

varying operating conditions. Simulation results indicate the studied TBE system can meet a heating demand to maintain the desired room temperature at 20 °C when the lowest outdoor temperature is at -26.3 °C, with a seasonal heating COP near 1.1, demonstrating a better heating performance than electric heaters. It suggests a potential energy-efficient alternative to the traditional natural gas furnaces and electric heaters for space heating.

1. INTRODUCTION

Thermoelectric technology uses thermoelectric materials to realize the mutual conversion between temperature differences and electricity (Luo et al., 2020). Researchers have integrated thermoelectric materials and devices into building walls for space heating and cooling (Ahmad Gondal, 2019; Aksamija et al., 2019; Ibañez-Puy et al., 2018; Irshad et al., 2019; Martín-Gómez et al., 2021; Zuazua-Ros et al., 2018, 2019). As shown in Figure 1(a), the TBE-building system is a highly integrated thermal-activated heating and cooling without the requirements of transporting energy and synergy among subsystems. Meanwhile, the TBE system requires no refrigerant and no release of chemicals, making it environmentally friendly. The TBE-building system has great flexibility due to the ultra-low-profile thermoelectric devices (e.g., TEM) and expandable modulus TBE components. A typical TBE component, as displayed in Figure 1(b), has three primary parts, including (1) TEMs, (2) heat dissipation (e.g., heat sinks and circulation fans), and (3) associated wall design.

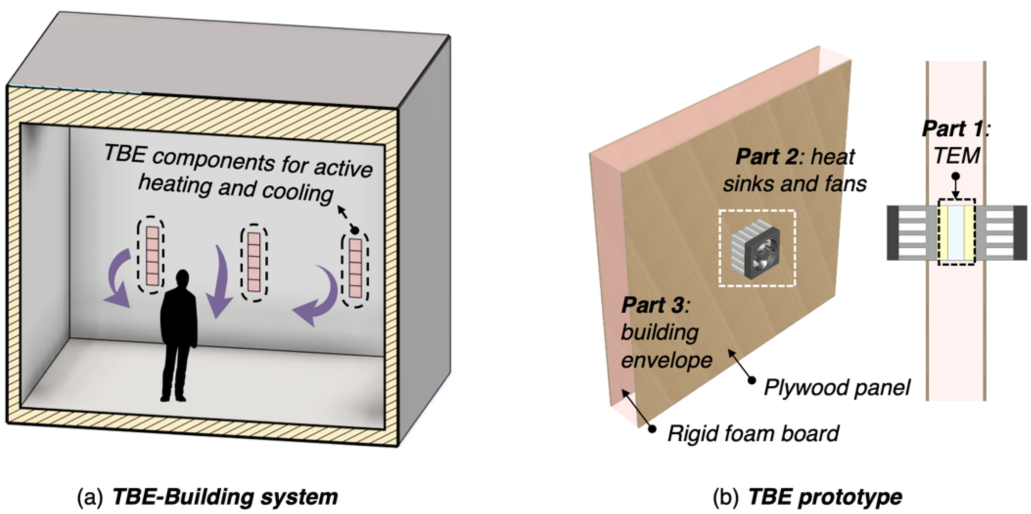

Figure 1: The schematic diagrams of (a) a TBE-building system and (b) a ventilation-type TBE prototype.

However, the research on the TBE system is still at an early stage. Due to physical and technical challenges, only a few experimental studies have been carried out under limited weather conditions. Martin *et al.* reported that the TBE's heating COP including and excluding fan power at an ambient condition were 0.82–1.01 and 1.02–1.91, respectively (Martín-Gómez et al., 2021). Researchers seek approaches to improve the energy conversion efficiency of the TBE system and to investigate the adaptivity of the TBE system in different climates. Therefore, models of a complete TBE-Building system are highly needed to comprehensively guide the system design and operation and the adoption of thermoelectric technology in buildings.

Most models developed to evaluate a TBE device focused on TEMs used in the device and only reflected the steady-state performance without considering varying outdoor conditions and system control. Then in 2020, Luo *et al.* developed a state-space model of a photovoltaic-thermoelectric wall system demonstrating a net-zero heat flux through the building envelope via a model predictive control (Luo et al., 2020). This study pointed out a limitation in whole building simulation and optimization, which is rather critical for building energy system analysis. However, limited studies integrated the TBE model within building energy modeling for seasonal performance analysis. Wang *et al.* conducted the annual energy analysis of a TBE system utilizing renewable energy for domestic heating by only comparing the heating demand of a house with TBE's heating supply assuming a constant COP and a given renewable power supply (Wang et al., 2017). The model's result indicated a possible energy-saving of 64% and a reduction of CO_2 emission of 4305 kg/year for the proposed system. However, this model ignored the impact of varying outdoor temperatures and controls of power on the TBE's annual performance. To study the thermoelectric technology for room temperature control, Hagenkamp *et al*. established a steady-state model for thermoelectric elements with optimized power input to meet the fixed heating demand (Hagenkamp et al., 2022). This model indicated an efficient heating performance of thermoelectricity elements by using an advanced control system. Since the TBE system is still a new system for space air conditioning, current modeling methods cannot reflect a comprehensive performance of a TBE system. It is necessary to develop a holistic approach toward the optimum performance of the TBE system. Hence, our study aims to establish a TBE-building system model to guide the optimal system design and operation.

In this paper, a transient TBE system model for space heating was investigated by using Modelica language. The system model integrated a verified TBE prototype model employing a Proportional-Integral-Differential (PID) power controller within a residential house. The model was used to predict the transient heat transfer and energy efficiency of a TBE system integrated into buildings with feedback control to maintain the desired indoor thermal comfort. The seasonal indoor air temperature, current input, heat deliverable, and COPs of TEM and TBE under historical weather conditions were computed and analyzed. Key contributions include the whole system simulation, transient heat transfer analysis, and seasonal energy analysis. Finally, conclusions and suggestions were provided to guide the design, sizing, and control of a TBE system to facilitate the deployment of thermoelectric applications in buildings.

2. METHODOLOGY

2.1 Methodology Overview

As displayed in Figure 2, the heat and electric transfer models at three different hierarchical levels have been investigated in this study. First, at the module level (level 1), an analytic model for a single TEM was established based on the energy conversion and thermoelectric principles, including the Peltier effect, Joule heating, heat conduction, and heat storage, as described in Section 2.2. Subsequently, at the prototype level (level 2), a TBE model was developed by combining the TEM at level 1 with the envelope design, as presented in Section 2.3. Experimental data have validated the prototype model. At the system level (level 3), the verified prototype model (at level 2) employing a PID controller was plugged into a residential house to construct the TBE-Building system model, as illustrated in Section 2.4. Three models were developed using the Modelica language and solved by an ordinary-differential-equation solver. Finally, the system model computed the overall building energy consumption under different operating conditions, including the outdoor temperature, power input to TBE, etc.

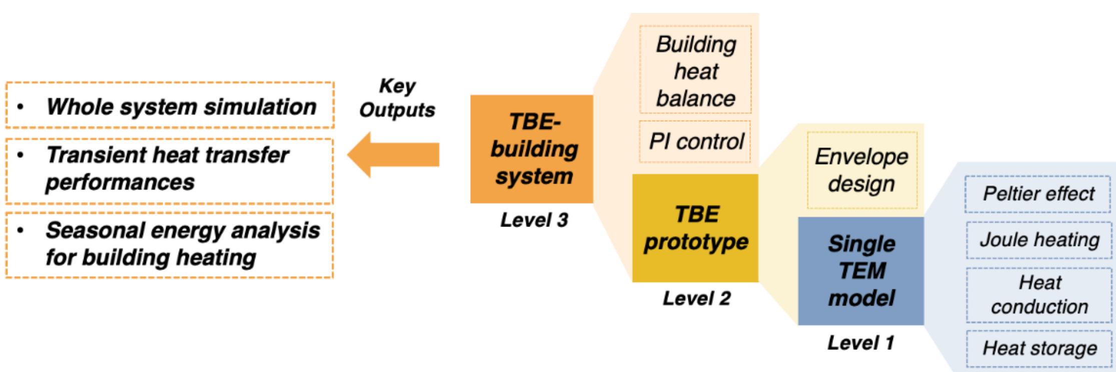

Figure 2: The hierarchy of three Modelica models developed in this study

2.2 Thermoelectric Module Model

A simplified theoretical model of thermoelectric elements has often been used for analyzing thermal and electrical power because it can be easily integrated with other sub-models and reduces computation time, making it suitable for simulating a complex system. The model holds several assumptions:

a) The material properties are independent of temperature.
b) Thomson effect and the surface heat losses of thermoelectric elements are negligible.
c) Joule heating contributes equally to the extremes of thermoelectric elements.
d) The model only considers one-dimensional heat transfer for TEMs.

This first-principal model is based on energy conversion and thermoelectric fundamentals. The heating power ($\dot{Q}_h$) at the hot surface and the cooling power ($\dot{Q}_c$) at the cold surface of a thermoelectric element are given by

$$\dot{Q}_{h,te} = SIT_{h,te} - 2K_{te}\left(T_{h,te} - T_{m,te}\right) + 0.5I^2R_{te} \tag{1}$$

$$\dot{Q}_{c,te} = SIT_{c,te} - 2K_{te}\left(T_{m,te} - T_{c,te}\right) - 0.5I^2R_{te} \tag{2}$$

where S is the Seebeck coefficient; I is the current input; K_{te} is the thermal conductance, kA/L, where k is the thermal conductivity, A is the cross-sectional area, and L is the leg length of the thermoelectric element; R_{te} is the electrical resistance; $T_{m.te}$, $T_{h,te}$, and $T_{c,te}$ are middle-point, hot surface, and cold surface temperatures of thermoelectric elements, respectively. As can be seen from equation (1) and equation (2), the heat transfer model of a thermoelectric element contains three primary effects, including the Peltier effect (a heating power of $SIT_{h,te}$ at the hot surface and cooling power of $SIT_{c,te}$ at the cold surface), heat conduction ($K_{te}\left(T_{h,te} - T_{m,te}\right)$), and Joule heating ($I^2R_{te}$). Thermal storage in a thermal mass is considered to model the transient behavior of the component. For thermoelectric elements, the heat balance in the two-resistance-one-capacitance (2R1C) model can be written as

$$m_{te}c_{p,te}\frac{d\left(T_{m,te}\right)}{dt} = 2K_{te}\left(T_{h,te} - T_{m,te}\right) - 2K_{te}\left(T_{m,te} - T_{c,te}\right) \tag{3}$$

A TEM is a thermoelectric device containing a total number of N n-type and N p-type thermoelectric elements, N metal interconnects, and two ceramic substrates. Metal interconnects link thermoelectric elements electrically in series to expand the power output. Ceramic plates are thermally conductive but electrically insulative for insulation protection. For metal interconnects and ceramic substrates, the heat transfer equations modeled by a 2R1C thermal network are expressed as：

$$m_{me}c_{p,me}\frac{d\left(T_{m,me}\right)}{dt} = 2K_{me}\left(T_{1,me} - T_{m,me}\right) - 2K_{me}\left(T_{m,me} - T_{2,me}\right) + I^2R_{me} \tag{4}$$

$$m_{ce}c_{p,ce}\frac{d\left(T_{m,ce}\right)}{dt} = 2K_{ce}\left(T_{1,ce} - T_{m,ce}\right) - 2K_{me}\left(T_{m,ce} - T_{2,ce}\right) \tag{5}$$

where the subscripts 1 and 2 represent the left and right sides of material along the direction of heat flow. Since the ceramic-metal interface and the metal-thermoelectric interface are ideal surfaces without considering contact resistance, then the heat transferred to and out of the interfaces is balanced. Thus, the boundary conditions for interfaces include, $\dot{Q}_{2,me} = 2\dot{Q}_{c,te}$ and $N\dot{Q}_{1,me} = \dot{Q}_{2,ce}$ for the cold side, and $\dot{Q}_{1,me} = 2\dot{Q}_{h,te}$ and $N\dot{Q}_{2,me} = \dot{Q}_{1,ce}$ for the hot side of a TEM.

Modelica model can reduce such a physical problem to a thermal and electrical resistance network. The input of the TEM model is the electrical current signal (I), and the outputs of the TEM model are the temperature (T_{ce}) and heat flux ($\dot{Q}_{ce}$) at two ends of the TEM. An electric circuit is generated with an electric source, and resistances of metal interconnects in the electrical field and n-type and p-type thermoelectric elements. Once the current signal is given, the Joule heating due to electrical resistance is computed and transferred to the thermal field. The heat generated due to the Peltier effect can also be computed by combining the current signal with material properties and the computed surface temperature. In the thermal field, each thermoelectric element, metal interconnects, and ceramic substrates are modeled by 2R1C models. Joule heating and the Peltier effect are considered heat sources applied to the capacitance.

2.3 TBE Prototype Model

The TBE model contains a TEM model, an envelope model, and boundary conditions (i.e., heat sinks and fans). The TBE prototype studied in this paper has three TEMs connected both electrically and thermally in series. The detailed design of the TBE prototype can be found in the literature (Liu et al., 2022). The 3D rendering image of a prototype is shown in Figure 1. Two TEM surfaces are attached with heatsinks and fans to help dissipate heating and cooling power generated from the surface. The overall thermal resistance of the heatsink and fan in operation are obtained from manufacturers' datasheets. Thus, the heat balances for heat sink at TEM's hot and cold sides are expressed by:

$$m_{hs}c_{p,hs}\frac{dT_{h,hs}}{dt} = \dot{Q}_{h,ce} - h_{hs}A_{hs}(T_{h,hs} - T_{h,air}) \tag{6}$$

$$m_{hs}c_{p,hs}\frac{dT_{c,hs}}{dt} = \dot{Q}_{c,ce} - h_{hs}A_{hs}(T_{h,hs} - T_{c,air}) \tag{7}$$

Moreover, the model employed a three-dimensional thermal network to capture the spatial heat transfer of the envelope associated with the prototype design. The TBE prototype model developed in Modelica combined the equations above by referring to the physical construction of the TBE prototype.

2.4 TBE-Building System Model

As shown in Figure 3, the TBE-building system model has four parts: a TBE prototype model, a heat balance model for a residential house, the weather data as an input, and a PID controller to control the current provided to the TBE prototype for room temperature regulation.

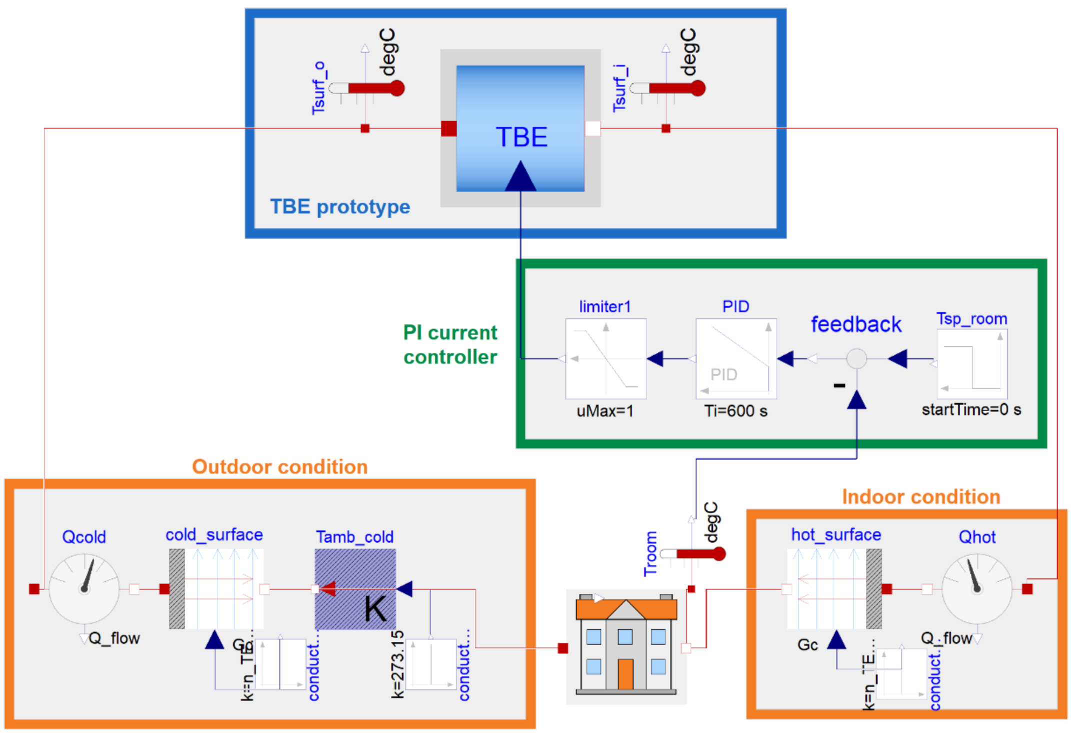

Figure 3: Thermal network of a TBE-Building system model using Modelica language

In this paper, the heating performance of the TBE-building system was investigated during the heating season. Given the outdoor and indoor air temperatures, the controller regulates the power input to the TBE prototype based on the temperature difference between the indoor temperature and the setpoint. Meanwhile, the TBE prototype dissipates heat to the indoor space to meet the heating demand required by the house and adjusts the air temperature to reach a set point of 20 °C in this study. The residential home has a volume of 3.05 × 3.05 × 2.44 m^3 (10 × 10 × 8 ft^3) with 0.102 m (4-in) thick foam boards covered on four exterior walls and floor with a thermal resistance of R-20 and a 0.305 m (12-in) thick foam board covered on the roof with a thermal resistance of R-60. The house model includes the envelope heat losses, 18 CFM infiltration, and 80 W internal heat gain in the heat balance. Both daily and seasonal performance were investigated under different outdoor conditions: three heating days and a heating season from January to March in Chicago.

2.5 Solver and Performance Indicators

The overall model is a combination of ordinary differential equations (ODEs) with respect to time only, which is also named the differential-algebraic equation (DAE) system. The Modelica model can be transformed into an ODE representation to perform simulation by using numerical integration methods. The solver is DASSL to solve the ODEs using the implicit and backward differentiation formula. The model can compute transient profiles of the air and surface temperatures and heat flux for desired materials and intersections.

The performance analysis of this TBE-building system includes the study of room air temperature, heat deliverable to the room, electricity consumption, and heating COP of TEMs. In this study, the COP of the TEM ($COP_{h,tem}$) is the ratio of heat flux at hot surfaces ($\dot{Q}_{h,tem}$) to the electrical power consumption of the module (W_{tem}), given by

$$COP_{h,tem} = \frac{\dot{Q}_{h,tem}}{W_{tem}} \tag{8}$$

3. MODEL VALIDATION

A convective TBE prototype designed by the research team was tested in Herrick Lab at Purdue. The test setup mainly contains a TBE prototype for heat generation installed between a pair of psychrometric chambers to simulate different indoor and outdoor conditions, a DC power supply unit for controlling power input, and thermocouples and DAQ for temperature measurement. Three TEMs used are from the market (model number: TEM-199-1.4-0.8, TEM-127-1.4-2.5, and TEM-199-1.4-0.8) and connected thermally and electrically in series. A tall heat sink and DC fan were used to dissipate the heat to the surroundings effectively. The experimental data (Liu et al., 2022) was used to validate the prototype model. Two groups of tests in heating scenarios were selected, with the indoor temperature at 22 °C and the outdoor temperature at 12 °C and current inputs of 0.5 A or 1 A. Simulation results from the TBE prototype model were compared with the measured data. The comparison of TEM's surface temperatures versus time is presented in Figure 4. The solid lines show TBE modeling results, and they yield good agreement with the measurement data represented by the dashed lines. The most significant discrepancy between the measured data and the modeling results is about 0.47 °C in winter scenarios, 3%. In conclusion, the Modelica model can accurately simulate the heat and electric transfer in a TBE prototype and can be used to predict the heating behavior in building system simulation.

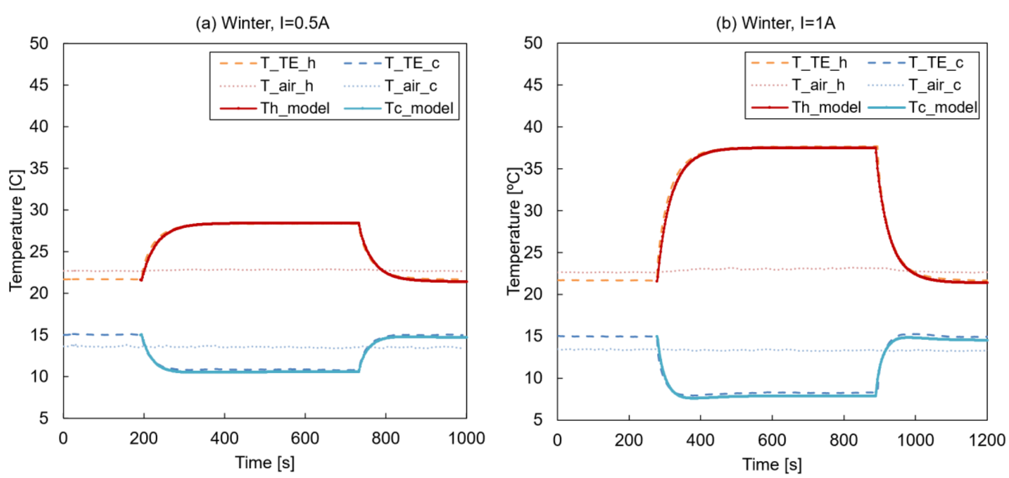

Figure 4: Comparison of test results and model-predicted temperatures for a TBE with (a) I=0.5A and (b) I=1A in winter.

4. SIMULATION RESULT

The developed TBE-building system model is used to predict the performance of the TBE prototype using TEMs (HP-127-1.4-2.5) for heating a residential house with a volume of 22.6 m^3 (800 ft^3). The number of TEMs was selected for two reasons. One must provide sufficient heating and maintain the indoor air temperature at 20 °C. The other reason is to lower the indoor surface temperature under 46.7 °C for safety operations. Two cases were investigated in this study, including the operation of the TBE-building system at an outdoor air temperature fluctuating within -2.5–2.5 °C and a historical weather condition in Chicago from January to March.

4.1 System Performance in Three Heating Days

Figure 5 displays the simulation result of using TBE with 22 TEMs for heating a residential house for three days. As shown in Figures 5(a) and (d), a cosine wave is used to simulate the change in outdoor air temperature within -2.5–2.5 °C. With different outdoor air temperatures, the heating demand of the space to reach a setpoint of 20 °C is different. A PID controller controls the current input and the heat rate deliverable to the space changes from 389–513 W accordingly (Figures 5(b) and (e)). As a result, the indoor air temperature can be maintained at 19.86–20.14 °C. The system has a fast response and can accurately regulate indoor air temperature. The studied system demonstrates a heating COP of TEMs ($COP_{h,tem}$) at 1.00–1.14 and 1.05–1.22, for TEMs with boundary thermal resistance of 0.9 K/W and 0.75 K/W, respectively, excluding the system startup.

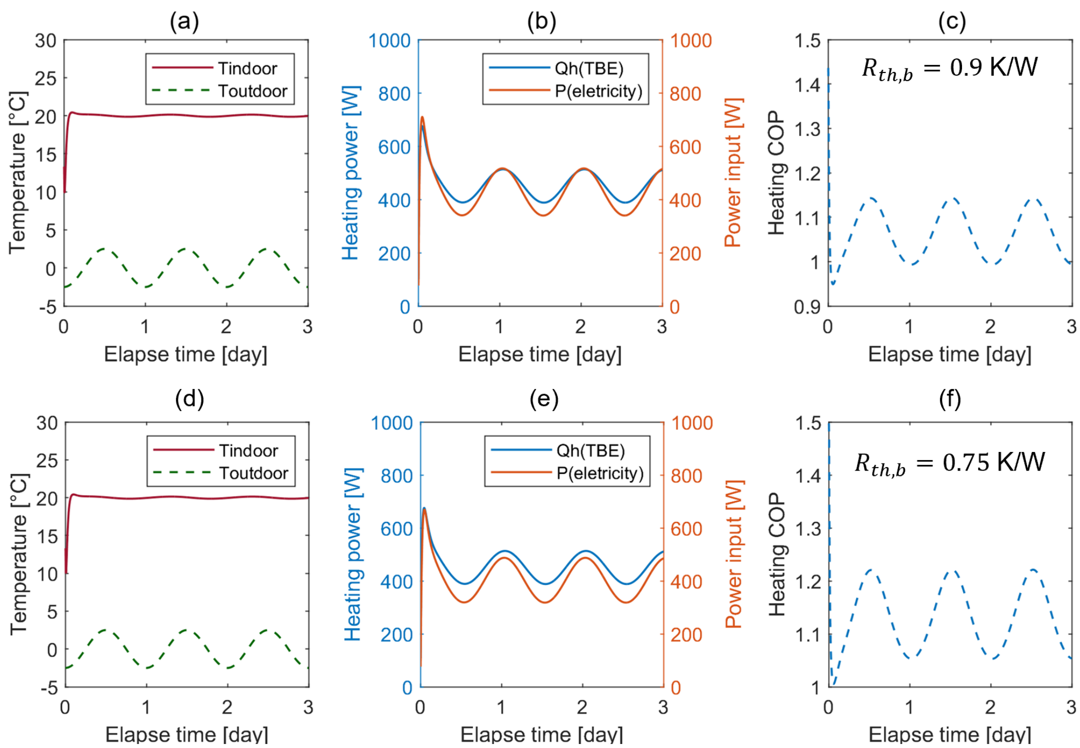

Figure 5: Simulation results of TBE-building system on three heating days: (a) indoor and outdoor temperatures, (b) heating power and electricity, and (c) heating COP with thermal boundary resistance of 0.9 K/W; (d) indoor and outdoor temperatures, (e) heating power and electricity, and (f) heating COP with thermal boundary resistance of 0.75 K/W.

4.2 System Performance in a Heating Season

Figure 6 presents the simulation result of heating a residential house from January to March in Chicago using a TBE system with 35 TEMs. As shown in Figure 6(a), the outdoor air temperature (T_o) fluctuates from -26.3 °C to +21.5 °C. The average value of these 90-day temperatures is -2.36 °C. The TBE system is the only source of heating power for the space. The indoor air temperature (T_i) can be kept at 20 °C, and the heating demand can be fulfilled by TBE even under extremely cold outdoor conditions. When T_o is -26.3 °C, a large current is needed to provide a heating power of 1217 W to the space (Figure 6(b)). The TBE system demonstrates a high ability in air temperature elevation. In this operating condition, the heating COP of TEM ($COP_{h,tem}$) is lower than one due to the significant heat loss, as can be seen in Figure 6(c). The COP of TBE varies with different outdoor air temperatures. A higher T_o leads to a higher heating COP. When T_o is -5 °C, $COP_{h,tem}$ is around 1. When T_o is +5 °C, $COP_{h,tem}$ is around 1.34. The seasonal heating COP of TEMs is about 1.07, which is higher than the efficiency of an electric heater.

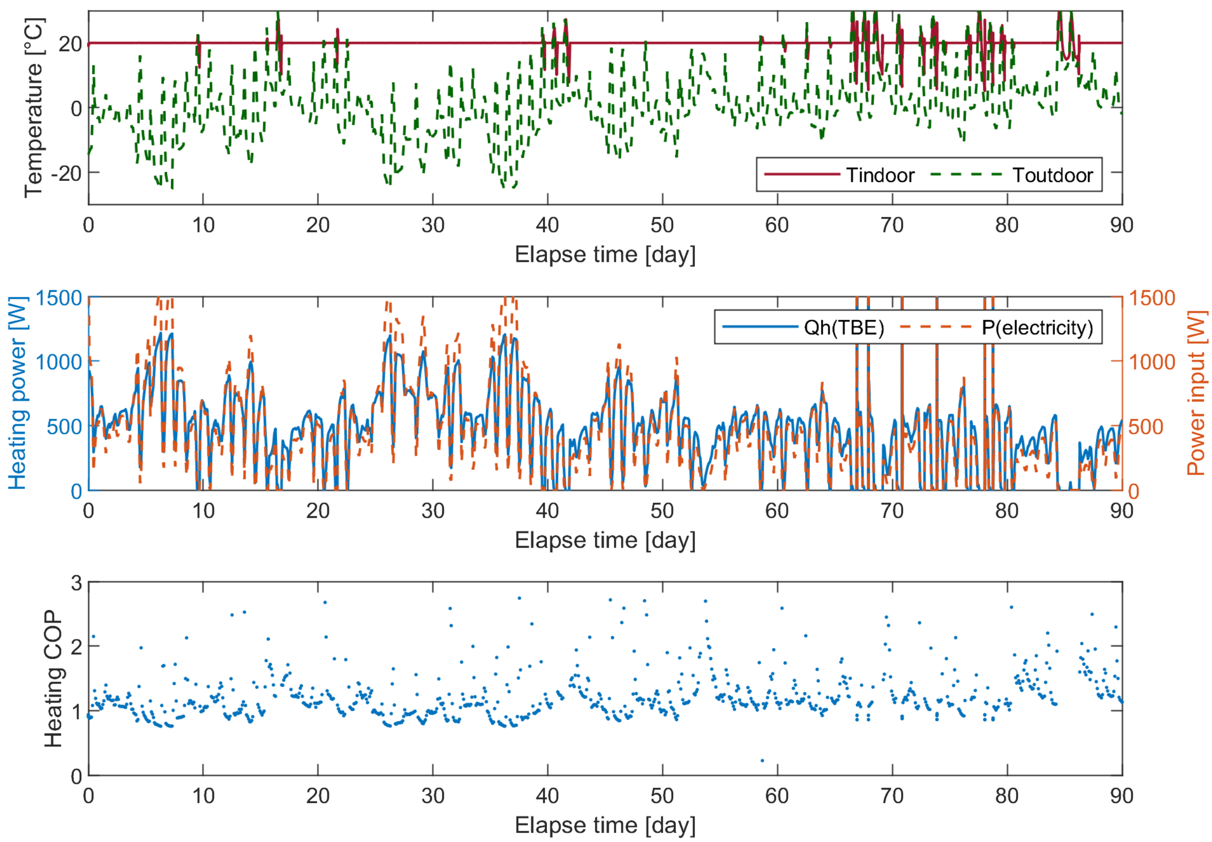

Figure 6 Simulation results of the TBE-Building system model in a heating season: (a) indoor and outdoor temperatures, (b) current input and heat deliverable, and (c) COP.

5. DISCUSSION

The TBE system integrates the building envelope, heating generation system, and heating delivery system into one system to provide accurate temperature control and reduce the heat loss from traditional HVAC subsystems. Thus, the performance of the TBE system is sensitive to outdoor conditions. This study combined a building envelope model, a control model, and a TBE model into one TBE-Building system model to comprehensively predict the system's transient behavior under varying operating conditions. The critical parameters influencing the COP include the design of TBE (e.g., the geometry of TEM, the heat dissipation technology, and the heat loss), the number of TEMs used, and the temperature difference between indoor and outdoor air, etc.

Energy-efficient technology for heat dissipation is the key to improving a TBE's heat deliverable and COP in the TBE design. In the study, every TEM is attached to heat sinks and a fan with thermal resistance at around 0.75–0.9 K/W on hot and cold surfaces. COP can be further improved by reducing the fan's power consumption or reducing the thermal resistance at TEM's boundary. Reducing heat loss is also critical in the TBE design. The heat loss might come from the heat conduction across the TEM, which can be reduced by optimizing thermoelectric elements' design (i.e., dimension) and physical properties (i.e., thermal conductivity) for lower heat flux through conduction. The leakage of the envelope also needs to be avoided to lower the heat loss through infiltration.

In terms of system sizing, the selection of the number of modules and the corresponding current input also affects the system performance. The larger current allows fewer TEMs but leads to a risk of high surface temperature exceeding the highest limit of a TEM and associated with more significant heat loss through conduction due to a large temperature difference. Therefore, the sizing of the system depends on the maximum operating current, voltage, temperature of a TEM, the outdoor temperatures (or the climate zone), the thermal load of buildings, the cost, etc.

A TBE's COP is a function of indoor and outdoor air temperatures. The greater the temperature difference, the more significant the thermoelectric material's surface temperature difference needs to be overcome. As a result, there is a greater loss of thermal surface (indoor surface) due to heat transfer. The model developed in this study indicates that the heating COP can be near 1.1 in winter operation in Chicago, suggesting that the TBE system is an energy-efficient alternative to the traditional electric heater. Some strategies to cope with extreme weather can be referred to. Firstly, heat recovery technology can be used to reduce the temperature difference by increasing the air temperature on the cold side, thus improving the TEM performance. In addition, using high-performance TE materials that can hold a larger temperature difference to reduce heat loss can also improve the overall TBE performance.

6. CONCLUSION

This study developed a TBE-Building system model for space heating using Modelica language. The model integrated models of the building's heat balance, a PI controller, and the TBE prototype to predict the transient performance of air temperatures, heat fluxes, and energy efficiency under dynamic operating conditions.

The daily simulation result demonstrates that when the outdoor temperature fluctuates from -2.5 to +2.5 °C, the TBE with 22 TEMs can deliver heating power of 389–513 W to the space to maintain a desired indoor temperature, with heating COP of TEMs ($COP_{h,tem}$) at 1–1.34, depending on outdoor conditions and boundary thermal resistances. Seasonal simulation in a colder climate with 35 TEMs presents the seasonal heating COP ($COP_{h,tem}$) of 1.07.

Key parameters influencing the heating COP include temperature difference between indoor and outdoor air, the electricity input to the TEM and the number of TEMs used, the design of the TEM construction, and the heat transfer on the wall. In addition to the thermoelectric materials. Strategic items to improve the performance might be energy-efficient heat removal, high-performance (larger ZT) thermoelectric materials, optimum TEM design, and minimization of heat leak in TBE devices.

In summary, the TBE-building system developed in this paper provides critical guidance to the design and operation at a system application level. The TBE system demonstrates a better heating performance than a backup electric heater for the state-of-the-art heat pump, which has a lower COP under a cold climate. It also suggests potential energy-efficient replacement options for the traditional natural gas furnaces and electric heaters for space heating.

NOMENCLATURE

Symbol

c	specific heat	($J\text{-}kg^{-1}\text{-}K^{-1}$)
I	current	(A)
K	heat conductance	($W\text{-}K^{-1}$)
$\dot{Q}$	heat flux	(W)
R	electrical resistance	(ohm)
S	Seebeck coefficient	($V\text{-}K^{-1}$)
T	temperature	(°C)
t	time	(sec)
V	volume	(m^3)
ρ	density	($kg\text{-}m^{-3}$)

Abbreviation

DC	direct current
PI	proportional-integral
TBE	thermoelectric building envelope
TEM	thermoelectric module
2R1C	two-resistance-one-capacitance

Subscript

c	cold side
ce	ceramic substrate
h	hot side
hs	heat sink
me	metal interconnect
te	thermoelectric element
tem	thermoelectric module

REFERENCES

Ahmad Gondal, I. (2019). Design and experimental analysis of solar thermoelectric heating, ventilation, and air conditioning system as an integral element of a building envelope. *Building Services Engineering Research and Technology*, *40*(2), 220–236. https://doi.org/10.1177/0143624418814067

Aksamija, A., Aksamija, Z., Counihan, C., Brown, D., & Upadhyaya, M. (2019). Experimental Study of Operating Conditions and Integration of Thermoelectric Materials in Facade Systems. *Frontiers in Energy Research*, *7*(FEB), 6. https://doi.org/10.3389/fenrg.2019.00006

Hagenkamp, M., Blanke, T., & Döring, B. (2022). luo *International Journal of Energy and Environmental Engineering*, *13*(1), 241–254. https://doi.org/10.1007/S40095-021-00424-X/TABLES/3

Ibañez-Puy, M., Martín-Gómez, C., Bermejo-Busto, J., Sacristán, J. A., & Ibañez-Puy, E. (2018). Ventilated Active Thermoelectric Envelope (VATE): Analysis of its energy performance when integrated in a building. *Energy and Buildings*, *158*, 1586–1592. https://doi.org/10.1016/J.ENBUILD.2017.11.037

Irshad, K., Habib, K., Saidur, R., Kareem, M. W., & Saha, B. B. (2019). Study of thermoelectric and photovoltaic facade system for energy efficient building development: A review. *Journal of Cleaner Production*, *209*, 1376–1395. https://doi.org/10.1016/J.JCLEPRO.2018.09.245

Liu, X., Qu, M., & Yazawa, K. (2022). Performance Assessment of Integrated Building Envelopes Using Thermoelectric Modules for Temperature Regulation. *2022 ASHRAE Winter Conference*.

Luo, Y., Zhang, L., Liu, Z., Yu, J., Xu, X., & Su, X. (2020). Towards net zero energy building: The application potential and adaptability of photovoltaic-thermoelectric-battery wall system. *Applied Energy*, *258*, 114066. https://doi.org/10.1016/J.APENERGY.2019.114066

Martín-Gómez, C., Zuazua-Ros, A., del Valle de Lersundi, K., Sánchez Saiz-Ezquerra, B., & Ibáñez-Puy, M. (2021). Integration development of a Ventilated Active Thermoelectric Envelope (VATE): Constructive optimization and thermal performance. *Energy and Buildings*, *231*, 110593. https://doi.org/10.1016/j.enbuild.2020.110593

Wang, C., Calderón, C., & Wang, Y. (2017). An experimental study of a thermoelectric heat exchange module for domestic space heating. *Energy and Buildings*, *145*, 1–21. https://doi.org/10.1016/J.ENBUILD.2017.03.050

Zuazua-Ros, A., Martín-Gómez, C., Ibañez-Puy, E., Vidaurre-Arbizu, M., & Gelbstein, Y. (2019). Investigation of the thermoelectric potential for heating, cooling, and ventilation in buildings: Characterization options and applications. *Renewable Energy*, *131*, 229–239. https://doi.org/10.1016/J.RENENE.2018.07.027

Zuazua-Ros, A., Martín-Gómez, C., Ibáñez-Puy, E., Vidaurre-Arbizu, M., & Ibáñez-Puy, M. (2018). Design, assembly and energy performance of a ventilated active thermoelectric envelope module for heating. *Energy and Buildings*, *176*, 371–379. https://doi.org/10.1016/j.enbuild.2018.07.062

ACKNOWLEDGEMENT

This material is based upon work supported by the National Science Foundation under Grant No. CBET-1805818.