ABSTRACT

Title: Thermoelectric Building Envelope: Material Characterization, Modeling, and Experimental Performance Evaluation

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Buildings in the U.S. are responsible for almost 40% of the country's total energy and 38% of total greenhouse gas emissions. Researchers seek sustainable and efficient energy generation and utilization solutions for buildings as society continues to cope with the intensifying energy crisis and environmental deterioration. Thermoelectric technology is one such solution that can lead to significant energy recovery and conversion between waste or excess thermal energy and electrical energy. A promising application is to integrate Thermoelectric materials into the Building Envelope (TBE) for power generation and heat pumping for building heating and cooling without the requirement of transporting energy among subsystems. TBE can combine structural support and thermal storage with power generation and thermal activated cooling and heating, thereby contributing to sustainable living and energy creation.

The TBE technology is still in the early developing stage. The dissertation aims to develop a fundamental understanding of the characteristic, behavior, operation, and control of the TBE system as energy-efficient measures for thermal energy harvesting and thermal comfort regulation to address the significant research gaps concerning high-conversion efficiency material, optimal module configuration, and system deployment related to real-world applications. Accordingly, the research in the dissertation contains three key objectives: (1) develop and characterize new thermoelectric composite materials; (2) identify the optimal design and control of TBE and establish mathematical models for performance simulation; and (3) quantify energy-saving benefits of TBE. The research has investigated the five following aspects:

(1) *Material development and characterization*. New thermoelectric cement composites were developed with cement and various additives, concentrations, and fabrication methods in the laboratory. Their thermoelectric properties (e.g., Seebeck coefficient, thermal conductivity,

electrical conductivity, power factor, and the figure of merit) were measured simultaneously and characterized at 300–350 K.

(2) *Module evaluation.* Two commercially available thermoelectric modules (TEMs) were assessed in both heat pumping and power generation modes using well-designed test apparatus. Test results validated the numerical model developed, which has been used to assist material selection and performance comparison between cement-based and commercial TEMs for the TBE prototype.

(3) *Prototype assessment.* A convective TBE prototype and a radiant TBE prototype were designed, assembled, and evaluated in a controlled testing chamber. The surface temperature, thermal capacity, and COP of TBE were studied and assessed under both summer and winter conditions.

(4) *Prototype modeling.* The first-principle-based numerical models of both convective and radiant TBE prototypes were developed in Modelica. Modeling results yielded a good agreement with the experimental data. The verified models have been used for parametric studies for TEM design and operation.

(5) *System simulation.* A TBE-building system model was established by integrating the TBE prototype model within a building's heat balance model, considering building constructions, climate conditions, power control, etc. Seasonal performances under various climate conditions were studied to identify the optimal operation and energy-saving potentials.

From the investigation of the study, there are several key findings in material development, TEM design, TBE system design and operation, energy benefit, etc. The TBE has higher efficiency of heating pump for heating than cooling generally. The TBE heating system performs better than a conventional electric heater (efficiency assumed at 0.9). The measures to improve TBE heating performance are enhancing material thermoelectric properties, optimizing TEM geometry, and enhancing boundary heat transfer. In conclusion, the TBE system can be a promising alternative to the conventional heating system in buildings. Studies in this dissertation strengthen the understanding of thermoelectrics in the building domain and guide further development in TBE. The insight can facilitate the operation of net-zero energy and carbon-neutral buildings.