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Tunable Cellular Materials for Adaptive Thermal Control

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Abstract. This research investigates a tunable cellular material system that can alternate between a thermal insulator and a heat exchanger. The capability to morph between these two distinctive thermal functions provide opportunities to create novel material systems that can dynamically adapt to its environment. The operating principle is to strategically deform the cellular material so that the shape and size of the cavities are optimized for the intended thermal function. In the compressed state, the cavity spaces are narrow enough to suppress convection heat transfer and utilize the low thermal conductivity property of still air. The expanded state has the optimum cavity dimensions for air to move through the system and exchange heat with the material system. The first stage of the research utilizes the existing thermal optimization studies for establishing the analytical model for predicting the performance of each state as a function of the geometric features. The second stage constructs a parametric model using the predictions and two separate material architectures were designed and fabricated based on it. The calibrated analytical model can be utilized in designing various dynamic thermal interaction systems at a wide range of conditions and parameters (e.g., climate, temperature, scale, and material).

Keywords. Dynamic Thermal Insulation; Cellular Materials; Thermal Design and Optimization; Adaptive Materials.

1. Introduction

Cellular materials such as wood, sponge, and bee’s honeycomb are ubiquitous in nature. A plethora of artificial cellular materials in the form of a lattice-structured material or foam are also commonly found in insulators, shock absorbers, and filters. (Gibson, Ashby, and Harley 2010) Cellular material systems are hybrid materials consisted of small compartments made of a solid material and void spaces within the compartments filled with fluid (e.g., gas or liquid). Due to this architecture, cellular materials have a unique set of thermal, mechanical, electrical, and acoustical properties (Gibson and Ashby 1997). Among the broad set of material properties, this study combines the thermal and mechanical properties to
develop a tunable cellular material system that can functionally adapt to its thermal environment.

There are many existing types of research relating to innovative material systems that utilize the thermal properties of cellular materials. Some examples include transparent honeycomb insulation (Suehrcke et al. 2004), metal foam heat exchangers (Odabaee and Hooman 2012), ceramic cellular thermal storage (Luo et al. 2014), and thermal insulation masonry blocks (Svoboda and Kubr 2011). These applications focus on controlling the porosity, anisotropy, pore connectivity and pore sizes of cellular materials to either limit or augment the heat flow through the cellular materials and components (i.e., thermal insulation or heat exchanger).

The limitation of heat flow through cellular solid is mainly achieved through reducing the volume fraction of materials using void cells small enough to suppress convective heat transfer (i.e., still air). A large number of solid and void transitions across the materials also decreases the overall radiation heat transfer. On the other hand, heat dissipation through cellular solid is achieved by flowing fluid through highly conductive and porous cellular solids with a large surface area. In this application, the size and shape of the voids need to be optimized to achieve the balance between maximum heat exchange and flow resistance.

In addition to thermal properties, this research also investigates the mechanical properties mainly relating to low density, low Young’s modulus and large compressive strain of cellular materials. These set of attributes allow the material system to change its thermal function via strategic de-formation. There have been studies that investigate variable cell geometry configuration including configuring smaller cells toward the heated edge for enhanced heat dissipation (Wang and Cheng 2005) and multi-objective optimization research such as combining heat dissipation and structural performance (Kumar and McDowell 2009). However, the potential of tunable thermal properties induced by cell deformation has not been investigated.

2. Operating Principle

The primary objective of this research is to design and fabricate a tunable cellular material system that can be used to enable building envelopes to adapt to its thermal environment. The strategy for achieving this is to deform the cellular cavities to the shape and size optimized for specific thermal functions including thermal insulation and heat exchanger (see Figure 1). The void spaces within the cellular material enable the material system to take advantage of the thermal properties of air. The configuration, number of the air cavity through the section of the material and the volume fraction of the cellular material will be the critical factors that influence the performance of each state.
In the solar chimney application (Figure 2, left), the material is deformed so that the interior side is compressed (thermal insulation) and the exterior side is expanded (heat exchanger). During the warm days, the air within the channels rises due to solar radiation heating the exterior side. When a vent is placed at the shaded side of the building (or using geothermal air channels), the fresh exterior air is pulled into the space, cooling the interior environment and exit out through the solar chimney. During the cold days, the interior air is circulated through the channels for harnessing the heat from the solar radiation.

In the heat recovery application (Figure 2, right) the interior side is expanded, and the exterior side is compressed. This system works by pulling in the fresh air from outside through the lower vent and precool or preheat it within the air channels before entering the interior space. The relatively consistent interior temperature regulated by active heating or cooling equipment provide the heat via conduction. Both solar chimney and heat recovery applications can also be used together as a hybrid system based on the orientation of the walls (e.g., solar chimney on the south façade and heat recovery on the north façade).
3. Thermal Property Characterization

The optimization of geometry and sizing of the proposed research is based on the studies conducted by Adrian Bejan including a vertical insulating wall with alternating layers of solid and air (Lorente and Bejan 2002), and parallel plates cooled by natural convection (Bejan and Lorente 2008). The optimum air cavity dimensions for the default state can be derived based on equation 1 and the constraints including minimum material thickness for constructability and mechanical strength. On the other hand, the optimum dimensions for the expanded state are derived from equation 2 and equation 3. Although the analytical model is based on parallel plates (see Figure 3) rather than a cellular honeycomb structure (see Figure 1), it is assumed that this is a sufficient geometric approximation (multiple layers and comparably small number of thermal bridging elements) at this stage of research.

Based on the equations and material constraints, two predicted performance curves were derived (see Figure 4). The first curve shows the heat exchange mode (i.e., expanded state) with the maximum heat transfer rate plotted as the function of air cavity thickness (D) and the number of cavities (n). The second curve shows the thermal insulation mode (i.e. compressed state) with the global thermal resistance values plotted as the function of air cavity thickness (D) and the number of cavities (n). This performance curve uses a 200mm high and 200mm wide panel with variable thickness (up to 200 mm using 0.6 mm thick solid layers) as the parameters.
for the analytical model. The conductivity of the solid material is 0.6 W/m.K, and the temperature difference (ΔT) is 10 degrees. The optimum deformation range can be calculated from the difference between the optimum spacing for maximum heat transfer rate and the optimum spacing for maximum global resistance.

Figure 3. Vertical parallel plates optimized to function as thermal insulation (left); and heat exchanger (right).

\[ R = \frac{R}{L} = \frac{k_b}{k_a} \Phi \left[ 1 \left( 0.364n^{-5/4} \Phi \frac{L}{H} Ra_{H,ΔT}^{1/4} \right)^{m/4} + 1 - \Phi \right] \quad (1) \]

\[ \frac{D_{opt}}{H} \approx 2.3 \left[ \frac{g \beta (T_{max} - T_0) H^3}{\alpha \nu} \right]^{-1/4} \quad (2) \]

\[ q_{max} = 0.45k(T_{max} - T_0) L \frac{W}{H} Ra_{H}^{1/2} \quad (3) \]

Where, \( R^{\ast} \) = global resistance; \( k_b \) = thermal conductivity of solid; \( \Phi \) = volume fraction; \( Ra_{H,ΔT} \) = Rayleigh number (H, ΔT); \( D_{opt} \) = optimum spacing; \( T_0 \) = initial temperature of air; \( Ra_H \) = Rayleigh number (H); \( \nu \) = kinematic viscosity of air; \( q_{max} \) = maximum heat transfer rate; \( R \) = overall thermal resistance; \( k_a \) = thermal conductivity of air; \( n \) = number of cavities; \( m \) = curve smoothing exponent; \( g \) = acceleration due to gravity; \( T_{max} \) = maximum temperature of air; \( \alpha \) = thermal diffusivity of air; and \( \beta \) = coefficient of thermal expansion.
4. Design and Fabrication

The design and fabrication process utilizes materials technologies ranging from studies including compliant mechanisms, parametric modeling, and additive manufacturing technologies. The analytical model is scripted into a parametric model so that the optimum deformation range can be extracted based on other parameters including the number of air cavity, thickness of the layers, thermal conductivity, and dimension of the material system.

4.1. MONO-MATERIAL HONEYCOMB SYSTEM

The first design iteration uses two-dimensional honeycomb configuration (see Figure 5). The material system is anisotropic (elongated hexagon section) so that there is a minimum number of bridging surfaces that contribute to direct conduction heat transfer (i.e., thermal bridging). The cellular material is fabricated with a fused deposition 3d printer using the Plasticized Co-polyamide Thermoplastic Elastomer (PCTPE) filament. PCTPE is a copolymer material of
nylon and thermoplastic elastomer which enables the system to deform when compressed or released.

4.2. COMPOSITE-MATERIAL SANDWICH SYSTEM
The second design iteration utilizes the 3d printed material only for the deformable frame component (Figure 6). Any conventional plate materials can be inserted into this frame and can be assembled for large-scale applications. Affordable opaque materials such as paper used in Figure 6 (left) can be integrated with this system and alternate between thermal insulation and heat recovery application. Similarly, transparent films such as polyethylene terephthalate (PETG) used in Figure 6 (right) can be integrated for switching between thermal insulation and solar chimney application.

4.3. DEFORMABLE COMPONENTS
The deformable components consist of the mechanism for controlling the cavity thickness and the operable vents. The cavity thickness control is achieved using
bi-stable or tri-stable compliant mechanisms (Machekposhti, Tolou, and Herder 2015). Figure 7 shows a cellular bi-stable compliant mechanism prototype that can alternate between two stable states inspired by the research on snapping mechanical metamaterials (Rafsanjani, Akbarzadeh, and Pasini 2015). The flexibility of the material and the micro-macro geometry variations activate the mechanism.

![Figure 7. Bi-stable compliant mechanism prototype.](image)

The operable vent that opens in the expanded heat exchange mode and closes in the compressed thermal insulation mode utilizes novel two-dimensional cut patterns. The cut-out pattern is influenced by the nanocomposite materials research inspired by Kirigami patterns (Shyu et al. 2015) that twist (buckle) when the material is stressed at a single axis (see Figure 8).

![Figure 8. Kirigami inspired deformable vent.](image)

5. Discussion

The graph of the analytical model in Figure 4 indicates that there exist two discrete optimum air cavity thicknesses for thermal insulation function and heat exchanger functions. Although these dimensions differ by a relatively small amount, the graph shows the difference regarding their thermal performance. This result is also advantageous as it only requires a small degree of deformation to switch between the thermal insulation mode and heat exchanger mode. It is also worth noting that the graphs can predict the thermal performance of each state at any given
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air cavity thickness (or amount of compression or expansion). This can provide the possibilities for utilizing the intermediate, transitional, or functionally graded states in novel ways.

The mono-material honeycomb system shown in Figure 5 utilizes the additive manufacturing process to create a relatively complex cellular geometry. This approach has many exciting possibilities such as a functionally graded cell geometry or multi-material system that have variable thermal and mechanical properties. However, the current state of additive technology is not yet efficient compared to the conventional industrial mass production process. On the other hand, the composite-material sandwich system shown in Figure 8 can utilize any existing sheet materials that have desired material properties. This hybrid approach can be used to create a versatile yet efficient modular system that takes advantage of both the mass production process and the additive manufacturing process.

The next stage of the research will focus on the physical testing of the prototypes to assess the degree of accuracy of the analytical model. This process will allow the analytical model to be calibrated and the parametric model can be adjusted accordingly for the next design iterations. The actuation method has not been investigated in detail at this stage of research. However, considering the relatively simple movement requirements, potential strategies can range from manual (e.g., pulley or lever) to automatic (e.g., electronic, or pneumatic) to material activated systems (e.g., stimuli-responsive materials or programmable matter).

6. Conclusion

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