Modulating Thermal Mass Behavior Through Surface Figuration

Dana Cupkova
Carnegie Mellon
School of Architecture

Patcharapit Promoppatum
Carnegie Mellon
College of Engineering

ABSTRACT
This research builds upon a previous body of work focused on the relationship between surface geometry and heat transfer coefficients in thermal mass passive systems. It argues for the design of passive systems with higher fidelity to multivariable space between performance and perception. Rooted in the combination of form and matter, the intention is to instrumentalize design principles for the choreography of thermal gradients between buildings and their environment from experiential, spatial and topological perspectives (Figure 1).

Our work is built upon the premise that complex geometries can be used to improve both the aesthetic and thermodynamic performance of passive building systems (Cupkova and Azel 2015) by actuating thermal performance through geometric parameters primarily due to convection. Currently, the engineering-oriented approach to the design of thermal mass relies on averaged thermal calculations (Holman 2002), which do not adequately describe the nuanced differences that can be produced by complex three-dimensional geometries of passive thermal mass systems.

Using a combination of computational fluid dynamic simulations with physically measured data, we investigate the relationship of heat transfer coefficients related to parameters of surface geometry. Our measured results suggest that we can deliberately and significantly delay heat absorption re-radiation purely by changing the geometric surface pattern over the same thermal mass. The goal of this work is to offer designers a more robust rule set for understanding approximate thermal lag behaviors of complex geometric systems, with a focus on the design of geometric properties rather than complex thermal calculations.
Why Thermal Mass
The role of passive systems in architecture has been historically framed within a technological imperative supported by the engineering paradigm of optimization associated with a singular high-performing variable that produces an average systemic solution. This approach limits the creative application of passive systems in design to a calculation for average performance (Fernández-Galiano 2000), and consequently produces architectural space that necessitates higher energy inputs for climate control. Even though current research proves that use of engineered thermal mass solutions can lower energy input needed for mechanical cooling by approx. 25% (Csáky and Kalmár 2015), these strategies are not widely embraced by the designers.

Expanding on the knowledge of geometry and computation, our work argues for a holistic material design approach that produces localized adaptive microclimates embedded and actuated by the form of the built environment. This is parallel to contemporary research focused on personalized thermal comfort (Matalucci et al. 2017), which argues that this approach is in opposition to the current status quo of building centralized mechanized climatic controls based on average understanding of thermal homogeneity. Thermal comfort in the built environment is centered on the understanding of temperature fluctuation between indoor and outdoor environments. To minimize the need for mechanical systems, architecture could take better advantage of managing heat loads and heat transfer through form and materiality. Understanding particular climatic profiles in relation to solar geometry could be more robustly mitigated by choreographing a set of thermal gradients between the object of architecture and its microclimatic effects. One can begin by suggesting more spatial relationships between a building’s mass articulation and its capacity to be a self-regulating heat storage system.

The effectiveness of thermal mass has been extensively described and studied from the engineering point of view (Balaras 1996), as well as speculated on as a more abstract energetic concept (Lally 2013). Our work focuses on exploiting concrete formal and topological principles of thermal mass surface geometry in an effort to better understand effective form-making and figuration from a design point of view. At the root of this research is the basic standard that an increase in surface area over a constant thermal mass significantly increases the rate of radiative and convective heat transfer, and delays the re-radiation of sensible heat in such systems. However, due to natural convection, the type of surface geometry—its size, proportion, and geometric articulation and character—make a significant difference in the actuation of thermal delays.

Previous Work
Material presented in this paper dovetails on our previous experiments, which mapped thermal behavior in response to surface geometry in a narrow setup of physical experiments with concrete
thermal mass tiles (Figure 2) (Cupkova and Azel 2015). The focus of the previous work was on visualizing the measured differentiation in thermal lag through digital heat maps. This revealed a potential to design a rate of absorption and release with greater fidelity and thus an ability to form a heat lag based on desired timeframe for a specific climate. Heat transfer is rooted in the combination of convection and radiation (Gan 1998). By focusing on the characteristics of increased surface area over the same mass, we are interested in changing the heat transfer coefficient primarily related to the convective abilities of the system. Heat transfer mechanisms at the surface of thermal mass is described in Figure 5, and convection is calculated as follows: \[ q = hA(T_{\text{wall}} - T_{\text{room}}) \]; where \( T \) is temperature, \( A \) is a wall surface area (\( m^2 \)), and \( h \) is the heat transfer coefficient (\( W/m/K \)). Based on the fundamentals of heat transfer, \( h \) is a function of surface geometry and temperature change. The graph in (Figure 5) is based on a simulation of a flat wall with varied \( h_1 \) (external) and \( h_2 \) (internal) values. It shows the difference in temperature delay and overall ability of the system to reach maximum temperature based on varied heat transfer coefficients. In this simulation the \( h \) values were assigned randomly to visualize a concept. This paper explores temperature gradient management based on the associative relationship between geometry and heat transfer coefficients, while maintaining constant mass, surface area and material properties. **Premise: From the Simulation of an Instance to the Observation of a Field**

The thermodynamics of complex three-dimensional surfaces are not trivial. In trying to visualize basic convective behavior and describe more generic rulesets, we took two-dimensional sectional cuts of geometry with different configurations of smoothness and roughness and varied orientation, but with the same line length, to explore the effect of convection on the \( h \) value of the surface while maintaining constant volume, and thus constant thermal capacity of each piece. We ran a series
Study of correlation between shape and heat transfer coefficient. Volume and surface area are the same for each of S1, S2, and S3 series. Heat coefficient decreases as a consequence of convection in shapes that produce decoupling of airflow along the surface. Only "active" surface affects the increase of the heat transfer coefficient along with increasing surface area.

Thermochromic progression of varied surface geometry associating the color change and temperature values showing an inconsistent field pattern to sectional simulation.

Thermochromic surface coating test: temperature measurement and temperature recording process.

Figure 3 describes the difference between sinusoidal and rectangular geometry. The characteristics of airflow are significant to the design of forms with varied thermal exchange rates; the smoother surfaces shaped to maximize contact with airflow precipitate a higher heat release rate, but a shorter heat lag. Rectangular geometries described by polylines trend towards the opposite, primarily because this type of geometry tends to reduce direct surface contact between airflow and wall surface area by creating air pockets. This formal strategy can be used in case we want to slow down the exchange rate process. The rectangular geometry causes the air to rise slower and with less direct proximity to the surface. The air gets trapped inside the unsmooth crevices, which eventually diminishes the overall heat transfer rate. Vertically, the lowest area of the surface that receives the most solar radiation is the most significant to changing the heat transfer parameters.

Size and proportion of surface variation, as well as orientation, are other performative factors. Figure 4 visualizes the difference in shape, size, and orientation. At the instance where the size of
METHOD: PHYSICAL EXPERIMENTATION AND TIME DELAY MEASUREMENTS

To better understand the behavioral trends from simulation sampling applied to field patterns, we set up a physical experiment. This process consisted of digital modeling, fabrication, heating of the fabricated panels, determining the specific measured values based on pattern and thermal scanning, and calculating pattern-specific time delays in thermal lag based on physical measurements. The goal was to measure how significantly we can form the time delay of re-radiation specific to a larger design agenda. The experiment included the fabrication of 45 concrete tiles that were heated up, thermal-scanned, and evaluated based on their thermal performance.

Computational Logic of Surface Topology:

We generated a sequence of geometric patterns with ranges of smoothness and roughness using curve degree, vector displacement, and orientation as variables (Figure 10). Constrained by genetic algorithms in Grasshopper using the Octopus plug-in (Vierlinger), we maintained constant volume across the whole matrix of 45 patterns while increasing surface area in five steps. Surface area increase is related to our previous understanding that shape, size, and proportion are significant factors in the heat transfer exchange. The geometry is algorithmically optimized to constrain the thermal mass to a constant, and all the panels have the same volume across the matrix (Figure 12). The surface area in each row of the matrix is the same, but increases evenly from top to bottom, while employing different geometric patterns.
from smooth to rough, computationally determined by using difference in curvature degree (1–3), from polyline to 3 degree nurb spline. According to the standard engineering approach, the thermal performance of each row of these panels should be the same because the thermal mass, material properties and surface area are the same. Our experiment proves that this is not the case, as the surface morphology has a significant impact on thermal lag. Executing our experiment allows us to determine the significance of the time delay in design space. The purpose is to gain a more specific measurement of temperature deviation and thermal re-radiation delay.

**Fabrication:**
The process of mold making and fabrication occurred as a part of funded research with our industrial partner TAKTL to test a possibility for thinner profiled modular thermal mass panels fabricated from ultra-high performance concrete (UHPC) (Figure 11), which would allow for higher structural compression and thus an ability to engage complex geometries. Forty-five high density foam molds were milled using CNC fabrication technology, then coated and prepped for casting. The tiles were cast in the manufacturing facilities in collaboration with our partner in a single pour. Tiles were vibrated, steamed, and cured to achieve optimal material consistency of UHPC. This process assures the material consistency of each tile. Each tile weighs the same, with a volume of 600 in³.

**Physical Testing:**
We are currently in the process of physical testing, which consists of heating up the concrete tiles in the electrical kiln to 60°C, setting them up vertically with an insulated back, and using thermocouples in combination with a thermal camera to measure the rate of heat transfer (Figure 13). We tested full sets of tiles...
Temperature Measurements and Time Delay Calculation:
The bar graph in Figure 14 shows the plot of time delay for each tile with surface areas of 400, 690, and 830 in² compared with flat tiles when $T_{\text{normalized}}$ is 0.4.

$$T_{\text{normalized}} = \frac{T - T_{\infty}}{T_{\text{initial}} - T_{\infty}}$$

where $T_{\infty}$ is the room temperature

with the surface areas of 400 in² and 690 in², and a partial set of tiles with an 890 in² surface area. All these objects have the same volume. The preliminary measured results suggest an ability to delay heat re-radiation by at least 75 minutes (1.25 hrs) by just using the articulation of the surface area.

Experiment Setup:
The experiment was designed to examine the cooling behavior of tiles and to use the measured temperature for the estimation of the heat transfer coefficient per each tile and geometry. To measure the local and overall thermal behavior of the 45 tiles, we used a combination of thermocouples, FLIR infrared thermal camera, and an infrared thermometer gun in each of the measurements. The sheathed thermocouples used in the experiment were attached to back and front surfaces of each tile, while the tile’s flat back and sides were insulated to minimize faster cooling from the edges and to focus on measurement of the front surface. The thermocouples we used were type J, with a diameter of 0.159 cm, and gave us the measurement uncertainty of 0.4%, or approximately 1.1°C, which is a statistically negligible deviation. The temperature data was recorded every 30 s with a response time for the thermocouple of 0.3 s. Two thermocouples were attached to the back of each tile to measure the average thermal behavior. Because the tiles are not significantly thick, and were insulated during the recording of the cooling process, the temperature difference between the back and front the surface is assumed to be negligible. The thermometer gun was used to measure and double-check the temperature of the front surface to further ensure the validity of measurement from thermocouples. The FLIR camera captured the temperature contours of tiles every 10 minutes to give us a better understanding of the geometrical influence upon more nuanced topological thermal behavior. The cooling duration and thermal measurements are 180 minutes long for each tile. The analysis of thermal images related to geometric surface is not part of this paper.

In the bar graph, the time delay plots are grouped by tiles with consistent volumes and surface areas. Hence these tiles shall behave the same, but because of the difference in surface topology this is not the case. As measured and observed, the temperature profiles of each tile are not identical, which results from the influence of surface geometry on the heat transfer coefficient. To illustrate the difference between how each geometric configuration influences the cooling time delay at the time where $T_{\text{normalized}}$ reaches 0.4 is plotted and compared against that of the flat tile. For example, tile S1A400 reaches a $T_{\text{normalized}}$ value of 0.4 forty minutes slower than the flat tile, whereas tile S1B830 is eighty minutes faster than the flat one. By considering the time delay plot, it is apparent that larger surface areas will always yield faster cooling. However, the effect of geometry on thermal performance is also observable, especially for tiles with 400 and 690 in² of surface area. On the other hand, the geometrical influence on the
thermal performance seems to be less obvious at the surface area of 830 in². The figuration of surface-area-to-mass ratio thus plays a significant role in geometric actuation.

**Calculation of Heat Transfer Coefficient:**
The temperature measurement from the thermocouples, which help us describe the average cooling behavior of each tile, could be used for calculating the average heat transfer coefficient specific to each time geometry. In the fundamental heat transfer, the classical approach, which describes the transient thermal behavior of tiles, is called the lumped capacitance method (LCM) (Holman 2010). The formula for this approach is shown in Figure 15.

**Calculation of Time Delay:**
Based on the geometry-specific h values shown in Figure 16, we can use the LCM formula to study the time-based cooling behavior of each concrete tile. This process enables us to determine the tile- and geometry-specific cooling time for each tile. To perform the calculation, the left-hand side of the equation is replaced by the following parameters: $T(t) = 27^\circ$C, $T_{\text{initial}} = 60^\circ$C, and $T_\infty = 25^\circ$C. This setting indicates that the tile has an initial temperature of 60ºC with a room temperature of 25ºC. The right-hand side of the equation describes the physical parameters of each tile, its material and physical properties, while the left-hand side is derived from our physical experiments and temperature measurements. By fitting the equation with the measured data, we can determine the specific h value per each tile’s surface morphology. The difference in thermal behavior caused by geometric differentiation is thus contained in a specific h value. The h values of each tile geometry are estimated as shown in Figure 16.

\[
\frac{T(t) - T_\infty}{T_{\text{initial}} - T_\infty} = \exp\left(-\frac{hA_j}{pc_jV}\right)
\]

The right-hand side of the equation describes the physical parameters of each tile, its material and physical properties, while the left-hand side is derived from our physical experiments and temperature measurements. By fitting the equation with the measured data, we can determine the specific h value per each tile’s surface morphology. The difference in thermal behavior caused by geometric differentiation is thus contained in a specific h value. The h values of each tile geometry are estimated as shown in Figure 16.
25°C. Consequently, the time required for the tile to cool down to 27°C is determined based on different $h$ values. Figure 18 shows the equation when all parameters except $h$ values and surface area are numerically replaced. We based this calculation on specific measurements, where the surface area of each tile is known and the $h$ value describes the difference in geometric articulation of the surface. The cooling duration is estimated and shown in Figure 19.

CONCLUSION

This paper formulates basic geometric behavior directly affected by surface-area-to-volume ratios. Based on our measurements from a physical experiment there seems to be a “sweet spot” in the surface-to-mass ratio range (1.12 in our case: 690in$^2$/600in$^3$), where the geometric articulation of the surface area more actively affects thermal behavior. We measured a maximum time delay of 75 minutes using randomized surface geometries. This means that we have the ability to strategically delay heat re-radiation of 35°C by 75 minutes within 3 hours, just through the figuration of mass to surface related to solar geometry. Because of convection, the smoother surfaces shaped to maximize contact with airflow precipitate a higher heat release rate, but a shorter heat lag. Rectangular geometries described by polylines trend towards the opposite. This phenomenon is primarily caused by the fact that this type of geometry tends to reduce direct surface contact between airflow and wall surface area by creating air pockets. We are currently in the process of defining more specific formal strategies that can be used to slow down the exchange rate process by articulating exact proportional and scalar surface formations related to specific behaviors. Expanding and propagating this knowledge within design strategies would have a significant effect on environmental dynamics in regards to energy savings and a decreased reliability on mechanized environments.

This paper argues for an architectural design framework amplified by thermodynamic behavior. Contextualized within Lally’s (2013) conceptual argument in describing processes where material energies are being shaped, and Rahm’s work on climate and meteorology becoming a source of inspiration and representational insight (Clement, Rahm, and Borasi 2007), we more concretely take on complex topological issues of surface articulation principles within mass figuration related to thermal behavior. These tactics and design strategies are central to the architectural discipline. Coupling the design framework with rigorous data analysis, this work is in the process of outlining the principles for more intuitive design of thermal gradients within...
the built environment. Just as Beesley (2010) argues for an environment that is nearly alive, we hope to expand the design knowledge rooted in thinking that brings architecture into a biosynthetic rather than a technological paradigm.

ACKNOWLEDGEMENTS
This project has been supported by New York State Council on the Arts Project Grant, Benkman Development Fund CMU, Liceaga Grant CMU, PITA (Pennsylvania Infrastructure Technology Alliance) Grant, Manufacturing Futures Initiative CMU, CFA Fund for Research and Creativity CMU; Industrial Partner: TAKTL, LLC; Principal Investigator: Dana Cupkova; Research Collaborator S.C. Yao; Research and Physical Experiment Team: Patcharapit Promoppatum, Shannon Lacino, Prerna Damani; Design and Fabrication Team: Yeliz Karadayi, Sinan Goral, Thomas Sterling, Colleen Clifford, Trent Wimbiscus, Noreen Saeed; Editing and text contribution: Marantha Putu Dawkins.

REFERENCES


IMAGE CREDITS
All drawings, photographs and images by the authors.

Dana Cupkova is an Assistant Professor at the Carnegie Mellon School of Architecture and is a principal of EPIPHYTE Lab, an architectural design and research collaborative. Her design work engages the built environment at the intersection of ecology, computationally driven processes, and systems analysis.

Patcharapit Promoppatum is a Ph.D. candidate in Mechanical Engineering at Carnegie Mellon University. His research interests involve the use of numerical modeling to predict and understand thermal behaviors in energy-saving applications. His recent works include the development of phase change material (PCM) heat exchangers and the geometric actuation of thermal mass. During his graduate studies, Mr. Promoppatum is awarded the Royal Thai Government Scholarship and the Bertucci Fellowship.