ABSTRACT

The Klimasymmetry research project is part of ongoing investigations that ask how the design of a surface emanating radiant heating and cooling can influence the non-visual spatial boundaries created by asymmetrical thermal conditions. This research investigates the nature of the surface as an initiator of a thermal environment in an attempt to locate thermal tactility and the spatial perception according to radiant heat transfer. Surface qualities such as the quantity of area and thermal capacity of the material affects the ability of the panel to emit or absorb electromagnetic radiation, informing the geometry, topography, and location of each panel relative to the human body. The integration of multiple behaviors develops a tectonic language that integrates thermal performance, material behavior, and digital fabrication processes within the architectural surface. The main objective of this research project is the production of a unique prototype capable of revealing a non-visual thermal environment created by an architectural surface. The prototype is developed as a series of radiant panels where the thermal behavior is embedded into the materiality of the surface, providing a method to test the interaction between people and the manufactured object. The surfaces are organized in relation to the physiological thermoreceptors within the human body, providing a geometric distribution of the panels. The prototype simultaneously provides the opportunity to research the thermal properties of one of the most ubiquitous materials in the built interior environment, gypsum, as a test to potentially expand the system to the scale of a building. The plastic behavior of gypsum allows the computational design of the surface topography to adapt to the thermal location according to the position on the viewer’s body. The fabrication technique for the gypsum radiant panels integrates automated manufacturing with fabric forming techniques, developing a process that is scalable from small to large deployments of the system.
INTRODUCTION

For the most part, we inhabit a world of objects defined by surface and geometry. Of the human senses vision dominates our culture, and the ramification on the field of architecture is that we tend to focus on structure, enclosure and atmospheric conditions such as lighting and optical illusions. Rarely are thermal conditions investigated beyond the functional efficiency of standardized comfort levels, rendering them benign as a design opportunity (Lally 2014). Thermal conditions of our environment are ubiquitous, yet subtle, and we tend only to notice when they are imbalanced or stray away from the ASHRAE standardization (ASHRAE 1997). An imbalance could be the perception of moving between two spaces with noticeably different temperatures, a space where the temperature is striated and vast difference can be felt between a person’s head and feet, or a condition where there are different temperatures on the right side versus left side of their body. People perceive thermal conditions through conduction and convection, but radiant heating is the most effective influence on thermal comfort in the built environment (Moe 2010). It is a system that is so pervasive in architecture, yet at worst it is misunderstood or, more commonly, underdeveloped for its generative potential in the design process. The oversight could be attributed to the dynamic nature and gradient boundary conditions that tend to problematize how to spatialize heat transfer. The result has been radiant heating and cooling embedded in floors, walls and ceilings that is a-tectonic due to the non-visual nature of thermal conditions.

The research avoids a purely building science or physics of heat flow approach in favor of investigating thermal conditions for their reciprocal relationship with architectural surfaces. Surface definition informs the thermal performance while the inverse is simultaneously true. Surfaces in the built environment initiate the thermal spatial conditions due to their temperature, thus simultaneously defining space visually and thermally. This multi-dimensional nature of the surface allows it to be considered for its capacity to initiate the definition of space non-visually, but also as a visually perceived boundary (Figure 1). This research seeks to ask the question about how thermal conditions can become an initial conceptual idea for a project, informing the geometry of a surface and defining the boundary of space.

THERMAL PERCEPTION

The sensation of temperature is subjective, but there are predictable patterns that emerge in a large sample group when considering a person’s age, gender, and the climate in which they live. Even on the surface of one’s own body there are regions that sense temperature in predictably different amounts. As such, people do not feel thermal comfort evenly across different zones of their own body (Boron and Boulpaep 2012). Beyond the extremities including hands and feet, the core of the body senses temperature differently. According to physiological research, the main zones of the body can be classified as the face, chest, abdomen, and thighs and have been ranked in order of effectiveness for perceiving thermal comfort. Furthermore, the different zones
of the body vary in importance of thermal sensation relative to the temperature of the surrounding environment. The four zones are ranked in different order of importance for perceiving temperature sensation in a primarily hot environment compared to a cold environment. As such in a hot environment, the most effective region of the human body to receive cooling is the face followed by the chest, then abdomen and lastly the thigh. In a cool environment, the ranking is shuffled so that the most effective region of the human body to receive heating is the abdomen, followed by the chest, then thigh and lastly the face (Nakamura et al. 2008) (Figure 2). The result of the study reveals that for architecture, the design of the built environment can consider micro-climates on the localized scale of a person’s body as a method to determine the relationship to their context. The distinct location on the human body produces a specific geometry associated with the way a person perceives the built environment. Translating the zones of the body into geometric location spatializes the perception of thermal conditions at the scale of the human. Within a built environment, many of the sources that produce thermal conditions are designed, managed, or at least coordinated by the architect.

The built environment is not homogenous, but rather a highly differentiated space that can be mined to augment and purposely affect one’s perception. Seeking an opportunity to uncover spatial differentiation offers the ability to define spaces through visual and non-visual sensations (Borasi 2006). Non-visual perception of space can be sensed
by subtle changes in the environment. In particular, a space can be associated with a specific thermal characteristic, which can differ from a space with another characteristic. The separation between the two spaces may not be visually distinct, yet a person can still perceive the change in the environment and that they have moved from one distinct thermal space to another. Thermal conditions create gradient boundaries due to the constant flux of heat flow (Banham 1969). The differences are perceptible, albeit subtle. The ability to perceive non-visual gradient boundaries provides an interesting design opportunity using thermal conditions as a means to define the limits of space. Furthermore, if we consider that a person’s thermoreceptors are located in their skin, we can reevaluate thermal conditions as a tactile sensation; therefore, temperature difference can produce a tactile boundary.

HEAT TRANSFER AND SURFACE AREA

Interaction, in terms of heat transfer, between people and their environment is in constant flux where heat flows from an object of higher intensity to one of lower intensity according to the second law of thermodynamics. Of the three types of heat transfer, conduction, convection, and radiation, the latter is the most influential in terms of the exchange of heat between a person and their built environment (Moe 2010). All objects are in a dynamic state of either emitting or absorbing radiant heat and the rate of heat flow is dependent on material, temperature difference, and quantity of surface area. Thus, radiation places the importance on surface temperature for heat transfer to and from the human body, embedding the architectural surface with thermal behavior. The quantity of surface area affects the thermal behavior where more surface area increases the effectiveness of heat transfer, thus requiring less temperature difference to induce the flow of heat (Lechner 2009). Thus, a radiator with small surface area requires a higher temperature to transfer heat similarly as a radiant ceiling with large surface area and lower temperature. Therefore, the ability of a surface to generate a thermal space is dependent of the geometric quantity of surface area, establishing a relationship between geometry and thermal behavior. Assigning dimensional qualities further reinforces the idea that thermal qualities are part of the palette of materials available to use when designing a space (Figure 3).
FORMAL / SPATIAL DEFINITION

In order to render thermal conditions as an architectural material, the investigation purposely generates a thermal imbalance in the form of two asymmetrical micro-climates; one on each side of the object. The perception of thermal environments is sensed more easily when there is an imbalance, calling attention to the difference in the quality of space (Moe 2010). The heightened attention to thermal conditions enhances the sensation as a tactile perception of temperature. The thermal imbalance is defined as an asymmetry on either side of the prototype, creating a warm environment on one side of the object and a cool environment on the opposite side. Thus the organizational logic creates climatological asymmetry (klimasymmetry) within the radiant surfaces of the prototype for people to interact with it. The deployment of the radiant panel system in the prototype is condensed into a cohesive human-sized object that contains both hot and cold panels instead of being applied as a layer to the floor, wall or ceiling. The compact deployment of the panels creates a full scale prototype in order to test and analyze the system (Figures 4, 5).

ASYMMETRICAL PANEL DISTRIBUTION

Asymmetry occurs at the scale of the prototype as an object, creating an organizational logic where hierarchical thermal conditions of either hot or cold climates dominate, yet it requires an opposing condition for people to perceive comfort. Introducing an opposing thermal condition creates an asymmetry within the series of panels on each side. Thus, within a series of panels that create a warm climate, a cooling panel is needed to absorb...
heat from the body while on the cool side a warm panel is needed to provide warmth. Within the either warm or cool panels, no further thermal subdivision is created. The human body perceives thermal comfort in different regions of the body depending on the context of the climate. The relation to the human body establishes an organizational logic and geometric location to generate an architectural formal response for the radiant panel system. The opposing panel is located on the specific geometric location on the body that perceives comfort most effectively. Therefore, on the side of the prototype that creates a warm climate, the cooling panel is located at the height of the viewer’s face while on the cool side the warm panel is located at the height of their abdomen (Figure 6).

Figure 6
Geometric location of the cool radiant panel system in a warm environment and warm panel in a cool environment according to the human body.

GEOMETRIC PANEL TRANSITION
Given that the efficacy of the panel to transfer radiant heat to or from a person is related to the surface area, the geometric positioning of large surfaces determines the predominant thermal environment. For example, the warm environment has a larger surface area of panels into which a cool panel with smaller surface area is inserted at face height while the cool environment has a warm panel inserted at abdomen. But since the conditions on the cool side require a different geometric location and surface area, it requires geometric adaptation modifying the surface area as the panels transition from the warm
side to the cool side (Figure 7). The prototype is developed as a compact and continuous object where the panel geometry adjusts as they wrap around from one side to the other. As the panel wraps the geometry of the prototype, the panels transition from narrow to wide or vice versa to increase or decrease the surface area to affect its thermal capacity. Referring to the warm side with the large surface area with the cool panel inserted at face height, the cool panel then wraps around the object to the cool side where the surface area increases to create a cool environment. Within this context, a warm panel with a small surface area is inserted at abdomen height. Therefore, the warm panels and cool panels are constantly adjusting their surface area and geometric position according the directive of primary thermal environment and relative to the human body as they wrap around the prototype. Thus the constantly shifting position and quantity of surface area as someone walks around the human-sized object creates a system to formalize thermal conditions as an architectural material.

**PANEL MATERIALITY**

The thermal radiant surfaces at the scale of the prototype require subdivision into smaller panels for fabrication and installation with consideration of the material behavior and the capacity of the digital fabrication to ensure precision when the panels are assembled. The thermal conditions determine the location and surface area according to the climatic condition of either warm or cool panels, but further subdivision of the panel is based on the location of geometric transitions and panel length. The panels are not thermally subdivided, but consistent within each panel. The selection of the material for the prototype is based less on its thermal efficacy than on its ubiquity in interior environments: the panels use gypsum in order to investigate the potential to activate a typically benign material. More specifically, the material uses gypsum as a composite in GFRG (glass fiber reinforced gypsum) because it is a medium that is scalable to typical architectural applications yet has the plasticity to allow for more customized surface conditions. The thermal properties of the GFRG places it between materials that provide good conductance of heat flow and others that provide good insulation against heat flow. The specific gypsum used in the panels is hydrocal gypsum cement, which has a fast curing time and high yield strength. These two properties make it ideal to develop thin panels that are quickly formable as a continuous surface and have good strength to thickness ratio. GFRG is typically applied as a thin mixture onto a formwork resulting in a morphology that is as plastic as the mold might require. The workability of the material prefers a more horizontal application, thus the formwork for an individual panel should have a minimum of vertical surfaces when the material is applied. The application is sprayed from a hopper gun with an air compressor while the one inch chopped glass fibers are distributed on the surface during the spraying process to ensure random orientation of the glass strands (Figure 8). The spraying process mixed with glass fibers is repeated until the desired panel thickness is achieved, which in the case of this prototype, was determined by the embedded hydronic tubing.
In order to activate the surface with thermal properties, 1/2"-diameter tubing is embedded into the GFRG material during the spraying process, ensuring the tubes are fully immersed into the material (Figures 9, 10). Each panel has a different length of tubing depending on the surface area since the tubes are placed 3 to 4 inches on center apart. The tubes in each panel are attached to either the heating or cooling equipment, depending on the thermal attribute assigned to each panel (Figure 11). The heating and cooling equipment uses water as the medium to transfer heat to or from the panels via the hydronic tubes embedded into the surface (Figure 12).

**DIGITAL FABRICATION**

The material choice to use gypsum for its ubiquity in typical interior environments and its scalability also resonates with the application of digital fabrication methods that are scalable from small scale prototypes to building-scale fabrication of panels. The research project purposely avoids the temptation to CNC mill a continuous mold because the challenge that method produces when increasing the scale of the project. Continuous molds require massive amount of material that is wasted after the mold has been formed and does not present a reasonable method when considering scalability to the size of a building. Therefore, a system that utilizes digital fabrication to create a framework from a series of profile cut sheet material allows for precision at targeted locations such as the joints between panels and key locations in between (Figures 13, 14). The process of creating a precise frame and utilizing another material for the infill between the frame members can operate at the small scale of a prototype or for a large scale series of architectural panels for a building, providing an economy of means and materials while creating precision at key locations.

**FABRIC FORMING**

Integrated into the material research for the project is the employment of precise digitally fabricated frame and the infill that relies on material behavior during the fabrication process. The infill material is tensile elastic fabric that interacts directly with the frame and GFRG material during the spraying process. The elastic fabric stretches under the weight of applying the GFRG, creating a pillowing morphology of the surface between the frame members (Figure 15). In order to control the amount of deformation the space between each frame member is subdivided using tensile strings. The strings are place in a repeating pattern from frame to frame. While the pattern is similar between each frame, the resulting surface geometry is continually differentiated due to the geometry of the mold itself. The repeating pattern of the frame members and the subdivision simultaneously creates differentiation through repetition. The elastic fabric is lightly stretched over the frame and fastened to the sides to prevent undesirable wrinkles, yet still allowing the elastic behavior to deform under the weight of the GFRG material. The effect of the panel is a soft surface created from a stiff and resilient material.

Figure 9
Hydronic tubing laid in.

Figure 10
Embedded hydronic tubing in GFRG.

Figure 11
Thermal testing of a prototype of the panel system in cooling mode (temperature in degrees Fahrenheit).

Figure 12
Thermal imaging using a FLIR infrared camera of a single panel attached to the hydronic heating system (temperature in degrees Fahrenheit).
FUTURE DEVELOPMENT

The research project is a nascent investigation into potential surfaces to initiate and thus visualize non-visual thermal conditions. Future development of this project will be to increase the scale or number of radiant panels to create a habitable space whose surface definition could develop a series of thermal distinctive spaces to test the interaction and perception by occupants. Further testing is required to understand the required temperature difference between the panel and the person, the surface area for emitting and receiving heat, and the location relative to the body affect how we perceive the transition from one space to another. Future investigations that increase the scale of the panels could test the ability to compress or elongate the gradient transition of how we perceive the distinction of thermal spaces. If thermal conditions are to be used as an architectonic element, then more knowledge is required of the range of possible behaviors in terms of how people can perceive thermally distinctive spaces. With the compression or elongation of the thermal gradient, associated modification of the surface definition requires investigation. The surface modification affects the visual perception as a boundary of space in addition to its thermal characteristics. Therefore, the design of a multi-sensorial perceived space integrates thermal and visual characteristics into the performance of a radiant panel system.

Thermal characteristics are intrinsically related to the surface definition, which includes the topography and materiality. The GFRG material is a mid-level conductor of heat and further exploration of additives into the composite material and application processes could be developed. More conductive materials such as metal or metal-based composites will be investigated to understand the range of variability in surface topography and subsequent surface area available for radiating heat. This investigation was not focused on creating the most efficient system, but future investigations with more conductive materials can bring efficacy into the equation to be integrated into the thermal and visual performance of the panel system.
CONCLUSION

The nature of thermal conditions exists as a non-visual phenomenon and, therefore, presents a challenge in order to bring it into the visual realm. Michelle Addington argues that thermal properties are already inherently spatial, and she questions the architect’s desire to rely on the physical surface that emanates heating and cooling to define a boundary (Addington 2007). Her point is well taken as thermodynamics are illegible yet pervasive phenomenon that already defines space, but architecture has the ability to fold multiple methods of sensory perceptions into the design of the surfaces of the built environment. The role of the architect is to spatialize and materialize a range of often competing desires. As such, the Klimasymmetry project set out to investigate the ability of visual and tactile surfaces to initiate thermal spatial conditions not to challenge the visual regime, but to give three dimensional form, geometry and materiality to those phenomena. Investigations into thermal phenomena tend to minimize the architectural form and spatial definition in favor the performance-based system itself. The Klimasymmetry project instead focuses on the deployment of existing hydronic radiant technology to explore methods of integrating it into a surface that initiates a surrounding spatial thermal environment. Reyner Banham argued that the systems in the house defined the space more than the house itself, so why not minimize the walls, ceiling and floor to the thickness of a bubble (Banham 1965). Klimasymmetry challenges Banham’s notion of an independent thermal system by making it integral to the design of the surface. The surface, instead of being minimized, becomes the mechanical system that simultaneously defines the physical limit (visual & tactile) and thermal (non-visual & tactile) perception of space. Therefore, this new intensive surface can adapt to a broad range of geometric configurations, which can relate to the physiological thermoreceptors within human body at the scale of a freestanding object as in this project or the boundary of a larger occupiable space for future projects.

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Research Assistants: Faith Yi Feng, Joshua Dobken
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REFERENCES


CHANDLER AHRENS

Chandler Ahrens is Assistant Professor at Washington University in St. Louis as well as a co-founder of Open Source Architecture (OSA), which is an international research and design architecture practice. His focus is on the intersection of material investigations, environmental phenomena, and computational design processes. He has worked for several large international architectural firms including nine years as a senior project designer at Morphosis Architects. His work with OSA has been extensively internationally published and is part of the collection at the Fonds Regional de Architecture (FRAC) in Orleans, France. He has taught at Woodbury University and workshops at the Confluence Institute in Lyon and the Technologico de Monterrey in Mexico. He was a co-curator of the Gen(h)ome Project, co-exhibition chair of ACADIA2010, and has lectured internationally. Chandler holds an M. Arch. from the University of California Los Angeles and a B. Arch. from Savannah College of Art and Design.