Phase Change Materials, Collaborations with BASF and CMoG

This paper documents research that we began in 2009 into the development of a glass block facade component filled with PCM (phase change material) in collaboration with the chemical company BASF. The research has, more recently, included offshoots into experimentation with glass fabrication and researching the structural and architectural potentials of dry-stacked corbelled structures.

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Figure 1: Popular PCM-filled hand warmer for winter leisure activities

INTRODUCTION

This paper documents research that we began in 2009 into the development of a glass block facade component filled with PCM (phase change material) in collaboration with the chemical company BASF. The research has, more recently, included offshoots into experimentation with glass fabrication and researching the structural and architectural potentials of dry-stacked corbelled structures.

The research project stemmed out of our fascination with the use of PCM in non-architectural applications like the popular hand warmers used during cold months, shown in Figure 1. These are little cushions which start emitting heat when a metal disc inside is clicked. They recharge their heat capacity when immersed in hot water. How does PCM perform in this way? PCM materials store and release energy during their phase change from solid to liquid and back to solid.

All materials, when changing state from solid to liquid, remove heat energy from their environment. This energy is needed to break up the crystalline molecular structure of the solid state and charge the molecules with the required thermal movement energy of the liquid state. In the opposite direction, from liquid to solid, materials need to discharge the thermal movement energy of their molecules to be able to rearrange in a rigid and more compact molecular pattern. As a result, heat energy is emitted. These processes of charging or emitting heat energy happen at a fixed temperature, the melting temperature of the material. This fact marks an important difference to conventional thermal mass, which lowers its temperature consistently while releasing heat. PCMs stay at a consistent temperature while releasing heat. Only once all PCM material is solidified does its temperature drop. The melting temperature is therefore a crucial property in the application of phase change materials. The melting temperature of PCMs should be in the desired temperature range of an application. For physical comfort and in architectural applications, temperatures between 283K to 303K (10 to 30°C; 50°F to 86°F) are most desirable. This temperature window drastically limits the possible PCM materials that could be used. Two materials emerge as the main choices for architectural applications because they allow their melting temperatures to be engineered within these desired temperature ranges. These materials are paraffin wax and salt hydrates. In our research we focused on paraffin wax for reasons which will be discussed later.

Careful observation of the hand warmers described above reveals more than just their well-known technical properties. The hand warmer intrigued us with its experiential and tactile qualities and its radical transformation of physical properties. As the melting temperature is engineered to be physically comfortable, it is a pleasure to touch. The hand warmer also changes from soft to rigid, changing its haptic quality radically. We also experience a total visual transformation from a transparent liquid into an opaque crystalline solid. This PCM application engages us in multiple experiential aspects.

PCMs also question the assumption that materials are static, inert, form-defined entities. Contemporary building practice often favors a static view of materials. Most construction methods suppress visual changes in building materials over time like expansion, weathering and wear and tear. Acceptable tolerances shrink. Surfaces get covered in thin layers of coating. Once these fragile practices fail, the overall construction seems substandard as change and transformation were never incorporated as an inherent aspect of the building. PCM, on the other hand, has the potential to embody change and transform as a means to create a sensuous bond to the user as we can see in the case study of the popular hand warmer. It is this conceptual framework that led us to formulate the following research questions:

- What is the experiential potential of Phase Change Material in architecture?
- What are the formal potentials of Phase Change Material?
- How can Phase Change Material organize space?

EXISITING ARCHITECTURAL APPLICATIONS

PCM is already used in architecture. As described above, the two main materials used are paraffin wax and salt hydrates. Paraffin wax is more expensive and combustible, but it consists of a single material, so there is no segregation of materials over time. Salt hydrates are non-combustible but can deteriorate as salt and water potentially segregate over time. These raw PCM materials need to be encapsulated for architectural applications, because they liquify during phase change. There are 2 main categories for encapsulating PCM, macro-encapsulation and micro-encapsulation (also called carrier bound PCM). Macro-encapsulations are vessels, bags or panels at a size to be able to be mounted manually. The vessels need to accommodate for the pronounced volume expansion of PCM during phase change. Micro-encapsulations are granulates or powders in which tiny amounts of PCM are encapsulated by thin layers of sealants. Micro encapsulations can be filled in cavities or be mixed into existing building materials. For a comprehensive overview of current PCM applications refer to Pasupathy et al.[1]

Our industry partner, BASF was motivated to collaborate with us to explore the untapped experiential and design potentials that PCM could have for architecture.

THERMOMETRIC HOUSE

Existing architectural products that use PCMs exploit them solely for their technical ability to increase the thermal mass of building components. By integrating PCM in building components, the loads on mechanical services are decreased. But PCM in these known applications is invisible to the user in architectural space. The approach of increasing the technical performance of existing constructions and spaces can be seen, for example, in the research project of Scalat et al.[2] In their paper, the authors document the thermal performance of two dry walled rooms with identical dimensions. One room was lined with conventional plaster board while the second room was lined with PCM saturated plaster board. In collaboration with BASF we were rather interested in what an architectural space would look like that is developed out of the inherent logic of PCM. What is the potential for architectural design? How can we import the opportunities offered by PCM from the realm of engineering into architectural design?

Similar to the PCM in the hand warmer, wax PCM changes transparency and volume. We wanted to enhance these transformations and make them experiential instead of suppressing them like the macro- and micro-encapsulations do. We turned to the use of glass as a vessel material.

Our project makes use of PCMs volume expansion during the change of phase from liquid to solid and vice versa to develop a temperature-sensitive glass block. The glass block component is not only able to increase thermal storage capabilities of a wall assembly, but is also able to define temperature specific spaces and to modulate shading and views.

We were inspired by the traditional mercury-in-glass thermometer with its mercury filled bulb at the bottom. The contraction and expansion of the contained mercury is amplified by a much narrower bore at the top of the vessel. The mercury-in-glass thermometer utilizes the dynamic, material-specific behavior of mercury to its advantage. In fact, the whole form is defined by this material behavior. Similarly, we exaggerated the volume expansion and shrinkage that occurs in wax PCM by containing it in a vessel with a thermometer-like section. During volume expansion, the wax rises visibly within this cavity, acting as a sunscreen and

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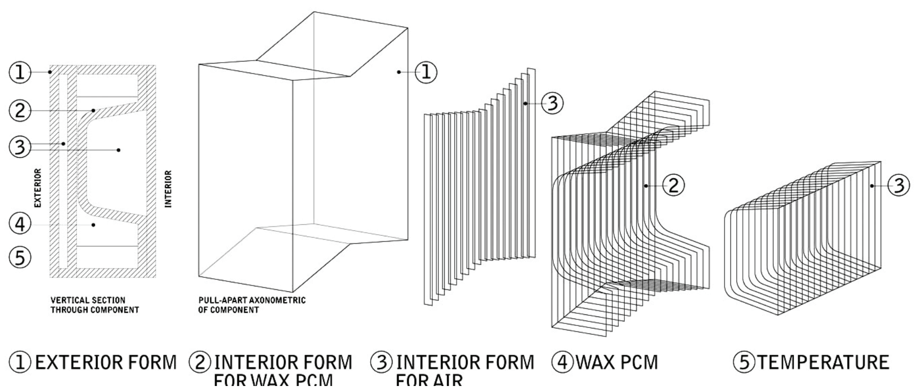

visual screen [Figure 2].

PARAMETERS OF THE MATERIAL SYSTEM

The main parameters of this system are the specific composition of the wax, the internal cavity geometry and the external shape of the glass block.

wax

For most of our tests, we used the specific wax PCM, Rubitherm RT21 (http://www.rubitherm.de/english/download/techdata_RT21_en.pdf). It is a standard, off-the-shelf product. There are several parameters of paraffin wax PCM which influence the behavior of our glass block. The most obvious is of course the melting temperature. RT21 has a melting temperature of 21°C. As soon as the environmental temperature exceeds 21°C this wax will melt and continue to draw heat from its environment until it is fully melted. Once fully melted, its temperature will also rise. Once the outside temperature falls below 21°C, the PCM will start solidifying and releasing heat until fully hardened. When fully hardened, its temperature will also drop. This means that this material will inherently support a constant temperature of 21°C as long as it is in process of changing its state (melting or solidifying). It acts like an air-conditioning unit set to 21°C.

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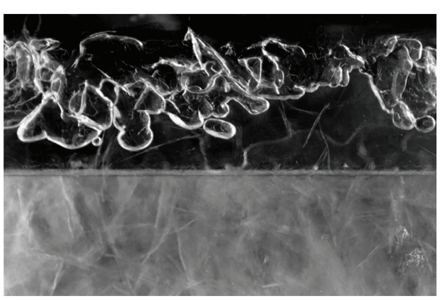


Figure 2: Build-up of the proposed glass block

Figure 3: Paraffin wax RT21 in the process of solidifying

Another parameter of PCM wax is color. Untreated PCM wax is clear when melted and translucent white when solid, similar to candle wax. Because we propose to use wax as a shading device in the glass block component, we wanted to experiment with a color that is less translucent than the untreated white wax. Blue was the darkest standard color available. The darker the color, the faster the wax reacts also to radiant heat like sun rays. Ismail et al. showed that dark colored PCM blocks radiant heat significantly.[3]

The third and main parameter of wax in our material system is its volume expansion. Wax PCM has a much higher expansion rate than salt hydrates. This was the main reason that we chose wax over salt hydrates. The wax that we used increases in volume by 14% when fully melted compared to the volume of its solid state.[4]

Internal cavity geometry

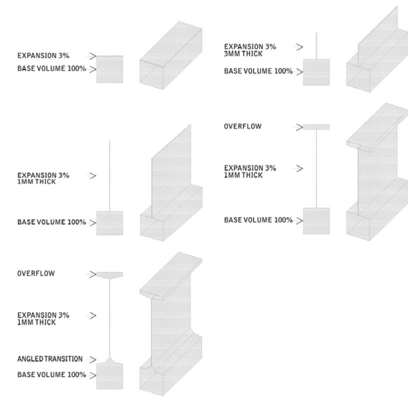
The second parameter of our material system is the internal cavity geometry of the glass block. We introduced two kinds of cavities, wax-filled cavities and air cavities. The air cavities control the thermal distribution inside the glass block. The wax-filled cavities contain wax and amplify its volume changes. Figure 4 shows the logic of the basic wax cavity typology. We aimed at amplifying the volume change as much as possible. For that reason, the volume of the lower wax container needed to be maximized inside the overall dimensions of a glass block while minimizing the thickness of the upper gap. Our tests showed that the minimum width of the upper gap is 1mm. Below that width, capillary forces take over. The effective volume expansion in our tests turned out to be just 3% instead of 14% because the solidified wax always embeds air pockets. It is not totally solid, but rather, like densely packed snow. A constantly changing volume of air, trapped in the wax, also causes inconsistency in the 3% expansion figure. A volume of space in addition to the approximate 3% expansion of the PCM is provided in the cavity for potential overflow due to air bubbles. The overflow cap and the base volume sit perpendicular to the expansion panel. The connection points between volume and panel need to angled to allow air bubbles to escape upward. These constraints form the basic wax cavity typology as shown in Figure 4 bottom.

By modifying and combining cavity typologies, a large variety of highly specific glass block performances can be achieved.

The simplest is the symmetric configuration with air vacuum pockets on both sides as shown in Figure 5. This element reacts mainly to radiant heat from both the exterior and interior. A possible application is sun shading. Phase change heat storage is not in effect.

The asymmetric configuration as shown in Figure 6 could be used as an exterior facade element. The outside vacuum pocket runs along the whole height of the element. A reflective foil shields the bottom wax tank from the sun. The interior air pocket insulates only the expansion shaft to keep it warm while the wax retreats into its tank. The wax tank is fully exposed to the interior and is responsive to the interior air temperature. In spring and autumn this configuration would allow low sun rays to reach deep into a space. The dark wax tank stores a portion of the solar energy, allowing the element to extend the warmth of the sun until deep into the night. Once fully melted, the wax shoots up acting as a sunshade. In winter, the wax would seldom melt fully, allowing the sun to heat the space. In summer the sunshade would be mostly up.

This asymmetric configuration shown in Figure 6 could be used for heat storage. It behaves as a smart, self-shading TWD-element (transparent insulation). The expansion shaft connects at the bottom part of the wax tank. Because of the vacuum effect in the wax tank, the wax does not drop into the expansion shaft except for volume expansion. In summer, the wax in this element would be always melted, protecting from summer sun. In spring and autumn it would buffer solar gains deep into the night.



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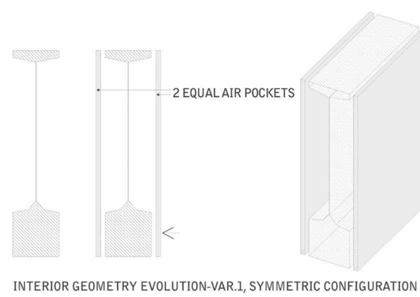

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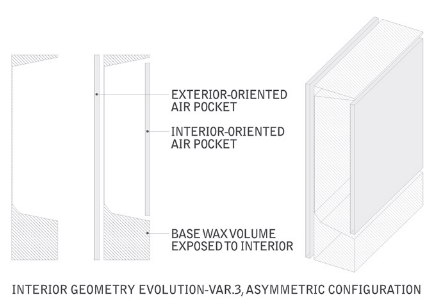

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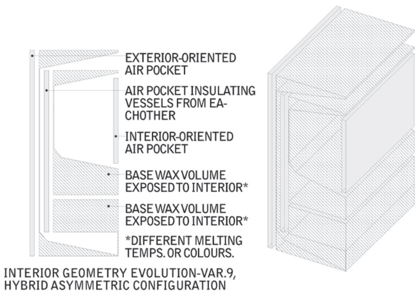
Figure 4: Evolution of the basic cavity typology

Figure 5: Symmetric Typology

Figure 6: Asymmetric Typology



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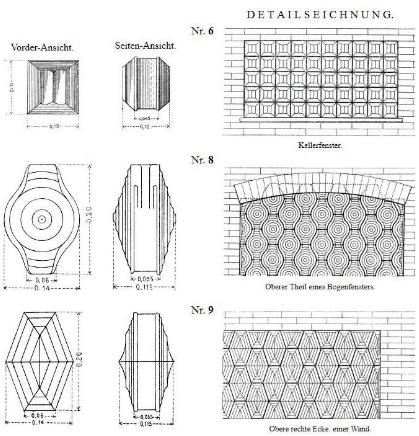

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Hybrid asymmetric configurations like that of Figure 7 combine the above configurations into a single glass block. They can form typologies highly adapted to specific needs. Figure 7 shows a hybrid asymmetric configuration which could hold different melting temperatures in a single glass block.

Exterior glass block geometry

The third parameter of the material system is the exterior shape of the glass block. It defines the assembly of the glass block into a larger structural entity. Current glass block designs are mainly cubic. Early glass block designs from around 1900 were often more complex in shape as can be seen in Figure 8.

Today, the mainly cubic glass blocks are reinforced by steel rods and mortar or adhesive to achieve a unified, stable assembly.

We were interested in shaping the glass block so that it would stack into a structural unity without the need for reinforcement and bonding agents. We started investigating angled surfaces with the intention to divert vertical loads into horizontal bonding forces that would interlock all blocks, forming a structural unity.

The proposed form of the glass block in the thermometric facade increases the structural bond between the blocks, increasing the structural bond of the whole wall in comparison to the conventional cubic form. The pitched horizontal surfaces of the glass block edges transform vertical loads into a vertical interlock; one block always holds the next two lower ones together (Figure 9). This increases the block bond significantly. Stresses from wind loads can be better transferred which leads to an increased free span of the wall segment. Additional reinforcement is not needed, which simplifies construction significantly. The additional structural stability allows the glass block assembly to act structurally and not strictly as infill. FEM analyses show that ceiling spans of up to five meters are possible.

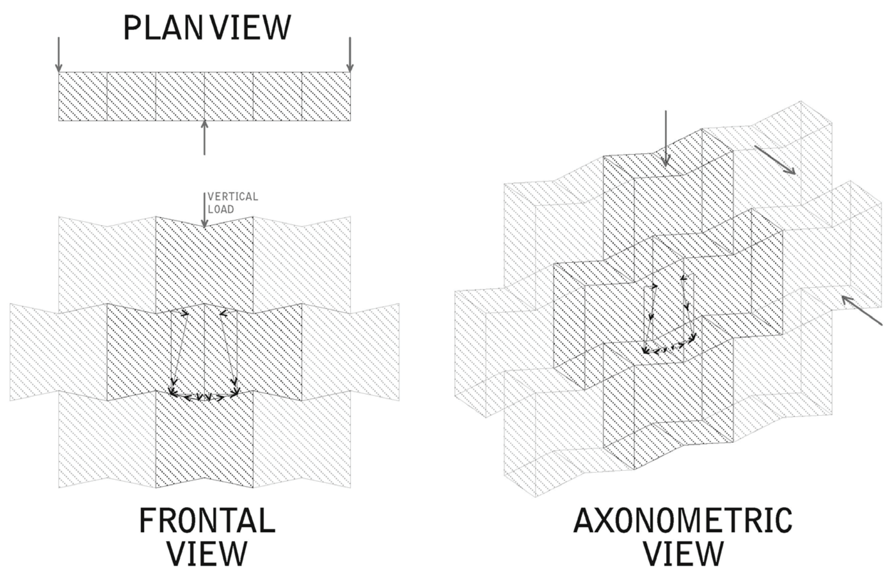

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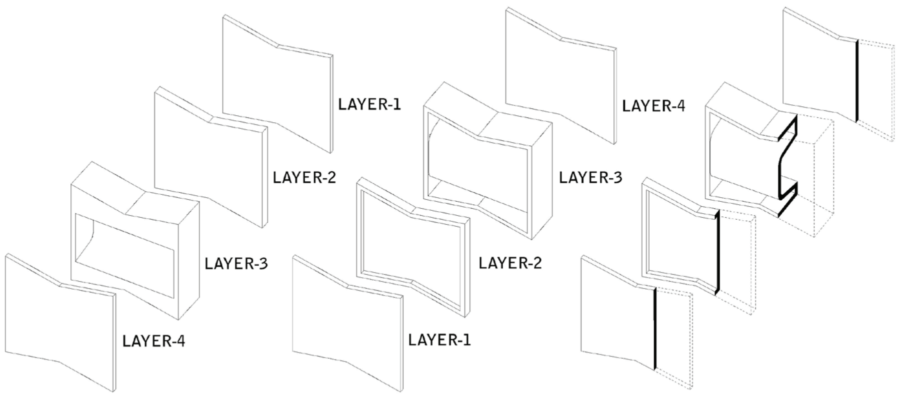
Figure 7: Symmetric Hybrid Typology

Figure 8: Excerpt from the glass block catalog of the company Reich&Co. from 1900

Figure 9: Diagram showing how the angled surface form a structural bond between the glass blocks

PRODUCTION

The complexity of the exterior as well as the interior shape is a significant challenge in the glass production process. In the production of larger numbers, press molding could be a suitable technique. Press molding is the process used to make conventional glass blocks. A fully mechanized assembly line process, conventional glass blocks involve precisely measured dabs of molten glass being sheared then pressed into a metal mold with a plunger. The body or the underside of the mold creates the outside form whereas the plunger creates the interior form. In the process of conventional glass blocks, one mold (body and plunger) makes one half of a block. Two halves are then fused together. Fusion is possible when heated pieces of glass soften, gradually becoming sticky without losing their basic form. Individual pieces can be joined together using the softened glass as adhesive.



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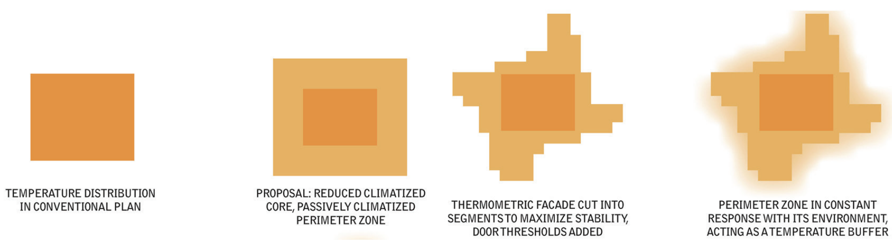
We propose the glass block component here as having four layers, two of which would be press molded, creating the form for the interior cavity to contain the wax. The outer two layers would be conventional float glass sheets fused onto the exterior of the press molded form.



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SPATIAL APPLICATION

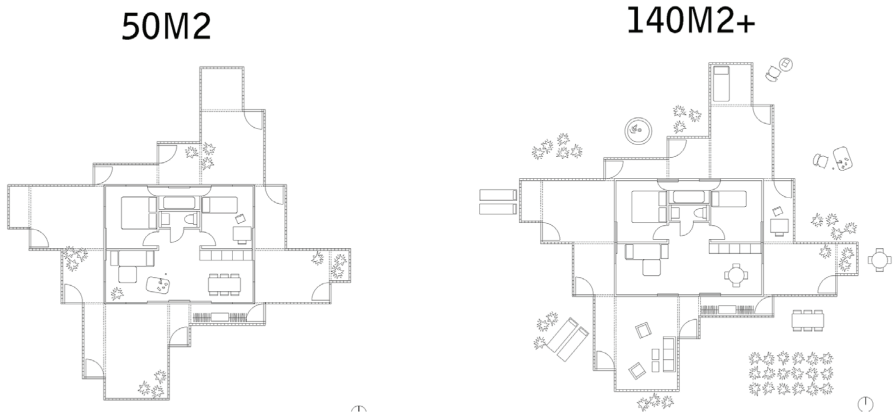
By overlapping the above described parameters, a site specific differentiation could be achieved. There can be wall segments with different melting temperatures, colors, transparencies and cavity typologies.

But what is the spatial consequence of such a material specific system? While in most contemporary buildings, a uniform temperature distribution is desired, we propose to minimize the conventional temperature-controlled room to a compact core, complemented by a surrounding, spacious room perimeter, defined by the environmentally responsive thermometric facade as shown in Figure 11.

In this spatial arrangement, the temperature-regulating capacity of the facade offers extended time windows of thermal comfort in the generous perimeter space. The program of the core area spills into the expansive perimeter space dependent on weather and season (Figure 12).

Figure 10: Diagram showing the four glass layers fused to form the glass block

Figure 11: Diagram showing the spatial and climatic strategy of the thermometric house



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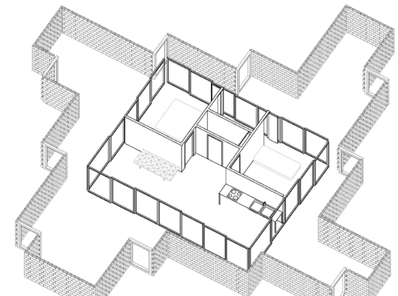

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Figure 12: Winter and summer plans of the thermometric house

Figure 13: Axon showing core and perimeter space

Figure 14: interlocking glass block study, students Olivia Arcara and Tim Ruhl, Instructor: Georg Rafailidis

Figure 15: warm glass, casting in glass kiln at the university.

To avoid additional lateral bracing, the maximum running length of each wall segment is limited to 5m, resulting in a folded facade (Figure 13). The folded facade creates spatial pockets with specific melting temperatures relating to different programmatic activities, for example a 24°C bathroom space or a 16°C sleeping area.

PEDAGOCIGAL AND RESEARCH OFFSHOOTS

While our first phase of research and design allowed us to make first-hand empirical observations about the material properties and behaviors of PCM, and develop several glass block cavity typologies that could harness the behavior of PCM and use it as a means to condition the temperature of spaces passively and experientially, it also pointed to the need for further investigation into the design of the exterior shape of the glass block and further attempts to get closer to prototyping with glass itself. These two aspects of the glass block design—material and form—were pursued in both a pedagogical context, in a design studio devoted to architectural glass, and in scholarly research, in form-finding and scale model production of blocks with forms optimized to stack without reinforcement or bonding agents.

Glass, although ubiquitous in architecture, is a challenging material for architects to work with first-hand. It requires special facilities and a specialized skill set. In previous speculation about how a thermometric glass block component could be made, reference was made to the cast iron plunger molds used in industrial-scale production. But in order to develop the thermometric façade component further, we need to make a series of prototypes using PCM and glass rather than a glass substitute, in order to draw conclusions about the performance of the component using a similar approach to Scalat et al. in their test using two identical full-scale constructions, one with PCM and one without.

Through two consecutive graduate design studios with a focus on the three dimensional, sculptural potential of glass, we familiarized ourselves first-hand with methods of glass fabrication: cold forming, warm glass and hot glass. Cold forming and warm glass were investigated at the university, whereas hot glass methods were explored with the support at the Glass Lab at the Corning Museum of Glass (CMoG) in Corning, NY. The project shown in Figure 14 for example shows a complex threedimesional hollow glass block with several fabrication iterations in a glass kiln at the university and in hot glass at CMoG. Figure 15 shows a project working with methods of glass casting. Figure 16 shows experiments in controlling heat absorbtion through colored glass.

These experiments using different fabrication techniques to create complex, three dimensional forms in glass allowed us to better understand the physical properties of the material and its limitations and potentials. Like our empirical research with PCM, working directly with glass gives us insight into how the material behaves, and allows us to, in a trial-and-error fashion, work toward the realization of glass prototypes of the thermometric façade component. Currently, because we need to address the high degree of precision needed to form the interior cavity of the thermometric façade component, we are exploring hybrid techniques that combine warm glass casting with cold glass machining. Our kiln-formed glass experiments with the students revealed the relatively imprecise nature of the process; objects cast in the kiln require a high degree of tolerance. While warm glass casting using a refractory mold could allow us to define an outer shape for our block, the interior cavity would need to be etched or routed. Our first attempts at prototyping in glass involve two kiln-formed or cast glass halves, with the interiors manually ground using silicon carbide, and the interior of one half routed to define the precise inner geometry to contain the PCM. Because PCM is heat-sensitive, the two cast glass halves will be fused with a bonding agent.

The second offshoot of research that emerged from the initial design for the thermometric façade component examines the formations of novel corbelled structures. This research takes the initial logic of the exterior form of the thermometric façade component further, and looks at how space could be enclosed through dry-stacking and corbelling as seen in Figure 16. The main aim of this research trajectory is to find new overall spatial typologies emerging from the logic of assembling small elements like bricks and glass blocks. The stacking methods found would allow full spatial enclosure—an aspect of the initial thermometric house design which wasn't addressed. Using the thermometric façade component to enclosing the ceiling condition as well as the walls would extend the performance of the thermometric glass block. Like our research into PCM and glass behavior, a primary research method in this work is empirical, using a variety of materials and scales to examine the potentials of dry-stacked corbelled structures (another pic). Although not a glass-specific study, this research will yield the exterior form and dimensions for the thermometric façade component prototype.

CONCLUSION

Too often material innovations end up as facade dressings or interior wall partitions without impacting the core spatial conventions of architecture. These so-called innovations seem disconnected to the actual building. The thermometric house is an attempt to rethink our spatial typologies through the latent material performances of phase change materials. The challenge was to tie the raw material, its element geometry, tectonic logic and spatial formation into a coherent whole. The resulting spatial typology does not follow the usual logic of minimizing the exterior envelope of a building. On the contrary, the increased length of the self-shading, folded geometry enhances the effect of the thermometric facade. The thermometric facade also does not follow the principle of a uniform temperature distribution throughout a building. Instead of sealing the interior environment from the outside, this architecture increases its performance by maximizing the relationship with the exterior. The thermometric house allows us to argue for a radically different spatial relationship to the environment, to a more dynamic pattern of using architecture and to a more sensuous bond to architecture by carefully looking at the specificities of phase change materials. It is an ongoing research project that is only made possible through intensive empirical research and experimentation with materials as well as a close collaboration with industry, where technical knowledge about fabrication methods and new materials can inform architectural design in a deep and fundamental way.

ENDNOTES

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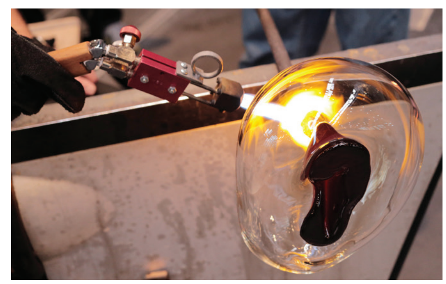

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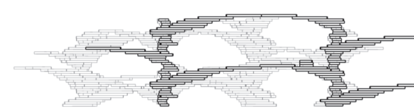

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Figure 16: black glass as heat absorbtion in hollow glass block. Hot glass fabrication by CMoG. Student Orghya Bhattacharjee, Instructor Georg Rafailidis

Figure 17: Novel typologies in corbeled structures.