Thermally Active Surfaces: Physiology and Thermodynamics

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Abstract

This research focuses on thermally active surfaces and structures. In this transformation of energy and building practices, the hydronic thermal conditioning of a building is decoupled from the ventilation system, using the mass of the building itself as the primary thermal system. This approach reinvests the fabric of the building itself with a more a poignant role: the structure is the primary mechanical system. It also yields a cascading set of advantages for the building design and construction industry: radically lower energy consumption, more durable buildings, more healthy buildings, and prompts more integrated building systems and design teams. An important aspect of thermally active surfaces is that they are low-tech yet high performance and are thus equally applicable in the developed and developing worlds. As such, thermally active surfaces are central to multiple aspects of sustainability.

The basic physiological and thermodynamic principles of this approach are presented in this paper, followed by an example of these principles in practice.

Keywords: thermally active surfaces, building component conditioning, radiant transfer, de-fragmenting buildings, sustainability

1 Introduction

Departing from the deceptively simple question "Why do we heat and cool buildings with air?" this paper focuses on the role of thermally activate surface systems in buildings. This is an integrated approach to material and energy systems (structure, exterior envelopes, finish surfaces, heating, and cooling systems). The structural and material systems are the primary thermal system in thermally active surfaces. The thermal activation of matter ultimately engenders more ambitious effects for architecture and more promising life for the technical and formal life of architecture. By converging the material and energy systems of a building, thermally active surfaces, based upon hydronically activated massive material systems such as cermatized concrete and low-fly ash concrete, trigger a set of cascading effects: more durable buildings, lower embodied energies, radically more energy efficient thermal strategies, more integrated design on physical and social levels, and open new formal potential for architecture.

Increasingly, architecture will not be shaped by its material system, but equally its energy systems simultaneously for more integrated solutions. Thermally active surfaces are applicable equally in the developed and developing worlds, pointing towards other forms of sustainability as well. While low energy systems are frequently proposed in architecture, durability remains a central problem for sustainability in architecture. This paper describes this approach to integrated, thermally active material and energy systems.

Before I describe the system itself, I will begin, as energy systems in architecture should, with the body and the physiological basis of the system that underwrites the efficacy of the system's energy efficiency and human comfort. In the second section, I describe the physical properties of the rudimentary mass and water (specific heat, its mass and fluidity) are central to the thermally active architectures. I will then articulate the benefits of this approach in respect of human comfort, energy practices, construction and design. This report closes with an example of a thermally active surface building, Peter Zumthor's Bregenz Kunsthaus.

2. Thermodynamic and Physiological Properties

2.1 Body

The modulation of the body's own production of heat energy is central to human comfort. The body produces about 400 BTUs per hour from its metabolic processes (figure 1). 90 BTUs are used to maintain life functioning. The additional energy must be dispersed from the system or the body over heats. In most common situations inside a building, the body transfers about 190 BTUs through radiant transfer. About 110 BTUs are transferred by convection. The remainder is transferred via respiration and other processes. Thermally active surface systems, based primarily upon radiant transfer, target the most significant physiological heat transfer mode and thus modulate human comfort more directly. Additionally, radiant transfer is almost instantaneous.

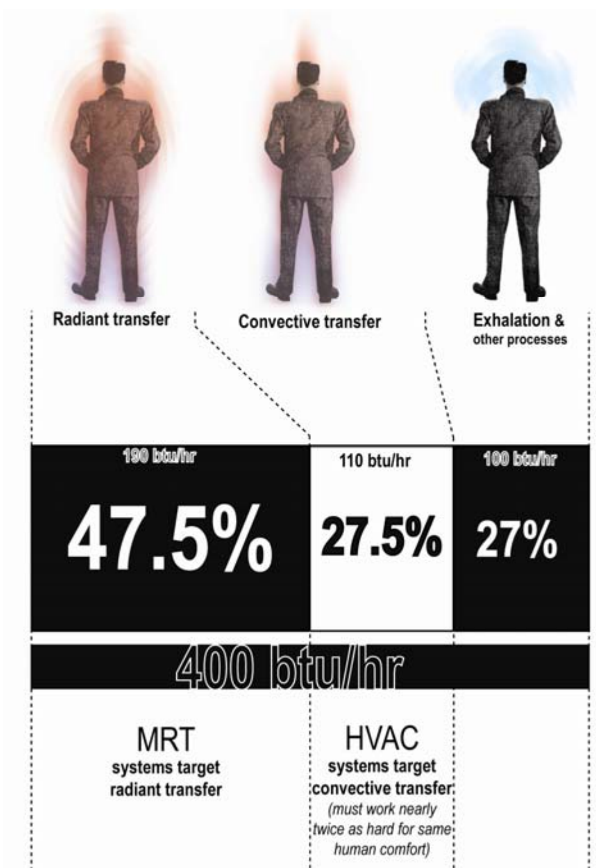

Figure 1: Human Heat Transfer Modes

The body's largest organ is its skin—about 15% of its mass and over 2 square meters in surface area—regulates deep and surface body temperature through hydronic exchanges with the integumentary and circulatory systems that uses the skin as a thermal sink and source. One square inch of skin contains up to 4.5m of capillary mat blood vessels, the contents of which is heated or cooled before flowing back to influence the deep body temperature. As further evidence of the importance of radiant heat exchange to the body's thermal equilibrium, living human skin developed extraordinarily high absorptivity and emissivity (0.97), greater than most architectural substances. Consequently, we are highly responsive to changes in radiant temperature. The body is essentially an efficient hydronic heating and cooling system with most of the transfer occurring in its own dermal thermally active surfaces.

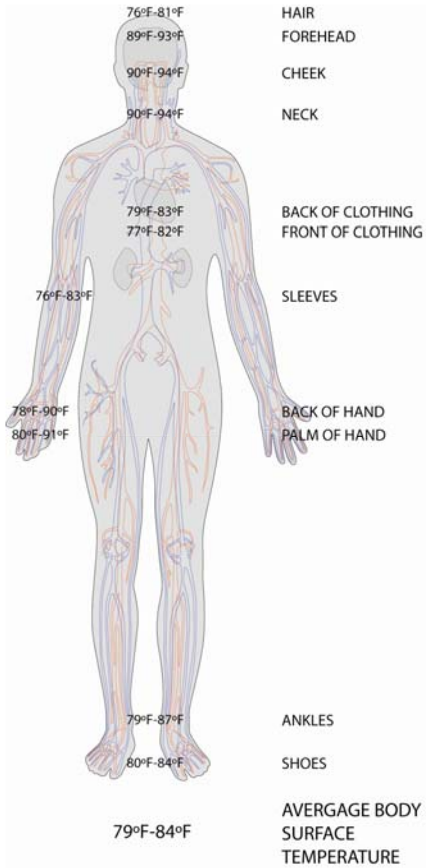

Figure 2: Human Surfaces Temperatures

When you consider a body in a space, it is clear that different technical systems yield varying temperature profiles with varying effects for human comfort and energy efficiency. These temperature profiles illustrate the relative mix of radiant heat and convective heat in each type of system. The relationship between these temperature profiles in space and a body demonstrates that the various radiant sources yield the most even and therefore ideal temperature milieus, largely due to the volatility of convection patterns in even the simplest of spaces and systems. This establishes a close relationship between thermally active surfaces, energy efficiency and thermal comfort.

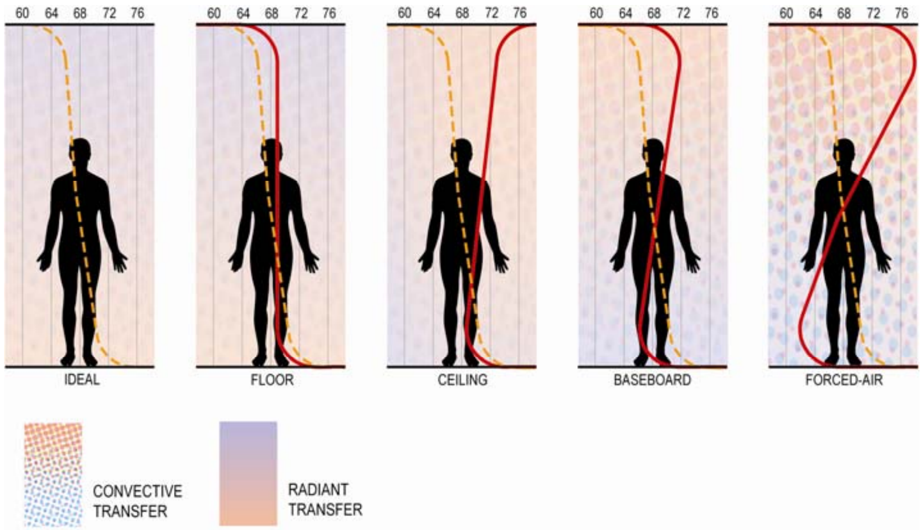

Figure 3: Temperature Profiles

Thermally active surfaces are based upon radiant heat exchange between a body's skin and the mean radiant temperature (MRT) of a thermally active space. Routinely overlooked within the more dominant modes of air conditioning and thermal comfort, the MRT is the average temperature of all the materials in a space. The lack of surface temperature effects in the development of conventional air-conditioning systems as well as the psychrometric chart throughout the twentieth century has created a radiant void in the discourse on human comfort and energy efficiency.

It is important to note that when Willis Carrier derived and codified the psychrometric chart in 1906, he overtly ignored the role of radiant transfer. This would be like a structural engineer ignoring seismic or gravity loads in the design of a system. It simply did not align with his agenda at the time: the conditioning of air for machines in the print and textile industries. Later, radiant transfer did not align with his ambitions for a bustling new air conditioning industry for buildings and bodies, despite the thermodynamic and physiological realities. Consequently, the role of radiant transfer in human comfort and building conditioning has been neglected since Carrier's derivation of psychometric principles.

More recently, ASHRAE uses the *Operative Temperature* (an average of the air and mean radiant temperatures) for evaluating thermal comfort and performance. This acknowledges the role of MRT, however it does not yet capitalize on the physiological and architectural efficacy of thermally active materials since the processes and systems remain focused on convective transfer. More than a curiosity of human comfort, however, the effects of MRT extend well beyond the physiological. The new role of MRT stands to advance critical energy, construction and architectural practices.

The aim of this research is to finally elucidate and disseminate the principles and practices of thermally active surfaces to radically alter strategies for low-to-no energy buildings in the twenty-first century buildings.

2.2 (Operational) Energy in Thermally Active Surfaces

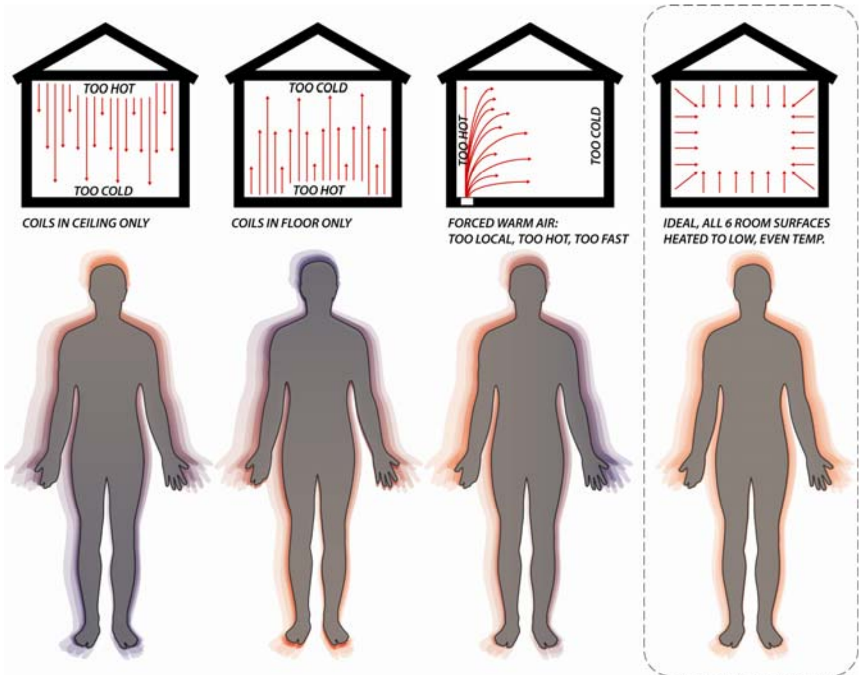

Figure 4: Fitch's Thermal Asymmetry

As James Marston Fitch noted, it is optimal to have thermally active surfaces on six sides of a space. This would achieve two primary ends. First, it would eliminate the perception of thermal radiant asymmetries that are problematic for human comfort. Second, it would allow the system to utilize the least amount of energy.

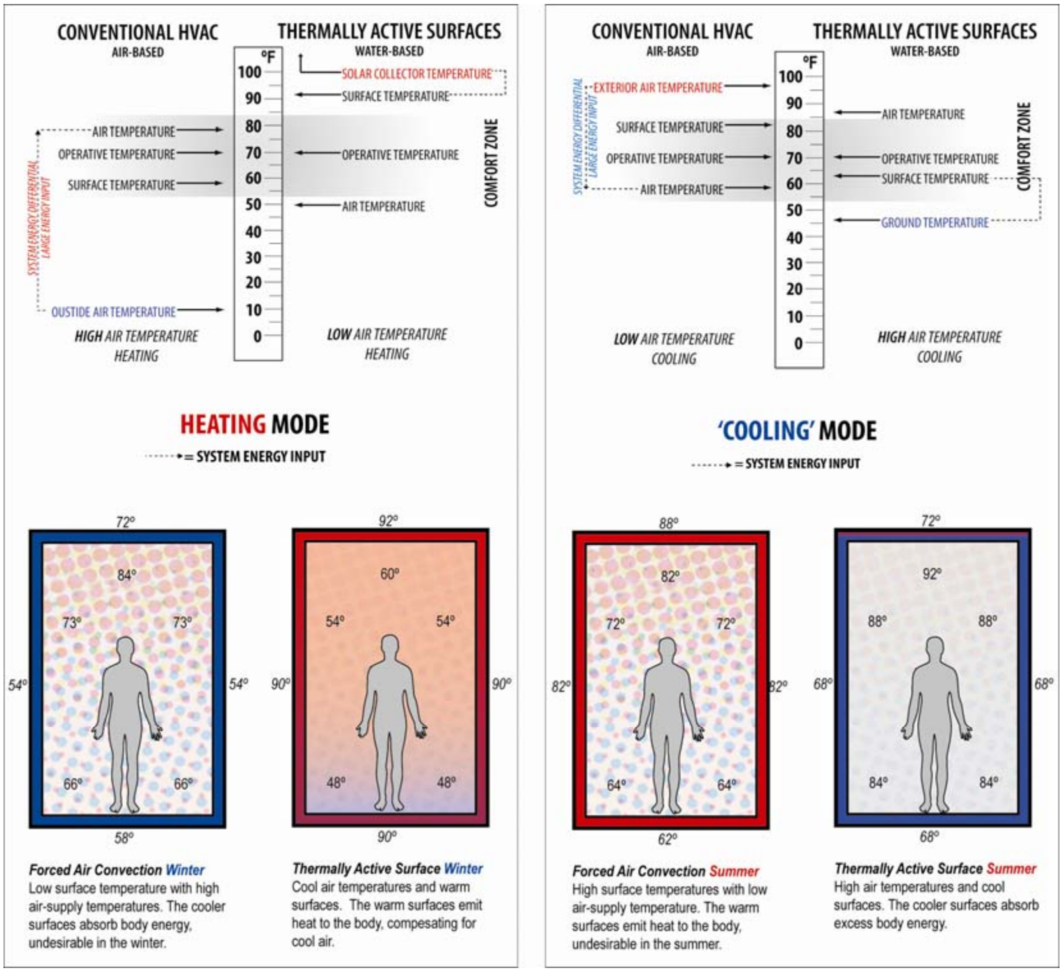

Figure 5: Typical Air and Water Thermal Strategies Compared

A key energy efficiency of thermally active surface systems is the unique ability to utilize low temperature heating and high temperature cooling. This saves significant amounts of energy when compared to the high temperature heating and low temperature cooling paradigm of typical HVAC systems.

The dominant modes for heating and cooling buildings are centralized, air-based HVAC systems. Air, however, is a poor medium for distributing energy. Since air is 800 times less dense than water makes it in fact an insulator—not a conductor— of heat energy. Further complications arise because air is more difficult to control. Infiltration, drafts, the buoyancy of air, and convective flows around equipment and people all make the airflow, and thus the heat flow, of buildings unpredictable and inefficient. Inversely, water based thermally active surface systems provide more predictable and reliable behavior for a range of occupancy conditions. Water retains has a much greater heat capacity and easier to control the distribution and application of heat energy. Hydronic systems also require a fraction of the space that typical HVAC require. Water-based heating and cooling captures and channels more energy, more efficiently, in dramatically less space. Not only does this open cubic footage and flexibility in building design but also minimizes spatial and systems coordination issues. Add to this the problems associated with indoor air quality and building sickness syndrome associated with convective-based heating and cooling, thermally active surfaces become even more logical for our current technics.

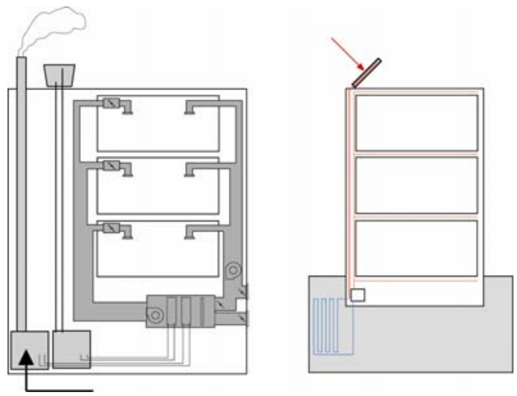

Figure 6: Volumetric Impact of Air and Water Systems

Another effect of thermally active surface systems registers in the increasing complexity and cost of conventional HVAC systems. While contemporary HVAC systems may absorb a third or even half of a building budget, thermally active surface systems redirect budget, time, coordination, and labor away from the detrimental effects of the multi-layered paradigm and reinvests those economic, legal, and intellectual resources in the thermally active fabric of the building itself, imbuing it with a more active role. This exactly the distinction Reyner Banham discerned between the paradigm of “power-operated solutions” and “structural solutions.”

2.3 (Embodied) Energy in Thermally Active Material Systems

Thermally active surface systems rely upon massive materials such as concrete for the structure, enclosure, and mechanical systems. The embodied energy for such a system is much lower than a comparable steel, glass, and aluminum building with a typical HVAC system. The life cycle costs are considerably lower due to its durability, energy efficiency and maintenance. The increasingly thin and immaterial layers of the HVAC paradigm require more maintenance on account of the increasing number of joints with each successive layer. Further, the thermally active surface system researched here uses the minimum amount of concrete, using it where it is most useful structurally, thermally, and as a durable surface. This further lowers the embodied energy and life cycle costs.

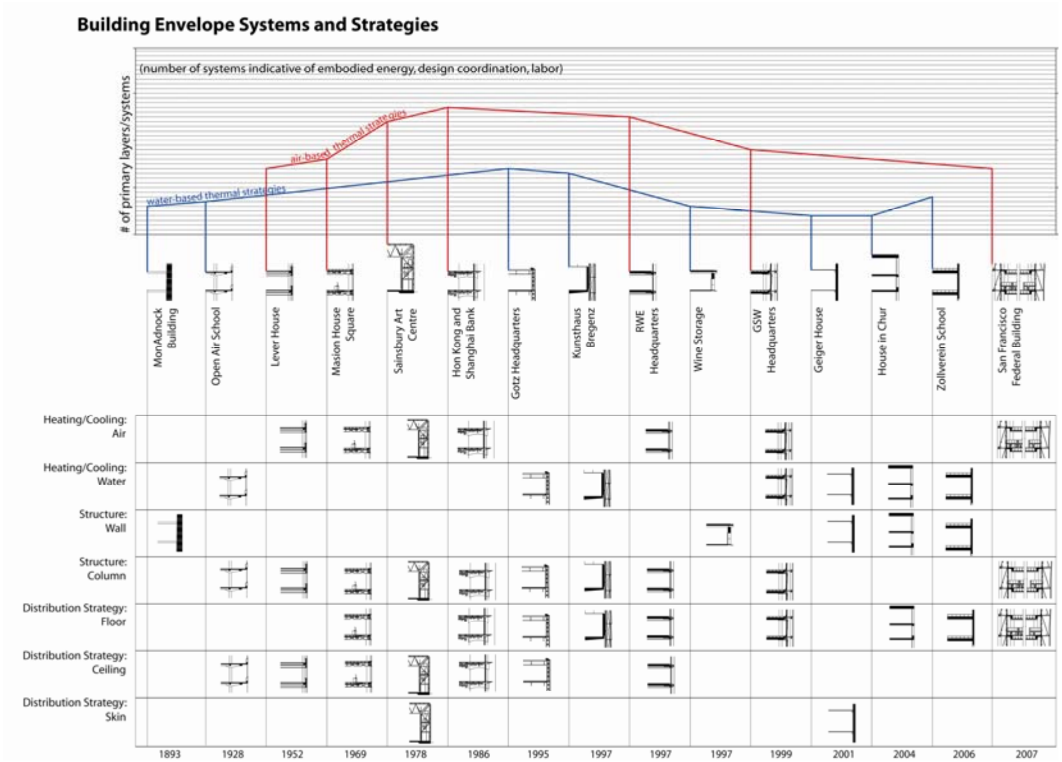

Figure 7: Volumetric Impact of Air and Water Systems

The logic of twentieth century building envelopes was to add more, and increasingly thin, layers of construction whenever a technical issue is encountered. This increased the organizational and physical layers of building practices. It also required multiple trades on site at multiple times during the construction process. This approach has often yielded delays, conflicts, endless RFI's and lawsuits. By obviating the need for these increasingly complex and multi-layered wall assemblies, a thermally active surface architecture collapses the layers of the increasing physical and organizational layers of building production into one more robust, and poignant layer of architecture. The simplicity of thermally active surface systems permeates the entire process, prompting more integrated design teams as well.

The advantages of more robust building systems and practices do not end with these organizational and physical outcomes of thermally active surfaces. Durability is a central problem in American sustainability that thermally active surfaces address. While the energy efficiency gains and the recycled content of material systems are on the rise, the short life span of buildings of American buildings stands to loose a far greater amount of energy. Thermally active surface systems use more durable and robust material systems for the structure, the enclosure and many interior surfaces. This radically increases the durability of our buildings and stands to alter the tendency for planned obsolescence and the conspicuous consumption of contemporary building practices. The same systems that make thermally active surface systems more durable also make buildings easier to maintain and allow the buildings to weather more gracefully.

3.1 Thermally Active material Systems and Integrated Design

There is considerable discussion today in architecture about 'integrated' design solutions. The aim is to more effectively coordinate the increasingly complex organizational and physical layers of building production. A key outcome of such efforts is improved energy efficiency that emerges from integrated solutions. Thermally active surface systems are inherently integrated solutions because the structure, enclosure, and human comfort systems are the same system. This saves not only energy for heating and cooling loads but design, coordination, organization, and labor energy in building production.

Unlike many approaches to integrated design such as BIM or digital fabrication, thermally active surface systems are not capital intensive economic proposals. Thermally active surface systems re-deploy existing material and energy systems, swerving them for better buildings and better practices. Thermally active surface systems stand to make large changes in energy, material, and design practices with only small changes to contemporary practices. On principle, one aim of this approach is simple but durable and high performance systems: 'intermediate technology' equally applicable in the increasingly globalized first and third worlds. This points to another, non-trivial, type of integration. The assumption here is that more and better integration will occur in systems that give simple solutions to the complexity of the physical and organization systems of architecture rather use it as an alibi for complex yet rather simplistic solutions.

3.2 Thermally Active material Systems and its Formal Implications

In addition to the energy and human comfort benefits, thermally active material systems make architecture more architectural by enabling new relationships amongst body, program, technology, material, and form. Thermally active surface systems create new thermodynamic figures for architecture. By maximizing the dynamic and sensorial aspects of the milieu with minimal means, thermally active surface systems make architecture more architectural. Suddenly the fabric of the building itself is no longer merely a passive container of space, but rather an active agent in the performance of the building. When structure, enclosure, and human comfort merge into one system, architecture gains new roles for itself.

In a context of increasing—if not misplaced or superfluous—complexity in architecture, thermally active surface systems situate complexity in the integration of material and energy systems with human physiology that are at once maximal in performance and minimal in means.

The most compelling thinking and work in sustainability today occurs in the integration of material and energy systems that bear the anomalous convergence of the maximal performance within the minimal means. Thermally active surfaces collapse high performance into minimal embodied, operational, organizational energies with minimal means.

4. Conclusion

Due to a few, very basic physiological and thermodynamic properties, thermally active surfaces trigger set of cascading effects that can make architecture more durable, integrated, efficient, and thus sustainable. It should be noted, however, that both this research and any physical manifestations of the research emerge not only form a few technical or physiological observations that trigger sustainable changes in the building industry but rather emerge from an overt mixture of historical, professional, technical, social, physiological, thermodynamic, and economic information. This points towards a broader view of the necessarily diverse techniques, technologies and justification that will advance architecture towards more sustainable practices. Many of the principles and practices are evident in the following building example.

5. Thermally Active Surface Example

Figure 8: Kunsthaus Bregenz

The Bregenz Kunsthaus is a prime example of thermally active surfaces in architecture. Architect Peter Zumthor and engineer Peter Meierhans designed a thermodynamically and physiologically novel figure for the Bregenz Kunsthaus that formalized a new relationship between body and building. Situated on the edge of Lake Constance in Bregenz, Austria, the visual and tectonic aspects of the Kunsthaus Bregenz are well known. The scheme presents a box of etched glass shingles that veil the concrete structure of the building, as described by Zumthor:

> The art museum stands in the light of Lake Constance. It is made of glass and steel and a cast concrete stone mass which endows the interior of the building with texture and spatial composition. From the outside, the building looks like a lamp. It absorbs the changing light of the sky, the haze of the lake, it reflects light and color and gives an intimation of its inner life according to the angle of vision, the daylight and the weather.

While these visual effects of the building are familiar, the thermally active surface system that enables the scheme's minimalism is less documented. The visual appearance and material presence of the building is best understood as the manifestation of novel immaterial strategies and systems. The Kunsthaus's architecture emerged from simple yet profound physiological understanding of the body as the context. Like the human body, the Kunsthaus is a hydronic heat and cool system with a decoupled fresh air ventilation system. The concrete surfaces in the Kunsthaus are hydronic, thermally active surfaces that temper the thermal comfort of bodies in the space through radiant heat transfer as opposed to the minimal air system in the building. While this system may initially seem simple, if not mundane, it engenders the austere appearance and low energy consumption of the building.

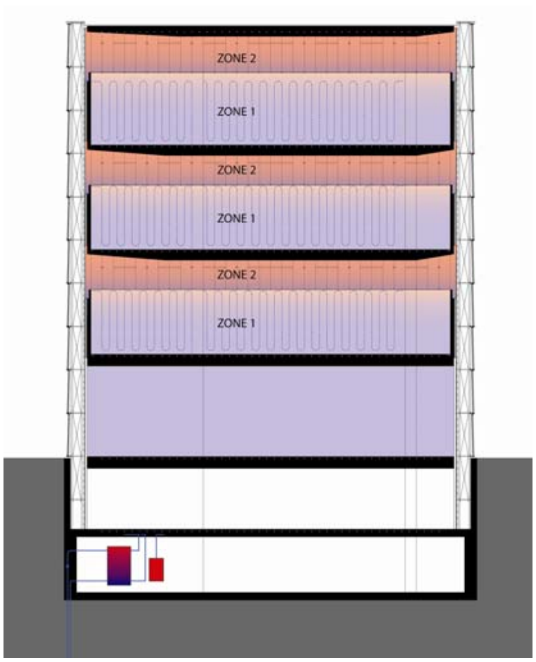

Figure 9: Kunsthaus Bregenz Section – Earth Coupled

The Kunsthaus is an example of an earth-coupled, thermally active surface building. The simplicity of the scheme are manifest in the clarity of its zoning. The building has three primary zones: first, the occupied spaces of the galleries, the entry floor and the subterranean levels;

second, a service zone above each of the galleries; third, a buffer zone that wraps the building. The galleries are supported and enclosed by a thermally active concrete structure. The concrete super structure bears on a set of twenty-four, one meter-diameter piles that distribute its load down twenty-six meters into the soft ground condition of the lakeside site. The building also has a earth-coupled perimeter slurry wall foundation that extends down to bedrock, isolating the construction from the flowing groundwater in the soil of the site. These foundation walls also serve as a heat sink and source. The water from the adjacent lake and on the site fluctuates annually from 60-72°F. This water cycles through the slurry walls and is used for cooling purposes. These earth coupled loops feed a 3800 liter storage tank that supplies the hydronic system for the concrete structure of the Kunsthaus. The design integrated 28,000 kilometers of tubing into the concrete pour. A gas-fired boiler supplies heat for the hydronic system in the winter months. The structural configuration of the galleries creates controlled, thermally active surfaces on five sides of a body in the gallery spaces. Together, this strategy minimizes perceived radiant asymmetries and thus allows a lower supply temperature because the system does not compensate for unheated surfaces in the space and the resultant thermal asymmetries.

The ventilation air for the occupied spaces is distributed through high-velocity, small diameter ducts cast in to the floor. A reveal around the edge of floor at the base of the wall is the distribution slot for the displacement supply air strategy. The ventilation slots around the perimeter of the space also accommodate differential movements between the terrazzo topping and the concrete structure. Again, the thermal loads in the gallery space are decoupled from the air system, allowing the use of a small volume of air. As the fresh air mixes with existing air a quarter of times per hour, the air is heated and rises through slots in-between the glass ceiling panels. The minimal fresh air exchange and humidity control allows for the systems in the galleries to be visually concealed. Within the galleries this effectively creates two distinct air zones: the gallery zone and the light-air plenum above. The incident heat gains from the daylight strategy as well as heat gains from the power-operated light system are captured and removed radiantly by the thermally active slab above as well as the exhaust air duct in the slab above the gallery. This results in significant cooling-load related operating costs. When decoupled from heating and cooling, the Kunsthaus only needs 750 cubic meters of supply air compared with 24,000 cubic meters of supply air for a comparable museum space, based on a conventional air-based approach to heating, cooling, and ventilation. The installation cost of this system is a third of a conventional HVAC system. Furthermore, the cooling system uses 80% less energy per annum compared to a conventional system.

In colder seasons, supply air is preheated by a heat recovery system. It is humidified and reheated to its supply condition. In the summer, the east face of the building's glazed envelope functions as the fresh air intake. The summer supply air is cooled and dehumidified with energy from the earth-coupled cooling system. Since the building's construction, it has been retrofitted with an additional a humidity control system that provides a greater degree of control for certain sensitive art installation standards that were not part of the original project design. The new special exhibition system ensures a constant 70°F temperature and a constant 50% relative humidity level. The original system, used on most days, allows great tolerance in these energy levels (64-75°F and 40-60% relative humidity.)

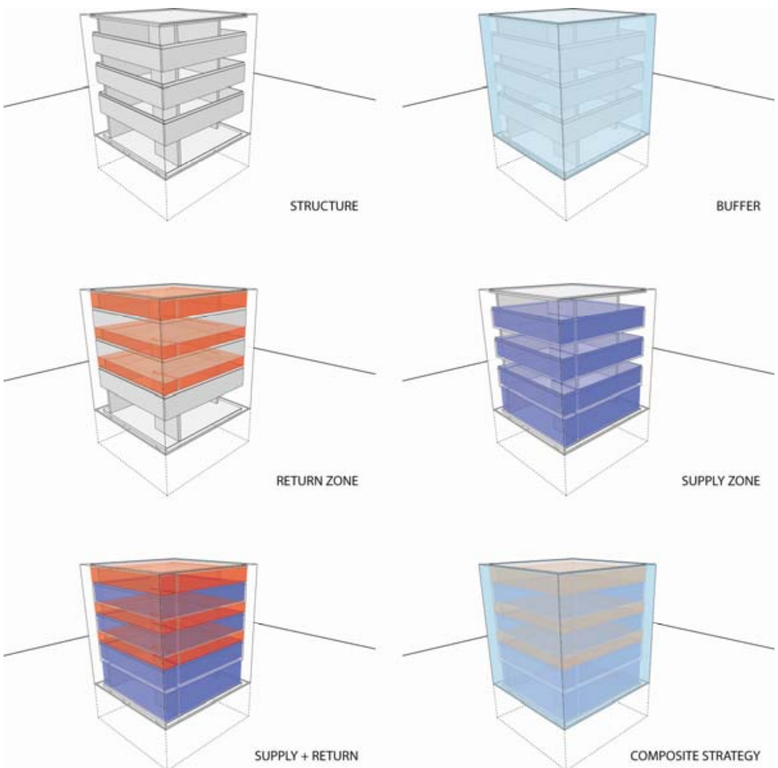

Figure 10: Kunsthaus Bregenz Zones

The third zone, the exterior glass shingle system, serves multiple functions: rainscreen, light diffuser, thermal buffer, and visual veil. The glass shingles bear on a steel tube structure that is thermally and structurally independent of the concrete core. This is important because it eliminates any breaks in the thermal envelope. The ninety centimeter-wide buffer space enables serviceability through a series of lifts that rise from the basement levels of the building. The inner layer of glass is part of the thermal envelope, and bears on the steel tube structure. A set of hydronic convectors run along the base of this glazing to offset thermal losses at the glazing. It is attached to the top of the concrete wall, to offset thermal loss from the glazing. Rigid insulation clads the concrete wall, completing the thermal envelope and provides reflective material that bounces light back through the glass shingle rainscreen. The intent here was to diffuse direct solar incidence as well as to create an unbroken thermal envelope around the concrete core. The zone also integrates a solar control strategy. A series of operable blinds that can drop in front of the clerestory glazing to control the amount of incident daylight, making the galleries a black box for video installations. These blinds are controlled by a building management system and a rooftop light level sensor. Finally, the steel structure integrates a series of spotlights that illuminate the veiled exterior of the building at night.

4. Conclusion

The thermally active surfaces are central to the aesthetic, organizational, and technical performances of the Kunsthaus Bregenz. The active surfaces minimize the size and scope of mechanical systems that could otherwise interfere with the performance of the gallery space. The clarity of the building's zoning in many ways represents in many ways an ideal diagram for thermally actives surfaces buildings. It boasts a high performance building envelope, decoupled thermal and ventilation systems, abundant daylighting, and exposed surfaces on multiple sides of the conditioned spaces. While minimal in appearance, the building can be seen as a maximal form of non-visual ornament for the nervous system. The Kunsthaus is an emblematic example that design, energy and logistics of materials, light, and sensible temperature gradients—from its source to its effect on a building and body—now constitutes a coherent form of thermodynamic figuration unto itself with new aesthetic potential and technical parameters.

5. Citations

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7. Illustrations

Figure 1: By Author
Figure 2: By Author
Figure 3: By Author (based on R. D. Watson and K. S. Chapman, *Radiant Heating & Cooling Handbook*. New York: McGraw-Hill Handbooks, 2002. p. 5.83)
Figure 4: By Author: based on James Marston Fitch, *American Building: The Environmental Forces that Shaped It*. Boston, Houghton Mifflin Company, 1972. p. 50 (figure 12).
Figure 5: By Author. Top: based on R. D. Watson and K. S. Chapman, *Radiant Heating & Cooling Handbook*. New York: McGraw-Hill Handbooks, 2002. p. 3.12, 3.13. Bottom: based on Richard Woolsey Shoemaker, *Radiant Heating*. New York: McGraw-Hill Book Company, Inc. 1948. p. 6-7 Figures 1-1 to 1-4)
Figure 6: By Author (base on Ed Allen.
Figure 7: By Author
Figure 8: courtesy Julie Janeo
Figure 9: By Author
Figure 10: By Author