Multiscale Thermal Design for Buildings

HARVARD UNIVERSITY
Graduate School of Design

THESIS ACCEPTANCE CERTIFICATE

The undersigned, appointed by the Doctor of Design Program, have examined a dissertation entitled

Multiscale Thermal Design for Buildings

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Multiscale Thermal Design for Buildings

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Abstract

This dissertation investigates the principles, processes, and strategies to develop multiscale material systems for buildings that interact with heat in novel ways. The overall theoretical framework consists of (1) utilizing the multiscale configuration of biological material systems as the principle for the design of building element; (2) using the shape and size of heat flow as the key parameter for the design and optimization of the building elements; and (3) applying the principles of materials and material processes for selecting and configuring the material systems. This framework is examined in Part I through literature review and case studies; and implemented in Part II through a series of experiments for the designing, prototyping and testing a thermally augmented building envelope system. The results of the analytical model and the physical testing show strong correlations which validate the usage of the analytical model in the thermal optimization of building elements at a wide range of geometric and temperature variations. To evaluate the performance of the system standards including the recommended U-value for building envelopes and the targeted ventilation and heat recovery rate per occupant is used. The overall dissertation can provide architects with the essential knowledge and strategies for developing thermally augmented building elements. Similarly, the research can also inform the scientists and engineers on the thermal design constraints and opportunities relating to building applications. Although this research is focused on heat as the key environmental factor, the theoretical framework can be extended to other factors such as light and sound.

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There are a number of people that I am greatly indebted. Without them, this dissertation would not have been completed.

To my dissertation committee Martin Bechthold, Salmaan Craig, and Joanna Aizenberg who has provided me unlimited inspiration, support and guidance throughout the thesis.

To my mother and father, who has always been there for me and cheering for the son studying at the other side of the world. I would also like to thank my sister Haeyoon and my brother-in-law Honam for always being supportive, considerate and thoughtful.

Finally, I would like to dedicate this thesis to my wife Sohee, my son Minjoon, and my daughter Hannah. Thank you for standing by my side throughout the long journey. I love you with all my heart.

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Part I

Literature Review

Chapter 1. Introduction

1.1 Background and Purpose

Buildings are multiscale material systems with an interconnected web of subsystems, components, and materials. For a specific building project, a team of architects, engineers and consultants take on the task of designing and configuring these systems. In every case, various factors including functionality, aesthetics, budget, and schedule need to be considered. Generally, architects focus on organizing and coordinating the complex relationships about the design intent; whereas the engineers and consultants ensure each subsystem and their components meet the functional and technological criteria.

When it comes to material technology[1], a practicing architect tends to be a consumer rather than a developer, essentially picking from a catalog of technologies with some limited degree of customization. Although there are cases where the team develops customized material system for a specific project, most of the fundamental research and developments are allocated to industries and suppliers relating to building materials and products (e.g. windows and wall systems). These industries and suppliers also have their team of architects, engineers, and scientists; and often initiate collaborations with academic or private research entities.

1 Materials and components such as bricks, tiles, gypsum board, and thermal insulation.

However, with the availability of accessible tools for developing building technologies[2] as well as the interest in environmentally responsive design, a new way of architectural practice is becoming prevalent. Instead of being a passive consumer of material technology, architects are increasingly engaging in research and development activities that have been previously considered as the domain of engineers and scientists[3].

This trend is particularly visible in the larger scale passive thermoregulation strategies (above components and materials scale) architects utilize (see Table 1). With the aid of accessible environmental simulation tools and accumulated knowledge, architects are creating innovations at the level of building form and organization that enhances the daylighting, ventilation, acoustics, and thermal performance.

The increased availability and references relating to passive thermoregulation strategies at the building system level is also enabling architects to experiment with assembling components and materials to achieve better thermal performance. Although there remains a significant technological barrier at the components and materials level, the recent advancement of multiscale material technology, especially in the small scale, is providing the enabling tools and technologies for the change.

The prominent materials in the building industry such as concrete, masonry, and wood components have a long history of incremental developments that focuses on improving the constructability and durability of the components. The development of highly specialized materials (e.g. insulation, and exterior cladding) ushered the layered

2 Simulation software, rapid prototyping processes, and computational tools.

3 Before the building became more complex and the building technology more sophisticated, the role of architect as master builder included the role of technological innovation.

construction approach (e.g. the layered wall section) which became the norm of the current building industry.

Table 1 Passive thermoregulation strategies in buildings
Passive thermoregulation categories and strategies based on scale

Scale	Category	Strategies
meter ↕ micrometer	**Form and organization**	Building form and organization Shape, size and orientation of openings Relationship with context[4]
	Building Systems	Trombe wall system Convective-loop system Direct-radiant cooling system Daylighting and natural ventilation systems Transpired solar collector
	Components and Materials	Thermal insulation Heat exchanging components Thermal storage

However, with the current development of advanced material technologies such as hybrid (or architectured) materials that echo the novelties of biological materials, the fundamental approach in developing multi-scale material systems for buildings is changing. The thesis builds upon this change, investigating the means and methods to increase the architect's domain in developing multiscale material systems for a broader scale range (i.e. from the meter to the sub-millimeter scale).

4 Landscape elements, adjacent buildings, soil, and micro-macro climate.

Although there are many research efforts made in multiscale material systems about structural performance[5], there are limited researches relating to thermal performance[6]. In the perspective of energy efficiency as well as human comfort in buildings, heat is one of the most critical environmental factors[7] that needs to be addressed. Therefore, this research is formulated around the topic of heat, and how to design multiscale material systems that augment the thermal performance of buildings, particularly at the building component and the material domain.

Heat is a complex phenomenon that has implications for virtually all fields of studies and industries, Therefore, it is necessary to narrow the scope of the research to gain deeper insights. Hence, thermal design methods and processes pertaining to building applications with the temperature range close to our living environment (approximately -50℃ to 50℃ in the United States) is the focus of the study.

In this temperature range, heat behaves more in a predictive way compared to the cryogenic or high-temperature conditions. This behavior enables researchers to utilize many of the existing materials and materials processing techniques which are essential for developing highly reliable, cost-effective and durable building components. Furthermore, there is a plethora of accumulated knowledge in the form or correlations, experimental data, and precedents that this research can reference and benchmark.

5 The development of micro-structured materials that is strong and lightweight is an active field of research.

6 Research relating to applications for extremely high or low temperatures is an active area of research.

7 Other critical environmental factors that affects buildings are light (or daylight), water (and water vapor), air, and sound.

Based on the scale analysis of both the physics of heat and the feasibility of building implementation (e.g. constructability, cost, and durability); length scale ranging from approximately 100 micrometers to meter scale is the primary scope of the research. (See sections 3.2 Classification by Scale and 3.3 Applications of Thermal Design)

The experimental phase described in Part II, utilizes advanced design and fabrication techniques (e.g. parametric modeling and additive manufacturing) to control and fabricate material features at the submillimeter scale precisely. Compared to the conventional materials design and processing techniques (e.g. cutting, folding, machining, and casting) this approach can enable researchers to quickly and more efficiently design, fabricate and test small-scale material features that further augments the intended thermal functions.

1.2 Organization of the Thesis

The overall thesis is organized into two parts. Part I investigates the overall research topic through literature review and case studies. Part II explores the strategies and methods identified in the previous chapters through a series of design experiments.

Part I consists of five chapters. Following the introduction**, Chapter 2. Theoretical Framework** summarizes the main concepts that guide the overall thesis. These includes (1) approximating multi-scale tectonics of biology; (2) optimizing design to facilitate the shape and scale of heat flow; and (3) selecting and structuring materials for thermal performance.

Chapter 3. Classification and Application of Thermal Design classifies and investigate the thermal design based on function and scale. The classification based on thermal functions consists of moving heat around and maintaining temperature. The former function includes sensible heat transfer and latent heat transfer modes; and the latter function includes thermal insulation, heat exchanger, and thermal storage modes. On the other hand, the classification based on scale presents the critical issues in macro/micro scale heat transfer regimes and macroscopic/ microscopic material features. Finally, an overview of the comparison between thermal design in biology and technology is presented, and a selected number of notable applications are evaluated.

Chapter 4. Thermal Design Methods review the thermal design methods based on the classification by thermal functions. Each of the design methods is examined in detail, and the most prevalent and effective strategies are emphasized. The chapter concludes with the review of selected research works that relate to the thermal design methods.

Chapter 5. Multiscale Materials for Thermal Design presents the fundamentals of material properties and material selection about thermal design. Following the individual thermal property descriptions, the general issue of multi-objective and multi-constraints in design, as well as the material selection processes, are presented. Existing fields of multiscale material system research including cellular materials, functionally graded materials, adaptive materials[8] are studied, and the fabrication processes and technologies are reviewed. These studies will aid in identifying opportunities for the direction of materials research for building applications.

Chapter 6. Adaptive Insulation for Building Envelopes provide a review of adaptive insulation systems which is an alternative method to the current airtight and heat

8 Adaptive materials include smart materials and programmable matter.

impenetrable building envelope design approach. The advantages and challenges of adaptive insulation system is discussed and the existing studies and developments are categorized and analyzed.

Part II also consists of five chapters that document the overall process of designing, fabricating, and testing an innovative building envelope system that channel, insulate, and exchange heat in novel ways. The experiment is aimed to become one of the key components of the overall research, contributing in gaining a deeper understanding of the principles, processes, and strategies for developing multiscale thermal design material systems for buildings applications.

Chapter 7. Thermally Augmented Building Envelope System presents the overall background, goals, and strategies used for designing and optimizing the proposed system. **Chapter 8. Experiment 1** and **Chapter 9. Experiment 2** describes the analytical model, experiment setup and results for the thermal insulation component using layered radiant barriers and passive heat recovery ventilator using extended heat exchanger surfaces.

Chapter 10. Experiment Discussion provides an in-depth analysis of the overall system design, experimental results of each component. The advantages, challenges, and opportunities of the proposed system are also discussed. Finally, **Chapter 11. Conclusion and Recommendations** summarize the findings, contributions, and implications of the overall research. The research is also situated in the context of building practice and suggestions for future studies are presented.

Chapter 2. Theoretical Framework

2.1 Approximating Multiscale Tectonics of Biology

> *Although many philosophers in the past have suspected one could abstract the laws of life and apply them elsewhere, it wasn't until the complexity of computers and human-made systems became as complicated as living things, that it was possible to prove this.*[9]
> *-Kevin Kelly*

The recent interest in biology in material technology started with the research in high-performance materials since the mid-20th century. To facilitate the specific and challenging demands from the military and the aerospace industries, material scientists needed to combine several materials into a hybrid material system. Hence, the traditional linear notion of structure, properties, and performance had to be replaced by a systems approach, utilizing feedback loops and iterations.[10]

Since the late 20th century, scientists started to realize that hybrid material systems approach is common for living organisms, and that their version of high-performance materials are far more advanced than what scientists have been creating. The hierarchical structures that living organisms create are not only versatile and multifunctional but also enable multi-level adaptation to chemical and physical stresses[11]. Moreover, these complex material systems are created at ambient temperature and

9 Kelly, Out of Control.

10 Bensaude-Vincent and Newman, The Artificial and the Natural, chap. 13.

11 This strategy fosters "growth, self-repair, and recycling." Ibid.

pressure via self-assembly processes, which occur across many material scale levels simultaneously.[12] Hence, the ingenious solutions of natural organisms are increasingly referenced by scientists and engineers.

A good novel example can be found on the wings of a butterfly. In the macroscopic scale, butterfly wings are shaped to move the maximum amount of air towards one direction efficiently. The flapping motion of the wings also takes advantage of the air vortexes. The wing itself, which is essentially a chitin substrate, is covered with tiny scales (each roughly 100 µm wide) which not only assist the air flow but also protect and thermally insulate the wing.

Under the microscope, each tiny scale consists of ridges and cross ribs that form three-dimensional nanostructures (less than 100 nm). As a material system, the hierarchical structure composed of scales; ridges and cross ribs; and nanostructures interact with certain wavelength of the visual spectrum causing color change[13]. (See Figure 1)

With the renewed interest in the natural multiscale and multifunctional materials, there are an increasing number of scientists and engineers that reference biology as the benchmark for developing novel material systems.

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12 Ibid.

13 The color of the iridescence changes based on the size of the nanostructure which interacts (constructive interferences) with a certain wavelength of the light spectrum. In combination with the pigment of the chitin substrate, various visual effects emerge that ultimately serve functions such as camouflage and communication. See Thomé, Nicole, and Berthier, “Multiscale Replication of Iridescent Butterfly Wings.”

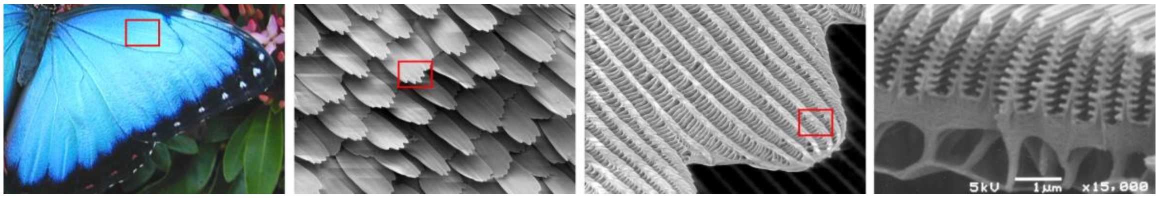

Figure 1 Multiscale tectonics of a Morpho butterfly
Butterfly wing observed at four distinctive scales (x5, x200, x1,000, x5,000, and x15,000).[14]

Julian Vincent points out that there is a fundamental difference between the solutions of biology and technology below the meter scale. If technology derives solutions mainly by changing the material type or the amount of energy input, biology does it through changing the information (stored in DNA) and space (shape and configuration). In other words, technology tends to create new materials using energy intensive processes for increasing the functionality.

Living organisms have a small number of information driven synthetic processes (e.g. proteins and polysaccharides) that can hierarchically configure various shapes and combination of materials customized for the intended functionalities. These processes build up the materials from the bottom-up and usually have the capacity to adapt to short-term and long-term changes.[15]

Joanna Aizenberg takes the “extreme biomimetic” approach which analyzes nature’s high-tech solutions to develop novel material systems. The emphasis is on creating a versatile material systems platform that can cut through industry boundaries and can be implemented on a broad range of applications. Among many unique attributes of

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14 “Butterfly Wing.”

15 Vincent et al., “Biomimetics.”

nature's materials, the multi-functionality and adaptability are the key focus areas of her research.

The scale domain of Aizenberg's research is mainly below the micrometer scale with a strong emphasis on bio-inspired synthetic routes and fabrication methods.[16] The body of work ranges from a self-healing slippery coating that can repel various immiscible fluids[17] to an iridescent coating that responds via a color change to different types of liquid[18]. These research are multi-disciplinary in nature and can be implemented in the various fields of research and applications.

Michael F. Ashby and Lorna J. Gibson provide valuable knowledge in cellular materials that is ubiquitous in nature. Wood and cork consist of anisotropic prismatic cells that resemble bee's honeycomb whereas trabecular bone, and plant parenchyma is composed of polyhedral cells that resemble foam. Natural material systems are architectured, in other words, density, material composition, and geometric configuration change based on the intended function. Among the various applications, the use of cellular solids as thermal insulation is efficient and widely utilized.[19]

In this context, this thesis aspires to follow the footsteps of the scientists and engineers mentioned above. Biological references are not only the inspiration for deriving strategies and concepts but also the ultimate benchmark that the material technology

16 "Extreme Biomimetics"; "Adaptive Material Technologies"; "Research overview"

17 Slippery Liquid-Infused Porous Surfaces (SLIPS) research. See Wong et al., "Bioinspired Self-Repairing Slippery Surfaces with Pressure-Stable Omniphobicity."

18 Watermark Ink (W-INK) research. See Burgess et al., "Wetting in Color."

19 Gibson, Ashby, and Harley, Cellular Materials in Nature and Medicine; Gibson and Ashby, Cellular Solids.

research should strive to surpass. Among the various novel aspects of biology, this study is interested in how biological material systems utilize multiscale configurations to augment its thermal performance.

The geometric configuration of the components and the composition of the materials at each scale domain (e.g. meter, millimeter, micrometer, nanometer) should be designed simultaneously at multiple scale domains. By doing so, it will be possible to create the multiscale material system that can not only perform efficiently for targeted functions but also be able to adapt better to the environmental and physical changes.

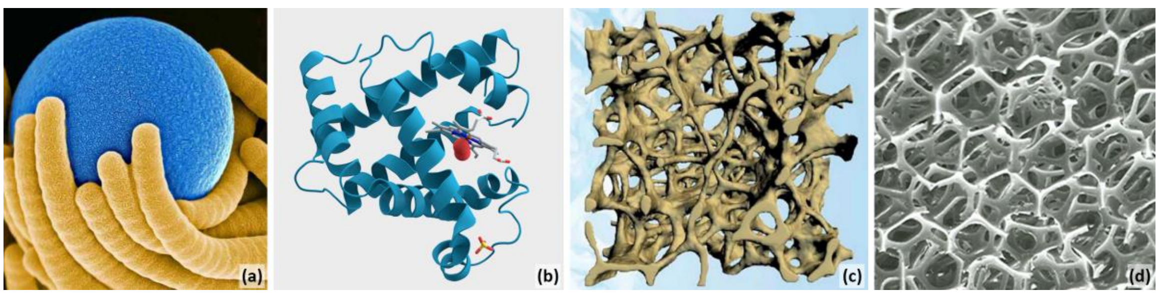

Figure 2 Multiscale tectonics of biology
(a) Self-assembled nanoscale bristles that can capture and release an object[20]; (b) 3D structure representation of the myoglobin protein[21]; (c) Micro-computed tomography image of the trabecular bone cellular structure[22]; (d) Closed-cell polyethylene foam.[23]

20 "Sphere in Hand."

21 "Myoglobin Protein."

22 Gibson, Ashby, and Harley, Cellular Materials in Nature and Medicine.

23 Gibson and Ashby, Cellular Solids.

2.2 Optimizing Design to Facilitate the Shape and Scale of Heat Flow

For a finite-size flow system to persist in time (to live) it must evolve such that it provides greater and greater access to the currents that flow through it.[24]
- Adrian Bejan

The traditional approach of developing thermal interaction material systems (e.g. heat exchanger) is to start with designing the physical entities such as channels and ducts (e.g. walls and fins). The next step is to assemble these entities within the allocated volume, and the fluids (e.g. water or air) are forcefully fitted through the spaces.

Bejan compares this approach to designing a shoe and stuffing the foot into it and emphasizes that it should be the other way around. Each flow phenomena, according to him, inherently have a characteristic shape and size, and the design of the structure around that should be customized to fit it. A good example can be found in optimizing the point to area heat flow which is manifested through a tree-shaped path that has specific thickness variation and bifurcation angles (see Figure 3).[25]

In a broader context, this implies that there is an appropriate (or characteristic) size for components within any given system (biological or technological). For instance, the flow resistance in channels of an animal organ or a car engine decreases as the size of the channels increases. On the contrary, the amount of energy required (or “fuel penalties”)

24 Bejan, “Constructal-Theory Network of Conducting Paths for Cooling a Heat Generating Volume”; Bejan, “From Heat Transfer Principles to Shape and Structure in Nature”; Bejan and Lorente, “The Constructal Law of Design and Evolution in Nature.”

25 Bejan and Lorente, Design with Constructal Theory, 96.

decreases when the components become smaller. This means that there is an optimum size that satisfies both contradicting constraints the best. (See Figure 4, left).[26]

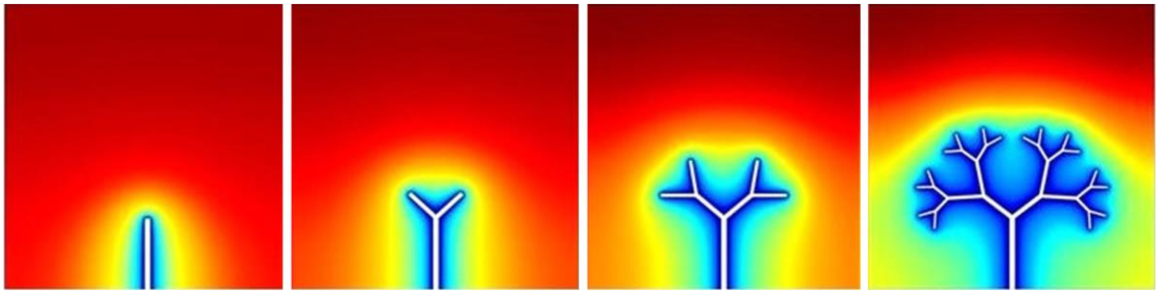

Figure 3 Characteristic size and shape of point to area heat conduction
Optimal bifurcation angles of the tree-shaped path in a conducting body.[27]

The way of thinking in both extremes, as explained above, is the basis of the problem-solving method developed by Bejan called the intersection of asymptote method. This approach essentially intersects two extreme cases (e.g. small and large spacing) to derive the solution that occupies an area within the two extreme conditions. The intersection of asymptote method is effective in solving non-intuitive questions (e.g. such as determining the optimal channel spacing for natural convection) in a straightforward and clear way with a reliable range of accuracy.[28]

Another important foundational concept for thermal design that Bejan proposes is the “optimal distribution of imperfection.” Since imperfections within a thermodynamic system cause loss of energy, thermal design is fundamentally about configuring the shape and size of the material system so that the least “perfect” element works (or

26 Bejan, “Constructal Law.”

27 Kobayashi et al., “Trees and Serpentines in a Conducting Body.”

28 Bejan and Lorente, Design with Constructal Theory.

stressed) as much as possible.[29] Bejan describes this concept in the context of thermodynamics as “the generation of entropy in the system - its irreversibility - is distributed in a relatively balanced way between the parts that operate with losses.”[30]

Finally, the optimization of thermal design (and any other design optimization) is inherently an ongoing process with a direction opposed to having the ultimate best solution. Bejan argues that optimization is a natural process for both biological and technological systems, involving persistent processes of mutations (and making changes) and selection of the fittest (or better alternative). This process is integrated into the constructal theory[31] that states “for a finite-size flow system to persist in time (to live) it must evolve such that it provides greater and greater access to the currents that flow through it.”[32]

A good example of this is found in the evolution of cooling technology. The phases of development take place stepwise in the order of natural convection, forced convection to conduction. This shows that the cooling technology has been evolving towards higher

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29 This is the key concept that governs the thermal design in biological system. Bejan, “From Heat Transfer Principles to Shape and Structure in Nature,” 432.

30 “Ibid.

31 Adrian Bejan proposes the constructal theory that provides the framework for predicting the flow structure and scaling laws of both natural (geophysical and biological) and artificial systems. Examples include lung design, animal locomotion, vegetation, river basins, etc. Bejan states that the patterns such as the vascular network that can be found in flow structures such as river basins and lung design is a phenomenon of physics and can be predicted based on the constructal law. Bejan, “Constructal-Theory Network of Conducting Paths for Cooling a Heat Generating Volume”; Bejan, “From Heat Transfer Principles to Shape and Structure in Nature”; Bejan and Lorente, “The Constructal Law of Design and Evolution in Nature.”

32 Bejan, “Constructal-Theory Network of Conducting Paths for Cooling a Heat Generating Volume”; Bejan, “From Heat Transfer Principles to Shape and Structure in Nature”; Bejan and Lorente, “The Constructal Law of Design and Evolution in Nature.”

transfer density and will continue to evolve towards the configuration (miniaturization) that allows easier volumetric heat flow (see Figure 4, right).[33]

In summary, heat as a physical phenomenon that has a specific shape and size; and the optimization of thermal design is to configure the material systems that fit not only this but also facilitate more flow of heat. The intersection of asymptote method provides a convenient way to derive the best shape and size of the material system. The optimum distribution of imperfection concept promotes the development of novel configurations and design to enhance the flow of heat, mass, and energy.

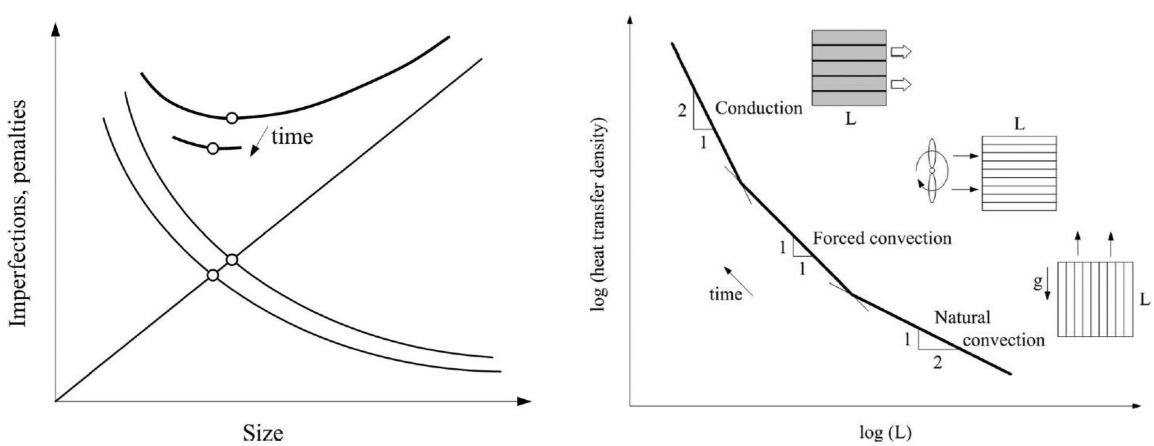

Figure 4 Thermal optimization and evolution of cooling technology
Optimizing the size of thermal interaction components using the intersection of asymptote method (left); and the evolution of cooling technology based on miniaturization induced heat transfer density change (right).[34]

33 Bejan, “Constructal Law.”

34 Ibid.

2.3 Selecting and Structuring Materials for Thermal Performance

The selection of the materials and structuring[35] them for the targeted functions is often the first step as well as one of the most important processes in thermal design. In order to select the best material, it is necessary to understand the essential material properties associated with independent and collective thermal function criteria.

The material properties that directly impact thermal functions include specific heat, thermal conductivity, thermal diffusivity, characteristic temperatures of a material at phase or behavior change, and latent heat.[36] The thermal function criteria relate to whether the amount of heat transferred[37] is sufficient for the required function at the condition it is exposed to (e.g. temperature and pressure)

The majority of the materials that exists today have been developed over the past 100 years starting from a few hundred in the 19th century to over 160,000 materials today and exponentially increasing in number and sophistication. Hence, there needs to be a material selection process that can systematically organize and compare the existing material databases in a logical and meaningful way that enables the designer and engineer to search through the current material databases and identify the most suitable material.

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35 Configuration of the material in terms of shape and geometry.

36 Ashby, Shercliff, and Cebon, Materials.

37 This can be assessed by identifying the independent or combined heat transfer rates.

The computer-aided material and process selection tools such as the Cambridge Engineer Selector (CES) software developed by Michael Ashby effectively do this. CES Selector provides the rational and graphical approach in the material selection process based on the performative requirement of the application and characteristic of the material (feature, material, geometry, and processes).

However, if selecting the right material for the right purpose is foundational to material design, structuring (or configuring) the chosen materials at various scales amplifies the capability of the chosen material. Biology commonly utilizes this approach of hierarchically structuring existing materials rather than creating an entirely new material for achieving specific functions and attributes. A spider web is a good example where the structure of the silk is customized for various types of applications[38] via varying the protein fold and the extrusion process (see Figure 5).

Ashby describes the strategy of reconfiguring materials to enhance or create functionalities as "filling holes in material-property space." These "holes" exist because, despite a significant number of materials available today, a single material on its own cannot satisfy the high levels of performance that are required for complex engineering demands.

Therefore, it is necessary to push the development of hybrid or architectured materials that combine two or more materials (one can be air within a void space) in specific ways to gain a new set of attributes. Ashby proposes that architectured materials should be

38 Dragline, capture, attachment, tough, soft, sticky, etc. See Römer and Scheibel, "The Elaborate Structure of Spider Silk."

assigned as a new material class with its unique set of bulk properties rather than attempting to categorize it by its constituent materials.[39]

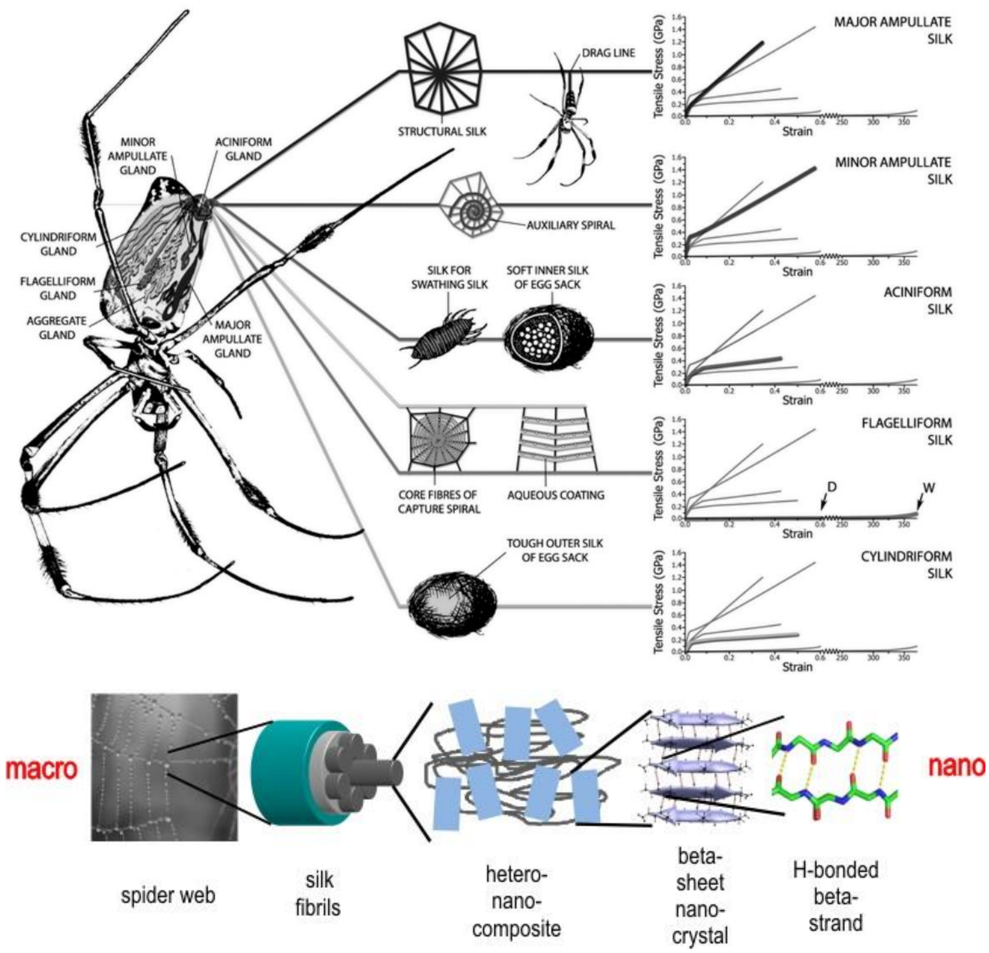

Figure 5 Spider silk properties by function and hierarchical structure
Functional variation of spider silk and its mechanical strength (top)[40]; and the hierarchical configuration of spider silk from macro (i.e. millimeter) to nanometer scale (bottom)[41].

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39 Ashby also categorizes the hybrid materials by it configuration (i.e. composite, sandwich, lattice and segment). Ashby, Materials Selection in Mechanical Design, 342.

40 Vollrath and Porter, “Spider Silk as Archetypal Protein Elastomer.”

41 Keten et al., “Nanoconfinement Controls Stiffness, Strength and Mechanical Toughness of β-Sheet Crystals in Silk.”

Although there are significant challenges that need to be overcome, the recent advancement in material technologies is fostering the development of novel multiscale material systems. The fields of research including cellular materials, functionally graded materials, smart materials, metamaterials and programmable matter are collectively pushing the boundary of artificial multiscale material systems.

The new hybrid materials emerging from this research are starting to approach the complexity and intricacy of biological material systems. The rapid advancement in material processing technologies particularly relating to additive manufacturing at the small scale as well as the sophisticated computational design and simulation tools are serving as a valuable enabling platform for research.

Chapter 3. Classification and Application of Thermal Design

> *Tell me the size of a mammal and I can tell you, to about 85 per cent level, pretty much everything about its physiology and life history, such as how long it is going to live, how many offspring it will have, the length of its aorta, how long it will take to mature, what is the pulse rate in the ninth branch of its circuitry.*
> *- Geoffrey West*

Thermal design, in the context of this dissertation, is the process of designing material systems that interact with heat.[42] Much like the process of architectural design, industrial design, and engineering design, thermal design involves both the scientific method of engineering as well as the creative process of design.

Heat is involved with a broad range of phenomena and heat transfer modes which occur simultaneously and dynamically. Furthermore, there is a certain time and length scale for each transfer mode where the continuum model of macroscale regime breaks down. These complications make it challenging to categorize the phenomena of heat as well as the heat transfer modes in a straightforward and clear way.

As a result, this thesis classifies thermal design using two different set of criteria: by its thermal function and by its characteristic length scale. Based on this categorization and analysis, examples of biology and technology is identified and discussed.

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42 Adrian Bejan used the term thermal design, thermal systems design, and design of thermal systems interchangeably. See Bejan, Tsatsaronis, and Moran, Thermal Design and Optimization.

3.1 Classification by Thermal Functions

This section organizes the thermal functions based on the classification that Steven Vogel applied to investigate the thermal design in biological organisms[43]. Although the framework is focused on natural systems, it is general enough to categorize the wide array of heat phenomena and heat transfer, and consequently, be applied to artificial systems. The framework summarized in this section (see Table 2) is applied to the scale analysis in the following section 3.2.

The two principal functional themes that Vogel uses are "moving heat around" and "maintaining temperature." These functions are critical to biological organisms since the uneven distribution of internal temperature has major effects on the physiology of the organisms. For example, the enzymatically catalyzed reactions typically increase two to three times for every 10 degrees rise in temperature; the viscosity of water decreases over 20% from 20°C to 30°C; and the diffusion coefficients of solutes also increase with temperature increase.[44]

The “moving heat around” function distributes heat around using various methods including sensible and latent heat transfer. On the other hand, the “maintaining temperature” function attempts to control the temperature fluctuations using material systems that are designed to insulate, exchange or store heat.[45]

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43 Vogel, “Living in a Physical World IV. Moving Heat around”; Vogel, “Living in a Physical World V. Maintaining Temperature.”

44 Vogel, “Living in a Physical World IV. Moving Heat around.”

45 Vogel, “Living in a Physical World V. Maintaining Temperature.”

Although there is a clear functional difference between the two categories, the modes are interconnected and often interchangeable. In the context of science and engineering, the former category describes the fundamental mechanic of heat transfer (e.g. conduction, convection, radiation) and the latter applies these to achieve a specific functional requirement.

Table 2 Thermal function framework
A framework based on thermal function, mode, and method.[46]

Function	Mode	Method
Moving heat around	Sensible heat transfer	Maximize conduction, convection, or radiation
	Latent heat transfer	Regulate state change for intended effect
Maintaining temperature	Thermal insulation	Minimize heat transfer at system boundary
	Heat exchanger	Optimize heat exchange at system boundary
	Thermal storage	Optimize heat capacity of system or object

3.1.1 Moving heat around

There are two key modes for moving heat around: sensible heat transfer and latent heat transfer. Sensible heat describes the exchange of heat by a thermodynamic system that involves temperature change without state change. The basic mechanisms of heat transfer include radiation, conduction, and convection. Radiation and conduction only depend on temperature differences whereas convection depends on both temperature

46 Framework based on Vogel, "Living in a Physical World IV. Moving Heat around"; Vogel, "Living in a Physical World V. Maintaining Temperature."

and mass transport of fluids[47]. On the other hand, conduction and convection only operate through matter (e.g. solids, liquids, and gasses) but radiation can take place both through matter and vacuum.

The thermal design strategy for sensible heat transfer is to optimize the rate of each heat transfer mechanisms. Since heat transfer mechanisms occur in combinations, strategies such as suppressing one or more mechanisms to control the heat flow in certain ways are often utilized. Although there are various similarities in sensible heat transfer strategies among biological systems and artificial systems (e.g. counter-current heat exchange and thermal window among many others), there is a fundamental difference. The majority of biological systems do not have access to materials with high conductivity such as metals. Therefore, contrary to artificial systems, biological systems mainly use conductive heat transfer mechanisms for suppression (i.e. for thermal insulation purposes), and amplification is achieved through convective and radiative heat transfer mechanisms.

On the other hand, latent heat describes the exchange of heat by a thermodynamic system via state-change without temperature change. Thermal design strategy using latent heat transfer is to regulate the state change based on the intended effect (e.g. heating or cooling). Among the types of state change, evaporation and condensation are the most prevalent means of thermal regulation both in natural and artificial systems.[48]

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47 The mechanics of heat conduction include heat diffusion (i.e. conduction) and heat transfer by bulk fluid flow (i.e. advection)

48 More recently, thermal storage applications using phase change materials (PCM) has been actively researched and developed. A recent discovery has been also made that blubbers in dolphins are also

3.1.2 Maintaining temperature

Strategies for *maintaining temperature* include three main modes: thermal insulation, heat exchanger, and thermal storage. The modes of *maintaining temperature* suppress or amplify the individual or combination of the modes of *moving heat around* presented in the previous section. In essence, the *maintaining temperature* category focuses on controlling the degree of heat transfer for specific applications.

Thermal insulation is intended to reduce the heat transfer through the boundary between two systems with different temperatures. This function can be achieved using various methods, shapes, and types of materials. The key principle is to minimize heat transfer at the system boundary.

On the other hand, a heat exchanger is a material system that maximizes heat transfer between two fluids of different temperatures. In the perspective of thermal functions, the key objective is to maximize energy exchange at the system boundary. This enables the system to recover or discharge heat to maintain a certain range of internal temperature.

Finally, thermal storage provides the capacity to store heat for certain duration of time. This capability can not only serve as a buffer to reduce the temperature fluctuation rate but also provide means to absorb or release heat at desired time intervals.[49]

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consisted of phase change material. Dunkin et al., "The Ontogenetic Changes in the Thermal Properties of Blubber from Atlantic Bottlenose Dolphin Tursiops Truncatus." Referenced by Vogel, "Living in a Physical World IV. Moving Heat around."

49 Thermal storage media include sensible heat, latent heat, and thermo-chemical heat thermal storage. Sensible heat thermal storage utilizes the heat capacity of the material to store heat (e.g. thermal mass) and latent heat thermal storage takes advantage of phase change in materials to store heat (e.g. PCM). Thermo-

3.2 Classification by Scale

3.2.1 Macroscale and microscale heat transfer regimes

The trend in miniaturization in various fields of engineering (e.g. microelectromechanical systems, photovoltaic cells, and thermoelectric materials) during the last three decades was possible with the exponential advancement of fabrication technology. It is now possible to design and fabricate structures down to the nanoscale which enables the development of high-performance devices and systems with an extremely compact form factor (e.g. compact heat exchangers for electronic devices). However, to successfully design, fabricate, and operate these systems in a reliable manner, it has been critical to research on how the submicron scale domain affects the energy transport mechanisms.

Consequently, the field of microscale heat transfer has emerged to investigate the energy transport mechanism at the microscale regime which significantly differs from the traditional heat transfer approach at macroscale regime. The transition scale between the microscale and the macroscale regimes vary based on factors temperature, heat transfer mechanisms, and types of materials.

The analysis of the macroscale heat transfer relies on the continuum model which consists of conservation of energy and Fourier’s law for thermal conduction. The time and scale effects relating to the heat carriers (i.e. electrons, phonons, and photons) is

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chemical heat thermal storage uses chemical reactions (e.g. magnesium sulfate, calcium sulfate, etc.), Fernandes et al., “Thermal Energy Storage.”

not considered.[50] On the other hand, the analysis of the microscale heat transfer requires considering the size effects of the individual heat carriers since the continuum model breaks down at this regime.

The analysis of microscale heat transfer is complex and challenging, and there are broadly two different approaches: numerical computational approach and the fundamental approach. The former uses a computationally intensive molecular dynamics approach to energy transport issues and is often extremely difficult and time-consuming. The latter utilizes the coefficients and thermo-physical properties that are approximated from the macroscopic theories (e.g. Boltzmann transport equation, Maxwell equation) and modifies them by factoring the size effect.[51]

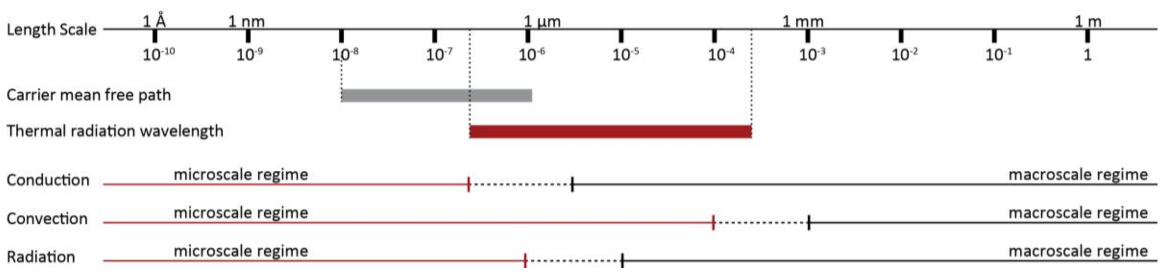

Figure 6 Microscale and macroscale regime boundary dimension
Based on temperatures (approximately -60℃ to 150℃) relating to earth surface temperature.

The conductive heat transfer in the microscale regime occurs when the characteristic length of the material system becomes comparable (order of magnitude) to the scattering mean path of the energy carriers, especially near the boundaries. Past studies indicate a significant reduction in thermal conductivity when the material thickness (e.g.

50 Flik, Choi, and Goodson, “Heat Transfer Regimes in Microstructures”; Tien and Chen, “Challenges in Microscale Conductive and Radiative Heat Transfer”; Sobhan and Peterson, Microscale and Nanoscale Heat Transfer.

51 Sobhan and Peterson, Microscale and Nanoscale Heat Transfer.

thin film) approaches this dimension. The main reason for this is because the amount of length reduction of the mean path at the surface (boundary scattering) increases as the thickness of the material decreases. The mean free path is also temperature dependent which decreases in value as the temperature rises. Flick, Choi, and Goodson report that the microscale regime starts when the characteristic dimension becomes approximately less than seven times the mean free path normal to the layer and four and half times the mean free path along the layer (see Table 3).[52]

Convective heat transfer at this regime is affected by the ratio between the molecular mean free path and the boundary layer thickness. Flick, Choi and Goodson derived the criteria for microscale convection heat transfer of air as $L<Re_L^{1/2}\Lambda_m$ where L is the characteristic length, Re_L is the Reynold's number, and Λ_m is the carrier mean path (see Table 3). The heat transfer in a gas such as air can be characterized by the mean free path of idealized carriers.

However, transport phenomena of liquids are complex due to various cohesive forces such as van der Waals forces and hydrogen bonds. This complexity poses significant challenges in developing microchannels for convection thermal management and is among one of the key areas of ongoing research.[53]

52 Ibid., 10.

53 Flik, Choi, and Goodson, "Heat Transfer Regimes in Microstructures."

Table 3 Microscale regime criteria[54]
Microscale conduction, convection, and radiation summary

Heat Transfer Mechanism	Microscale Criterion
Thermal conduction	$\mathrm{d} < 7\Lambda$
Thermal convection[55]	$\mathrm{L} < 55 Re_L^{1/2} \Lambda_m$
Thermal radiation	$\mathrm{d} < 0.63\lambda_{max}/n$

where: d = smallest dimension, m; Λ = carrier mean free path, m
L = smallest stream wise dimension, m; λ = wavelength in vacuum, m
Re = Reynolds number, dimensionless; n = refractive index

Finally, radiative heat transfer is governed by two length scales including the photon mean free path and the wavelength during the radiative exchange. In absorbing materials (e.g. for radiation detectors), the characteristics of the radiation are influenced when the thickness of the material is smaller than the photon mean free path. On the other hand, in non-absorbing materials, the reflectance of the radiation is significantly affected when the dimension of the surface or structures approaches (order of magnitude) the wavelength.

Flick, Choi, and Goodson derive the criteria for microscale radiation heat transfer of non-absorbing materials as $d < 0.63\lambda_{max}/n$ where d is the smallest dimension, λ_{max} is the wavelength, and n is the refractive index (see Table 3). According to this criteria, the

54 Summary based on Flik, Choi, and Goodson, “Heat Transfer Regimes in Microstructures,” 673.
55 Thermal convection of air, see Flik, Choi, and Goodson, “Heat Transfer Regimes in Microstructures.”

increase in refractive index of the material (n) decreases the regime boundary dimensions (see Figure 7).[56]

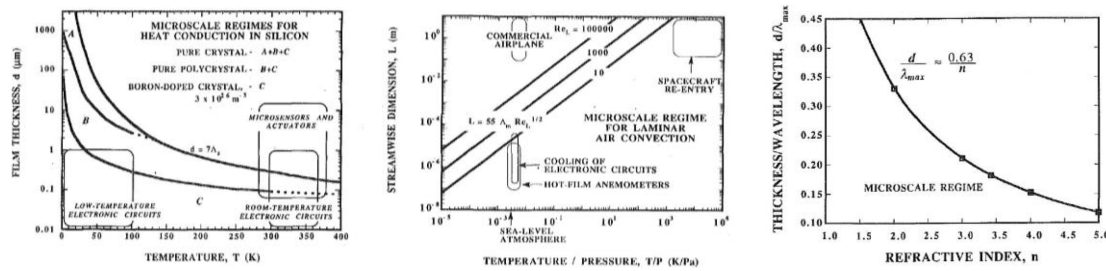

Figure 7 Microscale Regime Boundary
Regime map for thermal conduction normal to silicon film (left); approximate regime map for air convection (center); and global regime map for reflection from non-absorbing films (right).[57]

3.2.2 Macroscale and microscale shape factors

A material can be described regarding its macroscale and microscale shapes (see Figure 8). For example, the macroscale shape of structural beams (e.g. I-beam or hollow section) is effective in supporting bending and shearing loads using the least amount of material. The microscale shape of structural beams also contributes in providing the material properties required for the beam to function properly (e.g. strength, stiffness, and toughness).

The division between macroscale and microscale domains in the context of shape factors is more relative than absolute and can have various levels of hierarchy. For the I-beam example, the section profile is the critical shape that defines the structural performance of the overall beam (macroscale shape).

56 Sobhan and Peterson, Microscale and Nanoscale Heat Transfer.

57 Ibid.

On the other hand, the shape of the packed crystal lattices and grain structure of the atoms defines the capability of steel as a material for the structural component. In the case of a structural panel consisting of surface sheet metal and honeycomb core, the division of the macroscale and microscale shapes shifts according to the level of hierarchy (e.g. overall configuration and honeycomb structure or honeycomb structure and the materials microstructure).[58]

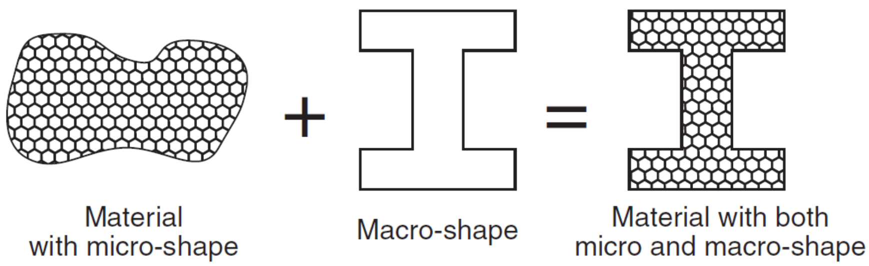

Figure 8 Macro-micro shape factor
The material property of materials is a result of the macro-shape and the micro-shape factors.[59]

There are many benefits of utilizing shape factors at multiple scales. This strategy is common in nature including wood (hexagonal-prismatic cells), palm wood (array of fibers separated by a foamed matrix), plant stems (axisymmetric structure of concentric cylindrical shells separated by a foamed matrix), and cuttlefish (layered structure). Biological materials can grow, repair, and regenerate shapes at most levels of hierarchy and adapt to the long-term and short-term changes. However, human-made material systems have challenges such as fabrication, cost, and reliability, and need for redundancy.[60]

58 Ibid.
59 Ashby, Materials Selection in Mechanical Design.
60 Ibid.

The multiscale shape factors are critical for various types of applications including the structural performance examples above. Other types of applications include the macroscale and microscale shapes that minimize or maximize electrical, optical, sound, heat, and textural properties. In the case of heat properties, thin shapes are effective in dissipating heat and cellular shapes are effective in insulating heat.[61]

Ashby categorizes the material properties based on the scale of microstructural features (see Figure 9). The microstructural features include cracks, surface roughness, grains, and atomic configurations. The material properties include friction, wear, corrosion, fracture strength, fracture toughness, Young’s modulus, and electrical/ thermal/ optical properties.[62]

The defects of the microstructures vary across length scales, and the implications also vary. For example, at the submicron scale, the defects are related to crystal packing (metal), atomic network (glass), atomic crystals (ceramics) and molecular chains (polymers). These defects directly affect the thermal, optical, electrical properties of the materials. On the other hand, at the micrometer to millimeter scale where the defects are manifested in the form of grains and cracks, the mechanical properties of the materials (friction, wear, ductility, strength, toughness) are mostly affected (see Figure 9).[63]

61 Ibid.

62 Ashby, Shercliff, and Cebon, Materials.

63 Ibid.

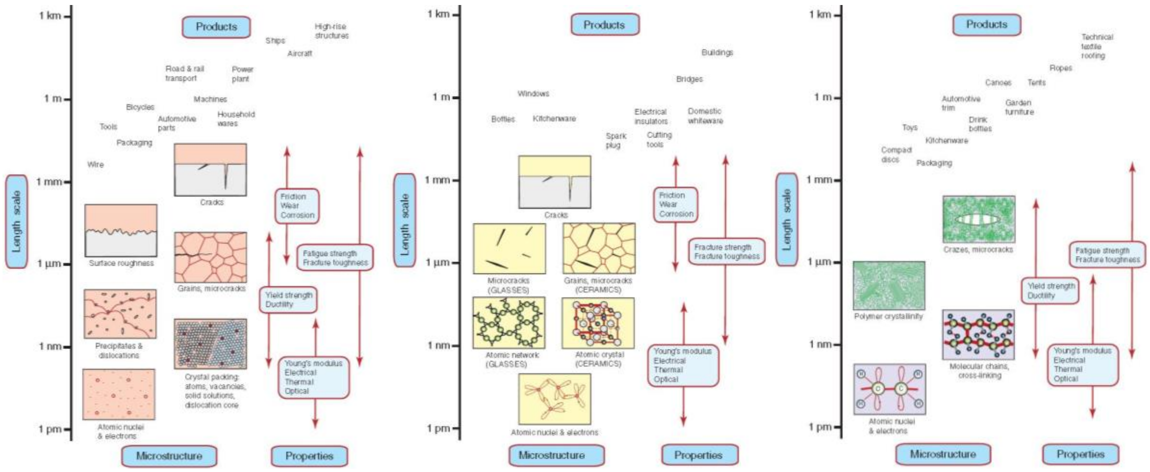

Figure 9 Microstructure and properties
Microstructural features properties of metals (left); microstructural features in ceramics and glass (center); and microstructural features of polymers and elastomers (right).[64]

3.3 Applications of Thermal Design

Biological materials are inherently living materials. The cells as building blocks not only undergo metabolic processes to maintain itself but also reproduce, grow and regenerate itself. The information embedded in the DNA provides a strong framework of how the material is assembled, maintained, and operated.

Although biological materials can adapt to its internal and external environment, there is a limit to its extent. This is because biological materials are strongly bounded within the complex system that has a variety of functional requirements and pre-existing assemblies that cannot be simply replaced (e.g. an organism cannot simply replace an existing organ or limb out of necessity). In other words, the adaptation process of biological material is mostly cumulative, and the solutions are often a trade-off between

64 Ibid.

the part-to-whole requirements (i.e. usually not the optimum solution for a specific function).

On the other hand, synthetic materials are typically bound by a comparably less complex system and less interconnected functional requirements. The development (or adaptive) process is a combination of breakthrough technology and iterative developments without compromises and trade-offs. Each synthetic material can be highly optimized for the targeted functional requirements. Another important aspect of synthetic materials is the diversity of materials that can be utilized.

Biological materials mainly consist of a combination of carbon and other elements such as oxygen, hydrogen, nitrogen, sulfur, and phosphorous. These limited number of elements are formed into proteins, nucleic acids, carbohydrates, lipids that make up the majority of biological materials. On the other hand, artificial materials that are available today is much diverse than of biology which provides vast potentials for innovation. For example, biological materials dominantly have low conductivities whereas technology has access to high conductive materials such as metals. This attribute allows significant improvement and opportunities in thermal design pertaining to components that need high heat transfer density.

In the following section, a number of novel thermal design applications is presented and analyzed. Each application utilizes the strengths of both thermal design approach in technology and biology in specific ways. By reviewing these, it will be possible to not only learn about the current state of thermal design but also help understand where the technology is heading towards (i.e. hybrid, hierarchical, multi-objective and miniaturization)

3.3.1 Fin-X Technology: Hierarchal geometry for increased thermal performance

Flare pan is a heating vessel developed by Thomas Povey which utilizes thermal design strategies to augment the efficiency in terms of faster heat up time. The key strategy is adding a series of fins on the conventional pan's smooth surface for better distribution of the heat. Although this might seem like a simple design, there is a complex and deliberate engineering process that enables the enhancement in performance.

The conventional pans are commonly in the form of a cylinder using metals with high thermal conductivity. However, when heated from below using a gas stove, much of the heat from the flame dissipates to the surroundings and only a portion of heat is conducted through the pan. The Flare pan improves this by creating a heat transfer structure that can capture the flame that slides up the side of the pan and conduct the heat into the contents. This mechanism enables the pan to heat up faster with less fuel usage.

The inventor claims that this new design can increase the efficiency of the energy transfer from the flame to the pan up to 30% to 80% compared to a conventional pan. The efficiency increases with the growth in the size of the flame and height of the pan. The fin spacing and fin length are optimized for maximum performance.[65]

65 Povey, HEATING VESSEL.

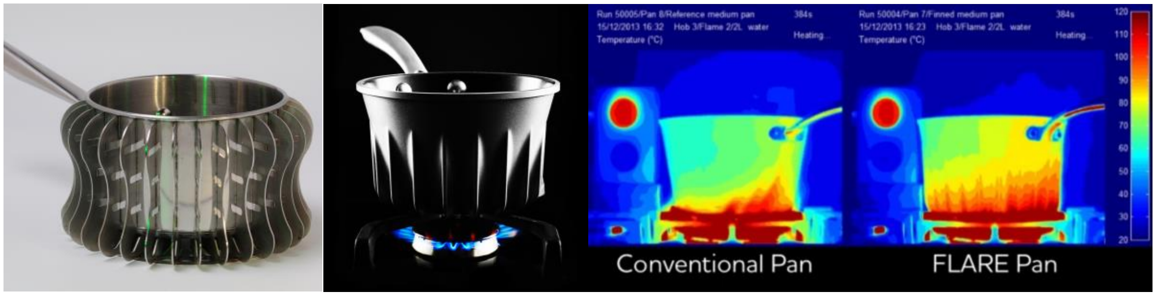

Figure 10 **Flare pan by Fin-X technology**
The simple finned pan increases the efficiency of 30-80 percent compared to a non-finned conventional pan.[66]

3.3.2 Apple Thermal Core: Innovative shape and configuration for cooling

The goal of the design is efficient heat dissipation for a compact, durable, and lightweight desktop computer[67]. The overall shape is cylindrical and includes a monolithic case with the integrated support structure and mixed flow fan. The fan which occupies in the core (top area) of the device delivers around 15-20 cubic feet per minute (CFM) of air during normal computing tasks at an ambient temperature of about 25° C. For more intense processing or for higher ambient temperatures; the fan can amplify the air supply to 25-30 CFM. The acoustic output increases with the speed of the fan (35 dbA to 40 dbA). A separate computing component controls the rate of the fan as well as the direction of the airflow based on predetermined operating temperature.

The solid case is made of aluminum oxide (alumina) which protects the inner components and provide the surface for radiative cooling to happen. The overall device

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66 “Flare Pan.”

67 The key challenge for compact computing system is the limitation of surface and volume areas for sufficient radiation or convection heat transfer to occur.

is zoned into the central thermal zone with a triangular cross section, and peripheral thermal zone which is defined between the circular outer edge of the device and the triangular cross section. The vertical heat sinks, consisting of planar faces fabricated from a single piece of extruded metal, forms the central thermal zone.

Two separate air vents are embedded in the case. The air intake vents are located at the bottom of the device, and the air exhaust vents are located at the top of the device. There is also a series of baffles, located near the intake vent that split the airflow into the central and peripheral airflow. The separate air flows are combined near the exhaust vent.

The heat from the heat sources (computational components) flows in two directions: towards the central thermal zone through vapor chambers; and towards the peripheral thermal zone directly. The thickness of the case (e.g. at the top circular lip portion) is customized to distribute heat across the case more evenly. Furthermore, the shape, angle, and the number of the fan blades are optimized.

The major thermoregulation process includes distributing the streams of cooling air towards multiple regions; dissipating heat from the circuit board via combination of direct conduction and heat exchange using fins and airflow; and combining the distributed air streams (containing the heat from the circuit boards) and exhausting through the top (see Figure 11)[68]

68 Degner et al., Computer thermal management.

Figure 11 Apple Thermal Core
Thermoregulation strategies based on geometry and heat source.[69]

3.3.3 X-Bionics: Multiscale configuration and combined heat transfer

X-bionics utilizes various technologies in developing functional clothing for athletes. The series of innovations highlights different aspects of the thermal design approaches investigated in this thesis. The multiscale design approach is utilized, and the combination of various heat transfer mechanics and thermal function categories are simultaneously implemented.

At the fiber level, the material of the fiber is customized for specific functions. The thin and elastic material (i.e. Windskin™ membrane) repels water and the wind but is permeable to heat and moisture, achieved via three-dimensional knitting pattern. The Macrotermes™ fiber embeds micro-channels in the form of three-dimensional patterns directly into the fibers. These micro-channels can be utilized to store heat or draw moisture away (inspired by the porous channels in termite mounds)[70]. The extremely

69. "Apple Thermal Core."
70 "| X-BIONIC® International."

conductive Xinanit™ fiber dissipates body heat effectively as well as simultaneously reflects thermal radiation using its reflective surface.[71]

At the fabric level, the different types of fibers are knitted into a fabric consisting of three-dimensional structures. The 3D-BionicSphere® System is structured in the form of micro-ducts that retain a thin layer of moisture produced through sweating.[72] X-BIONIC® Partial Kompression uses 1mm wide ridges rather than the entire surface area to compress the skin, stabilize the muscles (i.e. reduction of vibrations) and enhance the oxygen and nutrient supply for the athletes. The gaps between the ridges function as an evaporative cooling zone where the capillaries remain open and sweat can stay on the skin[73].

The AirIntake™ Technology is essentially a valve made of a synthetic mesh that allows fresh air to enter the fabric to prevent overheating[74]. The SpaceFrame™ Technology maintains a gap between the body and the fabric so that the air can circulate through it. The lightweight, soft and porous spacers allow the gaps to be consistent regardless of the athlete's position.[75]

Finally, at the clothing level, X-Bionics configures and combines the various technologies at multiple scales based on the types of activity and heat distribution rates within different zones of the body. The thermal design strategies differ significantly according to whether the athletes need to be cooled, heated, or combined. Within the human body,

71 "Technologies | X-BIONIC® International."

72 "3D-BionicSphere® System | X-BIONIC® International."

73 "X-BIONIC® Partial Kompression | X-BIONIC® International."

74 "AirIntakeTM Technology | X-BIONIC® International."

75 "SpaceFrameTM Technology | X-BIONIC® International."

areas such as chest, back, armpits generate more heat which requires a higher degree of control.[76]

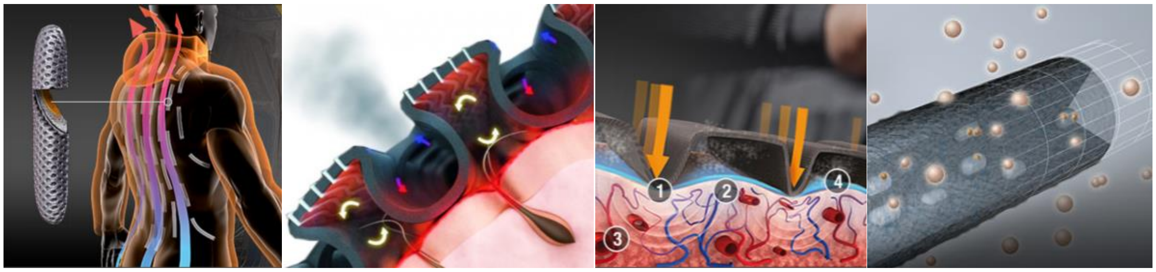

Figure 12 X-Bionics
Multiscale strategies used for regulating heat including The SpaceFrame™ Technology, AirIntake™ Technology, X-BIONIC® Partial Kompression, and Macrotermes™ fiber.[77]

76 Lambertz and W, Thermoregulating Item of Clothing and Method for Removing Humidity from Areas of the Skin.

77. "Technologies | X-BIONIC® International."

Chapter 4. Thermal Design Methods

> *For a finite-size flow system to persist in time (to live), its configuration must change in time such that it provides easier and easier access to its currents (fluid, energy, species, etc.).*[78]
> *- Adrian Bejan*

This chapter reviews the thermal optimization methods organized following the framework established in section 3.1 Classification of Thermal Functions. The various thermal optimization methods are thematically organized base on the modes of the thermal function framework (See Table 1). There is a plethora of ideas and applications that can be derived from each methods or from combination of methods.

4.1 Moving heat around

4.1.1 Conductive heat transfer

The conductive heat transfer in biology and technology differs fundamentally. Biological materials that consist of cells, tissue, organs, bones; and the immediate environment created by organisms such as nests, burrows do not use highly conductive materials such as metals. Hence, other than limited examples including animals resting on heated surfaces (e.g. rock heated by the sun) or burying itself underground to take advantage of

78 Bejan and Lorente, Design with Constructal Theory, 2.

the thermal mass of earth, conduction heat transfer has limited applications in moving heat around in organisms.[79]

Compared to biology, the relative importance of conductive heat transfer in human technology is significant. The extraction and development of highly conductive materials have been active since the early history of human technology. As of now, various types of conductive materials are used ranging from metals, diamonds, and graphite to metal-matrix composites and carbon matrix composites. The development of thermal interface materials also advanced along including materials and products such as polymer-based pastes, silicate based pastes, and solder.[80] Furthermore, the miniaturization of technology (e.g. electronic devices) requires using conductive heat transfer for cooling due to its higher heat transfer density compared to natural and forced convection heat transfer[81].

The optimization of conductive heat transfer in solid media at the macroscale regime can be derived from Fourier's law (see Equation 1). The rate of heat transfer (Q) is proportional to the cross section area normal to the heat flow direction (A) and the temperature difference (ΔT); whereas inversely proportional to the thickness (L) of the bulk material.[82] At the macroscale regime, the thermal conductivity (k) of the material is assumed to be independent of the length and time scale effects.

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79 Vogel, "Living in a Physical World IV. Moving Heat around."

80 Chung, "Materials for Thermal Conduction."

81 Bejan and Lorente, Design with Constructal Theory.

82 The equation applies for plane slab in steady state.

$$Q = \frac{\lambda A \Delta T}{L}$$ **Equation 1**

where: Q = rate of heat transfer; λ = thermal conductivity; A = cross section area; ΔT = temperature difference; L = thickness of the bulk material

However, in the regime below the microscale where the length and time scale does not adhere to the continuum assumption, Fourier's law alone is not sufficient (or inaccurate) to analyze or optimize conductive heat transfer.[83] Conductive thermal transport in this scale is believed to have a significant relationship (in order of magnitude) between the characteristic length and mean path of the energy carrier.[84]

4.1.2 Convective heat transfer

The optimization of convective heat transfer commonly relies on empirical relations due to the complexity[85] of the fluid flow conditions. The governing rate equation (see Equation 2) is Newton's Law of Cooling where the rate of heat transfer (Q) is proportional to the surface area exposed to the fluid (A), and the temperature difference between the temperature of the fluid (T_f) and the surface (T_s).

The convective heat transfer coefficient (h) is not a fixed property of the heat transfer media (i.e. surface material and fluid). Rather, it is a function of the type of flow (i.e.

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83 Sobhan and Peterson, Microscale and Nanoscale Heat Transfer.

84 The implications of microscale heat conduction are amplified towards the surfaces. Ibid., 1.

85 It involves conservation of mass, conservation of momentum, and conservation of energy at various boundary conditions. Thirumaleshwar, Fundamentals of Heat and Mass Transfer.

laminar flow or turbulent flow), temperature, geometry, and the property of the fluid (e.g. specific heat, thermal conductivity and viscosity).[86]

$$Q = hA(T_f - T_s)$$ **Equation 2**

where: Q = rate of heat transfer; h = convective heat transfer coefficient; A = surface area exposed to the fluid; Tf = temperature of the fluid; Ts = temperature of the surface

Laminar flows are governed by conductive heat transfer which occurs normal to the flow direction. On the other hand, turbulent flows are regulated by the amount of heat transferred via the fluid flow itself. The relative importance of conduction heat transfer through the internal channels walls reduce for turbulent flows.

The transition between laminar and turbulent flow can be derived using Reynolds number which is related to the fluid's viscosity, density, speed, and size of the channel. The Reynolds number increases when the density, speed and or size of the channel increases and decreases with the increase of viscosity (see Equation 3). For internal flows, the transition between laminar and turbulent flow occurs when the Reynolds number is between 1000 and 2000. For external flows, the transition occurs at Reynolds number between 20 and 200,000.[87]

The distinction between free convection and forced convection is whether the convection is driven by density difference of the liquid (e.g. gravity) or by external forces (e.g. wind or pump). The intensity of the free convection can be derived by the Grashof number

86 Ibid.

87 Holman, Heat Transfer; Vogel, “Living in a Physical World IV. Moving Heat around.”

which is a dimensionless index noting the ratio between buoyancy force and viscous force (see Equation 4). When the Grashof number is above 10^9, the free convection transitions from laminar to turbulent flow. In a mixed regime of free convection and forced convection, the Archimedes number which parametrizes the relative forces of each regime can be used. Forced convection dominates when the Archimedes number is below 0.1 and free convection dominates when above 16.[88]

$$\mathrm{Re} = \frac{\rho l v}{\mu}$$ **Equation 3**

where:
- Re = Reynolds number
- ρ = density
- l = diameter/ width of the pipe/channel
- v = average flow speed
- μ = viscosity

$$\mathrm{Gr} = \frac{\rho g \beta (\Delta T) l^3}{\mu^2}$$ **Equation 4**

where:
- Gr = Grashof number
- ρ = density
- g = gravity
- β = volumetric thermal expansion coefficient
- ΔT = temperature difference
- l = characteristic length
- μ = viscosity

$$\mathrm{Ar} = \frac{Gr}{Re^2} = \frac{g \beta \Delta T l}{\rho v^2}$$ **Equation 5**

where:
- Ar = Archimedes number
- Gr = Grashof number
- Re = Reynolds number
- β = volumetric thermal expansion coefficient
- g = gravity
- ΔT = temperature difference
- l = characteristic length
- ρ = density
- v = average flow speed

88 Vogel, "Living in a Physical World IV. Moving Heat around."

Biological systems are highly dependent on convective heat transfer mechanisms over other heat transfer modes to move heat around. Organisms circulate fluids around the body via laminar flow for moving heat around internally. Since laminar flow relies on conduction between the liquid and the surrounding tissues, maximizing the transfer surface area (e.g. using a complex network of smaller channels) is an effective strategy. The external heat transfer usually takes place as a mixed regime of free and forced convection. Larger organisms (including human) can utilize free convection created by its own heat to transfer heat without solely relying on forced convection (i.e. wind).[89]

4.1.3 Radiative heat transfer

Every living organism is directly and indirectly affected by the sun. It is the primary source of energy. The sun which has a surface temperature of around 5,800K emits radiation mainly consisting of ultraviolet, visible, and infrared radiation. When solar radiation hit the outer boundary of the Earth's atmosphere, the composition of the radiation is 10% ultraviolet, 40% visible and 50% infrared. However, up to 70% of the ultraviolet radiation and several wavelength regions of infrared radiation is absorbed by the atmosphere before reaching the surface of the Earth.[90]

In nature, the visible color of the biological organisms does not coincide with how it responds to radiation. Fur, regardless of any color, absorbs a significant amount of radiation; and bird eggs, desert snail shell, and leaves reject a substantial portion of the

89 Ibid.

90 The water vapor (H2O) and carbon dioxide (CO2) within the atmosphere absorbs specific wavelength regions of infrared radiation and often re-emitted as longer wave infrared radiation.

radiation. There are also many examples in nature of changing the posture of the body to control the amount exposure to solar radiation. Several plant species including the silk tree modify the orientation of the leaves to minimize or maximize radiation exposure. Organisms such as insects and lizards change their posture to control solar exposure.[91]

The wavelength of thermal radiation ranges from 0.1 microns to 100 microns. When radiant energy hits a surface, portions of it gets absorbed, reflected and transmitted through the body. If the entire radiant energy is transmitted, the material is called transparent. If entirely reflected, the material is referred to as a white body. Finally, if entirely absorbed, the material is known as a black body. Most opaque solids and liquids do not transmit radiation through, and gasses have only a small amount of reflection.[92]

Every material responds to radiation in different ways and different quantities. Rock salt is transparent to heat rays but opaque to UV rays. Glass is transparent to visible light but opaque to UV and IR rays. The absorption and reflection of heat rays are influenced by the state of the surface rather than the color. Dark matt surfaces increase the absorption, and light shiny surfaces increase the reflection of radiation. If the roughness of the surface (height of the texture) is smaller than the wavelength of the incident radiation the reflection is specular and vice versa, the reflection is diffuse.

The governing equation for radiative heat transfer is based on the Stefan-Boltzmann Law. Radiation flux that is emitted by the body (E) is proportional to the emissivity of the

91 Vogel, “Living in a Physical World IV. Moving Heat around.”

92 Thirumaleshwar, Fundamentals of Heat and Mass Transfer.

surface and the fourth power of the temperature (T). Emissivity[93] is influenced by radiation wavelength, surface finish, and surface material (see Equation 6).[94]

$$E = \varepsilon\sigma T^4$$ **Equation 6**

where: E = radiation flux that is emitted by the body; ε = emissivity; σ = Stefan-Boltmann constant, 5.6697 × 10−8 W/(m^2K^4); T = Temperature

In the case of radiation exchange between two surfaces of a finite size, it is critical to implement the several factors which include the distance between surfaces, the emissivity of each surface, and the orientation of the surfaces (see Equation 7). The view factor[95] is a geometric relationship (i.e. geometry, area, and orientation) between two surfaces defining how much of the radiation emitted from one surface hits the other surface.[96]

$$Q = F_1 A_1 \sigma (T_1^4 - T_2^4)$$ **Equation 7**

where: F_1 = view factor; σ = Stefan-Boltzmann constant, 5.6697 × 10−8 W/(m^2K^4); A_1 = area of surface 1; T_1 = temperature of surface 1, K; T_2 = temperature of surface 2, K

93 The ratio between the radiation emitted by a surface and that of a same temperature black body.

94 Thirumaleshwar, Fundamentals of Heat and Mass Transfer.

95 Also called configuration factor, shape factor and angle factor, etc. Ibid.

96 Holman, Heat Transfer; Thirumaleshwar, Fundamentals of Heat and Mass Transfer; Incropera and Incropera, Fundamentals of Heat and Mass Transfer.

4.1.4 Latent heat transfer

Evaporative cooling in biological organisms has limited applications due to the extensive amount of water needed. Animals with a relatively large body (e.g. human, cattle, camel) use the surface area of the skin for evaporative cooling.[97] Smaller animals such as dogs, goats, rabbits and birds often use respiratory evaporation for cooling their body. Some animals including rats and cats lick their fur and use the evaporation of the saliva to cool down. The utilization of condensation in nature has been found as a strategy to create water (e.g. plants and insects) but utilizing its heat has not been yet proven.[98]

The rate of latent heat transfer is simply the mass of the substance multiplied by specific latent heat (see Equation 8). Specific latent heat is an intensive property of a material, and each material requires different amounts of heat per mass and temperature for the phase change to occur. Therefore, the optimization of latent heat transfer is dependent on the choice of the substance with the optimum phase change temperature, specific latent heat, and mass.

There are essentially three states of matter: solid, liquid, and gas. There are also six types of state change: condensation (gas to liquid), freezing (liquid to solid), deposition (gas to solid), melting (solid to liquid), evaporation (liquid to gas), and sublimation (solid to gas). Among the six types of state change, the first three releases energy during the process warming the surrounding whereas the last three absorb energy cooling the surrounding. The six type of state change produces different types of latent heat which

97 This strategy is effective but also have a downside of losing salt as well as being interrupted by the presence of fur and feather.

98 Vogel, "Living in a Physical World IV. Moving Heat around."

include the latent heat of fusion (between solid and liquid), the latent heat of vaporization (between liquid and gas), and the latent heat of sublimation (between gas and solid).

A good example of a thermal design using latent heat transfer can be found in the typical evaporative cooling towers. Water is mainly used as the substance for latent heat transfer due to its exceptionally high latent heat of vaporization (2264.76 kJ/kg). The rate of heat transfer for the cooling tower is also dependent on the quantity and distribution of the evaporation during the cooling process. Therefore, the factors such as the shape of the tower, the distribution of the phase changes, the contact characteristics (e.g. type, location, and time), and the efficiency of the contact between water and cooling medium significantly affect the efficiency of the cooling tower.

$$\mathrm{Q} = \mathrm{mL} \qquad \textbf{Equation 8}$$

where: Q = rate of heat transfer, kJ; m = mass, kg; L = specific latent heat, kJ/kg

$$\mathrm{Q} = \mathrm{m}C_p\Delta T \qquad \textbf{Equation 9}$$

where: Q = Energy per mass of material; m = mass, kg; C_p = specific heat, kJ/kg; ΔT = temperature interval

4.2 Maintaining temperature

The modes of maintaining temperature are involved with controlling (e.g. suppress or amplify) the individual or combined modes of heat transfer to achieve specific thermal functions. Therefore, the optimization method for these modes utilizes the same governing equation as the modes of moving heat around with one or several modes targeted to be a minimum value (i.e. suppress) rather than the maximum value (i.e. amplify).

4.2.1 Thermal insulation

The key method to optimize thermal insulation is to reduce the degree of individual or combinations of conductive, convective and radiative heat transfer based on the desired performance criteria. Biological organisms use several common strategies for thermal insulation. Fat or blubber tissue[99] of an animal (e.g. whales, and seals) is usually located in the peripheral layer of the body and has relatively low thermal conductivity.

This property enables the animal to maintain heat better by suppressing the conductive heat transfer. The blood circulation in this layer can be reduced via vasoconstriction of the blood vessels which limits the heat exchange between the internal organs and the external environment. Also, fur and feathers are used to trap a layer of air at the outer boundary layer. This layer serves as thermal insulation mainly through limiting convection heat transfer and can adapt to the temperature via piloerection (i.e. thickness change of the fur layer).[100]

The conductive heat transfer can be suppressed by using a material with low thermal conductivity, increasing the thickness of the material at the boundary and/or reducing the area of the cross section[101] (see Equation 1). The most common method in artificial and

99 Also called adipose tissue.

100 Vogel, "Living in a Physical World V. Maintaining Temperature."

101 This effectively minimize thermal bridging.

biological systems is to use still air, which has low conductivity, as the primary material for the insulation. This method is achieved using a cellular structure such as foam to trap the air or gas within the material. For cellular materials, the volume fraction of the solid material and the void space significantly influence the thermal insulation performance of the material. Various types of thermal insulation materials use this principle including polymer foams, glass wool, and cellulose.

Based on Newton's Law of Cooling (see Equation 2) the convective heat transfer can be minimized by reducing the surface area exposed to the fluid or reducing the temperature difference between the fluid and the surface which are both challenging to implement. Furthermore, it is also difficult to control the heat transfer coefficient since this value is dependent on various factors such as flow type, fluid properties (e.g. velocity and viscosity), temperature, pressure, and geometry of the bounding area and contact surface. Therefore, the common method for suppressing convective heat transfer is to separate the air into individual cells that are small enough for limiting convection to occur.[102]

The radiant heat transfer can be suppressed by reducing the temperature of the heat source and using materials with low emissivity at the wavelength that is intended to be regulated (see Equation 6). A typical radiant barrier is a highly reflective thin sheet made of low emissivity materials such as aluminum (e.g. aluminum foil, aluminum metalized Mylar). In a cellular structure, the radiation heat transfer is reduced by repeatedly

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102 E.g. an order of magnitude smaller than 10mm for temperature difference of 10°C at 1 atmosphere, see Gibson and Ashby, Cellular Solids, chap. 7.

absorbed and reflected by the solid and the cell walls respectively (Stefan's law and Beer's law).[103]

4.2.2 Heat exchanger

The heat exchanger mode for maintaining temperature maximizes the heat exchange between warmer and colder locations within the systems boundary to contribute to efficiently maintaining the system's core temperature within a certain range of temperature. This is most effectively achieved through the counter flow heat exchange mechanism, where the two bodies of liquids of different temperature (e.g. warmer internal blood and colder periphery blood) flow in the opposite directions. There are a plethora of counter flow exchangers in biological and artificial systems ranging from dolphins and leatherback turtle to various industries such as wastewater treatment and refrigeration.

It is also worth noting the counter-convection mechanism[104] which combines the convective heat transfer with conductive heat transfer. The principle of this mechanism is to use a porous and conductive boundary layer where the heat leaving from the warm side via conduction is transferred to the incoming fluid. If the cold air or liquid is preheated to the same temperature as the warm side, the boundary can theoretically become a perfect thermal insulator.[105]

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103 Ibid.

104 Vogal argues that this mechanism is also used in biological organisms although it hasn't been proved. See Vogel, "Living in a Physical World V. Maintaining Temperature."

105 Ibid.

In general, the optimization of a heat exchanger is involved with the temperature difference between the hot and cold media, overall heat transfer coefficient, and the area where the heat transfer occurs (see Equation 2). Since the temperatures of the media are often known or within a certain range, the thermal design of heat exchangers is focused on increasing the overall heat transfer coefficient and/or increasing the heat exchanger surface area.

The overall heat transfer coefficient is related to the combination of individual heat transfer coefficients as well as the thermal resistance of the material surrounding the fluid (e.g. pipe). Each individual heat transfer coefficient depends on temperature, characteristic dimension (e.g. pipe diameter), fluid velocity, and fluid properties (e.g. viscosity, specific heat, thermal conductivity, and density).

When one of the fluid in a heat exchanger is gas, the convective heat transfer at the boundary provides the most resistance. In this case, extended surfaces in the form of plates, fins and pins are used to increase the heat exchange surface area. When both fluids are liquid, the conduction through the boundary provides the most resistance so maximizing the conductive heat transfer at the boundary condition is effective.[106]

4.2.3 Thermal storage

Large size biological organisms can buffer the short term temperature fluctuations (minutes) but cannot buffer the long-term fluctuations (hours and days). A camel cope with the long term (hours) temperature fluctuations of the desert which consists of hot

106 Ashby, Materials Selection in Mechanical Design, 165.

daytime and cool nighttime, by permitting its core temperature to rise during the day (from 34ºC to 40ºC). This strategy also helps conserve the limited water by reducing sweating (i.e. evaporative water loss).

On the other hand, smaller organisms have a hard time even buffering short term temperature fluctuations due to its limited thermal mass. Therefore, organisms such as the stone plants utilize the thermal mass of the surrounding soil to buffer the daily temperature fluctuations. Leaves with thicker and smaller size and shape compared to larger and thinner ones can buffer better to short-term temperature changes. Although the difference is quite short (seconds), it still is significant since the air speed changes rapidly.[107] Recent research identified dolphin blubber (with melting point just below body temperature) as thermal storage.[108]

The optimization of thermal storage is essentially using the material system’s storage capacity to absorb and release heat at specific time intervals. Significant values that need to be considered when designing thermal storage systems include the domain of temperature level that the system operates; specific energy density; power (charging and discharging time); storage duration; and the storage capacity. The storage capacity depends on the storage process, storage medium, size or volume of the material system.

Thermal energy can be stored in the form of sensible heat, latent heat, or chemical energy. The sensible heat thermal storage uses high specific heat medium such as

107 Vogel, “Living in a Physical World V. Maintaining Temperature.”

108 Vogel, “Living in a Physical World IV. Moving Heat around.”

water in highly insulated storage tanks. The storage capacity is limited by the specific heat of the storage medium. Example applications include systems using the high thermal storage capacity of the soil or a large body of water.

The latent heat thermal storage uses phase change materials (PCM) as the storage medium. The storage capacity is usually higher than the sensible heat storage, and the temperature of discharge can be programmed. Several commercially available systems exist, and many are in the research and development stage. Example applications include micro-encapsulated PCM materials in building components (e.g. gypsum wall), macro-encapsulated PCM salts in air vent ducts among others.

Finally, the chemical energy storage utilizes several types of chemical reactions (e.g. adsorption) to store or release heat. The storage capacity is potentially the highest among the three types of thermal storage, and the timing of accumulation and release of heat can be controlled. However, chemical energy storage technology is mostly in the research and development stage.

It is important to note that in designing thermal storages, the volumetric heat capacity (VHC), rather than the specific heat capacity is the critical factor that defines the capability of the material system to store internal energy (see Equation 10). The specific heat capacity is the heat per unit mass required to increase the temperature by one degree, and this value is similar for all solids (within a factor of two). In designing material systems for thermal mass, the thermal conductivity, and thermal diffusivity rather than the mass is critical.

$$\rho C_p = \lambda / a$$ **Equation 10**

where: ρC_p = volumetric specific heat; ρ = density; C_p = specfic heat; λ = thermal conductivity; a = thermal diffusivity

The thermal mass of a building or its components can absorb and store heat. This property can not only reduce the temperature fluctuation rate of a space but can also be strategically designed to absorb or release heat at desired time intervals. Materials with high density (i.e. less captured air), high heat capacity, low reflectivity, and good thermal conductivity are ideal to use as thermal mass. Some good example materials include water, concrete, sandstone, brick which are commonly used in heavyweight thermal mass construction. More recently, phase change materials (PCM) such as paraffin wax and salt hydrates are increasingly being utilized in lightweight thermal mass constructions.

The performance of the thermal mass can be drastically improved with passive solar strategies (e.g. direct-gain system, Trombe wall, sun-space, convective-loop system, roof ponds) that consider the orientation and location within the building. Furthermore, controlling the conductivity of the thermal mass through insulation or thermally conductive materials is also an effective strategy. For instance, thermal mass with insulation on the exterior side stabilizes the interior temperature of the building with minimum impacts from the external temperature fluctuations. Also using thermally conductive materials in the interior side effectively distributes the asymmetric heat (hot spots) evenly across a larger area.

Thermal mass strategies differ across different climates. In hot and arid climates with the large temperature difference between night and day such as deserts, thermal mass functions mainly to suppress the conductive heat transfer. The thickness and heat capacity of the massive wall allows the hot daytime heat to re-radiate back into the cold night sky without entering the interior space.

On the other hand, in temperate and cold climates where the overall temperature drastically alternates between summer and winter, the thermal mass needs to be shielded from the hot summer sunlight and be exposed to the cold winter sunlight. This is often achieved through overhangs or shading devices that selectively allow the low angle sunlight reach the thermal mass. In order to prevent the overheating during the summer, night time cooling strategies (e.g. natural ventilation) are often utilized.

Finally, thermal mass in hot and humid climates where it is hot throughout the year with limited diurnal temperature variations, there are many challenges in utilizing thermal mass. To have any benefits in this climate, thermal mass needs to be completely shielded from the sunlight and must be cooled during the night time using natural ventilation or active radiative cooling.

4.3 Selected Work by Researchers

4.3.1 Optimum conduction path

A series of studies conducted by Bejan et al. provide good example of designing with conduction heat transfer mode. This involves optimizing the conductive paths of highly conductive material embedded within a disk-shaped body with a comparably lower conductive material. The paths are based on branching tectonics and optimized to distribute the heat load from the rim to the heat sink located at the center of the disk.

The goal of each iteration is finding the configuration and number of the paths to minimize overall thermal resistance. The four key configurations include two sets of radial patterns with a different number of branches (N and 2N), bifurcation pattern (one branching level), and loop pattern (see Figure 13).

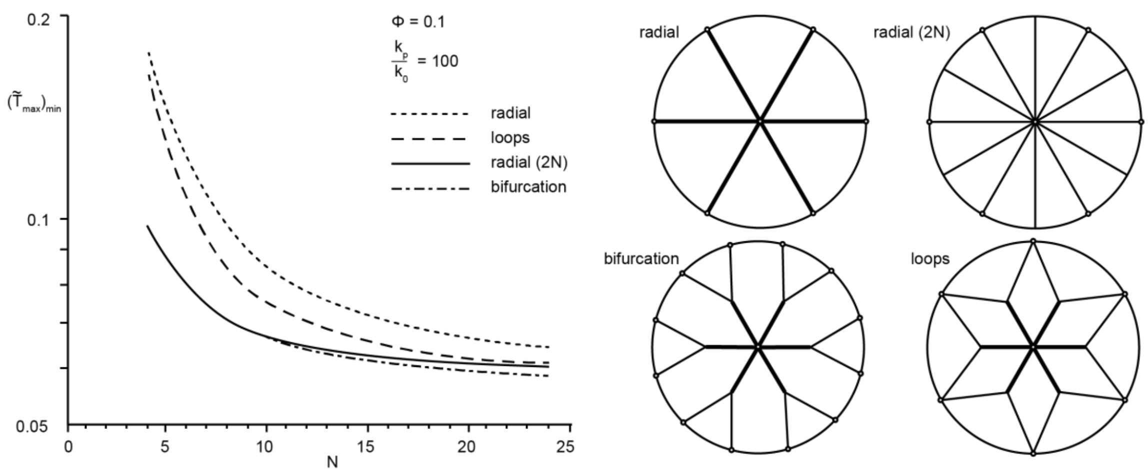

Figure 13 Conduction trees
Overall thermal resistance as a function of the number of central blades (left); and four types of geometric configuration (right).[109]

The analysis of the radial pattern is conducted with three assumptions: (1) the thickness of each branch is constant; (2) volume fraction (Φ) between the body and path is of small value; and the ratio of thermal conductivities ($\tilde{k}$) is of large value. The method of optimization is to analyze one branch from an elemental sector of the disk and equate

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109 Reconstructed from Bejan and Lorente, Design with Constructal Theory, Fig. 5.10, Fig. 5.16, Fig. 5.17, and Fig. 5.18.

the heat current generated at the rim with the heat flux leaving the heat sink at the center.

The resulting optimum size of the body (radius of the disk) can be derived from the values obtained from this analysis (elemental sector area, volume fraction and thermal conductivity ratio). The optimization method of the bifurcation and the loop pattern is essentially the same as the radial pattern with additional steps of analysis to consider the added complexity and freedom of the configurations.

The result of the four patterns is summarized in Figure 13 (left). The overall thermal resistance decreases as the number of branches increase. This trend is significantly reduced when the number of branches reaches around 10. It is also important to note that below the branch count 10, the bifurcation pattern merges with the radial pattern (2N) as it is better to use the radial pattern with twice the number of branches than the bifurcation pattern.

4.3.2 Internal spacing for natural convection

Bejan conducted a series of studies that determine the optimum spacing for three different configurations of geometry that generate heat and cooled via free convection. These include vertically oriented parallel plates, an array of staggered plates, and horizontal cylinders. The intersection of asymptotes method is used for the analysis, and the flow is assumed to be laminar.

Utilizing the first law of thermodynamics and substituting mass flow rate with the pressure drop formula, Bejan concludes that as the spacing (D) between the plates becomes closer to zero, the heat transfer rate decreases at the rate of D^2. On the other hand, when D is sufficiently larger than the thermal boundary layer thickness that occurs on both side of a plate the heat transfer rate decreases by D^{-1} as D increases. The optimum spacing lies between these extremes.

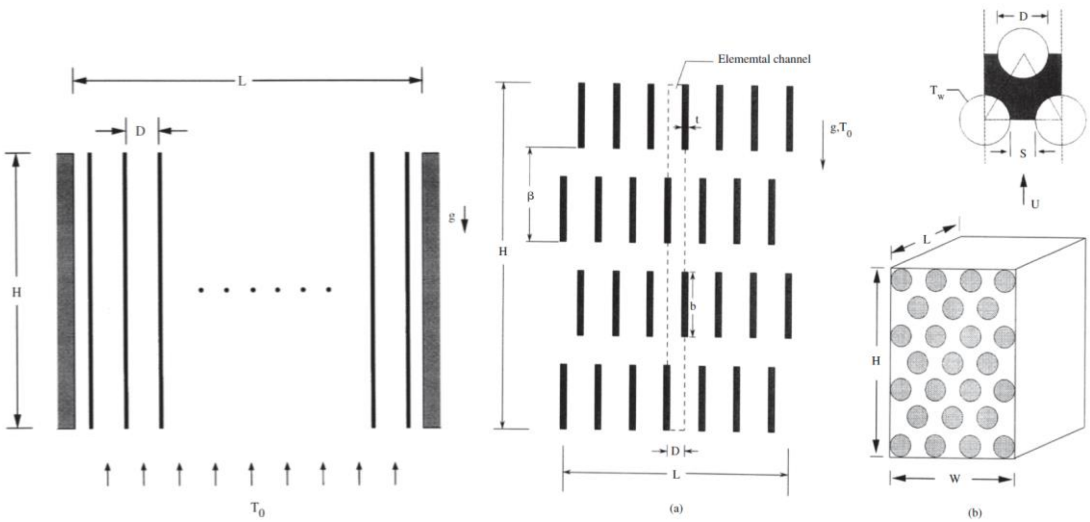

Figure 14 Internal spacing for natural convection
Vertically oriented parallel plates, an array of staggered plates, and horizontal cylinders.[110]

When the spacing is smaller than the optimum spacing, the fluid cannot flow easily through and when larger, the surface area of heat exchange is too small (the number of plates that can fit into the same volume reduces). Based on the two extreme spacing conditions, Bejan suggests an estimation of the optimum spacing (see Equation 11). This method is significantly easier compared to the other methods (e.g. finite-difference simulation) and within 20% accuracy.

110 Ibid., chap. 3.

$$\frac{D_{opt}}{H} \cong 2.3\left[\frac{g\beta(T_{max}-T_0)H^3}{\alpha v}\right]^{-1/4}$$ **Equation 11**

where: D_{opt} = optimum spacing; H = height of the plate

g = gravity; β = coefficient of thermal expansion

T_{max}= out temperature; T_0= inlet temperature

α = thermal diffusivity; v = kinematic viscosity

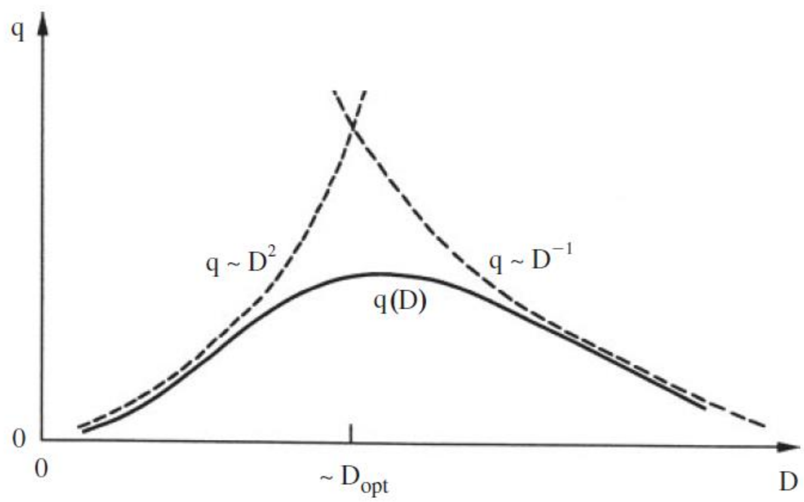

Figure 15 Intersection of asymptote method
Optimum spacing based on two extreme scales.[111]

4.3.3 Cellular materials as thermal insulation

The thermal conductivity of foam is a combination of four heat transfer mechanisms which includes conduction through solid, conduction through gas, convection inside the cells, and radiation through the solids and voids. The conduction through the solid and gas constitutes a significant portion of the conductivity and can be derived from the

111 Ibid.

conductivity of each material (e.g. polyurethane and air) and its respective volume fraction.

The convection inside the cells becomes significant when the ratio between buoyant force and viscous force that affect the convection (i.e. Grashof number, see Equation 4) is greater than 1000.[112] This makes the maximum size of the cell for suppressing convective heat transfer as approximately 10mm for air at 1 atmosphere, 20ºC and with a temperature difference of around 10ºC. If the cell size is significantly smaller than this (more than an order of magnitude) the convection is completely suppressed.[113]

The amount of radiation heat transfer (contribution ranging from 5 to 20 percent of the total heat transfer) across the material is reduced through the repetition of scattering, absorption, and reflection at the cell boundaries[114]. Hence, as the cell size decreases (i.e. more transitions between solid layers and void space) the contribution of radiative heat transfer decreases. Furthermore, since the absorption of radiation is through the solid material of the foam, the radiation contribution increases as the foam density decreases (i.e. less solid material). The figure below shows the conductivity based on relative density and cell size.[115]

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112 Gibson and Ashby, Cellular Solids. referencing Holman, Heat Transfer.

113 Gibson and Ashby, Cellular Solids.

114 Campo-Arnáiz et al., “Extinction Coefficient of Polyolefin Foams”; Larkin and Churchill, “Heat Transfer by Radiation through Porous Insulations”; Gibson and Ashby, Cellular Solids.

115 Gibson and Ashby, Cellular Solids.

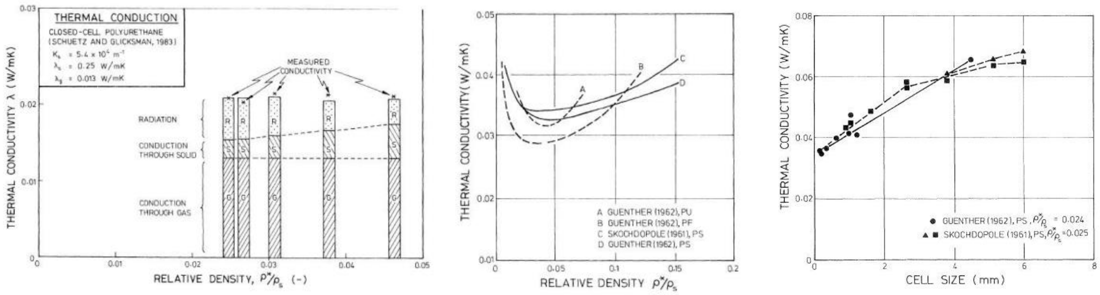

Figure 16 Heat transfer in cellular solids
Relative contributions of conduction through gas, solid, and radiation based on relative density of foam (left); thermal conductivity of foam as a function of relative density (center); and thermal conductivity of foam as a function of cell sizes (right).[116]

Gibson and Ashby provide an example of deriving the optimum density of foam based on the temperature differences and thickness of the thermal insulation. The size of the cells is assumed to be sufficiently small enough to suppress conduction. Using a fixed thickness of the two different application of thermal insulation (i.e. 3mm thick polymer insulation for a coffee cup and 50mm polymer insulation for a cavity wall) the optimum density decreases as the thickness increases (i.e. 0.08 for the coffee cup and 0.02 for the cavity wall). The optimum density is derived using Equation 12.

$$\left(\frac{\rho^*}{\rho_s}\right)_{opt} = \frac{1}{K_s t}\ln\left\{\frac{4K_s\beta_1\sigma t^2\bar{T}^3}{\frac{2}{3}\lambda_s - \lambda_g}\right\}$$ **Equation 12**

where:

$(\frac{\rho^*}{\rho_s})_{opt}$= optimum foam density

t = insulation thickness

K_s = extinction coefficient of solid polymer

β_1 = emissivity factor

σ= Stefan's constant, 5.67*10^{-8} W/m^{2}K^4

$\bar{T}$ = mean temperature

λ_s = conductivity of solid polymer

λ_g = conductivity of gas

116 Ibid., chap. 7.

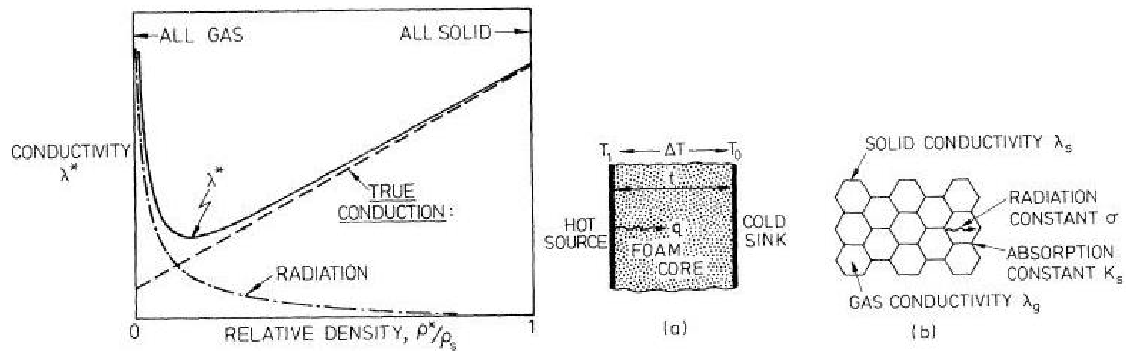

Figure 17 Heat transfer through foam

Heat flows through the foam via conduction and radiation. Convection of the gas is suppressed.[117]

117 Ibid.

Chapter 5. Multiscale Materials for Thermal Design

> *The greater system works best when its imperfection is spread around, so that more and more of the internal parts are "stressed" as much as the hardest working points. The more we think of engineered systems in this way, the more they look and function like living systems.*[118]
> *- Adrian Bejan*

This chapter presents the hierarchical material systems as the key approach and paradigm for developing artificial thermal interaction systems. In the first half of this chapter, material properties that are relevant to thermal design and the multi-objective material selection method based on these properties are presented.

Following this analysis, the hierarchical materials design approach is identified and further investigated through the review of related fields of studies including cellular materials, functionally graded materials and adaptive materials research. In addition to this, the developments in enabling material processing technologies are also reviewed. The potentials of these research can be used as the enabling technology to create the physical material systems that are optimized for thermal performance.

5.1 Thermal Properties of Materials

Thermal properties of materials have a major impact on the design and optimization of building elements. The performance of the material system can be only achieved if the

118 Bejan, "From Heat Transfer Principles to Shape and Structure in Nature."

materials with the right thermal properties are matched with the targeted thermal functions. Therefore, it is critical to understand the fundamentals of thermal properties and how to strategically use them for developing material systems that interact with heat in novel ways.

Among the various thermal properties of materials, specific heat, volumetric heat capacity, thermal conductivity, and thermal diffusivity are essential for controlling how heat interacts with the material.[119] Specific heat (C_p) is the amount of energy to heat a unit mass of 1 kg by 1 Kelvin. Volumetric heat capacity[120] is defined as the ability of a unit volume of material to store internal energy during certain temperature change without phase transition. Since the difference of specific heat and density[121] of most solids is small, volumetric heat capacity can be regarded as constant (i.e. approximately 3×10^6 J/m^3·K).

Thermal conductivity (λ) is the rate of heat that is conducted through the solid material at steady-state, and the unit is W/m·K. Finally, thermal diffusivity (α) describes how fast the material responds to the change of temperature at unsteady (transient) state. The relationship between specific heat, thermal conductivity, and thermal diffusivity is stated in Equation 10.

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119 Characteristic temperatures of a material at phase or behavior changes is also an important thermal property but is less critical or developing building components exposed to typical temperature range of -50℃ to 50℃ which is the focus of this thesis, Ashby, Shercliff, and Cebon, Materials.

120 Volumetric heat capacity can be simply derived from multiplying the specific heat with the density of the material

121 The density of porous solids such as foams is significantly low so the volumetric heat capacity is lower than typical solid materials.

Figure 18 is a chart with thermal conductivity (λ) plotted against thermal diffusivity (a). Since volumetric heat capacity is similar within a factor of two for most solids ($\rho C_p \approx 3 \times 10^6 \ J/m^3.K$) the relationship between thermal conductivity and thermal diffusivity can be expressed as Equation 13. This relationship is clearly visible in Figure 18, with the majority of materials aligning closely to a single line. Among the deviations, foam materials are the most significant because of its low density (i.e. lower volumetric heat capacity). It is also noteworthy to point out that foam has low thermal conductivity and relatively higher diffusivity.[122]

$$\lambda = 3 \times 10^6 a \qquad \textbf{Equation 13}$$

where: λ = thermal conductivity a = thermal diffusivity

Each material has a set of unique thermal properties that both enables and limits how much the system can perform specific thermal functions. Therefore, it is critical to understand the abovementioned thermal properties and utilized them as the basis for selecting and configuring thermal interaction material systems. The following sections investigate the process of selecting the best material informed by the thermal properties introduced in this section and optimizing the design of the material system for the intended thermal functions.

122 Ashby, Materials Selection in Mechanical Design; Ashby, Shercliff, and Cebon, Materials.

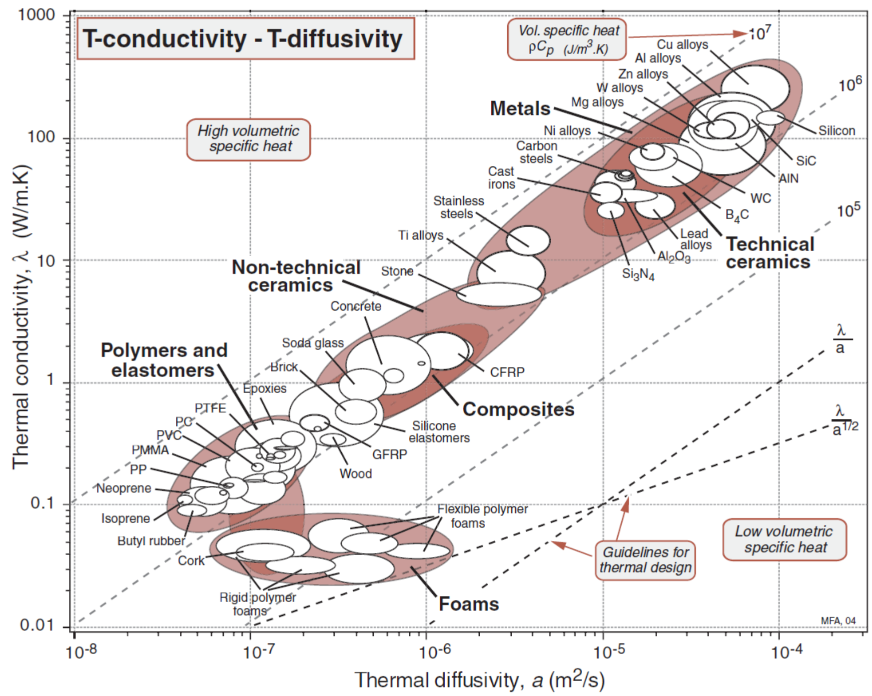

Figure 18 Thermal conductivity-thermal diffusivity chart
The volumetric heat capacity of most solids is similar within a factor of two. Foams are an exception to this tendency due to its low density (contains air).[123]

5.2 Multi-objective Material Selection Process

The design of material systems inevitably involves more than one objective and constraints that may conflict with or complement each other. Even within the context of thermal design, several methods of heat transfer mechanisms are utilized in concert rather than in isolation. Although this thesis focuses on thermal design, it is important to consider various other objectives that are critical to the design. In real-world applications minimization of mass, volume and cost are frequently required. Depending on the functionality, other constraints or objectives including mechanical property,

123 Ashby, Shercliff, and Cebon, Materials.

constructability, durability, and environmental impact also becomes an important factor in design.

The performance of a material is determined by the functional requirements. To select the best material amongst the vast array of materials, it is convenient to break up the functional requirements into several interrelated groups which become a unit of evaluation. A material index (minimum or maximum values) can be separately established for each of these units and applied for narrowing down the materials that satisfy the material index.[124]

The existence of multiple objectives and constraints make it impossible to get optimum solution that meets all the objectives due to its conflicts and influences. However, using them in a strategic way can assist in deriving the best option for the purpose amongst the vast amount of possibilities. The general method of designing with more than one objective and constraints is to iteratively screen and rank the targets and constraints. Once the top-ranked options are chosen, further evaluation through the review of supporting information and testing (e.g. simulation or physical testing) can assist in selecting the final choice.[125]

The approach described above drastically simplifies the material selection process since it allows to narrow down the possible materials without completely solving all the design

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124 For example, the structural system of buildings has many functional requirements (mechanical, thermal, electrical, etc.), constraints (e.g. stiffness, maximum strength, geometry, etc.), and objectives (minimize cost, minimize mass, maximize energy storage, etc.) Within the complex array of parameters, a sub-group consisting of structural column (function), stiffness (constraint), minimize mass (objective) can be set as a unit of evaluation. A material index (i.e. $M = \rho/E^{1/2}$) can be derived from this group to sort out the candidate materials, See Ashby, Materials Selection in Mechanical Design.

125 Ibid., chap. 9.

problem at once. Several sub-groups can be independently and iteratively assessed to ultimately choose the material that satisfies the overall functions, constraints, and objectives in the best way. The computer-aided selection tools such as the CES material and process selection software developed by Michael Ashby makes this process intuitive and straightforward by using comprehensive material databases and visual aid (e.g. graphs). The following section reviews a series of case studies that utilize multi-objective material selection process to choose the best material for the targeted thermal function.

5.3 Materials for thermal design

This section investigates the process of selecting and designing materials for specific thermal functions through case studies. The specific thermal functions include thermal insulation, heat exchanger, and heat storage. The multi-objective material selection process introduced in the previous section is also implemented in the case studies.

5.3.1 Case Study 1: Materials for thermal insulation

The material selection and design process of thermal insulations vary with applications and their requirements. The following two examples show two types of thermal insulation components that use different sets of criteria. One insulative material is for an energy efficient kiln wall, and the other is a short-term isothermal radio beacon container.

The requirements of the thermal insulation for an energy efficient kiln wall are minimizing the energy used in a firing cycle using optimum material and thickness. The chosen material also need to withstand temperatures up to 1000ºC, and the wall thickness need to be within a practical range. The key thermal design strategy for this example is to minimize the heat loss through the walls as well as to reduce the amount of heat required to increase the temperature of the kiln to its operation temperature. The former can be achieved by selecting materials with low conductivity and making the walls thicker, and later by selecting the material with low heat capacity and making the walls thinner.

The optimum solution for satisfying both of these criteria is to choose a material with a certain thickness that starts to dissipate heat as the entire firing cycle ends. Figure 19 (left) shows the relationship between thermal conductivity and thermal diffusivity suitable for the application. Among the possible materials within the search region, materials that cannot withstand the high temperature (e.g. polymer and elastomer foams) are eliminated from the list. Among the remaining materials (e.g. brick, concrete, and wood), brick is the most suitable material for the kiln wall regarding thermal properties and thickness requirements.[126]

The requirements of the thermal insulation for a short-term isothermal container are maintaining the internal electronics consistent for a minimum of one hour during temperature change over 30ºC. The thickness of the insulation is limited to 20mm to keep the device small. In this example, the criteria for the material selection is to choose the material that maximizes the time before the outer surface temperature change affects the inner surface temperature change. Figure 19 (right) shows that although foam which is a common material for thermal insulation applications has the lowest thermal

126 The best material can be evaluated using $\rho C_p = \lambda/a$ (see Equation 10). Energy consumption can be minimized when $a^{1/2}/\lambda$ is maximized., Ibid., 151.

conductivity, the thermal diffusivity is not the lowest. Therefore, the best materials for this application are polymers and elastomers such as neoprene, isoprene, and Butyl rubber.[127]

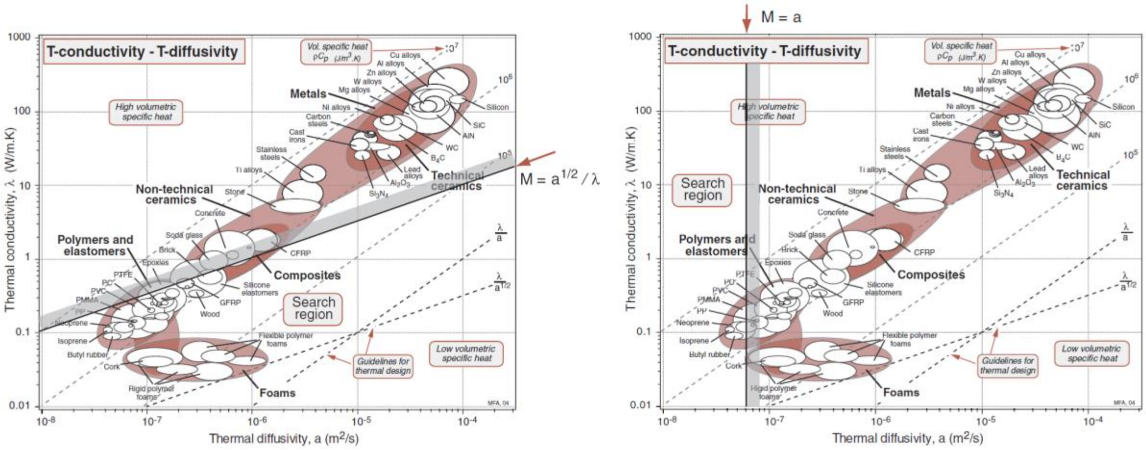

Figure 19 Thermal conductivity and thermal diffusivity charts
Material selection criteria for energy efficient kiln wall (left); and material selection criteria for a short-term isothermal container (right).[128]

5.3.2 Case Study 2: Materials for heat exchangers

Among the factors that influence the performance of heat exchangers, the type of working fluid (i.e. liquid or gas) has a significant impact on the material selection and design strategies. When both working fluids are liquid, the major thermal resistance occurs via heat transfer through the walls since the convective heat transfer of liquids are comparably more efficient and rapid. When one of the fluid is gas, the convective heat transfer at the surface via gas becomes the major factor for thermal resistance.[129]

127 Ibid., 150.

128 Ashby, Materials Selection in Mechanical Design.

129 See Ibid., 165.

Therefore, the most effective strategy for using two liquids is to improve the conductive heat transfer through the tubes or tanks that house the fluids. This can be achieved using thin walls with high thermal conductivity. On the other hand, the strategy for the using gas (e.g. air) is to improve the convective and conductive heat transfer at the interface of the gas and fluid enclosure. This can be achieved by using materials with high thermal conductivity for the surfaces as well as using extended surfaces (e.g. pins and fins) to increase the surface area.[130]

The following cases present the material selection process of two different heat exchangers. One is a thin-wall tube heat exchanger using two liquids as working fluids, and the other is a heat sink that maximizes the heat exchange between air and microchips using extended surfaces.

The requirements of the tube wall material include maximizing the heat flow rate between the two liquids; withstand the high pressure, temperature, and chemicals; and of low cost. As described above, conduction heat transfer through the wall is the major factor of thermal resistance and improving this has the most impact in increasing the heat exchange rate. The conduction through walls can be enhanced using highly conductive materials and decreasing the thickness of the wall. The former solution can be easily derived by looking at the thermal conductivity of the material. However, since the tube wall needs to support the pressure between the inside and outside fluids, the elastic limit needs to be high. Furthermore, maximum operating temperature, ductility (for manufacturing), and cost also need to be considered.

130 See Ibid.

Figure 20 (left) shows the Ashby chart comparing thermal conductivity with elastic limits. The best materials are the ones that have higher thermal conductivity and high elastic limit (upper right corner of the figure). Materials that does not meet the requirements regarding service temperature, cost and chemical resistance also need to be eliminated.[131]

On the other hand, the requirements of the heat sink are effectively dissipating the heat generated by the microchip; and simultaneously preventing electric current from conducting through the material. Therefore, the heat sink material needs to be a good electrical insulator ($\rho_e > 10^{19} \mu\Omega.cm$) and a good heat conductor. Figure 20 (right) shows the materials arranged based on electrical resistivity and thermal conductivity. According to the chart, aluminum nitride (AlN) and alumina (Al_2O_3) which is located on the upper right search region best fit theses criteria. Further detailed research of these candidate materials can reveal which one performs better over the other.[132]

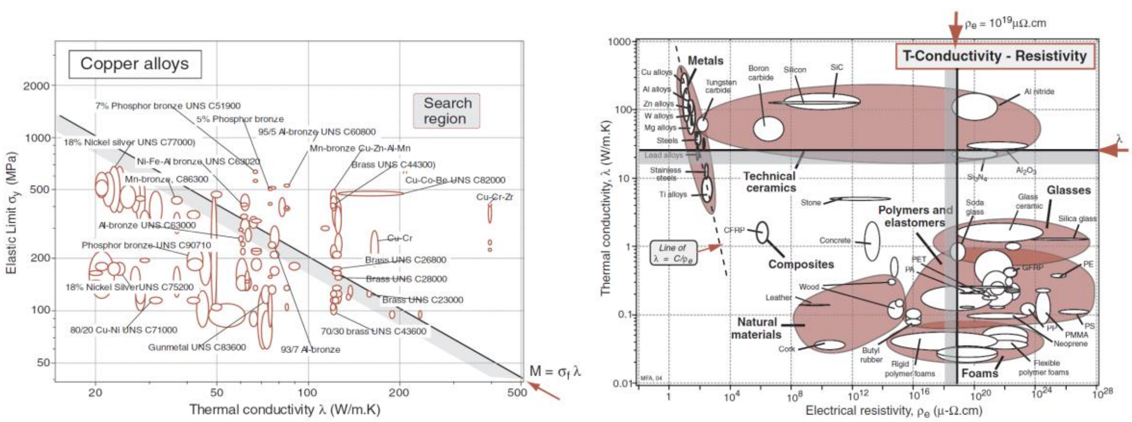

Figure 20 Relevant Ashby charts

131 Ashby, Shercliff, and Cebon, Materials, 265.

132 Ashby, Materials Selection in Mechanical Design, 85.

Chart of thermal conductivity against the elastic limit (left); and chart of thermal conductivity against electric resistivity (right).[133]

5.3.3 Case Study 3: Materials for heat storage

Heat storage systems require the material to be able to retain heat or diffuse heat through the material for a prolonged duration of time. The performance of the heat storage system can be controlled by selecting materials with specific thermal properties (e.g. heat capacity, conductivity, and diffusivity); surface color and texture; density; and thickness of the material.

The materials that are most suitable for thermal storage applications have high density, high heat capacity, low reflectivity, low diffusivity, and high conductivity (see Equation 10). These materials absorb heat effectively, retain a significant amount of heat, and slowly release heat towards the opposite side of the material. The following examines two different heat storage application: storage heater passive solar wall.

Storage heaters are commonly used to heat a material during the night time when the electricity is cheaper and use the heat that is stored in the material during the daytime by circulating fluid through it. The best materials for storage heaters can be chosen based on its heat capacity (see Equation 9), cost, and maximum service temperature.

Among the materials that have high heat capacity, concrete and refractory bricks are good candidates. Concrete has a comparably low service temperature of 150ºC but is the cheaper than refractory bricks. On the other hand, refractory bricks have higher

133 Ashby, Materials Selection in Mechanical Design.

service temperature of 1000ºC but are more expensive than concrete. Therefore, concrete is the best material for home storage heaters that operate in lower temperature range, and refractory bricks is suitable for industrial application that operate in high temperature range (e.g. heated wind tunnel material for testing aerospace vehicles.[134]

Another heat storage application is a passive solar heating wall. The outer surface of the wall is heated during the day by solar radiation and the heat stored in the wall is released to the interior space during the night. The design strategy is to design the wall to take approximately 12 hours for the heat from the outer surface to reach the inner surface. This strategy will allow the heating of the interior space take place as the sun sets. Other constraints such as the maximum thickness of the wall and the maximum working temperature (100ºC) needs to be considered.[135]

The relationship between thermal diffusivity and thermal conductivity is $\lambda/a^{1/2}$ which is derived from Equation 10 and heat-diffusion distances in time equation[136]. When this value is maximized; the heat capacity is also maximized. If the maximum allowed wall thickness is defined as 0.5 meters and use the 12-hour time constraint, the thermal diffusivity value should be equal to or smaller than 3×10^{-6} m^2/s. Based on Figure 21, the candidate materials include concrete, stone, brick, glass, titanium, etc. Similar to the previous example, concrete is the best choice in terms of cost and also satisfies the working temperature criteria.[137]

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134 Ashby, Shercliff, and Cebon, Materials, 267.

135 Ashby, Materials Selection in Mechanical Design, 154.

136 $w = \sqrt{2at}$ where w is wall thickness, a is thermal diffusivity, and t is time. Ibid., 155.

137 Ibid., 154.

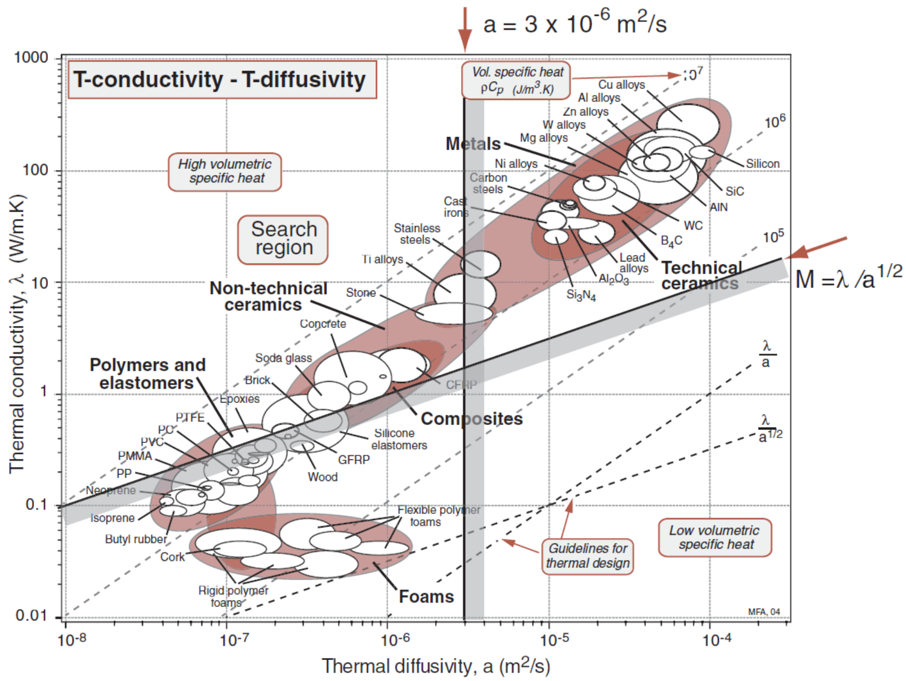

Figure 21 Thermal Conductivity – Thermal Diffusivity Chart
Criteria for choosing the material for a passive solar wall.[138]

5.4 Architectured Multiscale Materials

5.4.1 Introduction

Architectured materials (or hybrid materials) combine two or more materials in order to create attributes beyond a single material. It is important to note that the gas (e.g. air) contained in the void or space can be considered as one of the materials. This implies that not only do architectured materials include composites that focus on configuration (e.g. particulates, laminates, short fibers, etc.) of discrete materials but also include

138 Ashby, Materials Selection in Mechanical Design.

hierarchical materials that focus on the geometric shape and connectivity (e.g. cellular, lattice, segmented, etc.) of material and space.[139]

The material property of architectured materials are defined based on a number of factors. The constituent materials and their relative volume fractions defines the bulk material property of the architectured material. The shape, size, and connection methods between different materials also have significant effects in terms of mechanical and thermal properties. Depending on the configuration and connectivity, there can be many types of architectured materials such as unidirectional, laminates, short fiber, particulate, foam cell, lattice cell, strand structures, segmented structures, sandwich panels, and multi-layers (see Figure 22).[140]

To compare an architectured material with an un-architectured (or monolithic) material, it is convenient to regard the former as an independent bulk material with a set of unique set of properties. In the initial material development stage, it is effective to conduct a preliminary evaluation of multiple material combinations based on the key factors identified in the previous paragraph. Once the best material combination is chosen, more detailed methods such as optimization and finite-element analysis can be used to further refine the material selection and design.[141]

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139 Ashby, "Designing Architectured Materials"; Ashby and Bréchet, "Designing Hybrid Materials"; Ashby, Materials Selection in Mechanical Design.

140 Ashby, "Designing Architectured Materials."

141 Ashby, "Hybrid Materials to Expand the Boundaries of Material-Property Space"; Ashby, "Designing Architectured Materials"; Ashby and Bréchet, "Designing Hybrid Materials"; Ashby, Materials Selection in Mechanical Design; Ashby, Shercliff, and Cebon, Materials.

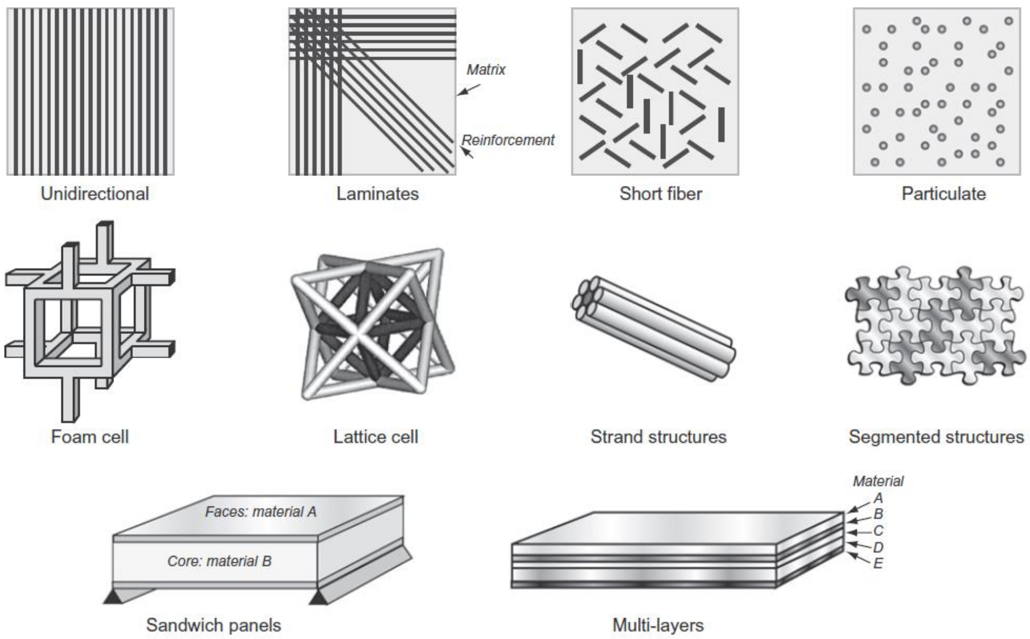

Figure 22 Types of architectured materials
Examples of architectured materials based on configurations and connectivities.[142]

5.4.2 Architectured materials for thermal performance

This section investigates three classes of architectured multiscale material systems: cellular materials, functionally graded materials, and adaptive materials. Each system has unique material configuration, composition, and behavior that make it respond to interact with heat in novel ways.

Cellular materials which can be commonly found in nature such as wood, sponge, and coral are essentially materials consisted of small enclosed volumes. These volumes are defined by a network of material components forming the edges and faces. Most of the

142 Ashby, "Designing Architectured Materials."

materials we use including ceramics, polymers, metals, glasses, and composites can be processed into cellular solids.[143]

The most important feature of the cellular material is the relative density (the density of the bulk cellular material divided by the density of the solid material). The relative density of 0.3 is the general threshold that separates whether a material is cellular solid or solid with isolated pores.[144] The key properties of cellular materials can be summarized as low thermal conductivity, low density, low Young's modulus, and large compressive strain.[145]

The low thermal conductivity property enables the material to be used widely in thermal insulation applications. Three major factors contribute to limiting heat flow. First, the low volume fraction of the solid material and large volume fraction of void spaces which enclose air or gas with low conductivity minimizes heat conduction. Second, the sizes of the cells are small enough to suppress convection heat transfer. Finally, the large number of solid and void transitions across the material which increases the repetition of absorption and reflection of radiation decreases the overall radiation heat transfer.[146]

The critical factors that define the durability, permeability and structural integrity of the cellular materials include porosity, anisotropy, pore connectivity, and scale. The thermal

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143 Gibson and Ashby, Cellular Solids.

144 Ibid.

145 The low density property allows the material to be used to create lighter material systems. The low Young's modulus (stiffness) and large compressive strain properties can be utilized to create cushioning or energy absorbing application.

146 Gibson and Ashby, Cellular Solids.

performance of cellular materials as thermal insulation or heat exchanger[147] is mainly affected by the shape, size, and porosity of the air cells. These attributes define whether convection heat transfer is suppressed (thermal insulation) or reinforced (heat exchanger).[148]

Functionally graded materials (FGM) consist of two or more materials that are blended with each other through smooth and continuous transitions. This gradual transition strategy mitigates many problems such as thermal stress and structural defects associated with combining different materials.[149] Some of the common material properties that are investigated in FGMs include Young's modulus of elasticity, Poisson's ratio, the shear modulus of elasticity, and material density.[150]

FGM can be commonly found in nature including bones, skin, and tree. Each of these examples has variable material compositions and configurations that are graded to provide customized properties (e.g. mechanical or thermal properties). The composition and configuration also vary depending on the location within the body or element as well as the function that is required at that specific location. The history of engineered FGMs are relatively short[151] but is increasingly being researched and developed in applications

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147 Since cellular materials have large surface areas, it can be also used as an effective heat exchanger by strategically opening the cells to allow fluid to pass through.

148 Clyne et al., “Porous Materials for Thermal Management under Extreme Conditions.”

149 CPM, Varghese, and Baby, “A Review on Functionally Graded Materials.”

150 Ibid.; Jha, Kant, and Singh, “A Critical Review of Recent Research on Functionally Graded Plates.”

151 The first FGM was developed in 1984 for the aerospace industry requiring high temperature thermal barrier material within a thin material layer.

including spacecraft structural or heat shield components, thermal coating, rocket casing, biomedical implants, and flywheels.

Among these applications, the ceramic-metal FGM used as the thermal barrier (e.g. rocket casing) is a good example for understanding the potential of this material system. Since metal has high fracture toughness and ceramic has excellent thermal resistance, the composite between these two classes of materials render an idea interface between severe temperature differences. Compared to the conventional multi-layered composite materials, the gradual transition effectively prevents cracking, and delamination at the interface between the materials can be avoided.[152]

Adaptive materials in the context of this research are materials that have the capacity to change in terms of shape, size, and material property based on various types of stimulations (e.g. mechanical, thermal, or chemical stimulation). The tunable aspect of this material class provides opportunities to transition from two distinctive thermal functions (e.g. heat exchanger to thermal insulation).

The field of smart materials and programmable matter is an excellent example of adaptive materials. Although there are many similarities and overlaps between the two fields the former focuses on responding to stimuli and the latter focuses on information processing and control. Smart materials are architectured materials that change its property or shape to various external stimuli including temperature, stress, moisture, and electromagnetic fields. A large number of smart materials are available or actively being

152 CPM, Varghese, and Baby, "A Review on Functionally Graded Materials."

developed such as the piezoelectric materials, shape-memory materials, stimuli-responsive polymers, and self-healing materials.

The characteristics that differentiate smart materials from other materials are immediacy, transiency, self-actuation, selectivity, and directness. The immediacy and transience are related to the response time and plurality of states. The self-actuation and selectivity are related to the material's inherent "intelligence" and the discreteness of smart materials. Finally, the directness is linked to the spatial domain of the response which is essentially local to the stimuli or event.[153]

On the other hand, programmable matter emphasizes the information processing and the methods of control (opposed to response). The history of the field of programmable matter is relatively short[154] and hence at the conceptual phase compared to the field of smart materials where there are already a plethora of commercially available materials and material systems. The original concept was from the digital realm in the area of computer science but expanded to the physical realm with the advancements of miniaturization technologies such as the micro and nanoscale fabrication techniques.

There are various studies and developments relating to programmable matter. The more simplified class of programmable matter is essentially synonymous with smart materials and the more experimental class such as the field of synthetic biology operates in the domain of chemistry. It is noteworthy to mention the programmable matter research in

153 Addington and Schodek, Smart Materials and New Technologies, 10.

154 The term programmable matter was coined by Toffoli and Margolus in 1990. See Toffoli and Margolus, "Programmable Matter."

the field of robotics has the direct lineage from the original computation driven concept[155].

5.4.3 Processing Architectured Materials

The processing methods of materials in biological systems which ranges from bacterium and plants to animals are fundamentally more advanced, versatile, and efficient compared to the current processing methods of artificial systems. Biological materials are primarily grown from the cellular level using chemical processes at mostly ambient temperature and pressure. This bottom-up approach and low energy requirements allow the biological materials to not only repair and regenerate itself but also better adapt to the surrounding environment. Furthermore, since the cells as a unit of construction are programmable matter with the capacity to store, copy, and propagate information (e.g. DNA), it is possible to expand and improve itself way beyond its limited lifespan through reproduction and evolution.

Compared to this, processing methods in artificial systems rely on extreme amount of energy (high temperature and pressure) and often toxic processes. Until recently, the result of these processes fell short of the novel capabilities of biological materials (e.g. self-healing and adaptation to change). However, with the recent advancement in material technology including cellular materials, FGMs, and adaptive materials as well as

155 The robotic modules that have individual computing elements embedded can effectively process the information (e.g. neighboring modules, external stimuli, command, etc.) and execute a certain task (e.g. move). Many different types of programmable robotic modules are in development phase including shifting cubes or cylinders and folding structures. The current challenges are related with the scalability of the moving parts (e.g. electric motors)., Knaian, “Programmable Matter.”

additive manufacturing and self-assembly processes, the gap between biological and artificial systems are reducing rapidly.

Among the various advances in materials processing technologies, additive manufacturing (AM) method provide significant advantages in creating multiscale materials and system. AM process is capable of producing complex and intricate geometries that are not possible or feasible (e.g. time and cost) for subtractive manufacturing (SM) methods such as cutting, milling, and forming.

Moreover, the added complexity of the geometry has little effect on the cost and time for the production. In the case of lattice structures and cellular solids, the production cost can be potentially lower than the cost of a solid block of the same volume due to the savings in material. This feature also provides opportunities for customizable and variable design making low volume production economically feasible. Finally, AM processes have the additional advantages including minimum waste output and need for post-processing. There are also some disadvantages to the AM process that needs to overcome. These include the comparably low speed and limited precision of the production; lower surface quality compared to machining; and a limited material pallet.

However, these restrictions are increasingly being overcome with the development of advanced techniques which can 3d print faster (e.g. Carbon3D 3d printer) and in higher-resolution (micron scale). Also, the experimental hybrid manufacturing methods that integrate the subtractive manufacturing method into the process can improve the surface quality of the AM outcomes. Lastly, the recent interest in multi-material printing and development of 3d printable functional materials (strong, elastic, conductive, or porous) the potentials for utilizing the AM process for creating artificial multiscale materials and material systems is ever-growing.

Chapter 6. Adaptive Insulation for Building Envelopes

6.1 Introduction

The mainstream approach nowadays in designing building envelope for thermal management is to make the building as impermeable as possible to heat and air exchange between the external environment and the interior environment using multiple layers of materials (e.g. finishes, thermal insulation, and air/vapor barriers). Various high-performance thermal insulation and air-sealing technologies are being developed using this approach including vacuum insulated panels, aerogel insulation, and various liquid and membrane based air barrier systems.

Although the heat and air impermeable approach are effective in reducing the heat loss or heat gain through the building envelope, there are also a number of problems. Due to the significant decrease in heat flow and air infiltration, the moisture and pollutants tend to accumulate in the interior space. This results in an increased potential for mold growth, reduction in insulation performance, and degradation of the insulation material. To mitigate this, the ventilation rate of the HVAC system is often increased to manage the indoor air quality which results in increased energy consumption. Furthermore, the increase of the thermal insulation material increases the thickness of the building components which not only increase the cost of the construction but also reduce the habitable interior space (e.g. floor area and room height).[156]

In this context, adaptive insulation which has been proposed since the 1970s is reemerging as a viable alternative to this approach. Adaptive insulation, also known as dynamic insulation or breathing wall, is selectively permeable to air, moisture, and heat. The air and heat exchange is enabled by strategically integrating air channels and air cavities within the building envelope system.

Adaptive insulation can not only mitigate various issues relating to airtight and super-insulated envelope systems but also be utilized to vary the thermal resistance of the envelope based on seasonal or diurnal changes. Depending on the direction of the heat flow in relation to the air flow, the adaptive insulation can operate in contra-flux (heat recovery) mode or pro-flux mode (heat transfer).[157]

The following sections analyzes the benefits and challenges of adaptive insulation systems. Following the description, the review of existing adaptive insulation systems is presented.

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156 Taylor and Imbabi, "The Application of Dynamic Insulation in Buildings"; Imbabi, "A Passive–active Dynamic Insulation System for All Climates."

157 Taylor and Imbabi, "The Application of Dynamic Insulation in Buildings"; Di Giuseppe, Nearly Zero Energy Buildings and Proliferation of Microorganisms; Taylor, Webster, and Imbabi, "The Building Envelope as an Air Filter"; Dimoudi, Androutsopoulos, and Lykoudis, "Experimental Work on a Linked, Dynamic and Ventilated, Wall Component."

6.2 Benefits and Challenges of Adaptive Insulation

The benefits of adaptive insulation systems include the ability to adapt to the seasonal and diurnal temperature changes. This attribute can contribute to energy savings during the transitional periods between the indoor heating and cooling states. For example, during the hot summer days, it is beneficial to have a high degree of thermal insulation to prevent the outdoor heat from penetrating inside to the cool indoor environment.

However, during the transition to cool summer nights when the outdoor temperature starts to drop, the cooling system is often still required to be operational due to the accumulated heat within the interior space. The required cooling load can be drastically reduced with if the envelope can exchange heat (e.g. reduce the thermal insulation capacity) with the cold outdoor environment.[158]

The adaptive insulation systems, particularly the systems that use porous media, can also function as an efficient air particulate filter. Taylor et al. compares the filtration efficiency as a function of air flow rate between dynamic insulation and conventional air filter. The large area of the adaptive insulation is effective in filtering particles between 0.5μm to 5μm that can potentially cause damages to the human lung with significantly low pressure drop compared to other high performance filters (i.e. HEPA filters).[159] Furthermore, Di Giuseppe et al. investigated the thermal and filtration performance of a retrofit dynamic insulation wall (DIW) for a temperate climate (i.e. Italia). The

158 Kimber, Clark, and Schaefer, “Conceptual Analysis and Design of a Partitioned Multifunctional Smart Insulation.”

159 Taylor, Webster, and Imbabi, “The Building Envelope as an Air Filter.”

experimental results show that the DIW using cellulose as the porous insulation can filter 99.94% of harmful atmospheric particulate matter.[160]

There are a number of challenges of adaptive insulation systems that need to overcome. Since the system relies on precisely controlling the air movements through the building elements, a much higher standard is demanded for designing, detailing, constructing and maintaining the system. This requirement not only makes the system development and implementation less cost effective but also have potential to reduce the durability of the system (e.g. through operable vents, air leaks, and blockage of air channels).[161]

6.3 Review of Existing Adaptive Insulation Systems

In 1986, Arquis and Langlais categorized the general types of adaptive insulations (i.e. dynamic insulation) for building applications into parietodynamic, permeodynamic, and thermal dynamic insulation.[162]

The parietodynamic system utilizes impermeable air channel embedded within the wall similar to the ventilated façade systems.[163] On the other hand, permeodynamic systems utilize porous materials that function as a cross-flow heat exchanger with the capacity to control air flow. Many of the systems are activated by creating negative pressure in the interior space, and the heat recovery function (i.e. preheating or precooling) is

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160 Di Giuseppe, D'Orazio, and Di Perna, "Thermal and Filtration Performance Assessment of a Dynamic Insulation System."

161 Taylor and Imbabi, "The Application of Dynamic Insulation in Buildings."

162 Arquis and Langlais, "What Scope for 'dynamic Insulation'?"

163 Elsarrag, Al-Horr, and Imbabi, "Improving Building Fabric Energy Efficiency in Hot-Humid Climates Using Dynamic Insulation."

implemented in many of the existing systems.[164] Finally, thermodynamic insulation is similar to the permeodynamic system (counter-flow configuration) but uses a separate fluid (e.g. air or water) circulation system that is independent of the ventilation system. The fluid circulation system is channeled through a heat exchanger to recover the heat.[165]

The following sections investigate a number of recent studies and developments relating to adaptive insulation systems. The categorization of the system is a modified version of Arquis and Langlais', combining the thermodynamic system with the permeodynamic system. Furthermore, some of the recently developed systems which emphasizes the dynamic tunability (e.g. using moving plates or deformable configuration) is separately categorized as "tunable systems."

6.3.1 Parietodynamic systems

A number of novel adaptive insulation systems that fit in the parietodynamic system category has been developed by a number of researchers. Imbabi proposed the Void Space Dynamic Insulation (VSDI) which embeds an air layer between one or more layers of conventional insulation. The air layer utilizes a sheet-type spacer component that can be easily implemented during the assembly process (see Figure 23). The computational simulation results show that VSDI can equally work well in both hot and

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164 Homem, "Dynamic Insulation as a Strategy for Net-Zero Energy Buildings"; Fantucci, Serra, and Perino, "Dynamic Insulation Systems."

165 Elsarrag, Al-Horr, and Imbabi, "Improving Building Fabric Energy Efficiency in Hot-Humid Climates Using Dynamic Insulation."

cold climate, and the active and passive VSDI enables order-of-magnitude reduction in building energy consumption and carbon emissions.[166]

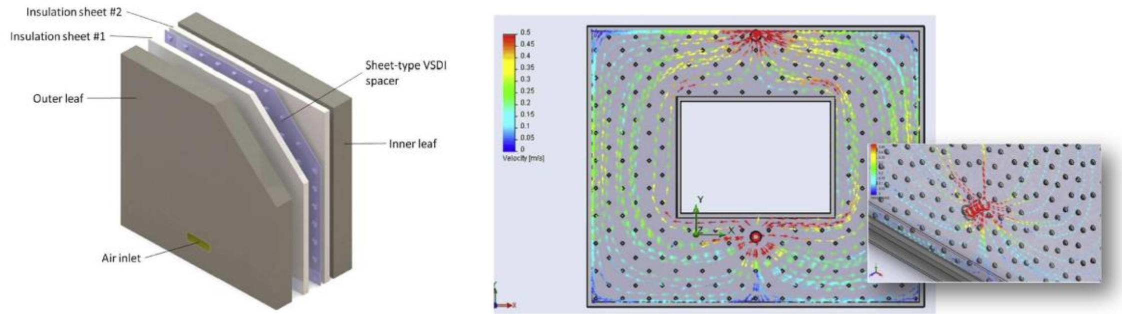

Figure 23 Void Space Dynamic Insulation (VSDI)[167]
Illustration of full-fill VSDI wall using two insulation layers (left) and computational model of the VSDI wall (right).

Nizovtsev et al. developed a prefabricated heat-insulating panel with ventilation channels directly embedded within the rigid insulation material (see Figure 24). This system is suitable for both new and retrofit building applications. The numerical analysis and physical inspection results verify the high thermal performance and moisture control capacity (i.e. minimum condensation and accumulation of moisture) of the proposed system.[168]

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166 Imbabi, “A Passive–active Dynamic Insulation System for All Climates.”

167 Ibid.

168 Nizovtsev, Belyi, and Sterlygov, “The Facade System with Ventilated Channels for Thermal Insulation of Newly Constructed and Renovated Buildings.”

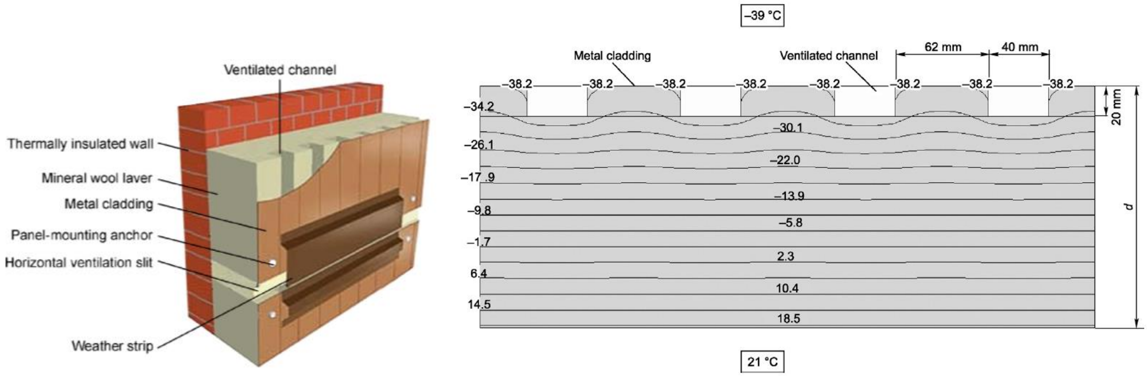

Figure 24 Heat-insulating panels with ventilated channels[169]
Façade system with the proposed system implemented (left), and thermal data calculated for a 160 mm thick heat-insulating panel.

Finally, Fantucci et al. studied two separate brick wall configuration with a ventilated opaque façade on the exterior side (see Figure 25). Depending on the location of the vents on the exterior façade and interior brick wall, the wall can function as an air heat recovery system (i.e. exhaust air façade configuration) or a supply air pre-heater (i.e. supply air façade configuration). A full-scale wall for each configuration was fabricated, and the thermal performance was verified using double climatic chamber and guarded heat flow meter apparatus.[170]

169 Ibid.

170 Fantucci, Serra, and Perino, “Dynamic Insulation Systems.”

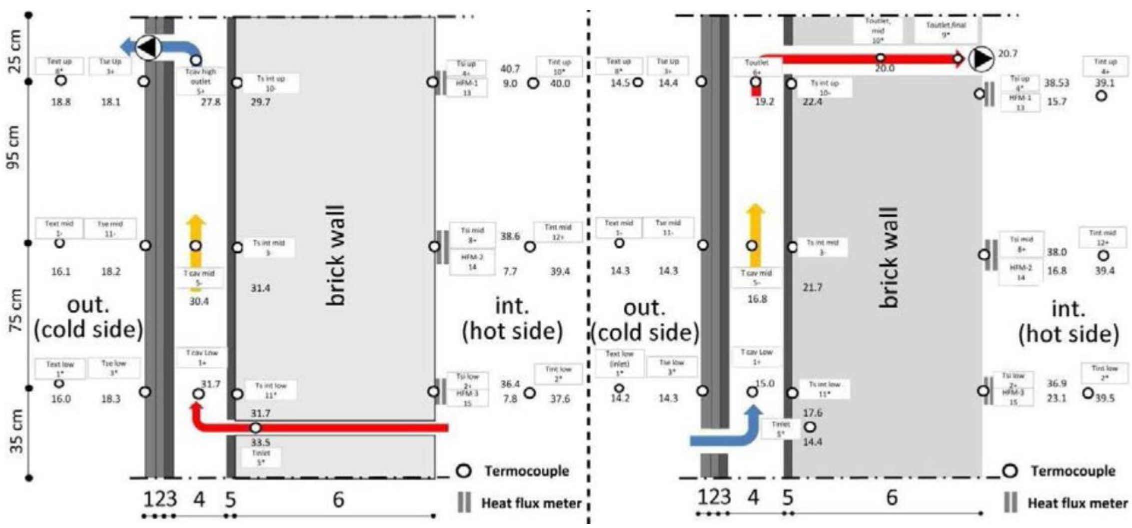

Figure 25 Opaque ventilated façade configurations[171]
Exhaust air façade configuration (left), and supply air façade configuration (right).

6.3.2 Permeodynamic systems

There are a number of permeodynamic systems that are being actively developed. Although there are more complexities involved with developing these systems (e.g. dealing with porous medium), the potential thermal performance (e.g. heat transfer density) and air filtering capacity is high.

Murata et al. proposed the breathing dynamic insulation (Breathing DI) system that utilizes breathable inorganic concrete (BIC) walls. The BIC is permeable to air and has desirable thermal properties including low thermal conductivity and large thermal storage capacity. The interior space is divided into two compartments and the embedded fan periodically alternates direction. This alternation of air pressure allows the wall to store the outgoing heat during exhaust mode and recover the accumulated heat when it switches to the supply side wall. The experimental results for heat and moisture recovery

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171 Ibid.

efficiencies showed that Breathing DI has the same effect of having a thicker thermal insulation equipped with a heat recovery ventilator with an efficiency of around 90%.[172]

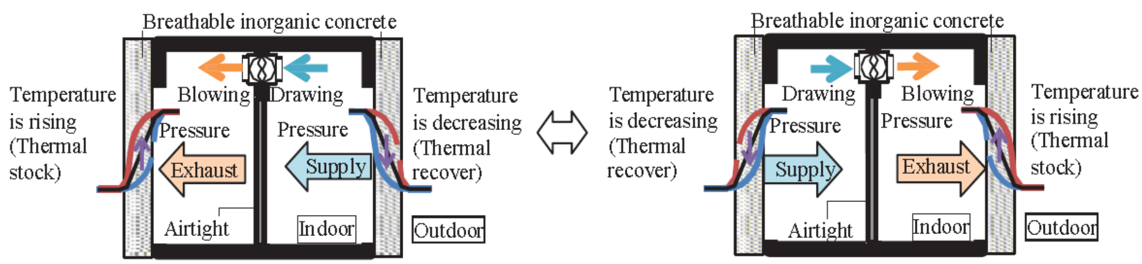

Figure 26 Breathing dynamic system[173]
Schematic diagram of the Breathing DI system.

Alongi and Mazzarella studied the microscopic effect of porous media used for adaptive insulation applications on the macroscopic scale heat transfer phenomena. The porosity and granulometry of two rock wool samples were evaluated, and the volume average method was to derive the averaged equation for heat transfer. Furthermore, numerical simulations were utilized to calculate the tortuosity and dispersion.[174]

172 Murata et al., “Periodic Alternation between Intake and Exhaust of Air in Dynamic Insulation.”

173 Ibid.

174 Alongi and Mazzarella, “Characterization of Fibrous Insulating Materials in Their Application in Dynamic Insulation Technology.”

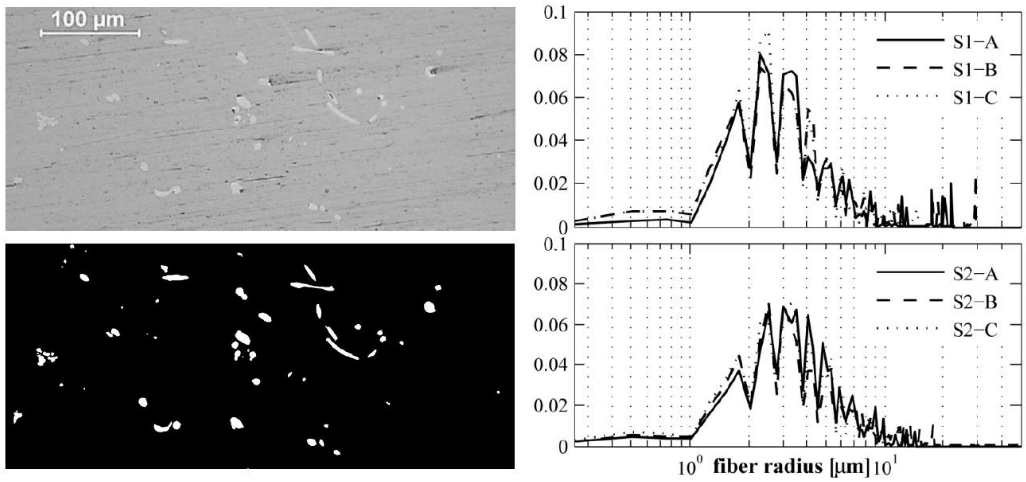

Figure 27 Fibrous insulating materials as dynamic insulation[175]
Microscopic image of rock wool sample (left), and distribution of fiber diameters (right).

Finally, Wong et al. investigated the potential of using air permeable concrete (APC) as a dynamic insulator material. An analytical model of the effective thermal conductivity was developed and validated experimentally using the hot wire method. The main factors that influence the effective thermal conductivity are volume fraction and thermal conductivity of the components; and the water-to-cement ratio of the cement paste.[176]

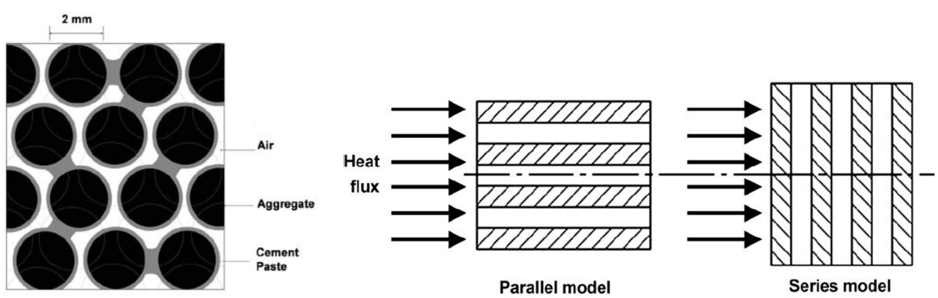

Figure 28 Air permeable concrete as breathing wall[177]
Idealized structure of permeable concrete (left), and multiphase material in parallel and series arrangement (right).

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175 Ibid.

176 Wong, Glasser, and Imbabi, "Evaluation of Thermal Conductivity in Air Permeable Concrete for Dynamic Breathing Wall Construction."

177 Ibid.

6.3.3 Tunable systems

There are a number of adaptive insulation systems that are capable of switching between thermal insulation mode and heat exchanger mode rapidly. Rather than relying on the outside air exchange or indoor air pressure differences, these systems utilize geometric configuration of the closed air cavity space to control the thermal resistivity of the system. The tunability is achieved through deformation of the cavity spaces using collapsible panels or movable partitions.

Kimber et al. developed multi-layered insulation system made of polymer membrane that can alter between thermally insulated state and thermally conductive states. The insulated state is achieved be extending the gaps between the layers to a dimension that suppresses air convection and vice versa compress the gaps into a single panel for the conduction to occur. The optimum geometric configuration and material selection process are presented using analytical models. The fundamental and analytical evaluation was conducted, and the results indicate that the limiting factor for the insulation state is the interstitial fluid properties and overall wall thickness; whereas the limiting factor for the conductive state is the thickness of each partition layers.[178]

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178 Kimber, Clark, and Schaefer, “Conceptual Analysis and Design of a Partitioned Multifunctional Smart Insulation.”

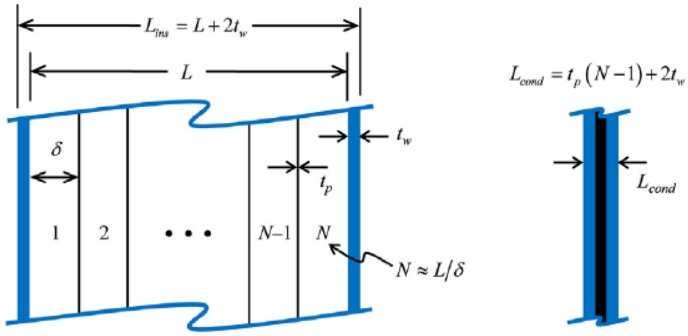

Figure 29 Partitioned multifunctional smart insulation[179]
Extended insulated state (left), and collapsed conductive state (right).

Pflug et al. developed a double glazing system that can switch its U-value using a translucent insulation panel that moves vertically within the cavity space. Variable configuration with different air gap dimensions and a number of insulation panels were tested, and a number of building simulations have been performed using the TRNSYS simulation method. The optimized configuration resulted in a 30% reduction of the cooling demand.[180]

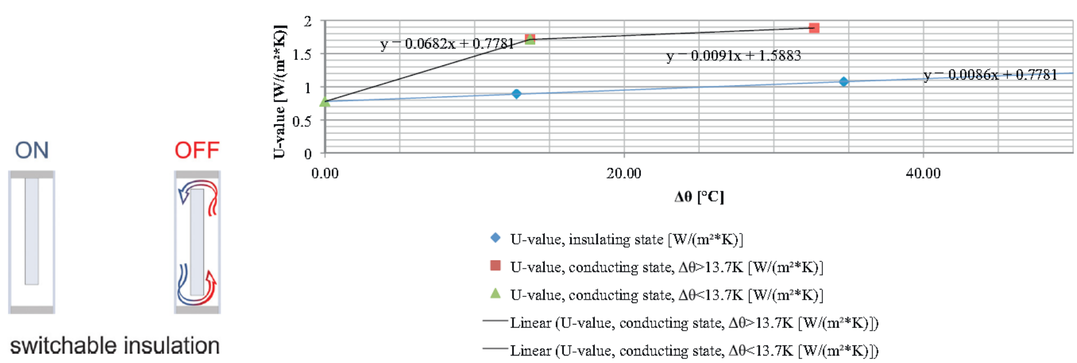

Figure 30 Closed translucent façade element with switchable U-value[181]
Diagram of translucent façade element (left), and TRNSYS simulation of U-value as a function of temperature difference (right).

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179 Ibid.

180 Pflug et al., “Closed Translucent Façade Elements with Switchable U-value—A Novel Option for Energy Management via the Facade.”

181 Ibid.

Part II

Design Experiment

Chapter 7. Thermally Augmented Building Envelope System

7.1 Overview

This chapter aims to contribute to applying the concepts, strategies, and processes discussed in the previous chapters through design experimentation. The key objective of the experiment is to enhance the thermal adaptability of buildings through the design of multiscale-functionally graded material systems that exchange, suppress, and channel heat in novel ways. The overall hypothesis is that through embedding functionally graded geometries (e.g. cavities, cells, and channels) into building components at multiple scales, it will be possible to adapt better to various climate, orientation, location, and functional requirements.

The overall envelope system is designed to operate at three scale domains. At the meter to centimeter scale, the dimension of the overall envelope and sizing of the subdivisions are decided. The optimum width and height of the panels are mainly affected by factors including cost, constructability, and structural capacity. These dimensions govern the sizing and shaping of the air channels at the component level due to its influences on buoyancy force and volumetric air flow rate.

At the centimeter to millimeter scale, the dimension of the components and their features including cavity and fin spacing are decided. This scale domain is closely related to the size, shape, and behavior of heat flow. The cavity spacing is optimized to suppress the air convection, and the fin spacing is optimized for maximum heat exchange between air and the fins.

Finally, at the millimeter to micrometer scale, the physical dimensions of the materials including insulation layer thickness, fin thickness, infill pattern, and surface texture are decided. Although this scale range has significant implications for the overall system, factors including mechanical properties, cost, and fabrication techniques often constrain the design.

The design of the envelope system is inspired by the morphology of plant stems which consists of three layers: dermal tissue, ground tissue, and vascular tissue. The dermal tissue which forms the outer surface of the stem functions as a protective barrier and also controls gas exchange. The ground tissue which is a soft filler layer surrounding the dermal and vascular tissue functions as storage, structural support, and photosynthesis. Lastly, the vascular tissue which is an interconnected pipe system distributes fluid and nutrients internally.

The proposed envelope system also follows the three-layer configuration with each layer having a discrete thermal function. The outer layer of the proposed system functions both as a protective layer and solar chimney. The intermediate layer between the outer and inner layer functions as the structure and thermal insulator. Lastly, the inner layer functions as interior finish and heat recovery ventilator.

Each separate layer is shaped and sized based on the thermal environment and performance criteria defined by existing standards and guidelines. Also, the choice of material for each component is optimized for the functional requirements (e.g. mechanical and thermal properties).

7.2 Building Envelope Design

The overall envelope system consists of thermal insulation layer sandwiched between two separate layers of heat exchangers. The thermal insulation is designed as a series of air cavities divided by thin film radiant barriers. The still air captured within the cavity spaces functions as the key insulation material (low conductivity) and the radiant barrier films reduce the radiant heat transfer through the air spaces. A mechanically strong material with low heat conductivity is used for frames to hold the films in place as well as to make the cavities air-tight (see Figure 31).

The heat exchangers are designed to be attached to the interior and exterior side of the insulation component and composed of finned surfaces made of conductive material. The exterior side heat exchanger can function as a solar wall, and the interior side heat exchanger can operate as a heat recovery ventilator. Depending on the availability of sunlight, the envelope system can switch between these features by strategically opening and closing the vents located at the bottom and top region of the envelope system (see Figure 32).

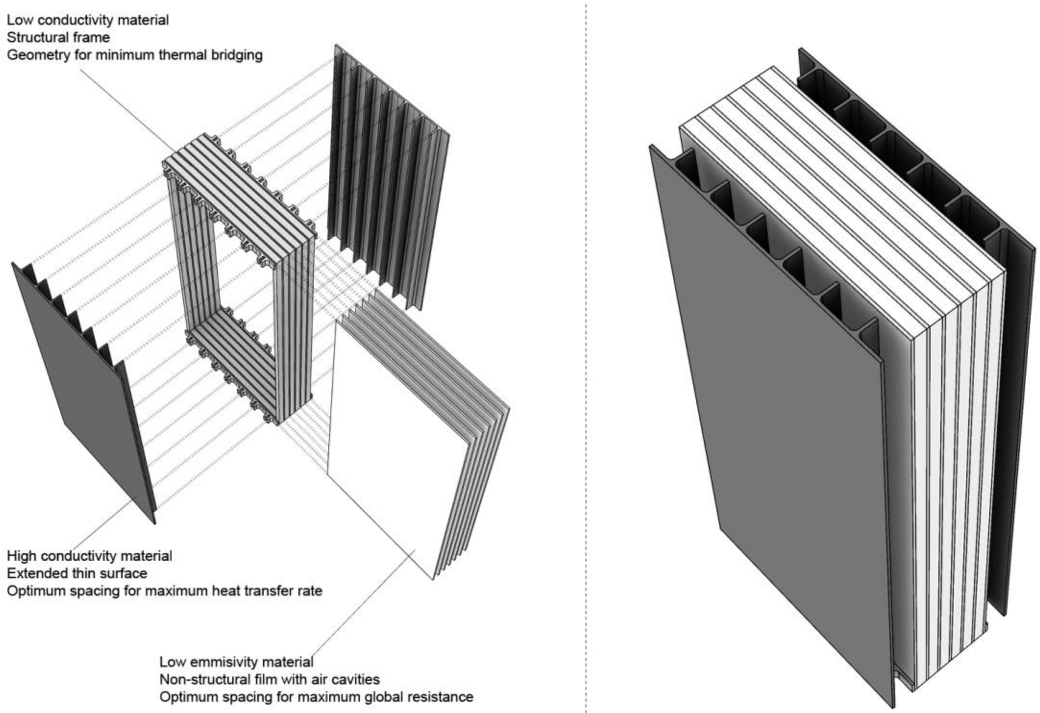


Figure 31 Envelope system configuration and dimensions
Material properties, components, and assembly of the thermally augmented building envelope system.

During the warm days, the air within the channels rises due to the solar radiation that heats the exterior side. When a vent is placed on the shaded side of the building (or using geothermal air channels), the cool exterior air is pulled in, cooling the interior environment and exit out through the solar chimney. When there is not sufficient solar radiation input, the external air from the top of the wall can be channeled through the interior heat exchanger and pre-cooled via the interior environment regulated by active cooling equipment (see Figure 32, summer conditions).

During the cold days, the inside air is circulated through the channels for harnessing the heat from the solar radiation. When there is not sufficient sunlight available, the cold outside air can be pulled in from the bottom of the wall and pre-heated through the inner heat exchanger via the warm interior environment (see Figure 32, winter conditions).

Both solar chimney and heat recovery applications can also be used together as a hybrid system based on the orientation of the walls (e.g. solar chimney on the south façade and heat recovery on the north façade).

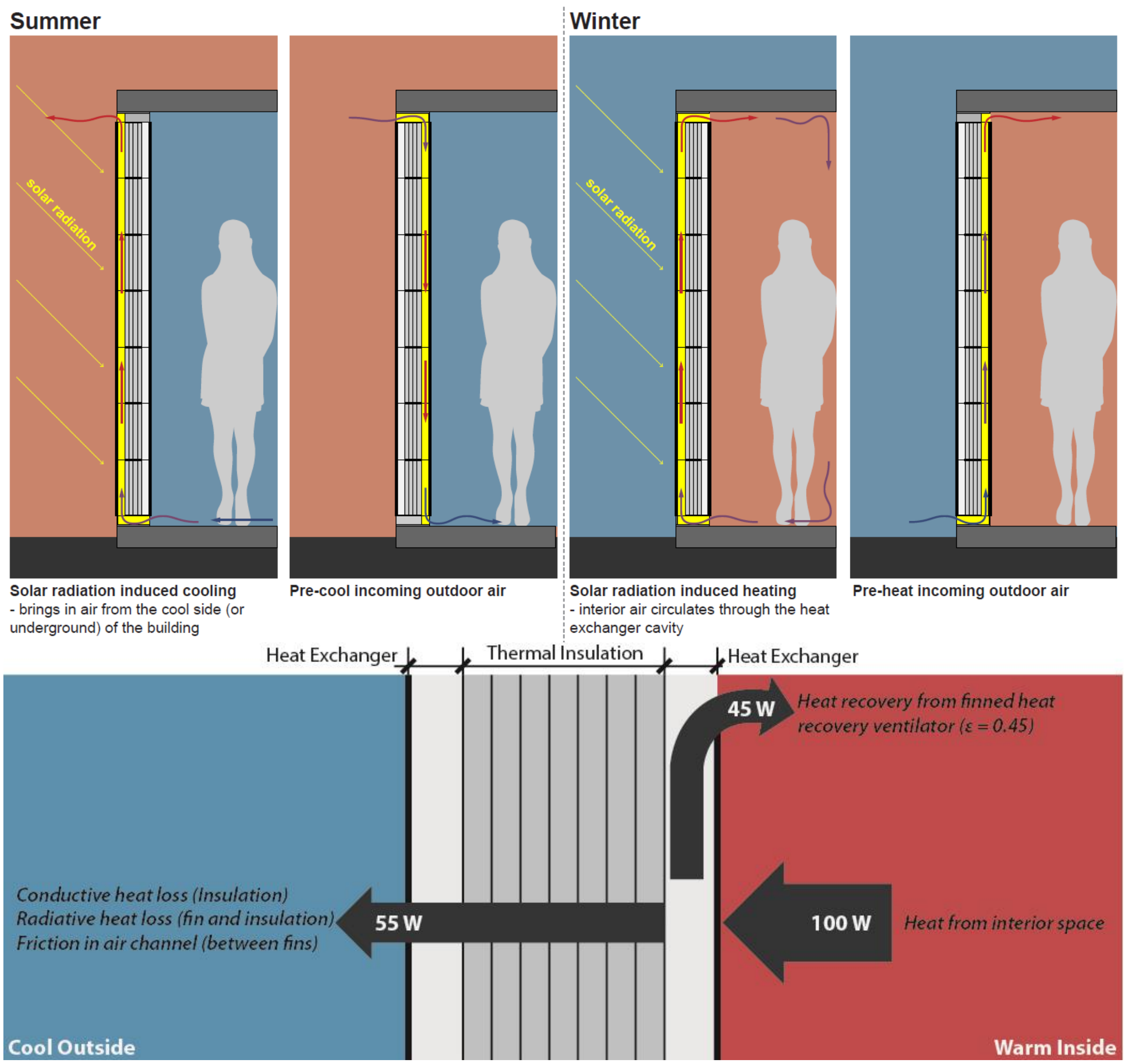


Figure 32 Adaptive heat exchanger configurations
The configurations of the proposed systems can be changed based on exterior temperature condition and sunlight availability (top). Sankey diagram of the winter heat recovery ventilator mode (bottom).

7.3 Thermal Performance Optimization

To maximize the thermal performance of the envelope system, the size, and shape of the components are optimized using correlations from existing research. According to the analytical model, the performance of both the thermal insulation component and the heat exchanger components are most affected by air cavity spacing (D) and fin spacing (S). The optimum dimensions of these factors depend on the height (H) and thickness (T) of the envelope system; and the temperature difference between the interior space and the exterior space (see Figure 33).

Figure 33 shows the horizontal section of the proposed system optimized for three different heights (200mm, 1000mm, and 2000mm). The optimization is based on the analytical model described in section 8.1 (see Equation 14) and the thickness (T) of each condition is fixed at 50mm. As the overall height of the system increases, the optimum air cavity spacing (D) of the insulation component increases. This implies that the required number of air cavity layers decreases as the air cavity height increases. Similarly, the optimum fin spacing (S) of the heat exchanger component also increases as the overall height of the system increase, requiring less number of fins per width (W).

To test the performance of the envelope system, the thermal insulation component, and the heat exchanger component are separately designed, optimized, fabricated and tested (see Figure 34). The base dimension of the prototype is 100mm (W) by 200mm (H) by variable thicknesses (L), and the temperature difference (ΔT) for the test setup ranges from 5ºC to 20ºC.

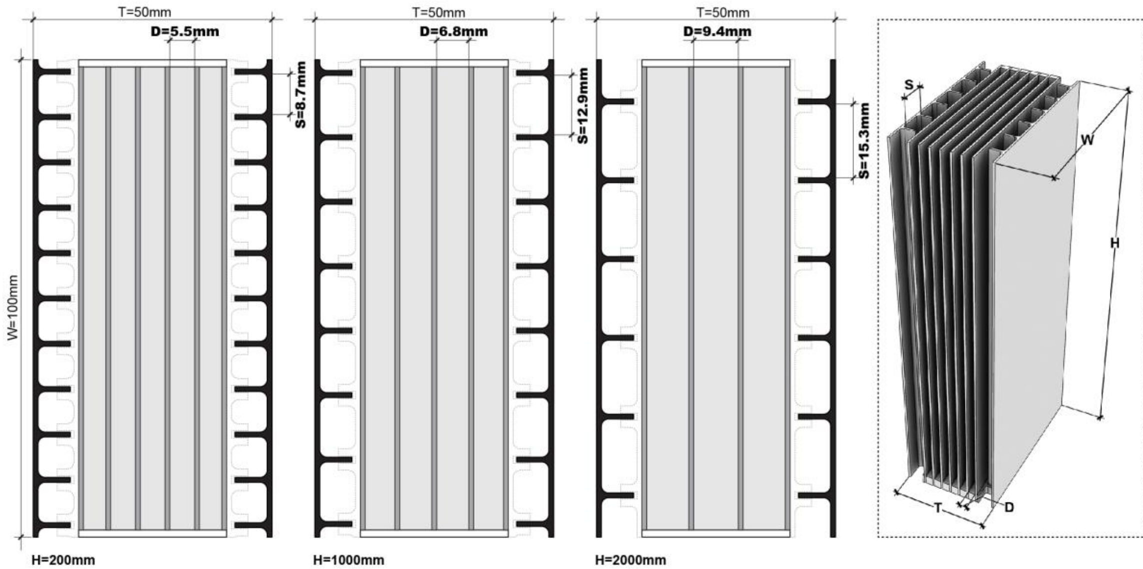


Figure 33 Optimum cavity spacing and fin spacing for variable wall height

The following chapters show the experiment setup for each component. The charts are used to compare the data from the analytical model and the data from the experimental results. Each section also includes the guidelines for optimizing the dimensions of the system to achieve the targeted performance criteria.

The benchmark used to evaluate the thermal insulation component is the recommended U-value for building envelopes (i.e. 0.35 W/m^{2}K)[1]. The evaluation criteria for the heat exchanger component (i.e. heat recovery ventilator) is to passively provide 0.01 m^3/s of the fresh outside air to the interior space per person[2] at 80 percent of the indoor air temperature.

1 ANSI/ASHRAE/IES Standard 90.1-2013

2 ANSI/ASHRAE Standards 62.1 and 62.2-2013

Figure 34 Prototype of optimized geometry
The material selection for each component is based on their structural and thermal requirements. The height of the system is not reflected in this prototype.

Chapter 8. Experiment 1

Layered Radiant Barriers as Thermal Insulation

This chapter presents the analytical model used for optimizing the thermal insulation component and the experiment process for physically testing it. The comparison between the predictions of the analytical model and the physical test results show a strong relationship. This result validates the analytical model to be utilized for optimizing the proposed thermal insulation system for various temperature and geometric conditions.

8.1 Analytical Model

The geometry and sizing of the thermal insulation component are based on the research conducted by Adrian Bejan on the vertical insulating wall using air cavity layers. The wall consists of alternating layers of solid and air, heated from one side.[3] (See Figure 35). The optimum air cavity dimensions can be derived based on Equation 14 which defines the global thermal resistance as a function of air cavity dimensions, volume fraction, and the number of cavities.

3 Bejan and Lorente, Design with Constructal Theory.

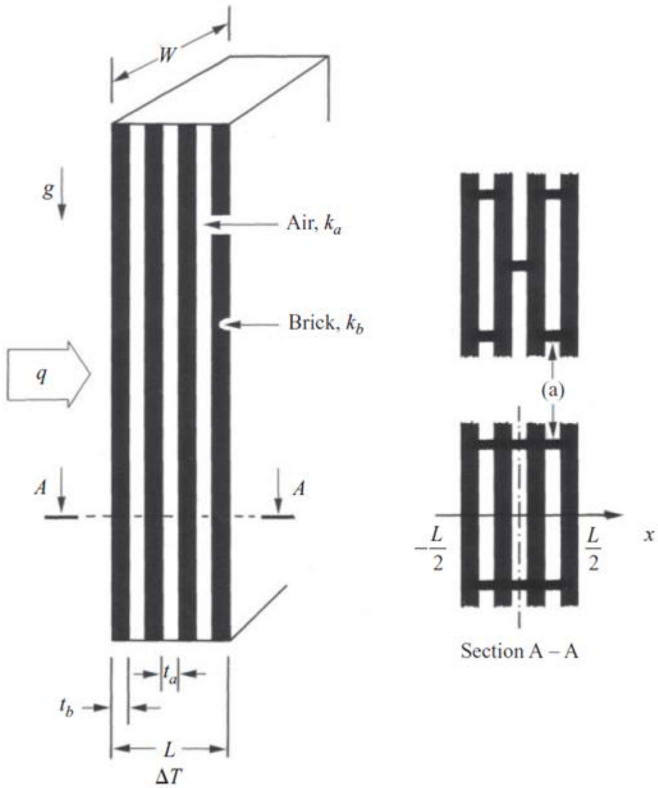


Figure 35 Vertical cavity wall
The wall consisting of alternating layers of solid and air, heated from one side (q).[4]

$$\tilde{R} = \frac{R}{L/(k_b HW)} = \frac{k_b}{k_a}\phi\left[1\left(0.364n^{-5/4}\phi\frac{L}{H}Ra_{H,\Delta T}^{1/4}\right)^m\right]^{-1/m} + 1 - \phi \qquad \textbf{Equation 14}$$

Where,

$\tilde{R}$ = global resistance | R = overall thermal resistance

k_b = thermal conductivity of solid | k_a = thermal conductivity of air

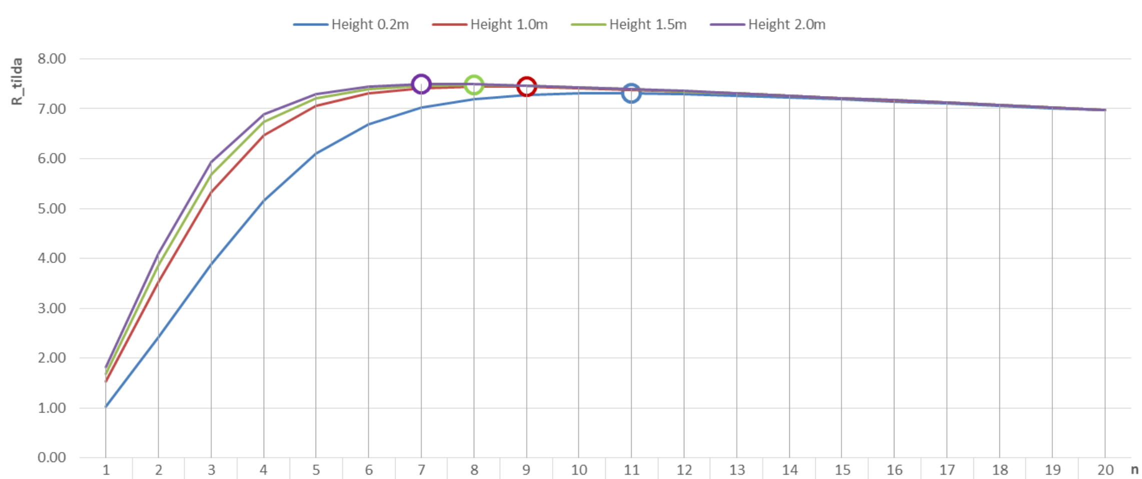
ϕ = volume fraction | n = number of cavities

$Ra_{H,\Delta T}$ = Rayleigh number (H, ΔT) | m = curve smoothing exponent

4 Ibid.

Figure 36 shows the global resistance of a preset cavity space (200mm high, 100mm, wide and 72mm thick) filled with still air as a function of the number of layers (n). The chart is created using the analytical model defined in Equation 14. The larger the number of layers (n), the smaller the air cavity spacing (D) becomes, and the thickness of the spacers affects the volume fraction of the component.

According to the chart, as the height of the component increases, the optimum number of layers decreases. The temperature difference (ΔT) between the interior and exterior space also influence the optimum number of layers (higher ΔT requires larger n or thinner D to suppress convection heat transfer). Figure 33 shows the optimized geometry as section drawings based on this chart.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Height 0.2m	1.03	2.42	3.88	5.16	6.10	6.69	7.02	7.19	7.27	7.30	7.31	7.29	7.26	7.23	7.19	7.15	7.11	7.06	7.02	6.97
Height 1.0m	1.53	3.53	5.32	6.48	7.06	7.31	7.41	7.44	7.44	7.42	7.38	7.34	7.30	7.26	7.21	7.17	7.12	7.07	7.02	6.98
Height 1.5m	1.69	3.86	5.68	6.73	7.21	7.40	7.46	7.47	7.46	7.43	7.39	7.35	7.31	7.26	7.22	7.17	7.12	7.07	7.03	6.98
Height 2.0m	1.82	4.11	5.93	6.89	7.29	7.44	7.49	7.49	7.47	7.44	7.40	7.35	7.31	7.26	7.22	7.17	7.12	7.07	7.03	6.98

Figure 36 Global resistance, number of insulation layers and height
As the height of the sample increases, the maximum value of global thermal resistance can be achieved using a fewer number of insulation layers.

8.2 Experiment Setup

A number of samples ranging from a single layered insulation up to eight layered insulation sample are fabricated and tested using a heat flux sensor and thermocouples (gSkin® U-value kit). The dimensions of the samples are derived from the analytical model defined in the previous section (see Equation 14). The DC regulated power supply and silicon heating pads are used as the heat source, and the prototype is encapsulated using foam insulation material.

The heat flux sensor is attached to the outer layer of the insulation component, and a cardboard cover is attached to the opening to minimizes the air movement around the sample. A thermocouple is placed in the space between the heating pad and the inner surface of the sample; and another thermocouple is positioned in the space between the outer surface of the sample and the cardboard cover (see Figure 37). ΔT between the internal and external thermocouple stabilizes at around 11ºC with 1.2W (1A, 1.2v) of continuous power input after 10-20 minutes.

Each of the samples that consists of 1, 2, 4, 6, and 8 air cavity layers are set up sequentially, and the data from the heat flux sensor and the two thermocouples are recorded using the data logger. The measurements for each sample is taken at 1-minute intervals for a total of 12 hours (see Figure 38).

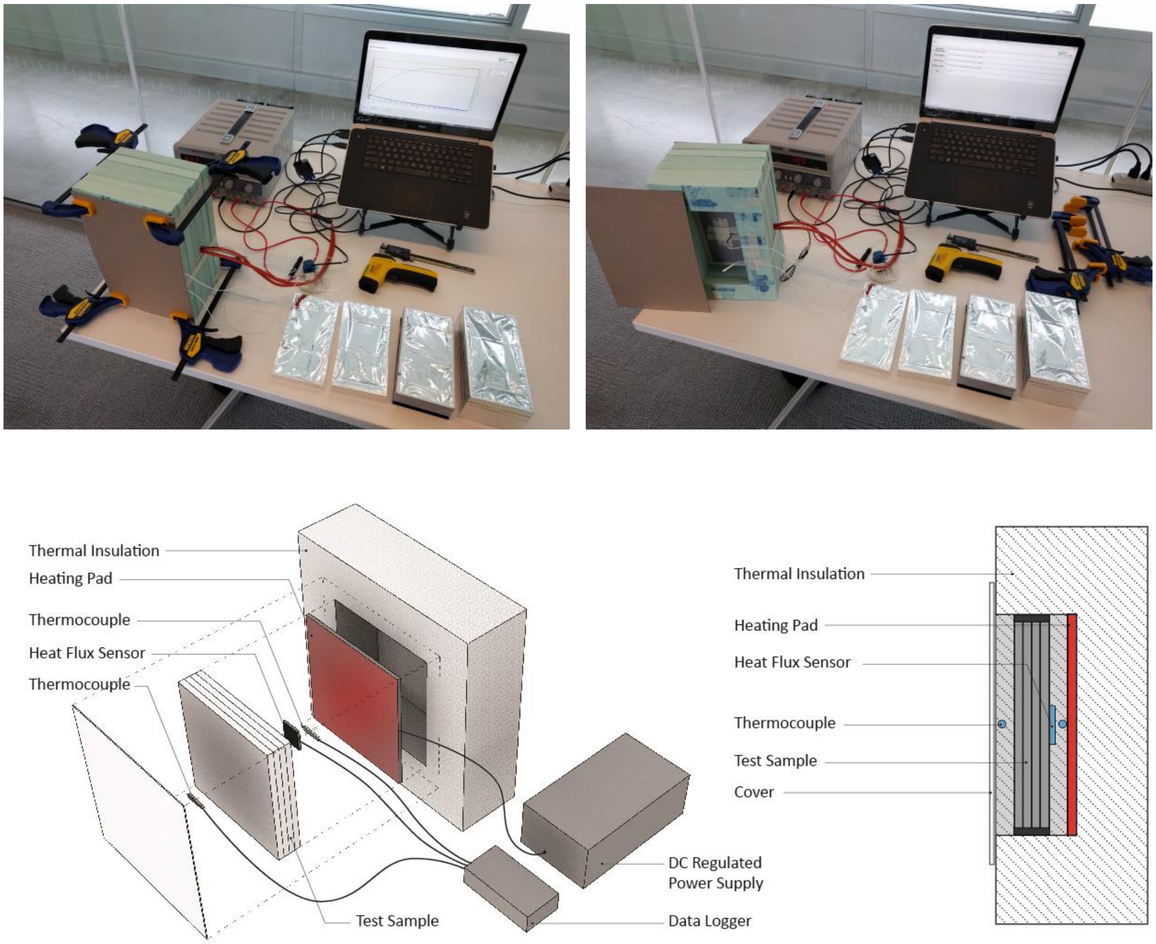


Figure 37 Radiant barrier insulation experiment setup
Experiment setup consists of DC regulated power supply, heat flux sensor, thermocouples, data logger, test sample, and insulative cover. The heat flux sensor and the outer thermocouple is protected from the surrounding air movement using a cardboard cover.

8.2 Experiment Results

The metric used for evaluating the performance of the thermal insulation system is the prescribed U-value of 0.35 W/m^{2}K for building envelopes.[5] U-value or the overall heat transfer coefficient is a convenient metric to evaluate the bulk behavior of building

5 ANSI/ASHRAE/IES Standard 90.1-2013

envelopes. Compared to the K-value which describes a specific material's thermal conductivity, the U-value measures the heat transfer rate of an assembly of materials (e.g. wall) over one square meter of the area at a standard condition (i.e. typically 24 °C, 50% humidity, and no wind).[6]

Once the data from the heat flux sensor and the two thermocouples are compiled, the mean U-value of the samples can be derived. Figure 38 shows the data set from the sample consisted of two air cavity layers measured for a duration of 12 hours. Thermocouple T1 which is located between the sample and the cardboard cover stabilizes at a mean temperature of 24.6°C (see Figure 38, red line). Thermocouple T2 which is located between the heating pad and the sample has a mean temperature of 67.7°C (see Figure 38, yellow line).

The mean heat flux of the data set is -16.1 W/m^2 which is calculated by dividing the measured voltage in V with a sensor-specific sensitivity of the gSkin sensor in μV/(W/m^2). The negative number signifies that the heat is flowing from the heating pad to the sample. Finally, the U-value can be derived by dividing the mean heat flux value with the mean temperature difference between T1 and T2. The chart indicates 1.33 W/m^{2}K as the mean U-value for this sample.

6 ASHRAE, 2013 ASHRAE Handbook -- Fundamentals, chap. 25.

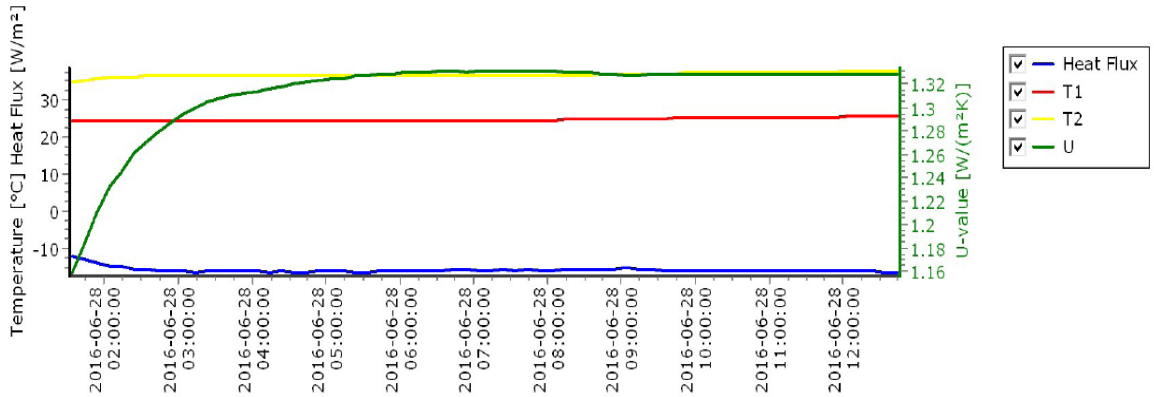


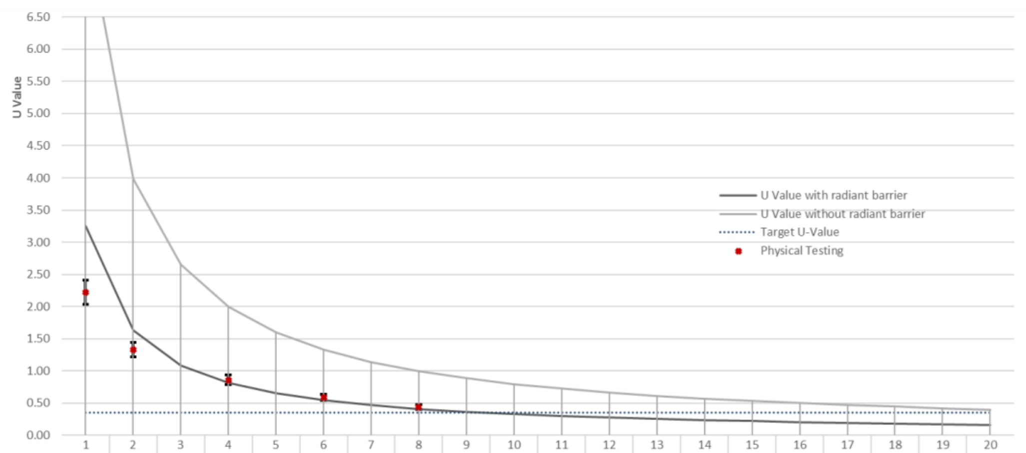
Figure 38 Data collection for the sample with two air cavity layers
The duration of the test is 12 hours and the calculated overall U-value based on the heat flux sensor, and the two thermocouples (i.e. T1 and T2) is 1.33 W/m^{2}K

Figure 39 shows the U-values from the experiments plotted against the U-values from the analytical model. This chart also shows the analytical model of the insulation component using conventional materials with an emissivity of around 0.9 as well as the insulation component using materials with an emissivity of 0.1 as spacer layers. Both the analytical model and the experiment results show that 9-10 air layers (optimum air cavity thickness of 8mm) separated by radiant barriers can achieve the targeted U-value of 0.35 W/m^{2}K.

The sources of the error propagation during the experiment include the accuracy of the gSkin® heat flux sensor, gSkin® data logger, thermocouple, air cavity spacing difference caused by the resolution of the 3d printer, and miscellaneous including heat loss through the foam encasing and placement of sensors (see Table 4). The error propagation is represented as error bars in Figure 39.

Table 4 Error propagation sources in Experiment 1

Source	Error (%)
gSKIN heat flux sensor	±3.00%
gSkin data logger	±1.33%
Thermocouple	±0.91%
Cavity spacing (3d print resolution)	±1.25%
Miscellaneous	±1.00%



n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
U Value with radiant barrier	3.25	1.63	1.08	0.81	0.65	0.54	0.46	0.41	0.36	0.33	0.30	0.27	0.25	0.23	0.22	0.20	0.19	0.18	0.17	0.16
U Value without radiant barrier	7.97	3.98	2.66	1.99	1.59	1.33	1.14	1.00	0.89	0.80	0.72	0.66	0.61	0.57	0.53	0.50	0.47	0.44	0.42	0.40
Target U-Value	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Physical Testing	2.22	1.33		0.86		0.59		0.44												

Figure 39 U-value and number of layers
U-value of Radiant barrier insulation against number of layers (optimum thickness based on the analytical model)

In order to further evaluate the analytical model, the measured data is compared with the predicted data. In addition to plotting the predicted data based on the Bejan model (see Equation 14), the predicted data using the analytical model developed by Kimber et al. is also plotted on the chart. Equation 15 presents the Kimber et al. model used for predicting the overall thermal resistance of the insulation system. For this model, Kimber, et al. uses the correlation between the Nusselt number and Rayleigh number developed by Wright[7] which is intended to be utilized for analyzing the natural convection heat transfer in multi-layered windows.

$$R_{ins} = (\mathrm{n}+1)\cdot\frac{t_b}{k_b} + n\cdot\frac{t_a}{k_a\cdot Nu_{t_a}}$$ **Equation 15**[8]

Where,

$$Nu_{t_a} = 0.0674\left(Ra_{t_a}\right)^{1/3} \quad for \;\; Ra_{t_a} > 5\times10^4$$
$$Nu_{t_a} = 0.0282\left(Ra_{t_a}\right)^{0.414} \quad for \;\; 10^4 < Ra_{t_a} \le 5\times10^4$$
$$Nu_{t_a} = 1 + 1.760\times10^{-10}0.0674\left(Ra_{t_a}\right)^{2.298} \quad for \;\; Ra_{t_a} \le 10^4$$

R_{ins}= overall insulation resistance	Nu_{t_a}= Nusselt Number
k_b = thermal conductivity of solid	k_a= thermal conductivity of air
t_b = thickness of solid layer	t_a = thickness of air layer
Ra_{t_a} = Rayleigh number (t_a)	n = number of cavities

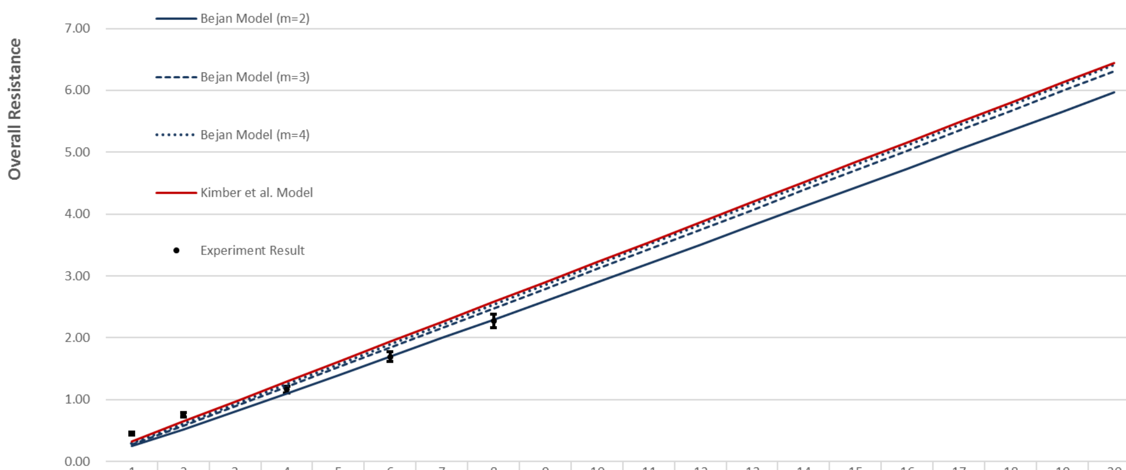
Figure 40 shows the measured and predicted overall thermal resistance of the insulation as a function of the number of air cavity layers. Each air cavity layer thickness is 8mm which is the maximum cavity dimension for suppressing convection heat transfer for a 200mm high cavity space. The trend of the curve is linear since the overall thickness of the insulation system increases proportionally with the increase in air cavity layers.

According to the chart, the predicted values for the Bejan model using curve smoothing exponent (m) of 3 (see Equation 14) and the Kimber et al. model is within the difference of 3%. As the curve smoothing exponent of the Bejan model increases, the difference

7 Wright, “Correlation to Quantify Convective Heat Transfer between Vertical Window Glazings.”

8 Kimber, Clark, and Schaefer, “Conceptual Analysis and Design of a Partitioned Multifunctional Smart Insulation.”

with the Kimber model decreases (within 1% when m = 5). The difference between the measured data and the predicted data is within the equipment error of 4.8% with the Kimber et al. model (and Bejan model with m value above 5) up to around three air cavity layers. For more than three layers, the measured data closely matches the Bejan model with m value below 4.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Bejan Model (m=2)	0.25	0.52	0.81	1.10	1.40	1.69	1.99	2.29	2.60	2.90	3.20	3.51	3.81	4.12	4.43	4.73	5.04	5.35	5.66	5.97
Bejan Model (m=3)	0.27	0.58	0.89	1.21	1.52	1.84	2.16	2.47	2.79	3.11	3.43	3.75	4.07	4.39	4.71	5.03	5.35	5.67	5.99	6.31
Bejan Model (m=4)	0.29	0.61	0.93	1.25	1.57	1.89	2.22	2.54	2.86	3.18	3.50	3.83	4.15	4.47	4.79	5.12	5.44	5.76	6.08	6.41
Kimber et al. Model	0.32	0.65	0.97	1.29	1.61	1.94	2.26	2.58	2.90	3.22	3.55	3.87	4.19	4.51	4.84	5.16	5.48	5.80	6.12	6.45
Experiment Result	0.45	0.75		1.16		1.69		2.27												

Figure 40 Comparison between measured and predicted overall resistance
The overall resistance of the insulation as a function of the number of layers for the measured data, Bejan model (for m=3, 4, and 5) and the Kimber et al. model.

Chapter 9. Experiment 2

Finned Heat Recovery Ventilator

This chapter presents the analytical model used for optimizing the passive heat recovery ventilator and the experiment process for physically testing it. The comparison between the predictions of the analytical model and the physical test results show a strong relationship. This validates the analytical model to be utilized for optimizing the proposed system for various temperature and geometric conditions.

9.1 Analytical Model

The design and optimization of the finned heat exchangers are based on the research relating to extended surfaces, natural convection, and solid to air heat exchangers. The simple finned configuration among various geometric possibilities (e.g. pins, waves, and honeycomb) is chosen to simplify the optimization and fabrication process. Figure 41 shows a vertical finned heat sink array that is cooled by natural ventilation. Equation 16 derives the optimum fin spacing (s) as a function of fin height (L) and fin efficiency (η_{fin})[9].

9 Fin efficiency is the ratio between heat transfer to actual fin and the heat transfer to an ideal fin (infinite conductivity)., Nellis and Klein, Heat Transfer.

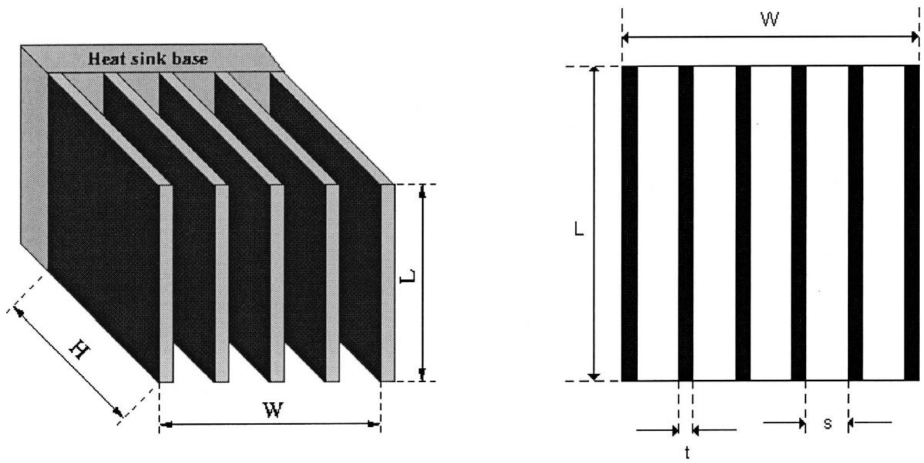


Figure 41 Finned heat sink array[10]
Vertical configuration (left); and 2-D schematic (right)

$$S_{opt} = 2.66(Lv^2/g\beta\eta_{fin}\,\Delta TPr)^{1/4}$$ **Equation 16**[11]

Where, S_{opt}= optimum fin spacing
v=mean kinematic viscosity of fluid
η_{fin}=fin efficiency
Pr=Prandtl number
L=fin height
g=gravitational acceleration, m/s^2
ΔT= ambient and base temperature difference

Figure 42 shows the overall heat transfer rate of an array of the finned surface as a function of fin spacing and fin height. The overall heat transfer is calculated using Equation 17. The colored curves which represent different fin heights (i.e. 0.2m, 1m, 1.5m, and 2m) increases as the fin spacing increases to a specific dimension and decreases afterward. The optimum fin spacing is at the peak of each curve, and this value matches the results from the analytical model presented in Equation 16.

10 Bar-Cohen, Iyengar, and Kraus, "Design of Optimum Plate-Fin Natural Convective Heat Sinks."
11 Ibid.

$$Q_T = n_{fin}Q_{fin} + h_{base}A_{base}\Delta T + Q_{rad}$$ **Equation 17**[12]

Where, Q_T= overall heat transfer rate

Q_{fin}= heat transfer rate of a single fin

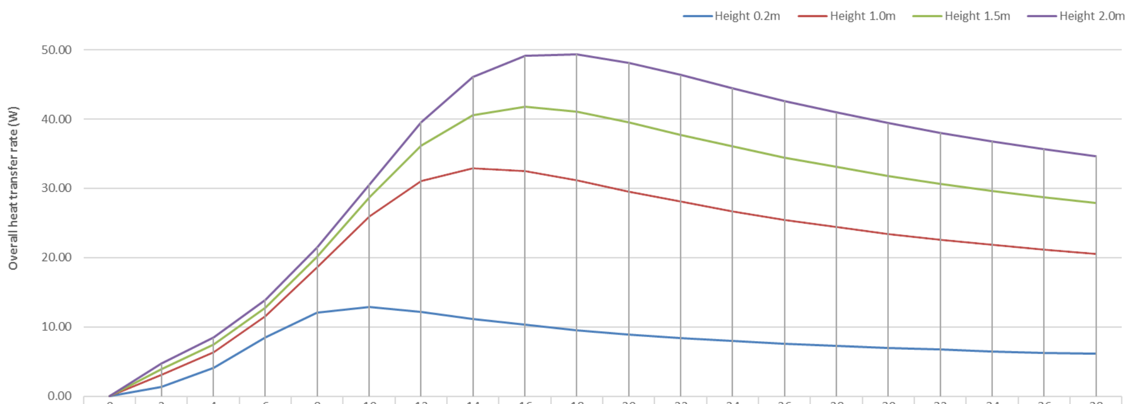
A_{base}= area of the unfinned base

Q_{rad}= radiation heat transfer rate

n_{fin}= number of fins

h_{base}= heat transfer coefficient of unfinned area

ΔT= ambient and base temperature difference



	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38
Height 0.2m	0.00	1.34	4.12	8.51	12.08	12.83	12.12	11.16	10.29	9.54	8.92	8.40	7.96	7.58	7.25	6.96	6.71	6.48	6.28	6.10
Height 1.0m	0.00	3.03	6.33	11.53	18.56	25.93	31.08	32.89	32.47	31.13	29.57	28.06	26.69	25.48	24.40	23.45	22.60	21.85	21.18	20.57
Height 1.5m	0	3.89276	7.43817	12.7896	20.1472	28.6703	36.2011	40.6129	41.8012	41.0511	39.4995	37.7461	36.0415	34.4726	33.0587	31.7934	30.662	29.6482	28.7365	27.9135
Height 2.0m	0	4.68196	8.45368	13.9263	21.4643	30.5737	39.5698	46.1148	49.1293	49.3836	48.1702	46.3855	44.4814	42.6499	40.96	39.4269	38.0447	36.7996	35.6761	34.6595

fin spacing (mm)

Figure 42 Heat transfer rate as a function of fin spacing and height

The optimum fin spacing (S) for achieving maximum heat transfer rate is largely based on the overall height of the fins (H- dimension in Figure 31). Other factors including the temperature difference and the length of the fins also have an effect.

9.2 Experiment Setup

Two samples with different fin lengths (i.e. 8.5mm and 17mm) were fabricated and tested to compare with the analytical model (see Figure 43). The overall height (200mm) and the width (100mm) are identical to the thermal insulation component, and the fin spacing is optimized for the height of 200mm and ΔT of 15ºC. In addition to the finned

12 Byon, “Optimal Design Method for Plate Fin Heat Sinks Subject to Natural Convection.”

surfaces, an unfinned surface with the same overall size is also fabricated and tested at the corresponding fin lengths of 8.5mm and 17mm (i.e. as an air gap without fins).

The DC regulated power supply and silicon heating pads are used as the heat source, and the prototype is encapsulated using foam insulation material. To allow buoyancy driven ventilation to occur, a slit that vertically exposes the fins is cut through the foam encasing. Furthermore, a hot-wire anemometer is inserted through the hole located towards the top of the foam encasing to measure the air flow between the fins.

Finally, three thermocouples are separately placed to characterize the thermal conditions of the sample. The thermocouple located near the bottom of the slit measures the temperature of the incoming air from the environment. The thermocouple placed near the top of the slit measures the temperature of the outgoing air which is heated by passing through the fins. Lastly, the thermocouple located between the finned surface and the heating pad measures the temperature of the heat source. (See Figure 43).

Four different states were measured using the experiment setup described above. These states consist of an air gap (i.e. slit width) of 17mm with fins, an air gap of 17mm without fins (i.e. surface without the fins), an air gap of 8.5mm with fins, and an air gap of 8.5mm without fins. The two states testing the air gap with unfinned surfaces is conducted to compare the heat exchange performance of the fins.[13]

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13 The metric used for evaluating this performance is the fin effectiveness which is the ratio between the heat transfer through the base surface with and without the fins., Cengel, Heat Transfer, chap. 3.

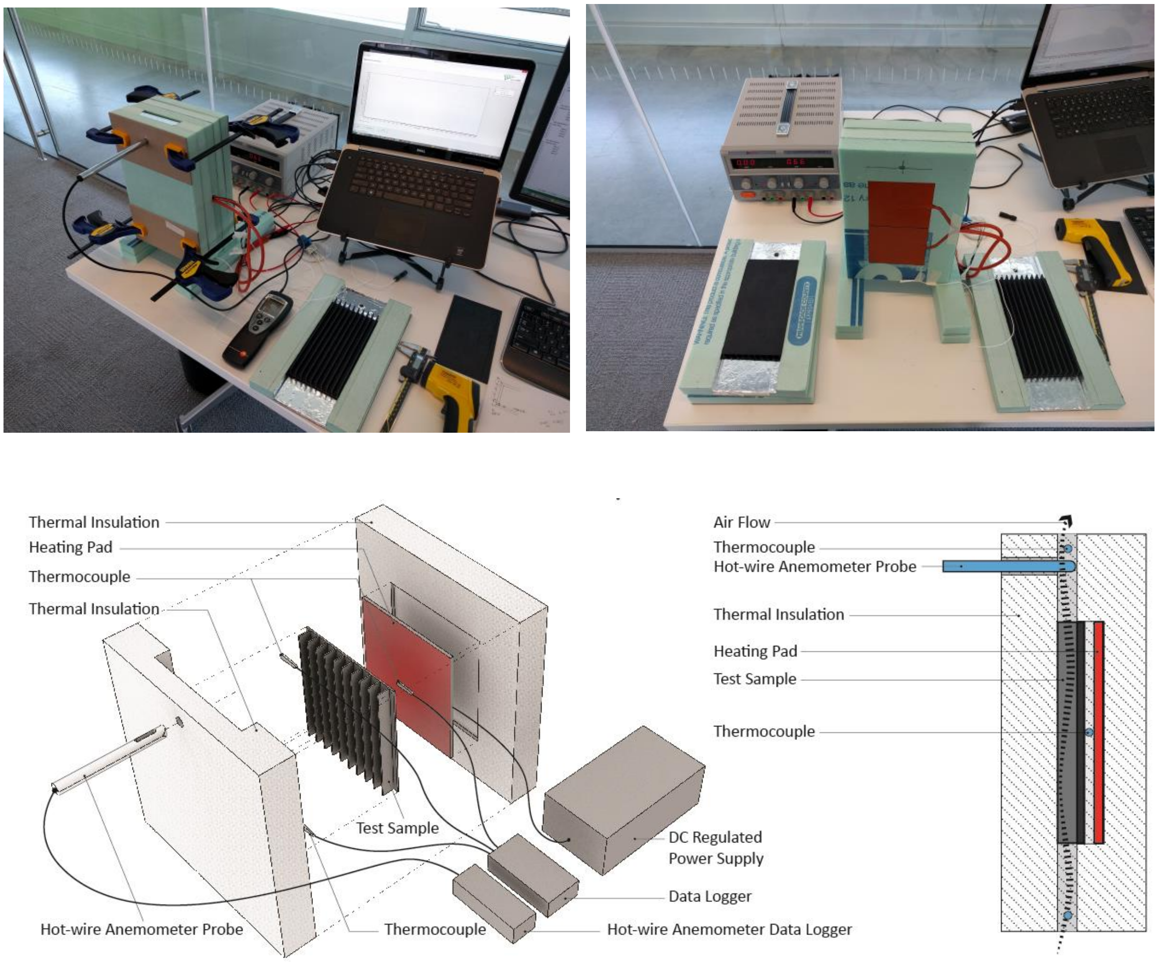


Figure 43 Finned heat exchanger (heat recovery) experiment setup
Experiment setup consists of DC regulated power supply, hot-wire anemometer, three thermocouples, data logger, test sample, and a heating pad.

9.2 Experiment Results

The evaluation of the heat exchanger as a buoyancy driven heat recovery ventilation is made using the heat transfer effectiveness (ε) metric in conjunction with measuring the air flow rate and the temperature difference between the air entering below the fin heat exchanger and air escaping above the fin heat exchanger (see Table 5). The heat transfer effectiveness (ε) is a dimensionless parameter used to evaluate the performance of heat exchangers and defined as the ratio between the actual heat transfer rate ($\dot{Q}$) and maximum possible heat transfer rate ($\dot{Q}_{\max}$).[14] (See Equation 18.)

Table 5 Experimental results

	Current (A)	Voltage (v)	Power (W)	T_b (ºC)	T_inf (°C)	deltaT (°C)	T_out (°C)	Air Velocity (m/s)	Heat transfer surface area (m^2)	Channel section area (m^2)	Volumetric flow rate (m^3/s)	C_min	q_max	q_dot	Effectiveness (ε)
Air Gap 17mm with Fins															
Test 1	0.86	1	0.86	28.8	22.8	6	25.3	0.05	0.1011500	0.0015160	0.0000758	0.0000933	0.86	0.36	0.417
Test 2	1.34	1.5	2.01	33.9	23	10.9	28.2	0.07	0.1011500	0.0015160	0.0001061	0.0001306	2.01	0.96	0.477
Test 3	1.71	2	3.42	37.8	23	14.8	29.9	0.08	0.1011500	0.0015160	0.0001213	0.0001493	3.42	1.59	0.466
Test 4	2.09	2.3	4.807	44.1	23.5	20.6	32.8	0.09	0.1011500	0.0015160	0.0001364	0.0001680	4.81	2.17	0.451
														Average	0.453
Air Gap 17mm without Fins															
Test 1	0.86	1	0.86	27.4	22.3	5.1	24	0.1	0.0200000	0.0017000	0.0001700	0.0002093	0.86	0.29	0.333
Test 2	1.34	1.5	2.01	33.4	22.4	11	25.5	0.14	0.0200000	0.0017000	0.0002380	0.0002930	2.01	0.57	0.282
Test 3	1.68	2	3.36	39.9	22.6	17.3	27	0.17	0.0200000	0.0017000	0.0002890	0.0003558	3.36	0.85	0.254
Test 4	1.9	2.3	4.37	44.6	22.8	21.8	28	0.18	0.0200000	0.0017000	0.0003060	0.0003767	4.37	1.04	0.239
														Average	0.277
Air Gap 8.5mm with Fins															
Test 1	0.66	0.8	0.528	28.8	23.1	5.7	25.4	0.02	0.0697030	0.0008010	0.0000160	0.0000197	0.53	0.21	0.404
Test 2	1	1.2	1.2	33.4	23.3	10.1	28.1	0.03	0.0697030	0.0008010	0.0000240	0.0000296	1.20	0.57	0.475
Test 3	1.51	1.8	2.718	40.6	23	17.6	31.1	0.02	0.0697030	0.0008010	0.0000160	0.0000197	2.72	1.25	0.460
Test 4	1.8	2.2	3.96	45.7	23.3	22.4	33.3	0.01	0.0697030	0.0008010	0.0000080	0.0000099	3.96	1.77	0.446
														Average	0.446
Air Gap 8.5mm without Fins															
Test 1	0.77	0.9	0.693	29.5	23.3	6.2	25.5	0.05	0.0200000	0.0008500	0.0000425	0.0000523	0.69	0.25	0.355
Test 2	1.14	1.3	1.482	33.6	23.1	10.5	26.9	0.06	0.0200000	0.0008500	0.0000510	0.0000628	1.48	0.54	0.362
Test 3	1.45	1.8	2.61	38.6	23.3	15.3	28.9	0.08	0.0200000	0.0008500	0.0000680	0.0000837	2.61	0.96	0.366
Test 4	1.7	2.1	3.57	44.1	23.3	20.8	31	0.09	0.0200000	0.0008500	0.0000765	0.0000942	3.57	1.32	0.370
														Average	0.363

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{C_c\left(T_{c,out} - T_{c,in}\right)}{C_{min}\left(T_{h,in} - T_{c,in}\right)}$$

Equation 18

where: ε = heat transfer effectiveness

$\dot{Q}$ = actual heat transfer rate

$\dot{Q}_{max}$ = maximum possible heat transfer rate

C_c = heat capacity rate (cold fluid)*

C_{min} = smaller heat capacity rate*

$T_{c,out}$ = outlet temperature (cold fluid)

$T_{c,in}$ = inlet temperature (cold fluid)

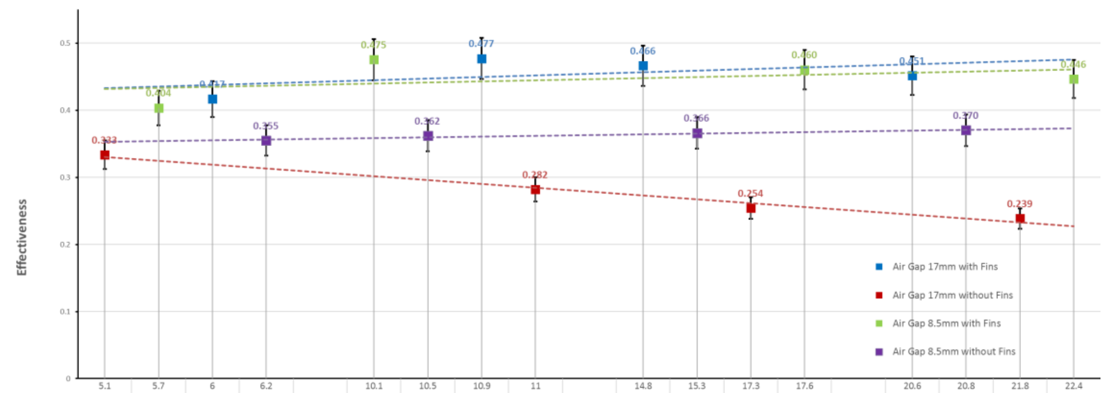
$T_{h,in}$ = inlet temperature (hot fluid)

*Heat capacity rate (C) is the product of the mass flow rate and the specific heat of the fluid. In the experiment setup, $C_{min} = C_c$ since the heated plate maintains a constant temperature ($C_h = \infty$).

The effectiveness of each sample setting can be derived from the air velocity and T_{out} (outgoing air from the top of the sample) measurements (see Table 5). The result fits well with the analytical model with the average effectiveness of around 0.45 for samples

14 Nellis and Klein, Heat Transfer, sec. 8.3; Cengel, Heat Transfer, chap. 13.

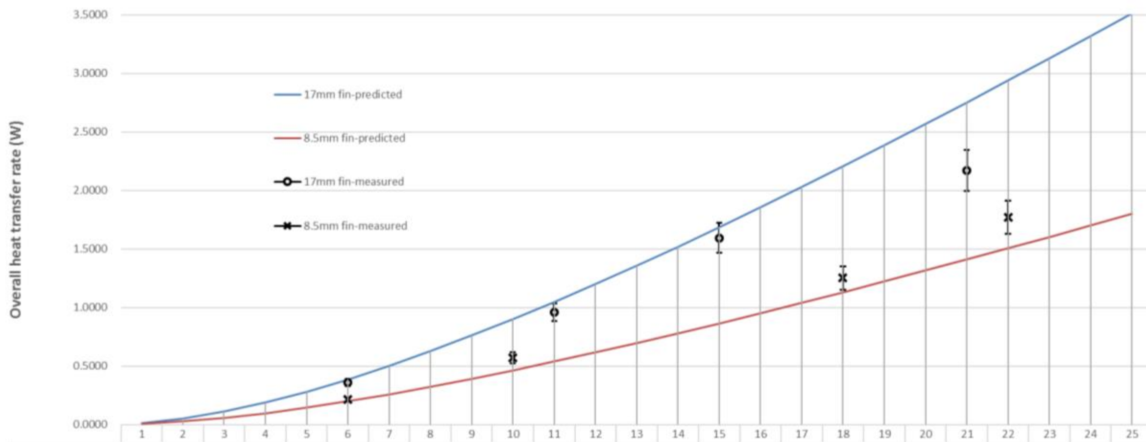
with fins and around 0.3 for samples without fins. This result is consistent with a broad range of temperature difference (5ºC to 20ºC) and two different air gaps (8.5mm and 17mm). (See Figure 44.)



	5.1	5.7	6	6.2	10.1	10.5	10.9	11	14.8	15.3	17.3	17.6	20.6	20.8	21.8	22.4
Air Gap 17mm with Fins			0.417				0.477		0.466				0.451			
Air Gap 17mm without Fins	0.333							0.282			0.254				0.239	
Air Gap 8.5mm with Fins		0.404			0.475							0.460				0.446
Air Gap 8.5mm without Fins				0.355		0.362				0.366				0.370		

Figure 44 Heat exchanger effectiveness (ε)
Experimental result of the heat exchanger effectiveness for each sample setup at different temperature difference.

Figure 45 shows the measured and predicted overall heat transfer rate as a function of ΔT. The values for both the 17mm fins and 8.5mm fins are plotted. It is clear that up to ΔT of approximately 20°C, the predicted and the measured values match closely. At this range of temperature difference, the radiation heat loss through the fin surface and the direct influence of the heating pad (8.5mm fins) contributes to the difference in value. However, above the ΔT of 20°C the friction in the air channels increase significantly due to the increase in buoyancy force (the fin spacing is optimized for ΔT of 15°C).



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
17mm fin-predicted	0.0140	0.0518	0.1105	0.1871	0.2791	0.3841	0.5001	0.6257	0.7594	0.9002	1.0473	1.1999	1.3574	1.5194	1.6855	1.8552	2.0284	2.2047	2.3839	2.5660	2.7506	2.9377	3.1272	3.3189	3.5127
8.5mm fin-predicted	0.0077	0.0275	0.0578	0.0972	0.1443	0.1980	0.2573	0.3214	0.3898	0.4618	0.5370	0.6150	0.6956	0.7784	0.8634	0.9503	1.0390	1.1293	1.2211	1.3144	1.4091	1.5050	1.6022	1.7005	1.7999
17mm fin-measured						0.3583					0.9589				1.5945						2.1702				
8.5mm fin-measured						0.2131				0.5703								1.2509				1.7679			

Figure 45 Measured and predicted overall heat transfer rate
The comparison between the measured and predicted overall heat transfer rate as a function of indoor and outdoor temperature difference. The heat exchanger effectiveness (ε) is based on the experimental data (see Table 5).

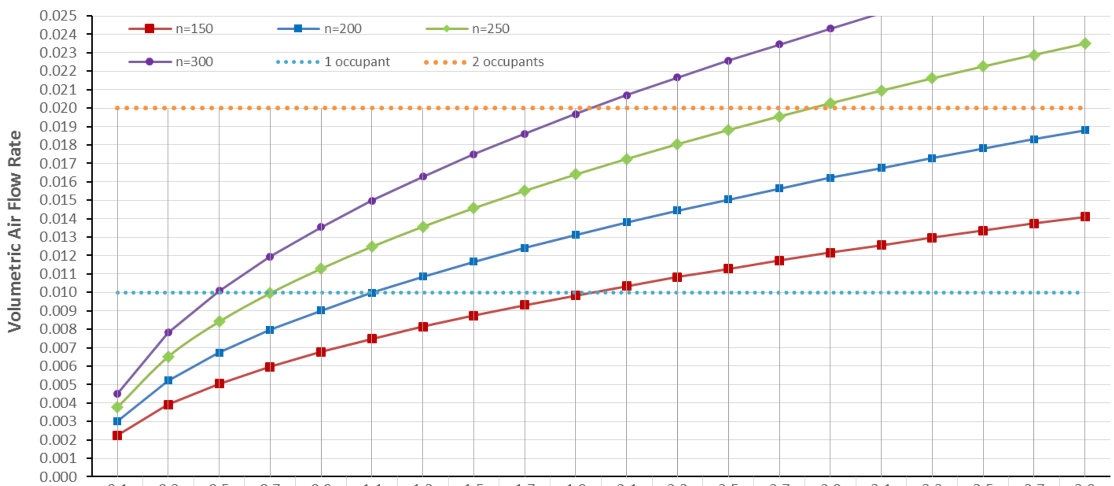
The sources of the error propagation during the experiment include the accuracy of the power supply reading, hot-wire anemometer, gSkin® data logger, thermocouple, fin dimensional difference caused by the resolution of the 3d printer, and miscellaneous including heat loss through the foam encasing and placement of sensors (see Table 6). The error propagation is represented as error bars in Figure 44 and Figure 45.

Table 6 Error propagation sources in Experiment 2

Source	Error (%)
Power supply reading	±3.00%
Hot-wire anemometer	±5.00%
gSkin data logger	±1.33%
Thermocouple	±0.91%
Fin and base plate thickness	±1.25%
Miscellaneous	±1.00%

Once the ε is derived using the experimental data, it is possible to size the heat recovery ventilator to provide sufficient amount of preheated fresh air to the interior space. In the case of this experiment, the target is set to passively provide 0.01 m^3/s of the fresh outside air to the interior space per person at 80 percent of the indoor air temperature[15].

The overall height, width, and thickness of the finned heat exchanger can be designed using the criteria to provide 0.01m^3/s of the fresh outside air to the interior space per person[16] at 80 percent of the indoor air temperature. Figure 46 shows the volumetric air flow rate based on the height of the finned heat exchanger for a different number of fins (i.e. overall width of the heat exchanger).



	0.1	0.3	0.5	0.7	0.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5	3.7	3.9
n=150	0.002	0.004	0.005	0.006	0.007	0.007	0.008	0.009	0.009	0.010	0.010	0.011	0.011	0.012	0.012	0.013	0.013	0.013	0.014	0.014
n=200	0.003	0.005	0.007	0.008	0.009	0.010	0.011	0.012	0.012	0.013	0.014	0.014	0.015	0.016	0.016	0.017	0.017	0.018	0.018	0.019
n=250	0.004	0.007	0.008	0.010	0.011	0.012	0.014	0.015	0.016	0.016	0.017	0.018	0.019	0.020	0.020	0.021	0.022	0.022	0.023	0.023
n=300	0.005	0.008	0.010	0.012	0.014	0.015	0.016	0.017	0.019	0.020	0.021	0.022	0.023	0.023	0.024	0.025	0.026	0.027	0.027	0.028
1 occupant	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
2 occupants	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020

Height

Figure 46 Volumetric air flow rate based on number of fins (n)
The length of the fins used in the chart is 30mm and the target volumetric air flow rate for one and two occupants are marked using a dotted line (orange and blue).

15 ANSI/ASHRAE Standards 62.1 and 62.2-2013

16 ANSI/ASHRAE Standards 62.1 and 62.2-2013

According to the chart, the heat exchanger with 150 optimally spaced fins (total width of 1.5m at fin height of 30mm and overall height of 1.9m) has a volumetric flow rate of 0.01m^3/s which can provide fresh air to 1 occupant. Doubling the number of fins can provide sufficient air for two occupants. Some possible heat exchanger configurations using this chart is presented in section ***10.3 Heat Exchanger Component*** (see Figure 50).

Chapter 10. Experiment Discussion and Conclusion

10.1 Overall System Design and Fabrication

The proposed system is an adaptive insulation that can selectively control how air and heat permeate through the building envelope. Based on the literature review of adaptive insulation in Chapter 6, the system can be categorized as a *parietodynamic system* since it uses closed air channel for heat and air exchange. The air channels of the proposed system operate as an efficient heat exchanger due to the thermal conductivity of the material and extended surfaces using finned geometry.

Furthermore, the proposed system can also become a *tunable system* (see section 6.3.3 Tunable systems) by implementing the method developed by Kimber et al.[17] If the thermal insulation component is designed so that the thickness of each air cavity spaces can change, the thermal resistivity can also be controlled. Figure 47 shows the thermal resistance of one air cavity space as a function of thickness using Equation 14. This chart demonstrates that the thermal resistivity of a cavity space can change from 5.7 for air cavity thickness of 1mm to 7.3 for air cavity thickness of 7mm.

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[17] Kimber, Clark, and Schaefer, "Conceptual Analysis and Design of a Partitioned Multifunctional Smart Insulation."

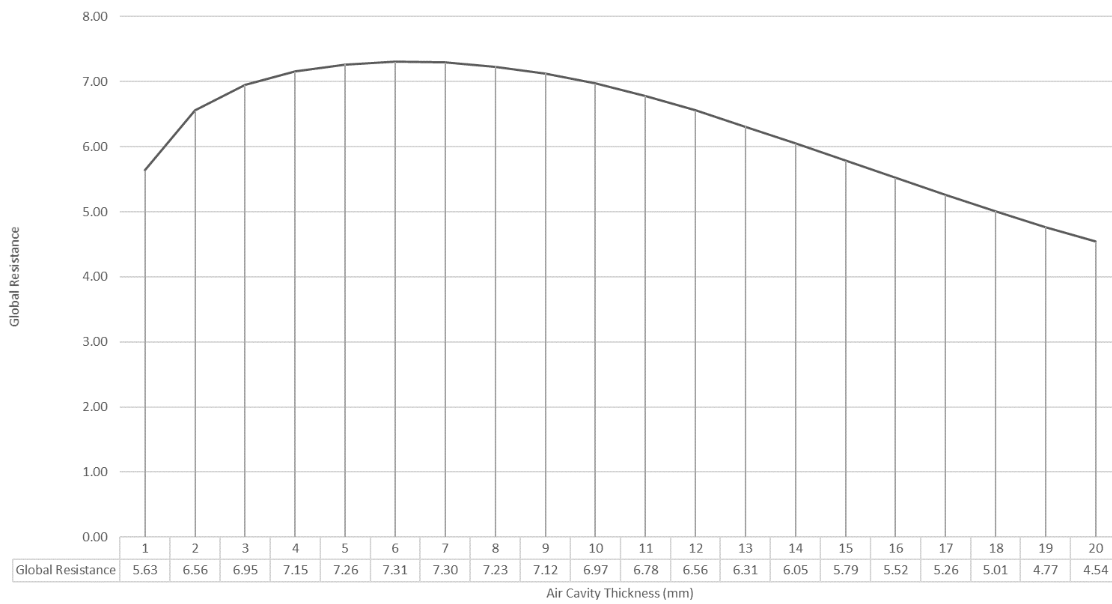


Figure 47 Thermal resistance of one air cavity space as a function of thickness
The thermal resistance can vary between 5.7 to 7.3 depending on the thickness of the air cavity.

The proposed building envelope system is the capacity to match or surpass recommended thermal performance criteria with an extremely lightweight, compact and efficient design. Compared to the complex and bulky construction of the commonly existing building envelope systems (i.e. masonry, concrete, and wood frame construction) the system is mainly composed of components made of plastic and polymer composites that can easily fit together and be assembled. However, for a wider range of building applications, it is necessary to develop the system to satisfy the criteria including mechanical and structural capacity; durability; and cost.

Based on the analytical models and physical testing results, the envelope system can be optimized for a wide range of temperature conditions, shapes, and sizes. To take advantage of this feature, the analytical models are scripted into a computer-aided-design (CAD) based parametric modeling tool (Rhino and Grasshopper) so that the various parameters that affect the geometry and sizing of the system can be seen in real-time. This procedure significantly contributes to simplifying the design and optimization process as it is possible to see and understand the relationships in real time visually (see Figure 48).

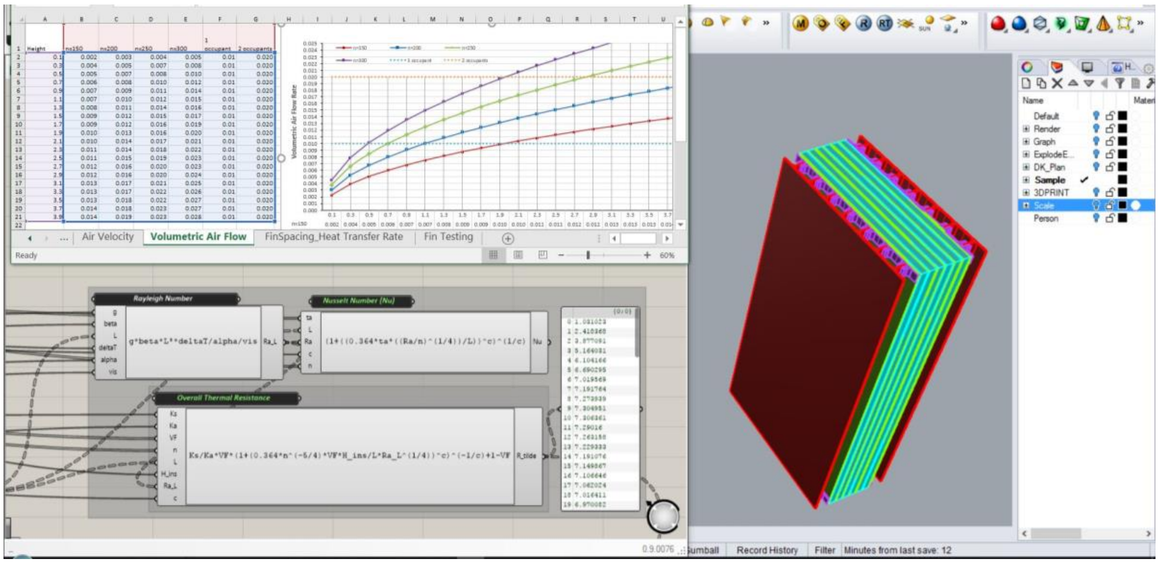


Figure 48 Parametric Analytical Model
Workflow between Grasshopper, Rhinoceros (CAD), and Microsoft Excel

The main fabrication method for the prototypes is additive manufacturing using specific materials that satisfy the functional requirements. For instance, the heat exchanger components not only has to be thermally conductive but also mechanically strong and tough to function as interior and exterior finishes. On the other hand, the frames that hold the low-emissivity films not only have to function as the main structure for the entire envelope but also need to have low conductivity to minimize thermal bridging.

The 3d printing method can allow more complex and intricate geometries that can further enhance the targeted functions of each component. The frames that hold the low emissivity films have low-density infill so that still air can occupy the empty spaces. The infill pattern itself is chosen to minimize the effect on mechanical strength. Also, the dark surface of the heat exchanger is also augmented by surface texture created by the 3d printing process. The linear patterned ridges reinforce the direction of the air flow, and the increased surface area further aids in the heat exchange between air and the fins. (See Figure 49).

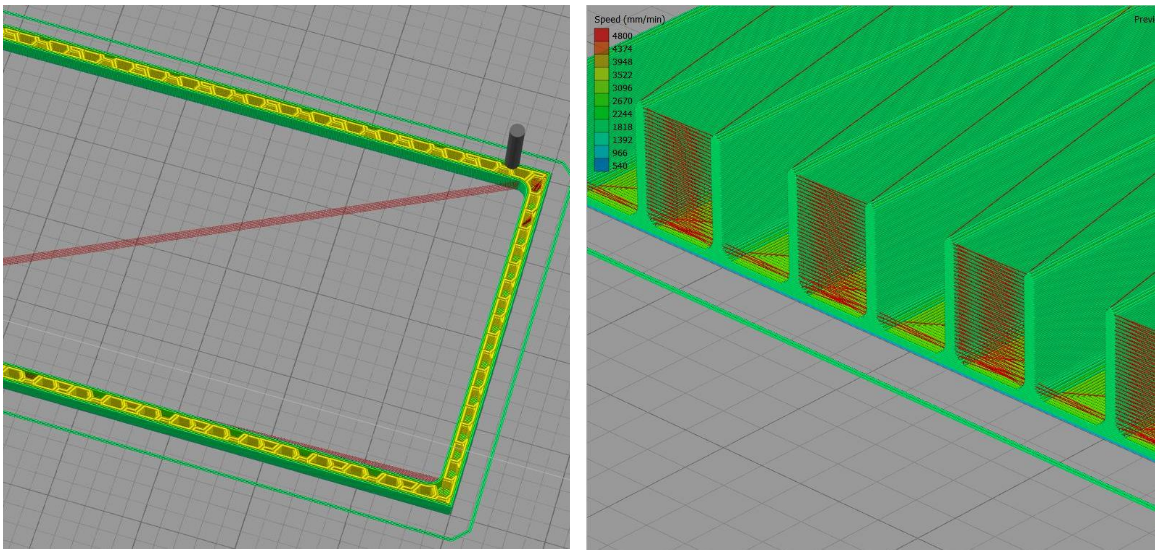


Figure 49   Infill pattern and surface texture
Infill pattern and density can be controlled based on the structural and thermal requirements (left); and the directionality and resolution of the surface texture can be controlled using the 3d printer setup (e.g. 3d printing sequence, the height of each layer, and print speed).

10.2 Thermal Insulation Component

The layered radiant barrier insulation experiment verifies that the performance of this system can satisfy the targeted U-value of 0.35 $W/m^2{\cdot}K$ using approximately nine air cavity layers. The optimized cavity thickness for maximizing thermal resistance is 8mm which makes the overall thickness of the system 72mm. This result is competitive regarding thickness compared to other existing thermal insulation materials. For instance, mineral wool and fiberglass quilt need 140mm; and rigid foam board needs 70mm to achieve the U-value of 0.35 W/m^2K.

The usage of radiant barriers also significantly improves the thermal insulation performance. According to Figure 39, more than 20 air cavity layers are needed to achieve the targeted U-value which makes the component 160mm thick. The metalized polymer films used as both radiant barriers as well as the air cavity dividers for the prototypes is also competitive to other common insulation materials.

Also known as space blankets, metalized polymer film is affordable, lightweight, and widely available; and is commonly used in insulation, packaging, decoration, and electronics products. These properties make it possible to create an extremely efficient thermal insulation system. However, further development of the design and fabrication method is needed to improve the mechanical properties, airtight seal method, and implementation strategies for a variety of envelope designs (i.e. shape and size).

Due to the usage of thin films as airtight dividers, it is necessary to have a structural element that maintains the overall form and also holds the film tight in place. The current method used for the prototypes is to 3d print a rigid plastic frame and use adhesive to assemble them into a unit. Since the frame requires mechanical strength and surface area for adhesion, there is a certain thickness that is necessary.

This can create a thermal bridge which transfers heat directly through the frames via conductive heat transfer. In order to minimize this effect, low-density infills are embedded within the frame (see Figure 49, left). This can be further mitigated using stronger materials and changing the method for creating an airtight connection between the films and frames.

10.3 Heat Exchanger Component

The experimental results of the finned heat recovery ventilation component show that the effectiveness of the component significantly improves when extended surfaces such as vertical fins are properly used (e.g. effectiveness of 0.3 for samples without fins and 0.45 for samples with fins). This data is consistent with a range of different temperature conditions and component sizing (i.e. from the temperature difference of 5ºC to 20ºC and fin height of 8.5mm and 17mm).

This signifies that it is possible to design and optimize a heat exchanger component that performs well in a wide range of temperatures and wall configurations. Figure 50 show some of the possible configurations that can achieve targeted criteria to passively provide a volumetric air flow rate of 0.01m^3/s at 80 percent of the interior air temperature per occupants.

Other parameters that need to be considered during the design and optimization of the component are the fin length and thermal conductivity of the fin material. These factors not only drastically affect the required height and width of the system but also the cost and spatial requirements of the system (see Figure 50). Taller fins require less wall surface with a sacrifice in efficiency which is largely related to the thermal conductivity of the fin material.

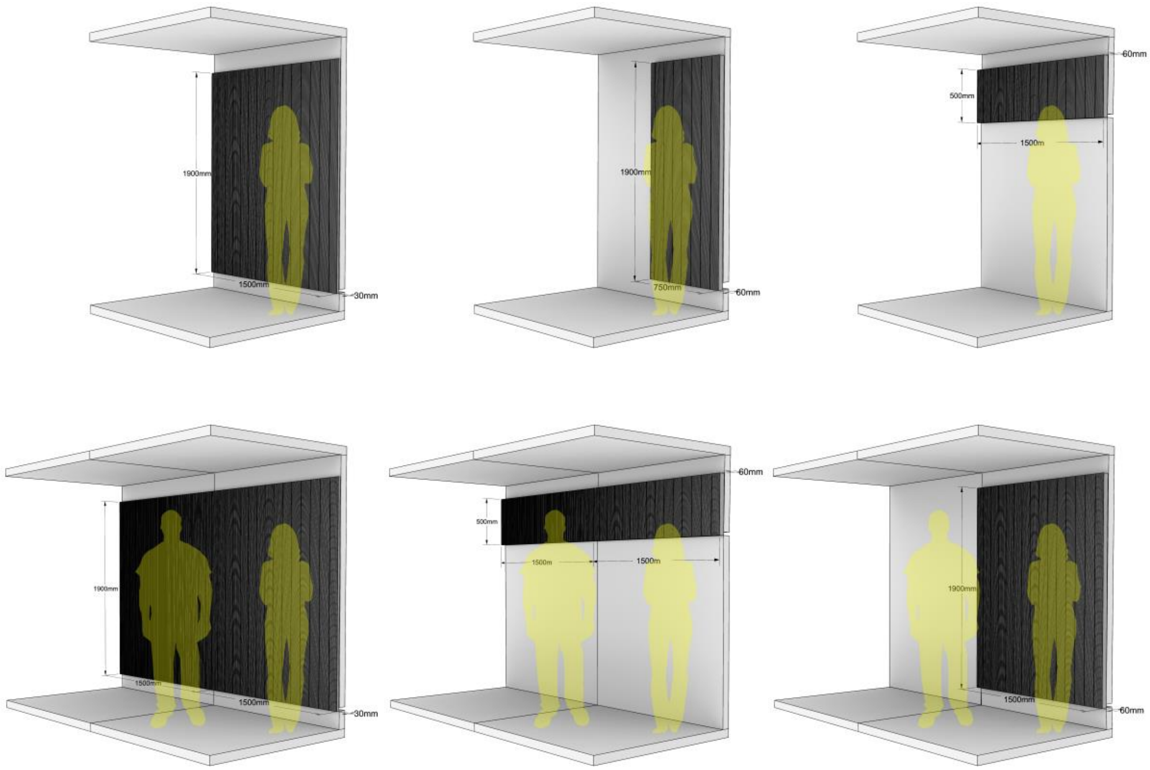
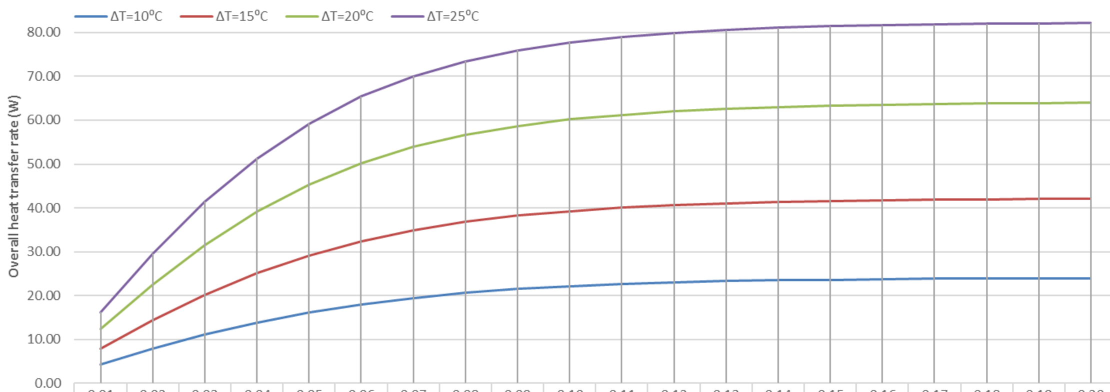


Figure 50 Possible configurations of the heat exchanger
The configurations are based on variable height, width, and thickness of the finned heat exchanger. The top row is designed for one occupant, and the bottom row is sized for two occupants.

According to the conductive heat transfer equation described in Equation 1, the rate of conductive heat transfer is proportional to the conductivity of the materials, cross section area, and temperature difference; and inversely proportional to the thickness (i.e. fin length) of the material. Therefore, selecting a material with high thermal conductivity is critical for achieving higher efficiency. For a given material, the heat transfer rate increases with the length of the fins with diminishing increase of rate (see Figure 51).



	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.20
ΔT=10°C	4.34	7.87	11.07	13.85	16.16	18.03	19.51	20.65	21.52	22.17	22.66	23.02	23.29	23.49	23.64	23.76	23.84	23.90	23.95	23.99
ΔT=15°C	7.90	14.38	20.18	25.15	29.22	32.45	34.95	36.84	38.26	39.30	40.07	40.63	41.04	41.34	41.56	41.73	41.85	41.94	42.01	42.06
ΔT=20°C	12.35	22.50	31.54	39.18	45.37	50.21	53.91	56.66	58.69	60.17	61.25	62.02	62.58	62.99	63.28	63.50	63.66	63.78	63.87	63.95
ΔT=25°C	16.20	29.57	41.39	51.29	59.24	65.39	70.02	73.43	75.92	77.71	79.00	79.92	80.58	81.05	81.40	81.65	81.83	81.97	82.08	82.16

fin length (m)

Figure 51 Overall heat transfer rate, fin height, and temperature difference
The mechanics of heat transfer through the fins via conduction (e.g. fin length, the conductivity of fins, and temperature difference) governs the heat transfer rate.

Some of the critical challenges with the current design of the component is related to the interior heat exchanger surface and vent for the incoming exterior air. The former challenge occurs because the current interior heat exchanger surface only relies on air convection and radiation for the heat supply which is not sufficient to maintain the surface at a constant temperature (the experiment uses an electric heating pad as the heat source). Therefore, strategies such as embedding thin water tubes that circulate water between the heat source and the interior surface of the heat exchanger needs to be investigated.

The exterior side heat exchanger is activated during the day when there is access to solar radiation, and this is a sufficient heat source for the buoyancy driven ventilation to occur. Furthermore, keeping the surface finish dark and matt can make the heat exchanger absorb and emit radiation at a faster rate.

The latter challenge occurs because of the temperature difference between the incoming fresh air from the outside and the interior side heat exchanger surface. This creates a condition, particularly near the vents, where condensation can occur on inner or outer heat exchanger surface. When the incoming air is colder than the interior space, water vapor can condense in the interior side of the heat exchanger surface. When the incoming air is hotter than the interior space, water vapor can condense in the outer side of the heat exchanger surface.

The condensation issues near the vent can be mediated using the following strategies. Using existing architectural detailing strategies such as using insulation near the vents to keep the temperature above dew point; using vapor retarders to keep the warm-side vapor in and ventilate the cold side to let the water vapor escape; and provide drainage channels and weep holes for channeling the water out as the second line of defense.

10.4 Experiment Conclusion

This chapter presented the design of a thermally augmented building envelope system that approximates the three-layered configuration and functional separation of plant stems. The overall system is designed and optimized at different length scale including material characteristics at the micrometer scale; air cavity and channel dimensions at the millimeter scale; and modular subdivision of the envelope in the centimeter and meter scale.

The key criteria for optimizing the system is the size and shape of the heat transfer mechanics (i.e. conduction, convection and radiation) and the required material properties to achieve the targeted thermal function. Other factors such as cost, constructability, mechanical properties, and fabrication techniques also influence the design of the system, particularly at the extreme ends of the scale spectrum (i.e. submillimeter and meter scale).

The physical testing results of both experiments support the predictions made using the heat transfer correlations. These results not only ensure that the performance of the envelope system will meet the targeted benchmark but also validates using the developed analytical models in designing the envelope system in a variety of locations, climates, shapes, and sizes. The geometry and size of the air cavities and channels can also be designed to operate in a wide range of temperatures and conditions.

Since the proposed envelope system is in its early development phase, many challenges that were presented in the discussion section needs to be addressed in the next phases of development. Some of the problems are related to the limitations of the materials and the fabrication methods, and others are linked to detailing and the design of the system which can be readily mediated. However, the issue of the heat exchange between the interior space and the interior side heat exchanger surface needs further investigation for the component to function as a heat recovery ventilator.

Finally, there can be two parallel tracks of the next phase of research and development. The first approach is to maximize the thermal and performance of the heat exchanger using more complex and elaborate geometries via 3d printing fabrication method. The second approach is to keep the geometry simple and use more conventional materials and material processing methods (e.g. extrusion or stamping sheet metals) for achieving maximum efficiency regarding cost and performance.

Chapter 11. Conclusion and Future Work

11.1 Summary and Contributions

This chapter will summarize and review the main methods, findings, and contributions of the overall research and discuss the implications of them in practice.

The overarching theoretical framework of the overall research consists of three key methods. The first method is utilizing the multiscale configuration commonly found in biological material systems as the tectonic for developing building elements (i.e. systems, components and materials). This method is investigated through comparing the multiscale thermal design strategies and applications of both biological systems and artificial systems. The classification of thermal design by its function and scale is deeply related to how the multiscale tectonic is applied in biological systems. The product design strategies from the other industries (both low and high tech) serve as informative precedents to the building industry.

The second method is the emphasis on the using the shape and size of heat flow as the key parameter for the thermal design and optimization of the building elements. This method is explored by looking into fundamentals of heat transfer and how experts in the field of thermal optimization utilize this method to conduct research. This principle is the governing criteria for optimizing the proposed building envelope system in the experiment chapter. The shape and size of the air cavities are optimized for suppressing convective heat transfer, and air channels are optimized to allow sufficient passive buoyancy driven heat exchange. Furthermore, microstructures within the rigid framing elements as well as the linear texture of heat exchanger surface augment the thermal performance of the system by minimizing the thermal bridging and increasing the surface area.

The third method is understanding the fundamentals of materials and material processes to strategically select and configure the multiscale building elements in novel ways. This method is investigated through studying the thermal properties of materials, the material selection process, and the related fields of architectured multiscale materials research including cellular materials, functionally graded materials, and adaptive materials. In addition to this, material processing methods of biological systems and artificial systems are evaluated, and additive manufacturing method is further discussed as a key enabling fabrication process.

The experiment chapter synthesizes the findings and methods identified and investigated in the previous chapters for developing a thermally augmented building envelope system. The proposed system consists of low-density plastic frame encased in metalized polymer sheet and a 3d printed finned heat exchanger using conductive plastic. This strategy makes the system an extremely lightweight and compact envelope system that can be customized and deployed in various temperature, dimension, and shape variables.

The proposed system follows the three layered multiscale tectonics of plant stems, and the optimization is applied in three scales. These include envelope configuration and subdivision scale (meter to centimeter); air channel and cavity dimension scale (centimeter to millimeter); and material thickness and surface texture scale (millimeter to micrometer). Each length scale domains are designed and optimized to perform a specific thermal function (e.g. heat exchanger, thermal insulation) as well as to satisfy other factors and constraints including constructability, cost, and mechanical properties.

The results of the analytical model and the physical testing show strong correlations which validate the usage of analytical models in designing a broad range of configurations and scales of components and systems that can successfully perform at a variety of temperature conditions. To evaluate the performance of the systems two separate target standards including recommended U-value for building envelopes; and ventilation rate and heat recovery rate per occupant is used.

Once the physical experiments validated the analytical models, correlations are integrated with a parametric CAD tool to virtually test a wide range of variables and conditions at the same time (i.e. multifunctional and multiscale optimization). This allows architects to easily apply different conditions (e.g. climate and envelope dimension) and quickly get the optimum system configuration for prototyping or manufacturing.

The overall dissertation can provide architects with limited experience and knowledge of thermal design and optimization, gain the essential knowledge, processes, and strategies to develop innovative multiscale material systems for maximizing the thermal performance. This will enable architects to not only understand the impact and potentials of managing heat in buildings but also allow them to actively participate in the design and development of innovative building materials and components. Although this research is focused on heat as the key topic, the principles and approaches can be applied to other environmental factors such as light and sound.

11.2 Recommendation for Future Work

The following recommends three key areas that this research can be further improved and expanded.

First, building envelope systems that can effectively adapt to the short-term and long-term thermal environment changes is a promising area for further research. The adaptive materials (i.e. smart materials and programmable matter) and adaptive insulation, introduced in Chapter 5 and Chapter 6 respectively, have high potentials for both passive and active control of the interior thermal environment. Some possible methods include using temperature-responsive materials that can deform the air channels or cavity spaces and utilize manual or automatic actuators (e.g. linear actuator, pneumatic actuators) to open or close a network of air vents strategically.

Second, the multi-objective optimization methods and processes can be further expanded for implementing them in a broader range of geometric configuration, types of materials, and functional requirements. Similar to the envelope system proposed in this thesis, synthetic polymer composites can be strategically designed to meet both the structural and thermal performance criteria for building applications. The building components made of this material can be extremely lightweight which can significantly reduce the structural load and span long distances. Furthermore, the durability and constructability of the synthetic polymer composites can allow a variety of air channels and cavity features be embedded within the building components and contribute to the thermal performance.

Finally, the architectured materials (e.g. cellular materials and functionally graded materials) and its processing methods can be further investigated for augmenting the thermal performance of common building materials. For example, the soil-based building materials such as bricks, ceramics, gypsum, and geopolymers among many others can be thermally augmented by introducing cellular void spaces. In addition to utilizing this strategy for common building materials, it is also possible to implement it in constructing habitats in isolated areas such as indigenous communities or even extraterrestrial habitats (e.g. Moon or Mars). In these areas, where it is too difficult or costly to use common building materials (e.g. thermal insulation), a 3d printer can be deployed and use the local soil to construct habitats. The microstructure of the soil-based material can be highly customized (e.g. cellular configuration, functional grading or texture) for the local thermal environment.

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