Optimal Thermoregulation Strategies for Building Roofs: A Multifaceted Approach Integrating Experimental Analysis and Finite Element Modeling

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ABSTRACT: This study investigated building roof heating and cooling mechanisms through experimental testing and finite element modeling. We hypothesized that an optimum operating point exists for minimizing heat absorption while maximizing heat convection and radiation. Experiments were conducted on a model home with various roofing materials and coatings in a controlled environment. 3-D Finite Element Modeling simulations were performed to study different heating mechanisms. Results showed that impervious layers blocking convective cooling were less efficient than expected. A porous cover on the roof offered the best performance. Simulations highlighted the importance of radiative and convective cooling mechanisms in preventing excessive heating. Based on these findings, we propose a smart roof design to conserve energy utilization. This research combines experimental data from a smaller-scale prototype under controlled conditions with simulation to understand the problem of designing season-agnostic smart roofs, potentially leading to innovative technological improvements in building energy efficiency.
KEYWORDS: Energy: Physical, Sustainable Design, Heat Transfer Optimization, Finite Element Modeling (FEM).

Introduction

In countries such as the United States, ~40% of the total energy consumption is in buildings, with ~50% of residential housing energy used for heating and cooling to maintain a desirable indoor temperature (~22°C).[1] The choice of roofing material significantly impacts building heat retention and energy efficiency. As global temperatures rise and energy costs increase, optimizing building thermal performance has become a critical area of research. Gaining a physics-based understanding of heat transfer into and out of a home can help design and implement intelligent roofing systems that adapt to changing environmental conditions.

Current research in this field often focuses on individual aspects of heat transfer or specific materials, with much attention given to increasing/decreasing radiative cooling. Radiative cooling refers to the process by which surfaces emit thermal radiation to dissipate heat. In building applications, this allows roofs to cool below ambient air temperature, even during daytime. Past research on daytime radiative cooling, while successfully reducing cooling energy consumption, typically used materials with fixed, cooling-optimized properties.[1] These materials efficiently emit thermal radiation even when the surface temperature of the surface is lower than desired, such as at night or in the winter.[1] This unwanted thermal radiative cooling will increase the energy consumption for heating and may offset the cooling energy saved in hot hours or seasons.[1]

The research community acknowledges this issue well.[1, 2] To cut the heating penalty from overcooling, techniques have been attempted to switch off thermal radiative cooling at low temperatures.[1] Although effective in switching, these techniques typically require either additional energy input or external activation, and in some cases, complex mechanical moving parts achieve switching.[1] Examples include temperature-controlled phase change structure,[3] deployable radiators with loop heat pipe, and 4 switchable cavitation coatings.[5] In an example of active control, Zhao *et al*. describe forming a bifunctional layer using a silicone film on a carbon block film that can be switched from one state that absorbs radiation to another state that allows radiative cooling.[5] On the other hand, a passive solution using vanadium oxide called temperature-adaptive radiative coating has been proposed that does not require active intervention.[1]

Despite this progress, such technology is still nascent and many years from commercial adoption, presumably requiring many years of development and testing. In addition, these solutions only consider minimizing radiative cooling and do not consider controlling conductive cooling, which is an equally important mechanism of heat transfer.

Thus, a significant gap exists in understanding how various heat transfer mechanisms interact in real-world conditions. While finite element modeling has been extensively applied to building thermal analysis, including roof heat transfer optimization and envelope performance studies, these approaches typically examine static material properties or focus on individual heat transfer mechanisms rather than investigating adaptive systems that can dynamically respond to seasonal variations. While it is nearly impossible to systematically study a real home's energy usage as a function of the external environment due to large variations in outside weather, a model home with a lower heat capacity can be studied within a constrained environment, providing valuable feedback.

This study aims to bridge this gap by combining experimental analysis with finite element modeling to investigate the complex interplay of conduction, convection, and radia-

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tion in roofing systems. Using a scaled model and controlled environment, we can isolate and analyze these heat transfer mechanisms more precisely than possible in a full-scale building. Our research specifically focuses on exploring the potential of porous materials and adaptive systems in roofing, hypothesizing that an optimal balance exists for a specific use case. This approach differs from traditional methods that often prioritize insulation at the expense of beneficial heat transfer during cooler periods.

The goal of this work is twofold. First, we want to comprehensively understand the thermal behavior of various roofing materials and designs under controlled conditions. Second, we want to use this understanding to propose a smart roof design that can adapt to seasonal changes, minimizing energy consumption year-round.

By integrating experimental data with computer simulations, we aim to provide insights that can guide the development of more energy-efficient and climate-responsive building technologies. This innovative approach, combining small-scale experimental analysis with finite element modeling, offers a unique perspective on roofing system optimization. We are unaware of any other work that used a combination of experimental data performed on a smaller-scale prototype under a controlled environment and simulation to understand this problem of designing a season-agnostic smart roof.

The findings from this research can contribute significantly to sustainable architecture and energy conservation efforts in the built environment. They could potentially lead to the development of adaptive roofing systems that dramatically reduce energy consumption in buildings across various climates.

Background Information:

Conduction, convection, and radiation are the primary heat transfer mechanisms in building roofs. While these mechanisms are generally well understood in isolation, their complex interplay in real-world conditions presents significant challenges.

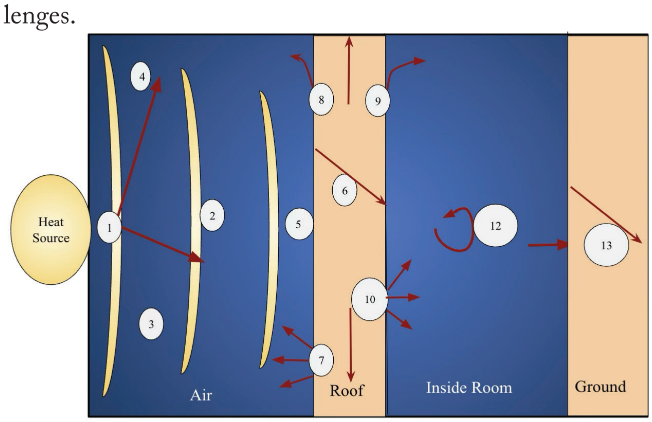

Figure 1: The various heat transfer mechanisms are at work when heat flows across the roof of a home. Straight arrows indicate conduction, curved arrows show convection, wavy lines represent radiation, and dashed lines show reflection. Numbered mechanisms correspond to detailed descriptions in the text.

1. Absorption by air of Electromagnetic Radiation (EMR) from a heat source: The air around the house absorbs a small fraction of the light from the heat source, typically contained in the infrared spectrum, increasing the ambient air temperature.

2. Conduction through air: Heat transfer occurs, especially in structures with a high surface-to-volume ratio, despite the air's poor thermal conductivity.

3. Convection through the air: Convection is the primary heat transfer phenomenon in fluids and is likely important. The hot air around the home can cause a convection current, with hot air rising away from the house and cold air moving toward the house.

4. Radiation through air: All objects emit radiation based on their temperature, including the air itself, which radiates heat in all directions.

5. Reflection / Absorption of heat at the roof: The roof absorbs any remaining electromagnetic radiation that is not absorbed by the air or reflected. The amount absorbed depends on the roof's material and color.

6. Conduction through the roof: Various layers of the roof conduct heat into the main body of the home. Traditional solutions focus on limiting this component, but this can also reduce beneficial heat gain during cooler periods, such as on a sunny winter day, as is typical in the Southwest US winters.

7. Radiation from the roof: The roof of the building radiates heat back into the atmosphere. It is typically the hottest part of the building.

8. Convection between the roof and air: As cold air from above contacts the warm roof, it absorbs heat and rises, contributing to heat transfer.

9. Convection between the roof and inside the house: Similar to the roof/air boundary, air currents within the home contribute to heat transfer.

10. Radiation in the home: The hot roof also radiates heat into the house's interior.

11. Conduction within the room: While likely playing a minor role, heat conducts through the air inside the house.

12. Convection within the room: As the room heats up, convection currents are established inside the house.

13. Heat transfer to the ground: Heat can transfer to the ground via the floor through conduction, radiation, and convection.

The complex interplay of these heat transfer mechanisms in building roofs presents challenges and opportunities for energy-efficient design. Our study explores how various roofing materials and designs, particularly porous materials and adaptive systems, can influence these heat transfer processes. By examining the balance between conduction, convection, and radiation, we aim to identify innovative roofing solutions that can effectively manage heat transfer across different seasons and climatic conditions, potentially leading to significant improvements in building energy efficiency.

■ Experimental Details: Method For Phase 1 Roof Experiment:

The steps below describe the process of collecting experimental data after building a model home, i.e., a smaller prototype with a lower thermal mass, which can be more easily tested. The model home contains two separate units that are brought together: a base representative of the house's living space and a roof structure representative of the attic. The roof structure can be attached to the base to form a model home. The roof structure is designed to be a triangular prism typical of home roofs. The model home dimensions were as follows: a base unit measuring 11in by 6in by 4.5in (length × width × height), with roof structures forming triangular prisms. Critical thermal components included roof material thickness of 3 mm, wall thickness of 5 mm, and internal air volume of approximately 9 liters. Several different roof structures were fabricated and attached for testing as needed. The roof structures were identical in size and shape, but the only difference was what was on the outermost layer facing the heat lamps. Besides the black roof (control), these included roofs painted with lighter-colored and photochromic paint. Sometimes, a layer (aka sun shade) was attached to the roof instead of having a different coating. This layer could be an impervious fabric or meshes with varying degrees of porosity.

The following describes the experimental procedure for collecting the data.

The control roof (black spray-painted) is attached to the base unit. The model home is positioned on a table under two 75-watt halogen lamps above the roof surface, providing a combined 150 watts of heating power. While the exact heat flux reaching the model was not directly measured, this setup simulates realistic solar heating scenarios. The heating cycle is initiated. After turning on the lamps, temperatures within and on the walls are measured every 10 seconds for 3 minutes, every 30 seconds from 3 minutes to 10 minutes, every minute from 10 minutes to 25 minutes, and every 5 minutes from 25 minutes to 45 minutes (recorded in seconds). Prior testing showed that 45 minutes was sufficient to reach a steady temperature. After measuring the heating rate, the lamps are turned off, and temperature measurements during cooling begin at the same time intervals to initiate the cooling cycle. This process is repeated at least three times. Following the control experiment, the model home is removed, and a different roof configuration is attached, following Table 1, for the types of sunshades. For each roof, steps 2-5 are repeated to obtain a series of heating and cooling curves.

Table 1: Phase 1 variables.

Independent Variable	Constants	Dependent Variable
Type of sunshade: No mesh (CONTROL) 0% porous mesh 50% porous mesh 80% porous mesh Impermeable mesh Photochromatic vinyl Silver colored roof	Box (size, walls) Distance from the box to the bulb. Placement of the box on the table. Relative placements of thermometer, light sensor, and bulb. Time intervals.	Internal and external temperature in Celsius of the box

Phase 2 – Simulated Experiments:

In this research phase, we developed the structure of the model home in 3-D solid modeling software. We simulated some of the thermal mechanisms described above in 3-D Finite Element Modeling (FEM) software.

Background Information:

We explored various tools such as Energy2D and [6] Octave before deciding on the ANSYS OnScale platform.[7] OnScale Solve is a cloud-based engineering simulation software.[8] OnScale is a 3D Finite Element Modeling software that can solve static thermal equations. Because it was a cloud-based platform, it provided an easily accessible high-performance computing platform for performing mechanical, thermal, and fluid analyses. However, OnScale Solve requires input from a solid model (CAD).

OnShape is cloud-based 3D solid modeling software that generates solids.[9] The output from OnShape can be input into OnScale, allowing us to explore the designs.

Creating a 3D Solid Model:

In this project phase, we developed the structure of the model home, as shown in Figure 2, in a 3-D solid modeling software called OnShape. This involved the following basic steps.

1. Measurements: The dimensions of the experimental prototype from phase one were measured along with the design elements. All relevant design elements, including roof angles, wall thicknesses, and internal structures, were documented.
2. Model Development: A 3-D virtual prototype home with a hollow triangular prism roof with a solid side wall with the same dimensions as the experimental prototype was created in Ansys OnShape.
3. The 3-D virtual prototype home was placed on a virtual table, as in the experiments.

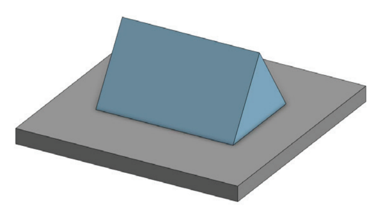

Figure 2: The 3-D Solid Model of the prototype gable roof. Figure 2 shows a prototype gable roof with the same dimensions as the experimental model created through OnShape.

Creating 3D FEM Model:

The steps below can be simulated to produce a thermal distribution, as shown in Figure 3. The solid model from OnShape was imported into OnScale, and various material and simulation parameters were set.

OnScale allows the materials to be selected. For our simulation, all the walls and roof of the virtual prototype home were chosen to be made of wood, while the table was selected to be made of plastic.

Next, the thermal simulation parameters and boundaries were set up in the Physics tab. The ambient temperature was selected to be 20 degrees C. A radiative boundary condition

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was added to all the surfaces by setting the emissivity to 0.8, which is representative of wood (which was changed in the special simulations below). In the experiments, the heat lamps faced only one roof surface, so a similar surface was selected to have a heat flux. The amount of heat flux was defined as 300 W/m2, which was the total heat power of the lamps combined divided by the area on the side of the roof facing the lamps. This heat flux of 300 W/m^2 represents approximately 30% of peak solar irradiance at Earth's surface (1000 W/m^2 at solar noon), simulating moderate daytime heating conditions rather than extreme summer solar loading.

All outside surfaces were included to have convective heat transfer. The convective heat transfer coefficient of air with no wind was selected as 12 W/m2C.

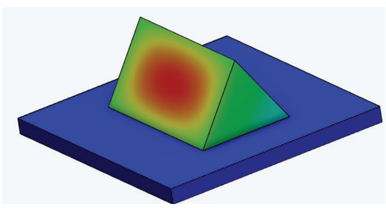


Figure 3: An example of thermal distribution in a simulation. Figure 3 shows the preliminary heat distribution on the prototype gable roof on the OnScale platform.

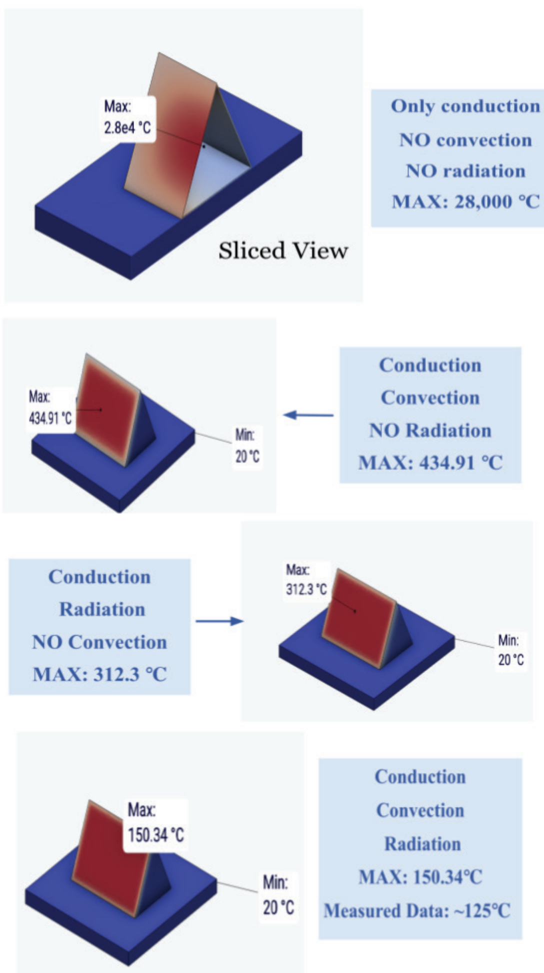


Figure 4: Four figures of the simulated conditions. Figure 4 shows the four trials tested on OnScale to understand the effect of heating mechanisms in a closed system.

The FEM simulations quantified the relative contribution of each heat transfer mechanism by systematically including or excluding specific physics. Figure 9 shows the temperature distributions for four simulation conditions, with the following maximum roof surface temperatures recorded:

Experiment (A) - Conduction Only: Maximum temperature of 245°C, demonstrating that conduction alone produces unrealistically high temperatures due to a lack of heat dissipation mechanisms.

Experiment (B) - Conduction + Convection: Maximum temperature of 156°C, showing that convective cooling reduces peak temperatures by 36% compared to conduction-only conditions.

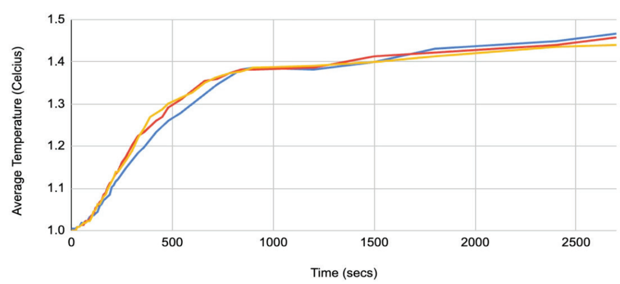
Experiment (C) - Conduction + Radiation: Maximum temperature of 78°C, indicating that radiative cooling is more effective than convection for heat dissipation in this system.

Experiment (D) - All Mechanisms: Maximum temperature of 68°C, closely matching experimental observations of approximately 65°C and validating the simulation approach.

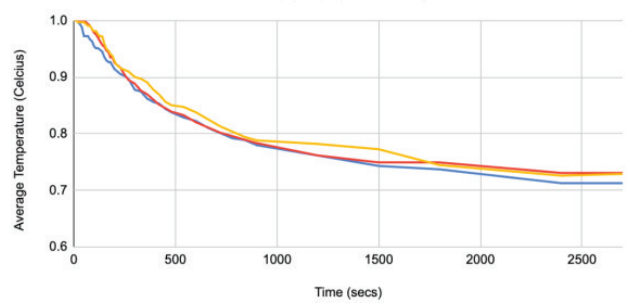
These results demonstrate that radiative cooling contributes most significantly to thermal regulation, while convective cooling provides important secondary benefits. The combined mechanisms are essential for realistic thermal modeling.

Results From Experimental Data

Figures 5A and 5B below show a representative normalized heating and cooling data plotted with time. During the early stages, there is a rapid increase in heating/cooling followed by a steady temperature.



(A)



(B)

Figure 5A: Heating curve plotting average (3 trials) temperatures of the black roof without mesh ℃ with time (s). Figure 5A shows rapid heating followed by reaching a quasi-steady state in which the temperature increase saturates.

Figure 5B: Cooling curve plotting average (3 trials) temperature of the black roof without mesh ℃ with time (s). Figure 5B shows rapid cooling followed by reaching a quasi-steady state in which the temperature decreases and saturates. followed by reaching a quasi-steady state in which the temperature increase saturates.

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Results of Of Experimental Data

Figure 6 below compares the different types of roofing structures described above. Undoubtedly, the black roof causes the most heat to penetrate the prototype home, while the roof coated with silver paint blocks most of the heat. Both are understandable as the black painting absorbs the most heat (minimal reflection), and the silver paint (reflects the most heat).

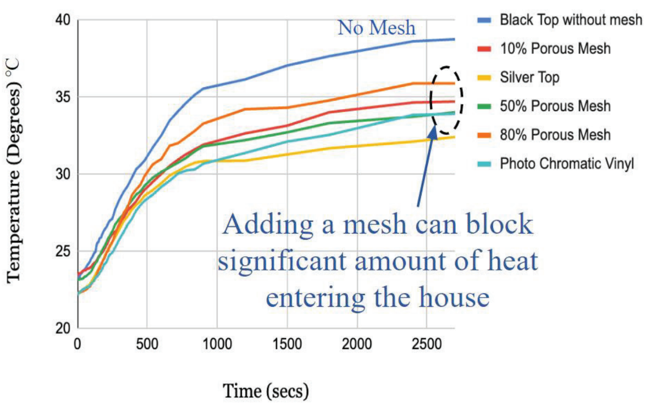

Figure 6: Heating curve comparing all sunshades by plotting time (s) with temperature °C. Figure 3 shows the difference in steady-state temperatures after rapid heating across 5 sunshades and a control (black top without mesh).

Figure 7 below compares the temperature reduction using a silvered roof (labeled as a colored roof) with a porous mesh. The silver-coated roof (silver paint coated over the black paint) is 20% better than the control black roof. The porous mesh below is about half as efficient as the silver-coated roof.

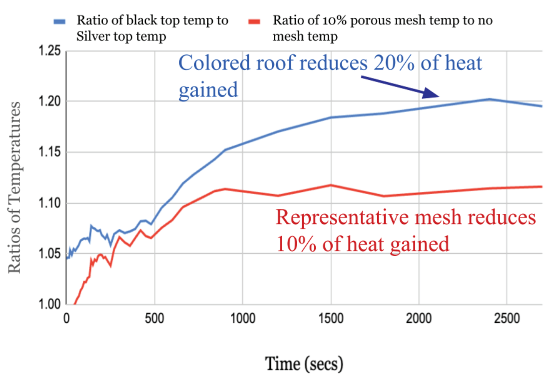

Figure 7: Ratios of temperature using color and mesh plotted with time (s). Figure 4 shows that the ratio of blacktop temperature to silver top temperature increases at a higher rate than the ratio of 10% porous mesh to no mesh.

Figure 8 below estimates the cooling rate for different roof structures with different porous layers. To estimate the cooling rate, the temperature difference for a short time window of 500s from the start of cooling was selected, as there is no difference at longer times. As the porosity of the mesh layer increases, the roof behaves almost like a roof without a mesh during cooling. In fact, at about 80% porosity, the mesh does not affect the cooling rate. While an impervious or highly non-porous layer is expected to form an insulative layer specifically by preventing convective heat transfer, the highly porous mesh layer does not limit convective heat transfer. Figure 8 reveals two distinct thermal behavior regimes separated by a critical transition around 50% porosity. Materials with low porosity demonstrate similar cooling rates, indicating that the mesh primarily functions as a radiation shield while limiting convective heat transfer. Beyond 50% porosity, the cooling rate increases dramatically, approaching the performance of unshielded surfaces as convective cooling dominates. This transition suggests that effective convective heat transfer requires a minimum threshold of pore connectivity, with isolated pores below 50% porosity unable to support meaningful airflow patterns.

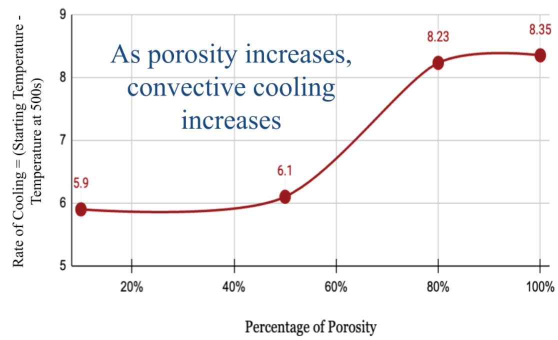

Figure 8: The cooling rate for different porous layers. Figure 5 shows that the rate of cooling, starting temperature minus temperature at 500 seconds, increases as the percentage of porosity increases.

Figure 9 below shows the steady-state temperature obtained with roofing structures with different porosities. Of course, the control with the black roof had the hottest room temperature. On the other hand, the prototype with the impervious vinyl was also quite hot at an average temperature of about 37 ˚C. The coldest structure is the structure with an intermediate porous layer attached to the roof.

This data is non-intuitive, and our simulation data explained below suggests that the following reasoning is likely correct. First, the cooling data clearly show that convective cooling of the roof surface plays an important part. Otherwise, the porous mesh will not cool faster than the less porous mesh (80% porous cools faster than 20% porous mesh). Based on the cooling data, it can be estimated that a highly porous mesh will allow convective cooling during heating compared to a less porous mesh. On the other hand, the highly porous mesh does not block the direct heat absorption on the roof's surface. For example, in an 80% porous mesh, 80% of the light energy will directly impact the roof surface, and much of that will be absorbed. On the other hand, in a 20% porous mesh, only 20% of the light energy will directly impact the roof surface. Thus, there is likely an optimum mesh porosity at which there is enough direct light energy is blocked while allowing some convective heat transfer. The experimental design was limited by available mesh materials, constraining us to discrete porosity values (0%, 50%, 80%, 100%). With greater flexibility in tailoring mesh porosities, more granular experimental data could precisely identify the optimal porosity range.

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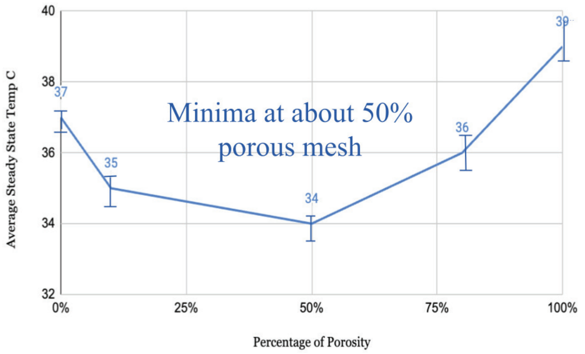

Figure 9: The average steady-state temperature °C of different porous meshes. Figure 6 shows a minimum of about 50% porous mesh when the average steady-state temperature of all variable porous meshes is compared.

■ Discussion Of Simulation Data

The maximum temperature value of the side facing the heat lamps is recorded in the simulations above in Figure 9. From our experimental data, I recorded the wall temperature for the control to be about 125 degrees. The final simulation (Experiment (D)) produced relatively comparable results. Note that the inside temperature within the model cannot be computed as the OnScale cannot simulate the airflow within the home caused by convection. Hence, the outside wall temperature was compared.

The simulation data quantifies each mechanism's contribution: convection reduces temperature by 89°C (245°C to 156°C), while radiation reduces temperature by 78°C (156°C to 78°C). However, convection is critical because without it, simulated temperatures (245°C) are 3.8 times higher than experimental values (~65°C), making the model unrealistic. This possibly explains why the minimally porous mesh layer attached to the roof provides the best result in the experiments. Unlike the impervious layer that blocks or eliminates most convective cooling, a porous mesh layer enables convective cooling while blocking direct radiation.

Phase III - Smart Roof Design:

Based on the knowledge gained from this work, a smart roof can be designed, as shown in Figure 10, to reduce energy consumption. This system can be a retractable porous fabric that can be mounted on the roof's side and receives the most sun (typically on the south side). This system could employ an active management system that could include different types of sensors. For example, sensors could roll open the fabric during the summer sun (blocking heat) and keep it retracted during the winter sun (allowing the sun's heat into the home to reduce heating bills). Unlike the various technologies under research, this technology is available and well-proven for reliability. For example, solar panels are installed on the roofs of many homes, and sunshades are installed on windows. Both technologies are currently available and can be easily repurposed.

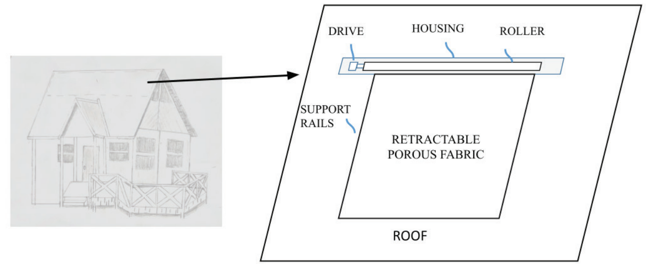

Figure 10: Figure 10 shows an active smart roof system that is relatively self-explanatory. A fabric is part of an electronic roll, similar to sunshades, but is supported on the house's roof.

Error Analysis of Experimental Data:

Before concluding with the data, the potential errors in our experimental data were reviewed. The observed results cannot be explained merely by experimental or statistical error. Possible sources of error include changes in ambient temperature and hysteresis between heating and cooling cycles. Due to the large amount of data collected during my school year, the experiment data was collected over a long period (about a month). During this time, the outside weather had some significant fluctuations, which caused the ambient temperature in my home, where all the experiments were performed, to fluctuate by a few degrees. However, since I normalized all the data, I do not think this could be a significant error source. Similarly, there was no significant hysteresis in the data. In addition, as shown in Table 2 below, the calculated standard error of the mean shown in the data is reasonably well-behaved.

Table 2: Standard error of the mean steady-state temperature (°C) for different porous mesh configurations based on three experimental trials. Table 2 shows that the standard error of the mean is low for all percentages of porous mesh.

Percentage of Transparency through Holes at steady state	Standard Error of the Mean
0%	0.26
10%	0.41
50%	0.40
80%	0.86
100%	1.1

Summary Of Experimental Data:

The experimental data clearly show that a porous sunshade is better than an impervious one. A roof with a 10-50% porous mesh is 10% better than one with an impervious mesh or no mesh. Although the silver-coated roof achieved superior thermal performance with a 20% improvement, the adaptive porous mesh system is recommended for practical implementation. The retractable mesh system offers dynamic control, allowing beneficial solar heating in winter while providing cooling in summer, making it more suitable for year-round energy optimization.

Conclusion

This study has successfully demonstrated the complex interplay of heat transfer mechanisms in building roofs and proposed an innovative approach to optimize thermal regulation. Through experimental analysis and finite element modeling, we have gained valuable insights into the thermal behavior of various roofing materials and designs. Our research revealed the effectiveness of porous materials in roof design, with a partially porous cover attached to the roof offering the best thermal performance. Specifically, a 10-50% porous mesh showed a 10% improvement in thermal regulation compared to impervious or non-mesh roofs. This finding underscores the importance of balancing heat blocking and dissipation, challenging the conventional approach of maximizing insulation at all times.

Both our experimental data and FEM simulations highlighted the significant impact of convective heat transfer in roof thermal regulation, a factor often underestimated in traditional roof designs. Based on these insights, we propose a smart roof design featuring a retractable porous fabric. This system could dynamically adapt to changing environmental conditions, optimizing energy efficiency across seasons.

These conclusions support our initial hypothesis and provide new insights that could spark a new generation of technological improvements in building energy efficiency. Our proposed smart roof system offers several advantages over existing solutions, including season-agnostic performance, targeted installation on high-heat absorption areas, potential for invisibility when retracted, and utilization of existing technologies for quicker adoption.

While our 3-D FEM modeling capabilities were limited, they provided crucial insights that complemented our accelerated testing experiments. This combined approach of small-scale prototyping and computational modeling offers a promising methodology for future research.

We envision collaborating with the North Texas Renewable Energy Group to discuss our findings and explore practical applications.[11] We also aim to partner with a roofing company to build and test a full-scale prototype of our smart roof design. Future work could involve enhancing our computational models to include more complex physics, such as improved convection modeling and time-dependent solutions, as well as investigating the potential of our adaptive roof system in various climatic conditions and building types.

In conclusion, this research contributes significantly to our understanding of roof thermal regulation and proposes a novel, practical solution for improving building energy efficiency. As global energy demands continue to rise and climate change presents increasing challenges, innovations in building design could play a crucial role in creating more sustainable and energy-efficient built environments. Our work paves the way for a new generation of adaptive, energy-efficient roofing systems that can significantly reduce energy consumption in buildings across diverse climates.

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