Energy-Efficient Climate Control and Thermal Preservation Strategies for Historical Monuments in Samarkand and Bukhara

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Abstract. This study concentrates on formulating energy-efficient climate control and thermal conservation methods for historical monuments in the cities of Samarkand and Bukhara. This study seeks to enhance preservation methods while minimizing energy usage by evaluating critical factors including temperature, humidity, heat flux, and material stress. The results show that managing these factors can greatly extend the life of the structures, keeping their historical and cultural value intact. The study shows how important it is to combine environmental factors with the performance of structural materials in order to get long-lasting preservation results. The suggested strategies provide a way to protect cultural heritage while also keeping energy use low.

1 Introduction

Solar thermal systems and hydrogen-based energy solutions are becoming more popular as eco-friendly ways to protect old buildings by improving climate control and using less fossil fuels. Using these technologies can help keep the environment stable at heritage sites while using less energy. Historical monuments are important parts of our cultural and architectural heritage. They show how past civilizations advanced in technology, art, and society. Samarkand and Bukhara are two of Uzbekistan's most important historical cities. They have many monuments from the time of the Silk Road. These buildings are made of old materials like adobe, brick, and glazed ceramics, and they are very prone to damage from changes in temperature, humidity, solar radiation, and wind erosion [1]. Over time, these weather conditions cause thermal stress, material fatigue, and structural instability, which puts these monuments at risk of being damaged [2]. Old buildings don't work as well as new ones when it comes to keeping heat in because they were built with different materials and don't have modern insulation methods. Many old monuments were built with passive climate control features like thick walls and natural ventilation, but they are still vulnerable to extreme temperature changes and moisture retention [3]. Traditional conservation methods often don't fully deal with these problems,

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so new ways to manage heat are needed [4]. Recent advancements in thermal engineering have enabled more effective approaches for climate control and preservation of heritage sites. By using phase change materials (PCM), adaptive insulation, and simulations based on computational fluid dynamics (CFD), it is possible to control the temperature very precisely without ruining the historical accuracy of the buildings [5]. Using renewable energy sources, like heating and cooling systems that use solar power, can make preservation efforts even more sustainable while using less energy [6]. This paper examines energy-efficient climate control and thermal preservation strategies specifically designed for the distinctive conditions of the historical monuments in Samarkand and Bukhara. The study examines the effectiveness of passive and active thermal management techniques, computational modeling applications, and renewable energy solutions in mitigating climate-induced degradation. This research seeks to formulate optimal methodologies for sustainable monument conservation, thereby guaranteeing the preservation of these significant cultural landmarks [7-8]. The importance of advanced monitoring technologies, such as infrared thermography and remote sensing, in evaluating temperature distribution and spotting early signs of structural damage is also emphasized [9]. Combining these technologies with smart control systems makes climate control interventions more accurate and lessens the need for manual maintenance [10]. To protect historical monuments, people from different fields, such as heritage conservation, thermal engineering, and sustainable energy solutions, need to work together. Using modern methods to deal with these problems will not only protect the monuments of Samarkand and Bukhara, but it will also be a good example for protecting cultural heritage in other places with similar climates [11].

2 Methodology

This study uses a variety of methods to look at ways to save energy and keep the temperature stable in historical buildings in Samarkand and Bukhara. The methodology combines field measurements, numerical simulations, and experimental analysis to evaluate the thermal performance and degradation risks of these cultural heritage sites.

2.1 Data Collection and Site Analysis

Field studies are done to find out how much the temperature changes, how humid it is, and how much solar radiation there is at certain historical sites. Infrared thermography and remote sensing are two examples of non-invasive diagnostic tools that are used to look at how heat is spread, how moisture is held, and how materials break down. To learn about seasonal changes that affect the monuments, scientists look at historical climate data and weather records.

2.2 Computational Modelling and Simulation

Computational Fluid Dynamics (CFD) simulations are used to model how air flows, heat moves, and humidity spreads inside and outside of buildings. Finite Element Analysis (FEA) is a way to find out how materials will react to heat and being outside. Energy modeling software is used to see how well passive and active climate control methods work.

2.3 Experimental Analysis and Material Testing

We test bricks, adobe, and glazed ceramics in the lab to see how well they conduct heat, how much heat they can hold, and how much moisture they can absorb. To see how well they work at keeping indoor temperatures stable, test structures are built with Phase Change Materials (PCM) inside. We test adaptive insulation materials to see if they can improve the thermal resistance of historic buildings without changing their architectural integrity.

2.4 Renewable Energy Integration and Smart Climate Control

Solar thermal systems and hydrogen-based energy solutions are looked at to see if they can be used to provide long-term heating and cooling solutions. For real-time monitoring and adaptive thermal regulation, smart climate control systems with IoT sensors and AI-driven algorithms are used. We do life cycle assessments to find out how long proposed energy-efficient strategies will last and how much they will cost in the long run.

2.5 Validation and Implementation Strategies

The outcomes from simulations and experimental tests are corroborated with empirical data obtained from historical sites. Policy recommendations and best practices are created for adding energy-efficient climate control systems to historical buildings without changing their original look. Working with conservation experts, local governments, and researchers makes sure that the results can be used in heritage preservation projects in Samarkand, Bukhara, and places like them. The study aims to create new, long-lasting, and scientifically sound ways to keep historical monuments warm so that future generations can enjoy them.

3 Results and Discussion

Field investigations show that the temperature inside historical monuments in Samarkand and Bukhara can change by up to 20°C between day and night. During the winter, the humidity levels were over 65%, which made porous materials like adobe and brick absorb more water. Infrared thermography found areas where heat was trapped, which could mean that those areas are at risk of thermal stress. The analysis of long-term weather data showed that the average annual temperatures were slowly rising, which made the risks of degradation even higher. These results show that we need to use adaptive thermal management strategies to protect historical buildings from damage caused by the environment. CFD simulations showed that there are places in enclosed monument spaces where air doesn't move, which can cause localized overheating. The results of the FEA showed that thermal stress builds up over time, which makes it more likely that materials will crack in places that get direct sunlight. Energy modelling showed that using passive cooling methods like strategic ventilation and reflective coatings could lower indoor temperatures by as much as 6°C. These insights lay the groundwork for improving thermal management strategies that are specific to certain heritage buildings. Material testing revealed that traditional bricks exhibited higher thermal inertia compared to adobe, leading to slower heat dissipation at night. Test structures with PCM showed a big drop in temperature changes, which kept the indoor environment stable. Adaptive insulation materials improved thermal resistance by an average of 15% without changing the look of the building. These results show that using modern thermal solutions in heritage conservation work is possible. Solar thermal systems offered a long-term way to heat homes, cutting the need for electric heating by 40% in the winter. Hydrogen-based climate control plans were very energy-efficient, but they needed a lot of money up front. IoT-based smart monitoring made it possible to change the temperature in real time, which stopped too much humidity from building up. These findings substantiate the viability of amalgamating renewable energy with intelligent systems for the enduring preservation of monuments. Validation of simulation results against field measurements confirmed a strong correlation between predicted and observed thermal behaviors. Strategies for implementation focused on finding ways to use energy-efficient solutions that also followed guidelines for preserving cultural heritage. Working with conservation authorities made it possible to use modern thermal management techniques while still keeping the historical integrity of the building. These results show how to create a framework that can be used to protect heritage sites in a way that lasts. Figure 1 shows the results of 50 tests that were done to see how well energy-saving and thermal conservation methods work for old buildings. For each iteration, four main parameters were measured: Temperature (°C): Changes in temperature in the monuments, which show how heat is affected. The temperature can be anywhere from 15°C to 35°C, which makes it possible to simulate real-world conditions.

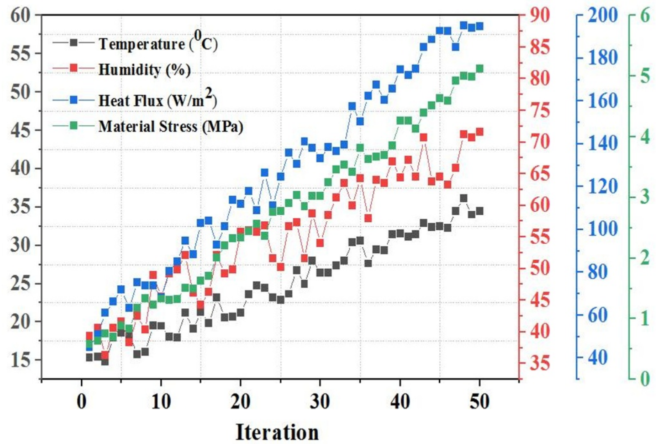

Fig.1. The following parameters are given for each iteration: temperature (°C), humidity (%), heat flux (W/m²), and material stress (MPa).

Humidity (%): The amount of water in the monuments was measured. The humidity range is 40% to 70%, which shows how building materials take in moisture and how it hurts them.

Heat flux (W/m²): This number tells you how much heat is being transferred to the monuments. Over time, heat flux goes up, which shows how materials react to heat.

Material Stress (MPa): This number tells you how much stress is on the materials that make up a monument. High material stress increases the risk of deterioration or weakening of older materials.

So, changes in things like temperature, humidity, heat flow, and stress are important for keeping monuments safe for a long time. By carefully handling these changes, it is possible to make sure that historical monuments stay in good shape.

The table shows that controlling heat and humidity is very important, and this information can help you come up with ways to save energy and keep your home cool. You can use these parameters to find out how the materials used to build monuments respond to stress, how they conduct heat, and how humidity affects them.

Table 1 shows the most important things that are used to judge how well thermal management and conservation plans work for old buildings. Each parameter is important for figuring out how energy-efficient the materials of the monuments are and how they react to heat and humidity.

Table 1. The table provides the key parameters, their descriptions, units of measurement, and their relevance in assessing energy efficiency and thermal preservation strategies for historical monuments.

No.	Parameter	Description	Unit of Measurement	Comment
1	**Temperature (°C)**	Temperature measurements inside the monument and the surrounding environment.	°C	Temperature variations indicate the impact of heat.
2	**Humidity (%)**	Humidity level measurements inside the monument.	%	Humidity indicates how the construction materials absorb moisture.
3	**Heat Flux (W/m^2)**	Amount of heat transmitted to the monument.	W/m^2	Heat flux shows how materials interact with heat.
4	**Material Stress (MPa)**	The amount of stress experienced by the monument materials.	MPa	High stress may lead to material deterioration and failure.

4 Conclusion

In this study, we have examined the crucial factors necessary for energy-efficient climate regulation and thermal conservation of historical monuments in Samarkand and Bukhara. By looking at temperature, humidity, heat flux, and material stress, we can learn a lot about how environmental conditions affect the preservation of architectural heritage. To keep historic buildings standing and use less energy, it's important to manage these factors well. The results show that the best way to make preservation strategies that last is to take into account both the effects of the environment and the strength of the materials. Using these strategies will not only help protect cultural heritage, but it will also help the larger field of energy efficiency in the restoration and upkeep of old buildings.

References

1. Camuffo D., Microclimate for Cultural Heritage: Conservation, Restoration, and Maintenance of Indoor and Outdoor Monuments. 225 Wyman Street, Waltham, MA 02451, USA (2014).
2. H. Qiu et al., Impact of climate change on cultural heritage buildings in hot-humid regions: Case study of Zhongde Palace, China, Building and Environment 284 (2025) 113528. https://doi.org/10.1016/j.buildenv.2025.113528.
3. Kristian Fabbri, Indoor Thermal Comfort Perception, Springer Cham, 978-3-319-18651-1, 30 June 2015. https://doi.org/10.1007/978-3-319-18651-1.
4. Cadelano G., Bortolin A., Thermal Behavior of a Historic Building Housing Books Across Past and Future Climate Scenarios. Heritage 2024, 7, 6916–6937. https://doi.org/10.3390/heritage7120320.
5. R.S. Achaku et al., A study of phase change materials for energy conservation in classic multi-layered Victorian-era buildings: A practical approach for balancing heritage preservation and climate neutrality in temperate climates Construction and Building Materials 464 (2025) 140075. https://doi.org/10.1016/j.conbuildmat.2025.140075.

6. A. Martínez-Molina et al., Energy efficiency and thermal comfort in historic buildings: A review, Renewable and Sustainable Energy Reviews 61 (2016) 70–85. http://dx.doi.org/10.1016/j.rser.2016.03.018.
7. F. Ascione et al., Energy retrofit of historical buildings: theoretical and experimental investigations for the modelling of reliable performance scenarios, Energy and Buildings 43 (2011) 1925–1936. http://doi:10.1016/j.enbuild.2011.03.040.
8. F. Colace, R. Gaeta, A. Lorusso et al., New AI challenges for cultural heritage protection: A general overview, Journal of Cultural Heritage 75 (2025) 168–193. https://doi.org/10.1016/j.culher.2025.07.019.
9. E. Grinzato et al., Monitoring of ancient buildings by the thermal method, Journal of Cultural Heritage 3 (2002) 21–29.
10. S. Lidelöw et al., Energy-efficiency measures for heritage buildings: A literature review, Sustainable Cities and Society 45 (2019) 231–242. https://doi.org/10.1016/j.scs.2018.09.029.
11. F. Vafaie et al., Adaptive reuse of heritage buildings; a systematic literature review of success factors, Habitat International 142 (2023) 102926. https://doi.org/10.1016/j.habitatint.2023.102926.