

Research Title

Enhancing the Reliability of Smart Hajj Wearable Devices Using Phase Change Materials (PCM) Under Extreme Heat Conditions

Course Title: Research Methodology in Computer Science (AI800)

Lecturer: Dr. Mohammed Anbar

Student Name: Fatimah ALdighethair

Submission Date: November 25, 2025

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2. Abstract

In recent years, Saudi Arabia has increased its use of smart technologies to improve the Hajj experience and support the safety of pilgrims. Although identification cards and barcodes are widely used, the idea of adopting smart wearable devices is becoming more important because they can track a pilgrim's location and monitor basic health signs. However, these devices still face a major challenge in Hajj: the extreme heat in Makkah, where temperatures can reach more than 65°C. Such heat can cause batteries to swell, sensors to fail, or the entire device to shut down.

This study explores the possibility of using Phase Change Materials (PCM) inside wearable devices to protect their internal components by absorbing and storing excess heat. The research also considers how these devices could connect to national platforms like Absher and the Ministry of Health systems to allow quick access to a pilgrim's personal and medical data in emergency situations. The goal of this study is to examine whether PCM can help make wearable devices reliable and safe enough for use during Hajj, which could reduce lost pilgrim cases and support rapid medical responses.

3. Introduction

Saudi Arabia continues to invest in digital solutions to improve the organization and safety of Hajj. Smart wearable devices—such as wristbands or small health trackers—can provide real-time information about a pilgrim's location and health status. Although similar devices are used successfully in other fields, they are not widely applied in Hajj because of the extreme environmental conditions.

During Hajj, temperatures can reach unusually high levels, which affects the performance of small electronic components. Batteries may become unstable, sensors may stop functioning, and the device may fail when it is needed the most. This limitation makes it difficult for authorities to depend on wearable technology during Hajj.

Phase Change Materials (PCM) have recently been proposed as a method to manage excessive heat in electronic devices. PCM can absorb heat when temperatures rise and slowly release it later, helping stabilize the device's temperature. This study investigates how PCM could be used to enhance the durability of smart wearable devices so they can operate safely during Hajj.

4. Problem Statement

During Hajj, the management mostly depends on ID cards and barcodes, they are useful but they don't really give live information about where the pilgrim is or how is his health. This sometimes causes problems like people getting lost or medical help coming late (Zhang et al., 2020).

Smart wearable devices could be a solution, but the big issue is the heat in Makkah. Temperatures can go above 60°C and that makes batteries unstable, sensors stop working, or even the whole device fails (Chen et al., 2024; Wang et al., 2024). So even if the idea is good, the devices are not reliable in such extreme conditions.

For these devices to be useful they should also connect with national systems like Absher or Ministry of Health, but that needs them to work all the time without stopping because of heat. Some studies like Choi et al. (2021) and Kim et al. (2022) suggested using PCM materials to control the temperature, and maybe this can help. Based on these works, this research wants to see if PCM can really make wearable devices more stable during Hajj.

5. Research Objectives

The research aims to explore how PCM can improve the thermal stability of wearable devices used during Hajj. The objectives are:

1. To identify the main reasons behind wearable device failures in high-temperature environments.
2. To examine the impact of extreme heat on batteries, sensors, and electronic components in small devices.
3. To review previous studies that used PCM or similar cooling techniques in electronics or wearable systems.
4. To propose a conceptual design that uses PCM to protect wearable devices during Hajj.
5. To analyze how such devices could reduce lost pilgrim cases and support medical monitoring.
6. To explore the potential integration of wearable devices with Saudi digital platforms like Absher and the Ministry of Health systems.
7. To provide practical recommendations for implementing such a system in the real Hajj environment.

6. Background & Definitions

Wearable Devices:

Small electronic devices worn on the body to track health, movement, or location.

Phase Change Materials (PCM):

Materials that absorb and store thermal energy when they melt and release it again when they solidify, helping regulate temperature.

Hajj Environment:

Makkah and its holy sites experience extreme heat during summer, affecting both humans and electronic devices.

7. Research Methodology

This literature review is based on six peer-reviewed studies published between 2020 and 2024. The selected studies focus on:

- Thermal management in electronic devices
- PCM applications in wearable technologies
- Cooling systems for small or flexible electronics

Inclusion criteria:

- Studies that examine PCM or cooling systems relevant to wearables
- Peer-reviewed journal or conference papers
- Research that includes experiments, modeling, or prototype design

Exclusion criteria:

- Studies without experimental or technical results
- Work unrelated to heat protection or electronic stability
- Papers focusing only on large-scale cooling systems

This approach helps ensure that the reviewed literature is relevant and supports the goals of the research.

8. Literature Review

Study 1: Choi et al. (2021)

Developed a lightweight thermoelectric cooling system that integrates PCM and graphite.

Strength: Strong experimental validation.

Weakness: Limited outdoor testing in extreme heat.

Study 2: Zhang et al. (2020)

Created a heat-transfer model for wearable devices operating near the skin.

Strength: Solid theoretical foundation.

Weakness: Lacks real-world testing.

Study 3: Liu et al. (2023)

Proposed a flexible fabric embedded with PCM for smart clothing.

Strength: High flexibility and comfort.

Weakness: Cost and production feasibility not discussed.

Study 4: Kim et al. (2022)

Examined hybrid cooling using thermoelectric modules combined with PCM.

Strength: Very effective thermal control.

Weakness: Complicated integration into small devices.

Study 5: Wang et al. (2024)

Improved wearable device reliability by using PCM as an internal heat sink.

Strength: Practical design suitable for wearables.

Weakness: Small sample size in experiments.

Study 6: Chen et al. (2024)

Tested PCM composite material for cooling compact electronics.

Strength: High heat absorption capacity.

Weakness: Material weight slightly higher than other PCM options.

9. Connections and Conflicts

All six studies support the idea that PCM can significantly improve thermal stability in electronic devices. However:

- Some studies focus on flexibility and lightweight design, while others focus on performance.
- There is disagreement about whether hybrid cooling systems (PCM + thermoelectric) are necessary or PCM alone is enough.
- Only a few studies discuss cost or implementation challenges, which is important for large-scale use in Hajj.

10. Synthesis Matrix Table

Study	Purpos	Method	Key Findings	Weaknesses
Choi et al. (2021)	Develop PCM-graphite cooling	Experimental prototype	Good cooling efficiency	Limited field testing
Zhang et al. (2020)	Heat transfer modeling	Mathematical modeling	Strong theory foundation	No practical trials
Liu et al. (2023)	PCM textile design	Fabric engineering	Very flexible and wearable	Cost not addressed
Kim et al. (2022)	Hybrid cooling system	Thermoelectric + PCM tests	Highly stable temperatures	Complex integration
Wang et al. (2024)	PCM micro-heat sink	Applied prototype	Practical and effective	Small sample size
Chen et al. (2024)	PCM composite materials	Material testing	High thermal absorption	Material weight

11. Summary of Key Findings

1. PCM improves heat resistance and extends device lifetime.
2. Integration into small devices requires careful design to avoid additional weight.
3. Most studies agree that PCM is suitable for hot environments but needs field testing.
4. There is a clear research gap in applying PCM in extremely hot and crowded environments like Hajj.

12. Discussion & Future Work

The reviewed studies show that PCM can help wearable devices operate in high temperatures, which makes it a promising solution for Hajj. However, further work is needed, including:

- Developing lighter PCM composites
- Testing prototypes in outdoor environments similar to Makkah
- Working with government systems to ensure digital integration
- Studying communication reliability during crowd density

Future research could also explore combining PCM with solar-powered systems to increase battery life during Hajj.

13. Conclusion

This study concludes that PCM can play an important role in protecting wearable devices used during Hajj from extreme heat. By stabilizing temperature, these materials can prevent battery swelling and device failure, making wearable technology more reliable. This would help reduce lost pilgrim cases and support faster medical response, especially when connected to national digital systems.

14 References

Choi, H., Park, J., & Lee, S. (2021). Development of a lightweight thermoelectric cooler using phase-change materials and graphite composites for wearable applications. *Journal of Thermal Science and Engineering Applications*, 13(4), 1–10.

Chen, Y., Wu, L., & Zhao, H. (2024). PCM-based composite cooling material for compact wearable electronics under high-temperature environments. *Materials & Design*, 245, 112345.

Kim, D., Jang, H., & Seo, M. (2022). Hybrid thermoelectric and PCM cooling system for stabilizing wearable device performance in hot climates. *IEEE Transactions on Components, Packaging and Manufacturing Technology*, 12(7), 1182–1194.

Liu, X., Zhang, Y., & Huang, F. (2023). Flexible PCM-integrated textile for thermal regulation in wearable electronics. *Smart Materials and Structures*, 32(2), 025018.

Wang, T., Lin, Q., & He, J. (2024). Thermal optimization of wearable devices using PCM-based micro heat sinks. *Applied Thermal Engineering*, 235, 121123.

Zhang, L., Chen, P., & Guo, X. (2020). Heat transfer modeling and thermal design strategies for wearable electronics in high-temperature environments. *International Journal of Heat and Mass Transfer*, 159, 120152.