Engineering Design of a Multilayer Passive Cooling Pillow Driven by Thermal Comfort

Ang Zhang*, Rui Wang, Xinyi Zhao
School of Design and Art, Shenyang Aerospace University, Shenyang, Liaoning, China
Corresponding Author: Ang Zhang (16627531413@163.com)

Abstract: This paper presents an engineering redesign framework for a multilayer passive cooling pillow based on experimentally identified thermal-interface requirements. A randomized, counterbalanced crossover experiment involved 16 healthy male university students taking 40-minute naps with a standard pillow and an existing cooling pillow at 32.0 ± 0.5°C. Mean and final pillow-surface temperatures were 29.19 ± 0.46°C and 30.78 ± 0.55°C in the cooling condition, compared with 36.35 ± 0.64°C and 36.59 ± 0.64°C in the standard condition; both differences reached $p < 0.001$. Forehead warming during the final 20 minutes was also smaller. These findings informed four design requirements: breathable contact, lateral heat spreading, temporary heat storage, and ventilation compatible with compliant support. The proposed structure comprises polyester fabric, a heat-spreading sheet, segmented phase change material modules, a ventilated support layer, and a polyurethane base. A modular assembly route and validation measures are also proposed. The contribution is an evidence-informed product design concept that offers a manufacturable structural reference for personal thermal management. The new structure has not been fabricated or tested, and the benchmark improvements cannot be attributed to it.

Keywords: Passive Cooling Pillow; Thermal Comfort; Product Design; Multilayer Structure; Phase Change Material

1. Introduction

Sleep-related thermal comfort depends on both room conditions and the body–bedding interface [1,2]. Thermal exposure affects sleep stages, while bedding and clothing modify responses to ambient conditions [3]. Thermoregulation is also associated with sleep initiation: distal vasodilation and heat loss from the hands and feet predict faster sleep onset [4]. These findings support attention to heat exchange, but do not imply that lowering every local skin temperature necessarily improves sleep.

Studies of thermally conductive beds and cooling bed linen demonstrate the relevance of local bedding conditions to thermal comfort [5,6]. For pillows, an initially cool surface alone does not establish sustained comfort. Heat transfer must be coordinated with moisture transport, contact compliance and head support throughout contact.

Phase change materials (PCMs) store and release latent heat over a limited temperature range, offering temporary thermal buffering [7]. Pillow integration requires coordination with heat spreading, ventilation and mechanical support. The design problem is therefore to allocate complementary functions within a usable structure.

This paper translates an existing human experiment into material-function allocation and

modular pillow design. It distinguishes measured benchmarks from proposed functions, providing a basis for prototype development without claiming validation of the new architecture.

2. Experimental Benchmark and Results

The benchmark experiment was conducted in July–August 2025. Sixteen healthy male university students completed both pillow conditions in randomized, counterbalanced order, with a three-day washout. Chamber temperature was 32.0 ± 0.5°C, relative humidity 50 ± 5%, and air speed 0.10 ± 0.02 m/s. Following adaptation and baseline measurement, each participant took a 40-minute nap with a standard pillow or an existing passive cooling pillow. The intervention pillow was distinct from the new multilayer concept.

Pillow temperature was averaged across five iButton DS1922T sensors in the occipital contact area; forehead temperature was recorded centrally. Thermal data were summarized in four 10-minute intervals. Post-nap measures included the psychomotor vigilance test (PVT) [8], a computerized Stroop task [9], thermal sensation and comfort, the Karolinska Sleepiness Scale [10], and a recovery visual analogue scale (VAS). Condition and time effects were assessed using repeated-measures ANOVA; paired tests were selected according to outcome distributions.

Table 1: Thermal Benchmarks (mean ± SD, n = 16).

Outcome (°C)	Standard	Existing cooling	p
Mean pillow surface	36.35 ± 0.64	29.19 ± 0.46	< 0.001
Final pillow surface	36.59 ± 0.64	30.78 ± 0.55	< 0.001
Final forehead	36.67 ± 0.31	36.32 ± 0.22	0.003
Forehead ΔT, last 20 min	0.677 ± 0.104	0.144 ± 0.065	< 0.001

Forehead ΔT denotes the baseline-normalized temperature during the last 20 minutes. The reported pillow-temperature condition effect was $F(1,15) = 953.061, p < 0.001$, partial $\eta^2 = 0.985$. Differences between the reported means were $7.16°C$ for mean pillow temperature and 5.81°C at the endpoint. These benchmarks motivate attention to late-stage thermal accumulation.

Table 2: Selected post-nap outcomes (mean ± SD, n = 16).

Outcome	Standard	Existing cooling	p
PVT mean response (ms)	396.67 ± 41.85	347.87 ± 41.06	< 0.001
PVT lapses (count)	18.56 ± 9.71	6.31 ± 4.47	< 0.001
Incongruent Stroop (ms)	1367.30 ± 285.06	1146.10 ± 313.43	0.002
Recovery VAS (0–100)	52.44 ± 11.14	70.75 ± 9.97	< 0.001

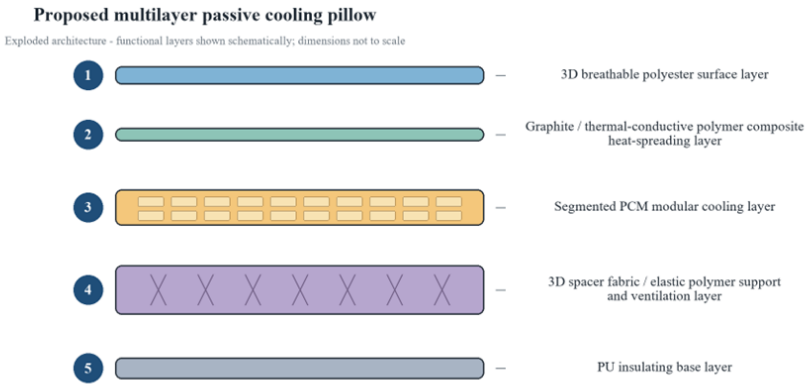


Figure 1: Proposed five-layer architecture; schematic, not to scale.

Table 3: Candidate Materials and Intended Functions.

Layer	Candidate material	Intended function
1	Breathable polyester textile	Contact comfort and moisture transport
2	Graphite or conductive polymer composite	Lateral heat spreading
3	Encapsulated, segmented PCM modules	Temporary heat storage and replacement
4	Spacer fabric or elastic polymer	Compliant support and air paths
5	Polyurethane base	Base support and reduced downward heat exchange

The layers represent functional assignments, not a finalized bill of materials. Thickness, conductivity, phase-transition temperature, latent heat and compression properties have not been determined. Segmentation is intended to accommodate deformation and module access; it may also introduce thermal discontinuities that require evaluation.

4. Thermal Path and Modular Assembly

Figure 2 summarizes the proposed thermal path. Heat entering through the contact fabric is intended to spread laterally and be buffered by the PCM layer. The support layer should retain connected air paths under head loading. The base limits downward exchange, although excessive insulation could impede heat release after PCM saturation. These interactions remain design hypotheses.

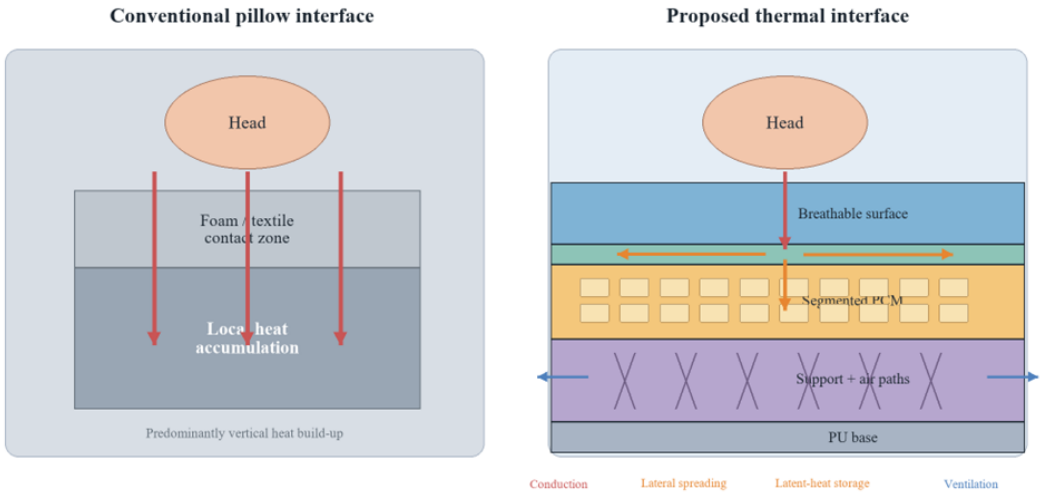


Figure 3: Proposed Assembly Sequence.

The route uses cutting, local lamination, module insertion and edge sewing or sealing (Figure 3). Bonding should preserve thermal contact without closing ventilation paths; module seals must resist repeated loading. A removable cover and accessible modules would allow separate cleaning and replacement. Manufacturing yield, cost, leakage resistance and durability have not been measured.

5. Validation Needs and Conclusions

Prototype validation should first measure material thermal properties, PCM cycling and seal integrity, then evaluate surface temperature, storage duration, contact pressure, airflow resistance and compression set under representative loads. A controlled comparison should include the standard pillow, the existing benchmark pillow and the new prototype under identical conditioning. Such testing is necessary to determine whether the proposed layers deliver the intended functions.

The benchmark is limited to 16 healthy male students and a 40-minute nap. It does not establish overnight efficacy, objective sleep-stage changes or performance in other populations. Intervention composition, initial thermal state and sensor calibration are insufficiently specified for full replication. No new participant testing was conducted for the proposed structure.

This study proposes a five-layer passive cooling pillow by translating measured thermal-interface differences into product functions and an assembly route. Its contribution is a traceable connection between human-response evidence and structural design. Prototype fabrication and controlled testing are required before thermal comfort, durability or recovery benefits can be attributed to the new architecture.

Acknowledgements and Disclosure

We thank the participants for their cooperation. The authors declare no competing interests.

Author contributions

A.Z. conceived the study, analyzed the data, and drafted the manuscript. R.W. performed the experiments. X.Z. contributed to the structural design and manuscript revision. All authors approved the final manuscript.

References

[1] Xu, X. and Lian, Z. (2024) Optimizing bedroom thermal environment: A review of human body temperature, sleeping thermal comfort and sleep quality. Energy and Built Environment, 5, 829–839. https://doi.org/10.1016/j.enbenv.2023.06.010

[2] Li, X., Halaki, M. and Chow, C.M. (2024) How do sleepwear and bedding fibre types affect sleep quality: A systematic review. Journal of Sleep Research, 33, e14217. https://doi.org/10.1111/jsr.14217

[3] Okamoto-Mizuno, K. and Mizuno, K. (2012) Effects of thermal environment on sleep and circadian rhythm. Journal of Physiological Anthropology, 31, 14. https://doi.org/10.1186/1880-6805-31-14

[4] Kräuchi, K., Cajochen, C., Werth, E. and Wirz-Justice, A. (1999) Warm feet promote the rapid onset of sleep. Nature, 401, 36–37. https://doi.org/10.1038/43366

[5] Hu, J., Hao, X., Huang, M., et al. (2023) An experimental study on human thermal comfort with thermal-conductive bed during sleep in summer. Buildings, 13, 1936. https://doi.org/10.3390/buildings13081936

[6] Zaki, S.A., Rosli, M.F., Rijal, H.B., et al. (2021) Effectiveness of a cool bed linen for thermal comfort and sleep quality in air-conditioned bedroom under hot-humid climate. Sustainability, 13, 9099. https://doi.org/10.3390/su13169099

[7] Mondal, S. (2008) Phase change materials for smart textiles – An overview. Applied Thermal Engineering, 28, 1536–1550. https://doi.org/10.1016/j.applthermaleng.2007.08.009

[8] Dinges, D.F. and Powell, J.W. (1985) Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. Behavior Research Methods, Instruments, & Computers, 17, 652–655. https://doi.org/10.3758/BF03200977

[9] Mueller, S.T. and Piper, B.J. (2014) The Psychology Experiment Building Language (PEBL) and PEBL Test Battery. Journal of Neuroscience Methods, 222, 250–259. https://doi.org/10.1016/j.jneumeth.2013.10.024

[10] Akerstedt, T. and Gillberg, M. (1990) Subjective and objective sleepiness in the active individual. International Journal of Neuroscience, 52, 29–37. https://doi.org/10.3109/00207459008994241