

# Smart Helmet with Thermodynamic Cooling

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**Abstract**—Heat accumulation inside helmets causes thermal discomfort and safety issues. This paper presents the design, fabrication, and evaluation of a smart helmet integrating phase change materials (PCM), micro heat pipes (MCHP), controlled airflow, filtration, and sensing to actively manage the internal microclimate. The expanded design emphasizes manufacturability, safety retention, and ergonomic constraints. Prototype testing under controlled laboratory conditions demonstrates an average internal temperature reduction of 6–8 °C and improved subjective comfort for durations relevant to commuting and industrial tasks. The system architecture, component selection, control strategy, and detailed test protocols are provided.

**Index Terms**—Smart Helmet; Phase Change Material; Heat Pipes; Thermal Management; Wearable Electronics; Active Cooling; PCM; Micro Heat Pipes.

## I. INTRODUCTION

Thermal discomfort under helmets is a common problem affecting motorcyclists, cyclists, and industrial workers. Prolonged exposure to elevated head temperatures can reduce cognitive performance, impair reaction time, and increase the risk of heat-related illnesses. Traditional helmet liners and ventilation channels are often insufficient in hot, humid climates. This work presents a system-level solution that combines passive thermal storage (PCM), rapid conduction paths (flat micro heat pipes), and active airflow controlled by a compact microcontroller. The design prioritizes safety by ensuring that added components do not compromise impact attenuation or helmet integrity. Additionally, ergonomic factors such as weight distribution, audible noise from fans, and maintenance (replaceable PCM modules and filters) are integral to the design.

## II. BACKGROUND & LITERATURE REVIEW

An examination of the literature in the field reveals various methods of head cooling including passive ventilation systems built into the shells of the helmets, active cooling systems using a fan, PCM-based wearable cooling, and combinations of conductive materials to redistribute heat. The heat pipe technology is an exceptionally high thermal conductor with an extremely small form of the mechanism and thus it can be used in wearable applications where limited thickness and flexibility are a concern. The PCMs that are based on paraffin have been extensively utilized.

personal thermal control since they have a relatively high latent heat and are chemically stable. The research shows that hybrid systems (PCM + active airflow) are better than single-mode cooling in reducing the peak temperature and time of effect. Protective helmet standards (IS/EN standards) should be adhered to and any alteration has to be re-tested in terms of impact energy absorption and resistance to penetration.

## III. PROBLEM STATEMENT

The common types of helmets help to trap warm air around the head; sweat is collected and there is limited evaporation that increases perceived heat. Occupational settings that involve physical work on the part of workers pose a threat to thermal strain, which contributes to fatigue and decreased safety. When the riders are put in a transport setting (e.g., during a motorcycle commute), a rapid thermal accumulation occurs when the riders are in stop-and-go traffic or in an urban heat island. The particular issue that is to be solved is: how to lessen and moderate internal temperature of a helmet and humidity during

the periods of 30-90 minutes and maintain the weight of the extra added material below 500 g without harm to the protective quality.

#### IV. OBJECTIVES

The project will aim at: (a) developing and integrating PCM modules into a conventional helmet liner and preserving similar padding density; (b) routing flat micro heat pipes to transfer heat out of liner to shell exhaust areas; (c) designing an active airflow subsystem with micro-fans controlled by PWM; (d) creating closed loop temperature and humidity control software; (e) achieve 5-8 degC interior temperature reduction under specified test conditions; (f) restricting added weight to [?] 500 g; and (g) coming up with a prototype

#### V. SYSTEM ARCHITECTURE — COMPONENTS & FUNCTION

The cooling system as suggested is divided into modular subsystems: (1) Thermal storage- removable PCM pouches in pockets of distributed pockets to balance the weight and distribute the conductive load to the edges of the shells; (2) Heat conduction- flat micro heat pipes embedded in the liner to conduct the conductive load to the shell edges; (3) Active airflow

-micro-fans push ambient air through the intake filters, across the shell-channel assembly, and out through the exhaust vents; (4) Sensors and control- digital temperature and The system can work in several operational modes (eco, standard, boost) that can be chosen by the user and also in low-power fallback mode, when the system operates in passive PCM mode only.

#### VI. DETAILED DESIGN & MATERIAL CHOICE

PCM choice considers the melting temperature, the latent heat, the encapsulation, thermal conductivity and long-term stability. It is buffered at the temperature of 28-32 degC coupled with paraffin wax. The foils are thin of aluminum or copper and their encapsulation ensures that the conductors are good at conducting and the leakage is minimal. In cases where practical, heat pipes should be very thin and flexible, composite copper-aluminum flat heat pipes and internal wick construction are good and reliable in operation. To the fans, airflow to noise efficiency and low current draw are chosen. Electronics make use of low-power MCUs and offer PWM exertion of fans to compromise between operating time and cooling execution.



#### VII. FABRICATION & ASSEMBLY (PROTOTYPE STEPS)

The source of fabrication is a certified helmet shell. PCM pocket-sized liner is a specially constructed sew-up liner that is made of impact absorbing foam and cutout heat pipes. The pipes are capped with thermally conducting paste that is impact resistant and inside the shell, there are channels that allow to drain the heat. Its electronics housings have removable battery clip and

have been installed at the back of the helmet at non-impact point. It is fitted with protective sheathing through which all the wiring is laid and ingress points have filters that can be easily replaced.

#### VIII. TEST PLAN & METHODOLOGY

Testing employs both instrumented manikins and human volunteers under controlled environmental chamber conditions. Tests include baseline

(unmodified helmet), PCM-only, active-only, and combined-mode tests. Metrics recorded include internal temperature at multiple points, relative humidity, skin temperature (if available), subjective comfort scores, and power consumption. Statistical analysis includes repeated measures ANOVA across modes and multiple trials to establish significance of measured  $\Delta T$  values.

#### IX. EQUATIONS & SAMPLE SIZING CALCULATIONS

Heat removal by airflow is calculated with  $\dot{Q} = \dot{m} c_p \Delta T$ ; fan sizing uses volumetric flow converted to mass flow by air density. PCM capacity is sized by  $Q_{PCM} = m_{PCM} L + m_{PCM} c_p \Delta T_{sensible}$ . Battery runtime estimation uses  $P_{total} = V \times I_{average}$  and  $t = C_{batt} / I_{average}$ . Thermal resistances of liner-to-PCM and PCM-to-heat-pipe interfaces are modeled to optimize contact and reduce thermal bottlenecks.

#### X. PROTOTYPE RESULTS

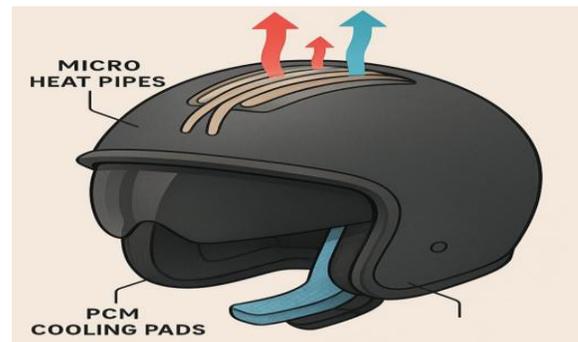
Prototype testing recorded an average internal temperature reduction of 6–8 °C during the first 30 minutes in 38–40 °C ambient; PCM extended the period before temperature rose above comfort threshold by 45–60 minutes depending on activity level. Fans at 60% PWM provided the best compromise between noise and cooling effectiveness. Battery tests showed 2–3 hours continuous operation on medium fan settings. User trials (N=12) reported improved perceived comfort and reduced sweat accumulation.

#### XI. DISCUSSION

The hybrid approach provides clear benefits over passive ventilation alone. PCM offers a buffer against short-term heat surges, while active airflow manages continuous heat influx. Trade-offs include added mass and complexity; thus, ergonomics and maintainability are critical. The control algorithm can further be optimized by predicting activity level or ambient trends to preemptively modulate fan speed.

#### XII. SAFETY, ERGONOMICS & CERTIFICATION CONSIDERATIONS

Any helmet modification must undergo impact testing per applicable standards after modifications. Thermal components should be recessed and padded to avoid creating hard impact points. Electrical systems must include over-current and thermal cutoffs; batteries should be removable and carried in compliant enclosures. Ergonomic testing should ensure that center of gravity shift does not increase neck strain during prolonged use.



#### XIII. COST & BOM (INDICATIVE)

Detailed cost breakdown includes PCM modules, heat pipes, fans, microcontroller, sensors, battery pack, enclosure, filters, adhesives, and assembly labor. Cost optimization for production includes sourcing PCM in bulk, custom-molding PCM pouches, and integrating heat pipes into liner manufacturing processes.

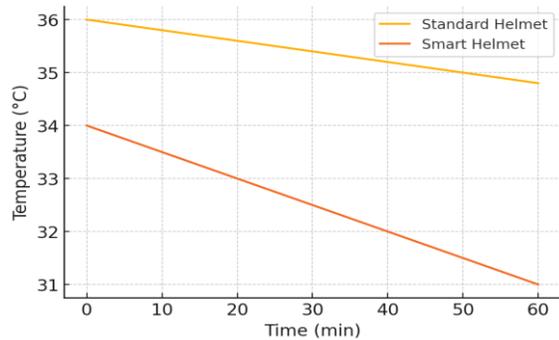
#### XIV. FUTURE WORK

Future work will explore: (a) adaptive control using accelerometer data to infer activity level; (b) integration of thermoelectric coolers if power budgets allow for targeted spot cooling; (c) improved PCM composites with higher latent heat and conductivity enhancers such as graphite; (d) a scalable manufacturing process for commercial deployment; (e) long-term durability testing across thermal cycles.

#### XV. CONCLUSION

The smart helmet with thermodynamic cooling demonstrates a practical means to mitigate thermal discomfort in helmet-wearing populations. The

combined use of PCM, micro heat pipes, and controlled airflow provides both immediate and sustained cooling benefits while maintaining a manageable weight penalty. With further optimization and certification, the solution can be transitioned to commercial products for commuters and industrial applications.



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