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Thermal Design for Externally Worn Wearable Electronics

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Introduction

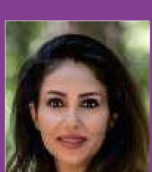
Thermal management plays a critical role in the performance, reliability, and longevity of wearable devices. Reliability must be considered even when components remain below their absolute maximum operating temperatures. This is due to increased diffusion rates, material fatigue, and electromigration effects which degrade electronics over time. Additional failure mechanisms—such as humidity, mechanical stress, or voltage fluctuations—also play a significant role in accelerating degradation. As wearables continue to integrate higher-power components and increased computational loads, understanding and mitigating thermal-induced reliability risks becomes even more essential for product success. **Table 1** outlines typical maximum temperature limits for internal components commonly found in wearable devices. It is important to note that this paper focuses exclusively on externally worn wearable electronics—such as smartwatches, fitness trackers, and smart glasses—where thermal interactions with human skin and the surrounding air play a significant role. Implanted or ingestible electronic devices, which are subject to entirely different thermal environments and biocompatibility considerations, are outside the scope of this study.

Component	Maximum Temperature (°C)
Memory chip (junction)	95–105
ASIC chip (junction)	125
Li-ion battery	45 (charging), 60 (discharging)
Display-agnostic	100 Note: These displays experience significant performance limitations within the 50-70°C range, requiring additional power and impacting thermal performance.

Table 1: Typical maximum temperature limits for components in wearable devices. These values may vary depending on the manufacturer.

For batteries, both the temperature magnitude and its spatial gradient are critical. Steep gradients can accelerate degradation and aging, while temperatures exceeding the limit can accelerate aging or lead to catastrophic events such as thermal runaway. These maximum temperature thresholds vary based on battery chemistry and are specified by manufacturers.

User comfort and safety are also important and are often linked to the temperature of the device's exterior surfaces. For compliance, standards define touch temperature limits based on use scenarios, materials, and contact durations, distinguishing between short and long-duration touch periods. **Table 2** summarizes example temperature limits from IEC 62368-1. It is recommended that the reader review references [1]-[3] to select the appropriate limits for their application.



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Part	Metal	Vitreous material	Plastic, rubber
Devices worn on the body (in direct contact) in normal use (>8 hr)	43-48°C	43-48°C	43-48°C
External surfaces held, touched or worn against the body in normal use (>1 min and <8 hr)	48°C	48°C	48°C
External surfaces held for short periods of time or touched occasionally (>10 s and <1 min)	51°C	56°C	60°C
External surfaces touched occasionally for very short periods (>1 s and <10s)	60°C	71°C	77°C
External surfaces that need not be touched to operate the equipment (<1 s)	70°C	80°C	94°C

Table 2: IEC 62368-1 standard touch safety temperature limits for users, categorized by material type and duration of contact.

Beyond safety, user comfort may impose stricter temperature and/or heat flux limits [4], with metals often on the order of 40°C, and plastics slightly higher due to their lower thermal diffusivity. Comfort limits also vary with usage duration, device material, etc. A deep dive on thermal comfort is available in reference [5]. It should be noted that the exterior surface of a wearable device may be divided into multiple zones to properly assign touch temperature limits, accounting for material differences and areas of direct skin contact.

Wearable thermal designs must also account for both heat exchange with the skin and the operational environment where the device will be used—including whether the device is intended for indoor or outdoor use, the expected ambient temperature ranges, humidity, and altitude conditions.

For devices incorporating active cooling solutions, acoustics and airflow direction play a vital role. Proper airflow management ensures that exhaust air does not create discomfort for the user, while acoustic optimization reduces noise. These considerations help achieve a balance between effective cooling and user satisfaction.

It is also crucial to account for factors such as cost, weight, form factor, manufacturability, serviceability, and coexistence between thermal components and other internal elements. Developing an effective thermal management system for a wearable requires close collaboration to balance constraints between cross-disciplinary teams, including industrial design, power, firmware, wireless, and product design.

Systematic Design Approach

Developing a thermal management solution for wearable devices involves a methodical approach to ensure required performance, reliability, user comfort, and safety. This foundation is set by first gathering critical information: the design intent, form factor, expected environmental operating conditions, and material choices. Designers must also identify the heat sources within the device, such as processors CPUs, GPUs, memory, Wi-Fi modules, displays, and batteries, along with rough estimates of their power dissipation to help determine the cooling needs.

The next step is to perform initial calculations to evaluate whether passive cooling is sufficient or if active cooling solutions are necessary. This evaluation involves simplified "back of the envelope" models to estimate the device's surface temperature and assess compliance with touch temperature limits. The surface temperature of the device can be estimated using the following formula:

$$\dot{Q}_{total} = hA(T - T_\infty) + \epsilon\sigma A(T^4 - {T_\infty}^4)$$

Where:

- Q: Heat dissipated from the device.
- h: Convection heat transfer coefficient, assumed constant across the device.
- A: Surface area of the exterior surfaces.
- T: Temperature of the device's exterior surfaces.
- T_∞: Ambient temperature.
- ϵ: Emissivity of the exterior surface.
- σ: Stefan-Boltzmann constant ($5.67\times10{-8}$ W/m^2K^4)

In this formula, the first term represents the contribution of convection, while the second term accounts for heat dissipation through radiation with the assumption that the system radiates to is at ambient temperature. For simplicity, heat exchange between the device and the user's skin is often assumed to be zero, and the temperature is assumed uniform across the device's exterior. In this calculation, the area should be limited to the intended heat rejection surfaces. For example, it may or may not be appropriate to include the surface area of the band on a wrist wearable. The heat transfer coefficient (h) is commonly estimated using Nusselt number correlations based on Rayleigh and Prandtl numbers (natural convection) or Reynolds and Prandtl numbers (forced convection).

For wearable devices operating under passive cooling at sea level, natural convection and radiation contributions are typically of the same order of magnitude. This calculation provides a quick but essential insight into the feasibility of passive cooling, enabling designers to decide early in the process whether to pursue active solutions. If the calculated surface temperature exceeds the touch temperature limit, active cooling solutions, such as fans or blowers, must be considered. For such cases, the required airflow from a fan or blower assembly can be estimated using the following formula:

$$\dot{Q}_{total} = hA(T - T_\infty) + \epsilon\sigma A\left(T^4 - {T_\infty}^4\right) + \dot{m}C_p(T_{air,out} - T_\infty)$$

Where:

$\dot{m}$: Mass flow rate of air.

$T_{air,out}-T_\infty$: Temperature difference between the exhaust and inlet air

Once the required airflow is determined, the appropriate type and number of air-moving devices can be selected based on the device's form factor. Fans or blowers can be chosen from their P-Q (pressure-flow) curves, which are typically provided for standard conditions at sea level. If the device is designed to operate in different environmental conditions, such as higher altitudes or varying temperatures, the P-Q curves must be adjusted accordingly. It should be noted that the delivered airflow by an air-moving device at a given RPM depends not only on the design of the air-moving device itself but also on the overall design of the wearable assembly. Wearable designs with lower air blockage allow the air-moving device to deliver greater airflow compared to designs with high pressure impedance. While first-order approximations of pressure drop can be performed using hand calculations, accurately estimating the delivered airflow typically requires detailed computational fluid dynamics (CFD) analysis. This allows the identification of the operating point where the system pressure curve intersects the fan's P-Q performance curve. It is important to ensure that the selected air-moving device will not operate at its maximum speed to achieve the desired airflow. Operating near maximum speed may compromise reliability, increase noise levels, and reduce the lifespan of the cooling system. According to fan performance relationships, airflow (Q) is approximately proportional to fan speed (RPM) ($Q \propto RPM$), while noise increases with the fifth power of RPM ($\text{Sound Power} \propto RPM^5$) and power consumption scales with the cube of RPM ($\text{Power} \propto RPM^3$). This means that a small reduction in RPM significantly reduces noise and power draw, making it essential to select a fan with an appropriate operating point.

With a cooling strategy identified, a preliminary thermal architecture is developed. Effective heat path design is critical in guiding heat flow from high-power components to designated cooling surfaces or heat sinks. This may involve thermal interface materials (TIMs), graphite sheets, vapor chambers, aluminum brackets, or direct heat spreading structures to efficiently bridge heat from the source to the exterior. Additionally, this stage requires collaboration across disciplines to address manufacturability, form factor, weight, cost, and electromagnetic interference (EMI) shielding.

The initial design is then optimized using **3D steady-state simulations**, which are crucial for understanding and optimizing thermal performance. These simulations incorporate detailed information about material properties, heat sources, and ambient conditions. Below are some key steps and considerations in developing a robust simulation model:

- **Simplify the CAD Model:**
  To improve computational efficiency, simplify the CAD geometry by removing unnecessary internal components, such as screws and thin wires, or by reducing the complexity of solder balls and similar features.

- **Assign Material Properties:**
  Include properties such as thermal conductivity, and emissivity for each material used in the device.

- **Define Ambient Conditions:**
  Set environmental parameters, including ambient temperature, air velocity, solar loading, and altitude, to reflect the device's expected operating conditions.

- **Account for the User:**
  Include components representing the user's skin in the simulation. Penne's bioheat equation [6] is commonly used for this purpose, with skin divided into four layers: inner tissue, fat, dermis, and epidermis. Blood perfusion and the user's hot/cold receptors are in the Dermis layer.

- **Set Heat Source Parameters:**
  Define power dissipation data. When detailed component-level modeling is unavailable, compact thermal models, such as Delphi-based or two-resistance models are recommended to estimate junction-to-case and junction-to-ambient thermal resistance, ensuring accurate heat distribution representation across the system.

- **Include Air-Moving Components:**
  Incorporate P-Q curves from supplier specifications and adjust for altitude or ambient temperature as needed. Common approaches to model air movers include momentum source methods, moving reference frame and multiple reference frame models, each offering varying levels of accuracy and efficiency.

- **Define Computational Domain and Boundaries:**
  Ensure that the size of the computational domain is large enough to make the simulation results independent of boundary conditions.

- **Discretize the Computational Domain:**
  Create a mesh for the domain, refining it in regions with high temperature or velocity gradients to capture detailed behavior.

- **Solve Governing Equations:**
  Use numerical methods to solve the continuity, momentum, and energy equations, generating temperature and velocity maps. Take proper steps to ensure convergence and accuracy of the results.

After generating simulation results, thorough verification and validation are essential to ensure accuracy. Start by confirming that the outcomes are independent of grid size, domain boundaries, and other computational parameters. Additionally, verify that the simulation adheres to energy balance principles and responds logically to changes in input parameters. If a physical representation of the device, such as a prototype, is available, it can be used to validate the simulation model. Care must also be taken to ensure that the test environment closely replicates the conditions modeled in the simulation to enable accurate comparisons. By following these steps, confidence in the simulation results can be established.

The validated simulation model becomes an invaluable tool for iterative optimization, enabling designers to fine-tune the thermal architecture and explore alternative design concepts. It provides critical insights for improving PCB layouts, refining heat spreaders, and optimizing the placement of internal components. Parametric studies can be conducted to evaluate different design scenarios and "what-if" questions. This may include reducing pressure drop, minimizing noise, ensuring air movers operate within optimal ranges, and avoiding air blockage or stall regions.

A key application of the validated model is in estimating the top-down power budget, which defines the maximum allowable dissipated power for reliable operation. The power budget is influenced by the detailed thermal architecture and environmental operating conditions, such as ambient temperature, air velocity, and radiation exposure. In practical use cases, the power budget also depends on the distribution of power within the device. Uniform power distribution allows for a higher power budget and improved thermal performance. Each use-case scenario may have a unique power profile, requiring careful assessment to meet thermal requirements.

As the design evolves, transient analysis is used to evaluate how the device responds to thermal fluctuations over time. This is critical for wearables, where touch temperature compliance under transient conditions must be ensured. Accurate transient simulations require defining additional material properties such as density and specific heat capacity, which influence heat storage and dissipation. Additionally, selecting an appropriate time step is crucial for accuracy and numerical stability.

Further testing must be conducted to assess performance under real-world user interface conditions, such as obstructions from hair, hats, or sleeves, which can impact heat dissipation and airflow dynamics. Necessary design adjustments are made to maintain performance across these scenarios. For wearable devices with active cooling, managing airflow and exhaust placement is crucial. **Figure 2** illustrates a notional head-mounted display (HMD) with an active cooling outlet at the top, where warm air is expelled to prevent heat buildup near the user's face.

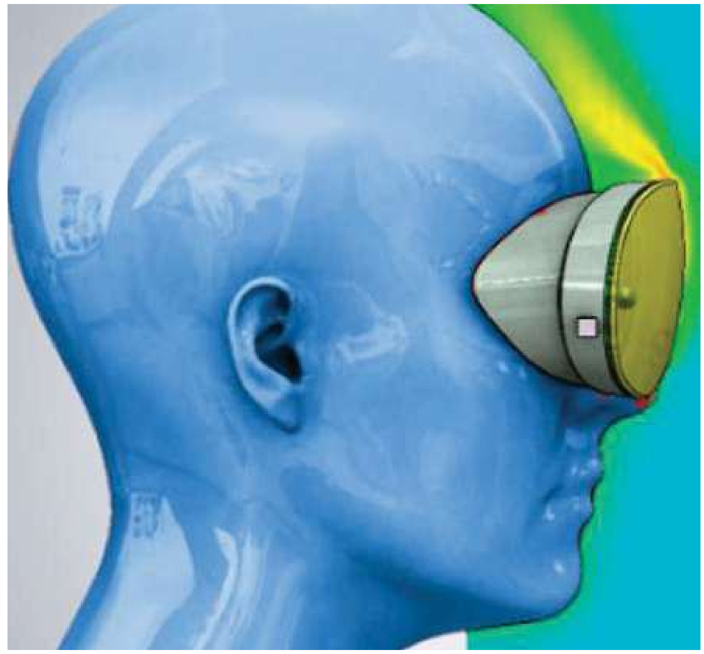

Figure 2: Illustration of a head-mounted display (HMD) showing the active cooling outlet

Thermal Throttling Policy

A thermal throttling policy ensures a graceful user experience over a wide range of conditions. Thermal throttling regulates power dissipation to keep both internal components and exterior surfaces within safe temperature limits during operation. The throttling strategy must be defined when developing the thermal architecture to ensure the necessary hardware hooks are in place.

Real-time temperature monitoring is crucial for implementing thermal throttling. Internal components are typically monitored using built-in temperature sensors. However, monitoring the exterior surface presents unique challenges. The location of hotspots can vary significantly based on use case scenarios and environmental conditions. Installing physical sensors across all potential hotspot locations can be impractical due to cost, space, and design constraints.

To address this, virtual sensors are employed to estimate temperatures at specific locations on the exterior surface. These sensors use real-time data from physical sensors located elsewhere in the device, combined with computational models, to predict surface temperatures. Virtual sensors enable dynamic monitoring of exterior hotspots, enabling throttling actions that ensure user comfort and compliance with safety standards while limiting the extent of the physical sensor deployment required.

Validation and Tuning of Throttling Policy

Once hardware prototypes become available, validation efforts play a critical role in refining the throttling policy. Correlation between simulation results and physical testing is necessary to confirm that throttling strategies effectively maintain thermal compliance without introducing unnecessary performance degradation. Key validation efforts include controlled thermal testing under representative environmental conditions, user trials to assess perceived comfort, and iterative tuning of throttling parameters based on real-world usage patterns.

Iterative tuning of the throttling parameters is essential to balance the design. If throttling is too aggressive, the device may experience unnecessary performance limitations, negatively impacting the user experience. Conversely, insufficient throttling could lead to overheating and discomfort.

Conclusion

While the structured design methodology presented in this paper can be applied to broader electronics systems, it is particularly tailored for wearables, where additional constraints—such as user skin contact, compact form factor, acoustic sensitivity, and comfort-driven surface temperature limits—introduce distinct thermal challenges.

The flowchart in **Figure 3** can be used as a reference by practicing engineers.

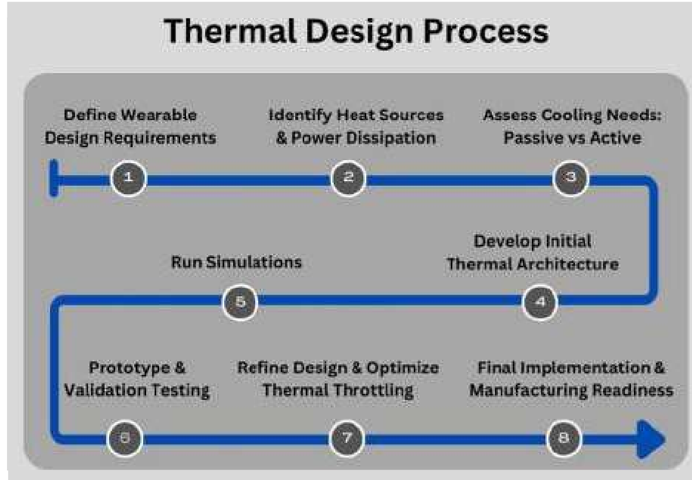

Figure 3: Flowchart of systematic approach to a thermal design.

The successful thermal design of wearable devices therefore demands a holistic approach that balances performance, reliability, safety, and user comfort, each of which plays a critical and sometimes competing role in shaping the user experience.

The techniques discussed—ranging from early-phase modeling and simulation to advanced cooling strategies, virtual sensors, and dynamic throttling—offer a practical framework for engineers aiming to deliver thermally robust and user-friendly wearables in today's high-performance landscape.

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