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Experimental validation of additively manufactured optimized shapes for passive cooling

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HIGHLIGHTS

- The superior performance of topology optimized passive heat sinks is demonstrated experimentally.
- Significant material savings and design improvements of passive LED coolers are confirmed.
- Easy manufacturable design interpretation demonstrates a methodology for cost reduction.
- Significant reduction of maintenance costs is estimated based on the measured reduction in the LED temperature.

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ABSTRACT

This article confirms the superior performance of topology optimized heat sinks compared to lattice designs and suggests simpler manufacturable pin-fin design interpretations. The development is driven by the wide adoption of light-emitting-diode (LED) lamps for industrial and residential lighting. Even for advanced lighting technology as LEDs, a large fraction of the input power is still converted to heat. Thus, efficient thermal control lowers energy waste, increases lifetime and reduces maintenance costs of this rapidly growing, expectedly soon to be governing, illumination technology. The presented heat sink solutions are generated by topology optimization, a computational morphogenesis approach with ultimate design freedom, relying on high-performance computing and simulation. Optimized devices exhibit complex and organic-looking topologies which are realized with the help of additive manufacturing. To reduce manufacturing cost, a simplified interpretation of the optimized design is produced and validated as well. Numerical and experimental results agree well and indicate that the obtained designs outperform lattice geometries by more than 21%, resulting in a doubling of life expectancy and 50% decrease in operational cost.

1. Introduction

Lighting in residential and commercial sectors accounts for up to 7% of the total US electricity consumption in 2016[1] and accounts for a significant share (14–60%) of the electricity bill in retail and office buildings [1–3]. Over the last decade, initiatives supported by governments around the world have accelerated development and adoption of light-emitting diode (LED) products as a replacement for century-old incandescent technologies and newer high-intensity discharge and fluorescent lamps. LED technologies are estimated to comprise anywhere from 25% to upwards of 80% of lighting by 2020, and their rapid development and improved efficiency will result in a 75% reduction in energy consumption for lighting by 2035 [2]. Other main positive factors are light output, longevity, light distribution, dimensions, chromaticity, control, stability, environmental impact, durability and cost.

Despite their efficiency compared to other lighting technologies, LEDs still only convert 25–35% of the input energy to light [4], the rest is lost as heat generated in a relatively small area of the light-emitting semiconductor. This contrasts incandescent and fluorescent lamps, where heat generated in voluminous bulbs is easily conducted through bulb walls and subsequently radiated and convected through the surroundings. Increased temperature or overheating results in a shift of emission wavelength, lower lumen output and lifetime reduction of LEDs. Large LEDs produce more light per unit area and generate a significant amount of heat, thus requiring external heat exchangers

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[1] U.S. Energy Information Administration (EIA), www.eia.gov.

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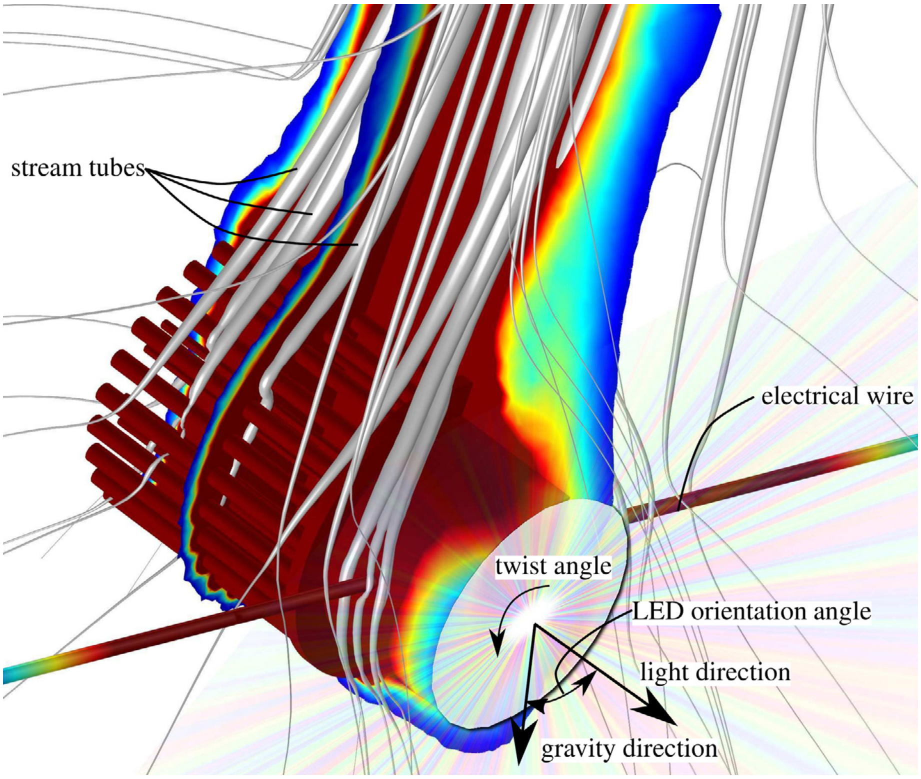

Fig. 1. Example of traditional pin-fin passive LED heat sink solution. Due to the directionality of the light source robust cooling performance is required for different orientation and twist angles. Colors represent the temperature, varying from dark blue (23.5 °C) to dark red (29.7 °C). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

which impacts size, reliability and cost. The excess heat must be removed either by active forced convection (fans) or by passive heat sinks relying on natural convection.

Fans are energy consuming, noisy and subject to mechanical failure, whereas natural convection needs careful design of heat sink geometries to ensure adequate cooling performance. A typical off-the-shelf fan, compatible with the dimensions of the presented coolers, consumes between 0.4 W and 1.2 W, increasing the energy consumption with 8–24% compared to a passively cooled solution for a 5 W LED illuminator.[2]

Natural convection, on the other hand, is a heat transport mechanism which accelerates fluids based on differences in fluid densities due to temperature gradients. Fig. 1 visualizes the process, where a sink attached to a heat source conducts heat to its surface, and the temperature difference between sink surface and ambient air generates a fluid motion which transfers the heat to the surroundings. The performance of the heat sink depends on a delicate balance between its ability to conduct heat away from the semiconductor and the excitation of a fluid motion strong enough to remove the heat by natural convection. The process continues to draw a lot of attention and has been studied extensively using experimental and numerical techniques, leading to a set of simple design rules utilized by designers and engineers. However, the simplicity of these rules, as well as the complexity of the physical phenomena may easily result in sub-optimal solutions leaving many opportunities for improvements [5–7].

We use state-of-the-art computing techniques and algorithms to design efficient passive heat sinks and validate the resulting structures experimentally. We find that topology-optimized natural convection coolers outperform traditional designs. The computational morphogenesis approach results in coral-like branching topologies resembling plants and organisms found in nature. The complex topologies can be manufactured using additive manufacturing technologies, or may inspire simplified and more easily manufacturable designs with a minor loss in performance. The process is verified by numerical simulations and confirmed experimentally. Methodology and findings may be further utilized and extended to cooling of electronic equipment, industrial machines, and processes, where robustness, low-maintenance cost and performance are of vital importance.

Fig. 2(a) shows a commercial LED bulb developed as a direct replacement for an incandescent one. Due to the small size of the semiconductor, designers have extensive freedom to propose aesthetically pleasing, and at the same time efficient, cooling solutions. The design is monolithic and includes the heat sink implemented as a ring with several straight fins along the body. The implementation targets a vertical orientation of the bulb, where the fins become parallel to the gravity vector and accelerate the air through a chimney effect. On the other hand, LEDs are strictly directional light sources, requiring different orientations for delivering light where needed. Thus, for positions different from vertical, the heat sink will perform inefficiently [8–10]. The presented experimental results confirm this effect as well.

Most research works investigate different variants of pin- or straight-fin heat sinks [11–15] due to their easy parametrization and simplified geometry. Various combinations of these primitives are often utilized for improving performance and building more complex products realizing designers' visions. Fig. 2(a) show expert industrial design solutions for larger industrial LEDs, designed by a project partner.[3] The intricate lattice-like sinks conduct the heat away from their base and transfer it to the surrounding air ensuring redundancy of conduction and flow pathways with the aim of achieving orientation insensitive performance. The complex topologies are realized in an aluminum alloy using metal 3D printing and provide the starting point for this study. Their performance is compared numerically and experimentally to the topologically-optimized designs. The optimization methodology with numerical studies on the influence of different symmetries on the design process is presented in [16]. In the present

[2] The power consumption is estimated by the authors using several commercial catalogs. The estimates are for fans matching the geometries of the heat sinks utilized in the article.

[3] AT Lighting ApS.