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Design of passive coolers for light-emitting diode lamps using topology optimisation

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ABSTRACT

Topology optimised designs for passive cooling of light-emitting diode (LED) lamps are investigated through extensive numerical parameter studies. The designs are optimised for either horizontal or vertical orientations and are compared to a lattice-fin design as well as a simple parameter optimised commercial pin fin design. The different orientations result in significant differences in topologies. The optimisation favours placing material at outer boundaries of the design domain, leaving a hollow core that allows the buoyancy forces to accelerate the air to higher speeds. Investigations show that increasing design symmetry yields performance with less sensitivity to orientation with a minor loss in mean performance. The topology-optimised designs of heat sinks for natural convection yield a 26% lower package temperature using around 12% less material compared to the lattice-fin design, while maintaining low sensitivity to orientation. Furthermore, they exhibit several defining features and provide insight and general guidelines for the design of passive coolers for LED lamps.

1. Introduction

Light-emitting diodes (LEDs) are highly energy-efficient light sources. However, it remains a challenge to adequately cool them since around 70% of the energy supplied to an LED is converted to heat. This generally leads to high package temperatures, which severely affect the LED light output and lifespan unless sufficiently cooled [1]. Generally, it is necessary to keep the LED package temperature below a given manufacturer-specified temperature, typically around 80 °C.

Above goal is often achieved using forced convection with the help of a small fan. However, the low-power and low-noise benefits of natural convection make it ideal for LED lighting systems in a world with scarce resources. Natural convection inherently does not need an additional energy source forcing the flow, since the temperature differences, caused by the heated LED lamp, cause the air to circulate. Thus, the cooling of the LED lamp is free, in the sense that the energy already supplied to the system is reused to provide the cooling.

Recently, there has been a lot of attention on the design of efficient heat sinks for LED applications in the heat transfer community, focusing mainly on variants of the classical pin or straight-fin heat sinks. Most of this work has been focused on performance for LED lamps in a downwards/vertical orientation, e.g.: Yu et al. [2] investigate various fin configurations for radial heat sinks; Jang et al. [3] perform multidisciplinary optimisation of pin fin radial heat sinks and found that the pin fin configuration lead to more uniform cooling performance due to repeated leading-edge effects; Jang et al. [4] examine pin fin radial heat sinks with different fin-height profiles and conclude that the fin height should be largest at the circumference and decrease towards the centre. The effect of orientation is less well investigated, but strong examples are: Jang et al. [5] show that the orientation effect for a cylindrical radial straight-fin heat sink is strong and find drag and convection efficiency to be inversely correlated; Shen et al. [6] investigate the orientation effect for rectangular straight-fin heat sinks and conclude that denser heat sinks are more sensitive to orientation; Li et al. [7] examine the effect of adding an outer chimney-rim to radial heat sinks, as well as the orientation effect on thermal performance, and concluded that a chimney can increase thermal performance by up to 20%.

The motivation for this work is the design of efficient passive coolers for LED lamps. From an industrial design perspective, LEDs offer a large degree of design freedom since LED units are generally quite small and the passive cooling elements have the opportunity to make up the majority of the full lamp design as illustrated by Fig. 1. Project partners AT Lighting ApS specialise in the design of

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Nomenclature

α	Brinkman impermeability
$\bar{h}$	average heat transfer coefficient
β	volumetric coefficient of thermal expansion
ΔT	temperature relative to T_0
ΔT_b	base plate temperature relative to T_0
$\dot{m}$	mass flow
γ	design field
Γ_{hs}	heat sink surface
Γ_{mf}	mass flow evaluation plane
Γ_{sf}	solid–fluid interface
$\hat{p} = p - \rho_0 g_i x_i$	augmented pressure field
μ	dynamic viscosity
ω	heat source domain
Ω_b	buoyancy evaluation domain
Ω_f	fluid domain
Ω_{hs}	heat sink domain
Ω_s	solid domain
ρ_0	density at reference temperature
A_{hs}	heat sink surface area
F_b	buoyancy force
F_d	drag force
f_{hs}	surface per volume ratio
F_r	resulting force on fluid
g_i	gravitational acceleration vector
k	thermal conductivity
k_f	fluid thermal conductivity
k_s	solid thermal conductivity
n_i	normal vector for given surface
$P = \int_\omega Q_0 \, dV$	power input
p	pressure field
Q	heat source term
Q_0	volumetric heat source
q_i	heat flux
T	temperature field
T_0	reference/ambient temperature
u_i	velocity field
V_{hs}	heat sink volume
x_i	spatial coordinates

LED lighting concepts combining function, aesthetics and additive manufacturing. Based on designer intuition and aesthetics, tapered lattice structures have been proposed to effectively conduct the heat away from the base to the through-flowing air, as well as providing redundant conduction and flow pathways ensuring performance independent of orientation.

Topology optimisation is used to fully utilise the large design freedom provided by the above functional design concept and additive manufacturing. Topology optimisation is a material distribution method that originated within structural mechanics [8–10] and is used to optimise the layout of a structure with respect to a performance measure under certain design and performance requirements. Topology optimisation allows for a vastly expanded design space compared to classical optimisation techniques, such as shape and size optimisation, as it is not restricted to having an *a priori* determined initial design and, thus, allows for the appearance of non-intuitive designs.

Topology optimisation for fluid systems began with the treatment of Stokes flow by Borrvall and Petersson [11] and has since been applied to Navier–Stokes flow [12], as well as passive transport problems [13,14], reactive flows [15], transient flows [16–18], fluid–structure interaction [19,20], amongst many others. The extension of topology optimisation to turbulent fluid flow is still in its infancy [21,22].

Fig. 1. Design concept of a LED spot with an additively-manufactured aluminium heat sink for passive cooling. Pictures are courtesy of AT Lightning ApS.

Conjugate heat transfer was originally treated in [23,24] and is a very active field of research today [25–29]. Most work focuses on forced convection, where the fluid flow is induced by a fan, pump or pressure-gradient. In contrast, the authors have previously presented a density-based topology optimisation approach for both two-dimensional [30] and three-dimensional [31] natural convection problems. A level-set method for steady-state and transient natural convection problems was presented by Coffin and Maute [32]. Recently, a density-based method based on a simplified convection model was presented for plane extruded structures [33] under natural convection. Although, well-performing structures are obtained using this approach, this cannot be guaranteed in general due to the simplified modelling [31,34] and also, despite being extremely efficient, the simplified model in [33] is only applicable to extruded structures with fixed spatial orientation.

This paper builds on the large-scale parallel topology optimisation framework previously presented in [31]. Initial results applying the framework to the design of heat sinks for LED lamps was presented in [35]. Major changes to the problem setup have since been made and will be presented herein, along with extensive numerical studies using COMSOL Multiphysics v5.2a [36]. The numerical studies have been validated experimentally through comparisons of an optimised design to two reference designs, but this will be presented separately in [37].

The layout of the paper is as follows: Section 2 briefly outlines the governing equations; Section 3 describes the problem setup and summarises the numerical implementation; Section 4 presents optimised designs and discusses their performance using extensive parameter studies; Section 5 discusses the design features of the optimised designs and attempts to provide general design guidelines for natural convection heat sinks; and Section 6 concludes the findings of the paper. Nomenclature is summarised in Appendix A.

2. Governing equations

In order to facilitate the topology optimisation of conjugate natural convective heat transfer between a solid and a surrounding fluid, the equations are posed in a unified domain, $\Omega = \Omega_f \cup \Omega_s$, where Ω_f is the fluid domain and Ω_s is the solid domain. The subdomain behaviour is achieved through the control of coefficients.