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Topology optimization of a pseudo 3D thermofluid heat sink model

Jan H.K. Haertel [a,*], Kurt Engelbrecht [a], Boyan S. Lazarov [b], Ole Sigmund [b]

[a] Department of Energy Conversion and Storage, Technical University of Denmark, Frederiksborgvej 399, 4000 Roskilde, Denmark
[b] Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé Building 404, 2800 Kgs. Lyngby, Denmark

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ABSTRACT

This paper investigates the application of density-based topology optimization to the design of air-cooled forced convection heat sinks. To reduce the computational burden that is associated with a full 3D optimization, a pseudo 3D optimization model comprising a 2D modeled conducting metal base layer and a thermally coupled 2D modeled thermofluid design layer is used. Symmetry conditions perpendicular to the flow direction are applied to generate periodic heat sink designs. The optimization objective is to minimize the heat sink heat transfer resistance for a fixed pressure drop over the heat sink and a fixed heat production rate in the base plate. Optimized designs are presented and the resulting fin geometry is discussed from a thermal engineering point of view and compared to fin shapes resulting from a pressure drop minimization objective. Parametric studies are conducted to analyze the influence of the pressure drop on the heat sink heat transfer resistance. To quantify the influence of the assumptions made in the pseudo 3D optimization model, validation simulations with a body-fitted mesh in 2D and 3D are conducted. A good agreement between optimization model and validation simulations is found, confirming the physical validity of the utilized optimization model. Two topology optimized designs are exemplarily benchmarked against a size optimized parallel fin heat sink and an up to 13.6% lower thermal resistance is found to be realized by the topology optimization.

1. Introduction

Forced convection heat sinks are used in a wide range of applications. This paper focuses on the design of air-cooled heat sinks as used for micro-electronics cooling since thermal management is increasingly becoming a bottleneck for advancement in the design of these systems [1]. Moreover, better heat management allows electronics to operate at higher performance for longer periods of time [2]. Classical heat sink designs applied to electronics cooling are mainly pin fin and parallel plate fin designs often with air as the coolant due to availability, simplicity of operation and low cost. Also microchannel heat sinks cooled by liquids such as water and oil have been investigated in various works as they allow for the rejection of higher specific power rates than air-cooled heat sinks. A comprehensive review of microchannel heat sinks considering channel geometry, flow conditions, and utilized coolants is given in [3]. The heat transfer and fluid dynamics in heat sinks are for example described in [4]. Various later works deal with the design and optimization of forced convection heat sinks: for instance Lee et al. [5] apply a simulation model based on analytical equations to the prediction and optimization of the thermal performance of fin heat sinks. Park et al. [6] use the results of 3D CFD simulations to create a Kriging metamodel which is used for shape optimization of a plate fin heat sink. With the above mentioned methods significant improvements in the thermal design of heat sinks can be achieved; however, they are limited in the sense that an a priori design parametrization is needed both for the fin shape and the position of the fins relative to each other. In contrast, topology optimization allows for almost unlimited design freedom which makes it possible to identify also unintuitive and complex optimized structures without relying on the design engineer's intuition. This aspect becomes even more important with the increasing maturing of additive manufacturing technologies as these methods provide unprecedented design freedom.

Topology optimization [7] was developed in the context of structural engineering but has since then been applied to a wide range of engineering disciplines such as acoustics, photonics, and fluid flow [8]. It is a means to optimize the material distribution in a given design domain subject to certain constraints. In density-based topology optimization, which is used in this work, a density-field is introduced that can take the value of 0 (solid) or 1 (void) in each point of a design domain. This binary optimization problem is relaxed to continuous values between 0 and 1 to

* Corresponding author.
E-mail address: jhkh@dtu.dk (J.H.K. Haertel).

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Nomenclature

A_{Ω_d}	design domain area
b_j	convexity parameter in interpolation function
c	heat capacity
C_j	parameter in RAMP interpolation
Da	Darcy number
$\mathbf{F}$	volumetric force
f	fin volume fraction
h	heat transfer coefficient
I_α	friction interpolation function
I_h	heat transfer interpolation function
I_k	conductivity interpolation function
k	thermal conductivity
L_c	characteristic length
$\mathbf{n}$	normal vector
n_{eval}	number of model evaluations
p	pressure
$\dot{q}_{inter}$	transferred heat between base plate and design layer
$\dot{Q}_{prod}$	produced heat in base plate
$\mathbf{r}$	residual of discretized multiphysics problem
r_{filter}	filter parameter
R_{th}	thermal resistance
$\mathbf{s}$	state vector of multiphysics problem
T	temperature
$\mathbf{u}$	velocity vector
$V_{base\ plate}$	volume base plate
$\mathbf{x}$	xy-coordinate vector
$\Delta z_{base\ plate}$	thickness base plate
$\Delta z_{channel}$	thickness channel

Abbreviations

2D	two-dimensional
3D	three-dimensional
min.	minimize
PDE	partial differential equation
s.t.	subject to

Greek symbols

$\overline{\alpha}$	maximum inverse permeability
β	projection steepness parameter
γ	design variable
$\tilde{\gamma}$	filtered design variable
$\bar{\tilde{\gamma}}$	projected design variable
Γ_j	domain boundary j
η	projection threshold parameter
μ_f	dynamic fluid viscosity
ρ_f	fluid density
Ω_j	domain j

Subscripts

air	air
av	average
d	design domain
f	fluid
i	counter subscript
in	inlet
j	counter subscript
max	maximum
out	outlet
s	solid
symm	symmetry
w	wall

allow for the use of efficient gradient-based optimization techniques. In the presented thermofluid design problem 0 corresponds to heat sink material and 1 to fluid passage, thus allowing for a flexible representation of arbitrary heat sink fin geometries during the optimization. Topology optimization applied to the design of thermal systems such as heat sinks and heat exchangers is an active field of research [9]. Early applications of topology optimization to heat transfer problems consider 2D heat conduction problems with convective heat transfer to an ambient fluid in the out-of-plane direction by assuming a constant heat transfer coefficient as e.g. [10]. When treating 2D conduction problems with convective heat transfer within the modeled plane, the design dependent convective boundary to the fluid needs to be captured which can be done by using an interpolation scheme [11–13], by applying level set based topology optimization to track the boundary [14], or by comparing the density of adjacent elements in the finite element mesh [15]. A constant heat transfer coefficient is assumed in [11,12,14] whereas [13,15] use a surrogate model for the heat transfer coefficient to capture the dependence of the local convective heat transfer on the geometry of the optimized structure to some degree. More recently published works present also 3D optimization models with diffusive heat transport in the solid and design dependent convective boundaries with a constant heat transfer coefficient using density-based [16,17] and level set [18] topology optimization. Dede and coworkers [16] use additive layer manufacturing to fabricate and subsequently experimentally evaluate an optimized heat sink design. The thermal integration of a thermoelectric cooler in a robotic downhole intervention tool using topology optimization to distribute conducting and insulating material in a 3D domain as well as fabrication and experimental validation of the prototype is presented in [19]. Pizzolato et al. [20] apply density-based topology optimization to the design of conducting fins in a phase change material (PCM) storage tank modeling the solidification of the PCM as transient thermal diffusion problem both in 2D and 3D.

The topology optimization works presented above simplify the heat transfer to the ambient fluid to Newtons law of cooling, i.e. assuming a constant heat transfer coefficient or a surrogate model for it. This limiting assumption can be avoided when using thermofluid, or conjugate heat transfer, topology optimization models which also explicitly consider the heat transfer in the fluid during the optimization. First fairly academic applications of topology optimization to 2D forced convection conjugate heat transfer problems are given in [21,22]. 2D topology optimization of water-cooled microchannel heat sinks is presented in [23] solving the Navier-Stokes equations and [24] assuming Stokes flow where [24] fabricate and experimentally evaluate an optimized heat sink prototype. Matsumori et al. [25] apply topology optimization to a 2D thermofluid heat exchanger model; however, assuming the same thermal conductivity in solid and fluid. Similar heat exchanger models are treated in [26] that apply 2D lattice Boltzmann modeling and [27] who use a level set topology optimization approach to generate optimized designs in 2D and 3D. Qian and Dede [28] present a thermofluid model for topology optimization under tangential thermal gradients. The abovementioned works on thermofluid topology optimization, except for [27] that also conduct 3D optimizations, rely on 2D optimization models. This approach was extended by [29] and later [30] to a pseudo 3D