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# Gradient-based design of actively-cooled microvascular composite panels

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ABSTRACT

Recent advances in manufacturing based on sacrificial fiber or template techniques have allowed complex networks of microchannels to be embedded in microvascular composites. In the thermal application of interest, a novel battery packaging scheme for electric vehicles is considered where each battery is surrounded by microvascular composite panels for temperature regulation and structural protection. We use simplified thermal and hydraulics models validated against more complex 3D FLUENT simulations and experiments to obtain the surface temperature distribution of the panel and the pressure drops across the microchannels. We further eliminate the cost and complexity associated with mesh generation by applying the interface-enriched generalized finite element method (IGFEM), which allows a non-conforming mesh to capture the discontinuous temperature gradient across the microchannels. The IGFEM thermal solver is then combined with a gradient-based shape optimization scheme to obtain optimal designs of a set of branched microchannel networks. The design parameters are the channel control points, which define the shape of the network. We use the *p*-mean as a differentiable objective function in place of the maximum temperature. To obtain accurate gradients with respect to the design parameters efficiently, we perform a sensitivity analysis based on a recently developed adjoint method for IGFEM. Starting from many distinct configurations, we obtain the optimal designs for a wide range of network topologies. We also investigate the effect of the coolant flow rate on the optimal design.



## 1. Introduction

Microvascular composites are a novel class of biomimetic materials that contain embedded microchannels resembling vascular systems found in nature. Recently introduced sacrificial fiber and template manufacturing techniques have allowed for the embedding of complex networks of microchannels in composite materials [1,2]. The resulting material can be used for multifunctional applications based on the choice of fluid present in the microchannels. For example, one can change the electromagnetic signature by using a ferrofluid, tune the electrical properties by using an electrically conductive fluid, enable self-healing of the material by allowing appropriate chemicals to flow to damage sites, and regulate the temperature of the material by circulating coolants [1,3–5]. The thermal applications include space reentry or hypersonic vehicles, high-power electronics cooling and car battery cooling [6–11]. While this work focuses on battery cooling applications, the method described here can be applied to other materials with embedded microchannels used for thermal management.

Battery cooling is essential to extend the range of electric vehicles and prolong battery life [12]. For batteries with high energy density such as those in electric vehicles, liquid cooling is the most effective cooling method [13]. A typical battery packaging for electric vehicles consists of stacks of battery cells separated by fiberglass or steel panels to provide structural protection and cooling plates to regulate battery temperature. Recently, a novel battery packaging scheme in which a single microvascular composite provides both cooling and crash protection has been proposed [11]. The crash protection is superior to conventional battery packaging because the carbon fiber reinforced composite possesses high specific strength, stiffness as well as energy absorbing ability [14,15].

The performance of battery cooling panels is usually analyzed using a fluid-thermal solver that combines the Navier–Stokes and

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energy equations [16,17]. Because the Navier–Stokes equations are nonlinear, the coupled fluid-thermal problem has to be solved iteratively until the residuals of the equations fall below a user-defined tolerance. To solve the equations, a sufficiently refined mesh aligned with the walls of the embedded channels has to be generated. Due to the large disparity in length scales between a microchannel diameter and the panel dimensions, many elements have to be created to ensure that the growth in element size from the interior of a microchannel to the domain boundary does not result in elements with high aspect ratios. As a result, a full-blown coupled fluid/thermal analysis of the microvascular panels is computationally expensive. This is especially the case when numerous designs have to be evaluated in an optimization or parametric study.

Therefore, in this work, we use a simplified thermal model based on a simple energy balance of an infinitesimal segment of a channel. The simple model only requires the solution of a linear heat equation with an extra source/sink term due to the microchannels. Moreover, because the microchannels are collapsed into lines or curves, the mesh generation burden is greatly reduced. By verifying the model with the commercial software ANSYS FLUENT v15.0 and validating the model with experiments, we show that this simple model is sufficiently accurate for the battery cooling application.

We further improve efficiency by using the interface-enriched generalized finite element method (IGFEM) [18,19], which allows capturing the discontinuous temperature gradient across the microchannels with a nonconforming mesh, thus eliminating the mesh generation complexity and cost. Due to the use of stationary and non-conforming mesh, a key advantage of the IGFEM, generalized/extended finite element method (GFEM/XFEM) and other Eulerian approaches over the standard FEM (SFEM) in shape optimization analysis is that they do not suffer from the severe mesh distortion that the SFEM often faces when the shape evolves [20,21]. Another key advantage is that only the nodal velocities of the enrichment nodes along the microchannels need to be evaluated, thus limiting the computational work for the sensitivity analysis to the enriched elements intersecting the microchannels.

Because the design of the embedded channels is a crucial factor in the performance of cooling panels, it has been the subject of multiple studies. A performance evaluation of different base channel designs such as parallel, bifurcating/tree-like, serpentine, spiral, coiled, bifurcating-parallel hybrid and other designs was presented in [17,22–24]. Within a base design, we can further optimize the performance by changing the shape of the channels. Due to the large number of associated design parameters, gradient-based shape optimization [16] is more tractable than parametric studies [25]. Other optimization methods that do not require a starting base design are topology optimization [26], discrete topology optimization connecting lattice points in space [27–29] or constructal theory [30]. It is also worth mentioning that optimization methods have also been applied to microchannel heat sink for microelectronics cooling, but with a typical topology of unconnected channels running parallel to each other [31,32]. In these studies, the design parameters are usually channel dimensions and spacing between channels.

In optimization studies of cooling panels, objective functions commonly considered are average temperature and standard deviation, a measure of temperature uniformity [16,26]. Temperature uniformity is important because non-uniformity causes variations in reaction rates that lead to incomplete energy utilization and shorter battery life [12]. However, average temperature alone as an objective function is not sufficient to keep the maximum temperature in the panel low. Furthermore, as seen later, the average temperature is relatively insensitive to the channel design. Besides, small regions with high temperature akin to the appearance of areas with stress concentration in a compliance-based optimization [33] may also appear in the optimal design. This suggests that the maximum temperature be minimized rather than the average temperature. Unfortunately, the maximum temperature is not differentiable in a classical sense [34] and therefore conventional gradient-based optimizer cannot be used when the maximum temperature is chosen as the objective function. Instead, following a standard practice in stress-based optimization [35,36,33], the $p$-mean of the temperature with a sufficiently large $p$ is used in this work.

The paper is organized as follows: In Section 2, we introduce the simplified thermal model, the IGFEM solver and a Streamline Upwind/Petrov–Galerkin (SUPG) scheme employed to stabilize the IGFEM solution. We then explain in Section 3 the hydraulics equations used to model the pressure drops and flow rates in the microchannel network. The numerical model is verified against more complex 3D, fully coupled FLUENT simulations and validated against experiments in Section 4. We then describe the general optimization problem and the sensitivity analysis relevant to this work in Section 5. Lastly, we apply the IGFEM-based shape optimization scheme to optimize different parallel network designs defined by the number of branches and validate one of the optimized designs in Section 6.

## 2. Simplified model and interface-enriched generalized finite element method

While prior works [25,37,8] model the microchannels with finite diameters, we take advantage in the present study of the low diameter-to-length ratio of a microchannel to collapse the microchannels into line sources/sinks [38,28,29,39]. In the case of non-circular cross section, "diameter" refers to the largest dimension of the cross section.

For brevity, we use hereafter the word "channel" to refer to a microchannel. Consider a channel with cross-sectional area $A$, axial velocity $u$ and average velocity $u_{\text{ave}}$. Let $T_m$ be the mixed-mean fluid temperature, defined as $T_m = \int uT\mathrm{d}A/(Au_{\text{ave}})$ [40]. Further, let $s, \dot{m}$ and $c_f$ respectively denote the parametric coordinate along the channel in the flow direction, the mass flow rate and the specific heat capacity of the fluid. A simple energy balance over an infinitesimal portion of a channel yields the following expression for the heat flow rate per unit length of the channel [40]:

$$q' = \dot{m}c_f \frac{\mathrm{d}T_m}{\mathrm{d}s}. \tag{1}$$

Let us further assume that $T_m$ is approximately equal to its wall temperature, $T_w$. Given the thermal conductivity tensor $\boldsymbol{\kappa}$ of the solid, a distributed heat source $f(\mathbf{x})$, the convection coefficient $h$ and an ambient temperature $T_{\text{amb}}$, the heat equation with contribution from $n_{ch}$ channels is given by

$$\nabla \cdot (\boldsymbol{\kappa}\nabla T) + f(\mathbf{x}) = \sum_{i=1}^{n_{ch}} \delta_l^{(i)}(\mathbf{x})\gamma^{(i)}\boldsymbol{t}^{(i)} \cdot \nabla T + h(T - T_{\text{amb}}), \tag{2}$$

where $\gamma^{(i)} = \dot{m}^{(i)}c_f$, $\boldsymbol{t}^{(i)}$ is the unit tangent vector of channel $i$ in the flow direction and $\delta_l^{(i)}(\mathbf{x}) = \int_l \delta(\mathbf{x} - \mathbf{x}^{(i)}(s))\mathrm{d}s$ is the line Dirac delta function associated with channel $i$. The assumptions made to derive this equation are discussed in Appendix A.

Let the boundary of domain $\Omega$ be divided into two parts, $\Gamma_T$ and $\Gamma_q$, where Dirichlet and Neumann boundary conditions are specified, respectively. Denoting channel $i$ by $\Gamma_f^{(i)}$ and the prescribed heat flux as $q''_{ps}$, the weak form of (2) is: Find the temperature field $T$ satisfying the Dirichlet boundary condition $T_{|\Gamma_T} = T_{ps}$ such that $\forall v \in \mathbb{V}$,