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Computational analysis of actively-cooled 3D woven microvascular composites using a stabilized interface-enriched generalized finite element method

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ABSTRACT

The computational design of an actively-cooled 3D woven microvascular composite plate with sinusoidal and straight microchannels is presented. The design objectives include minimizing the maximum temperature of the composite, the microchannel volume fraction, and the pressure drop needed to circulate the coolant in the microchannels. We study the impact of a variety of parameters on the optimal design of a microvascular composite plate subjected to a uniform heat flux over its bottom surface. These parameters include the spacing, wavelength, and amplitude of the microchannels, the coolant type and flow rate, and the applied thermal loads. To facilitate the computational design process, a mesh-independent Interface-enriched Generalized Finite Element Method (IGFEM) is employed to evaluate the temperature field in the actively-cooled composite. The IGFEM solver also includes the streamline upwind Petrov-Galekin stabilization scheme to eliminate the spurious oscillations in the temperature field due to the convection-dominated heat transfer in the microchannels. This study reveals that the straight microchannels are often the optimal configuration. Design maps are presented to evaluate the required flow rate as a function of the applied thermal load and the plate dimensions.

1. Introduction

Bio-inspired actively-cooled microvascular materials have found a variety of engineering applications, including those in biotechnology [1,2], chemical reactors [3], and micro-electro-mechanical systems (MEMS) [4–7]. Manufacturing techniques such as the direct-writing assembly allow creating microchannels with a wide rage of diameters and configurations in polymeric materials [8–11]. Recently, embedding microchannels in 3D woven composites has been made possible via the vaporization of sacrificial components (VaSC) technique [12]. In this technique, some of the fiber tows in the woven preform are replaced by catalyst-impregnated polylactic acid (PLA) sacrificial fibers and infiltrated with a low viscosity resin-like epoxy. After curing the sample, the composite is heated to about 200 °C to form hollow microchannels by vaporizing and evacuating the sacrificial fibers. The configuration of these embedded microchannels depends on the weave architecture and placement of the sacrificial fibers, i.e., in the warp, weft, or through-thickness directions. Fig. 1 illustrates a 3D woven glass fiber/ epoxy matrix microvascular composite specimen made by the VaSC technique. In this case, some through-thickness (z) fibers are replaced by PLA fibers during weaving and then removed by VaSC to form sinusoidal-shaped microchannels. Similarly, incorporating the sacrificial fibers in the warp or weft directions leads to straight microchannels.

Motivated by these recent advances in the manufacturing of microvascular composites, we present hereafter a design study of actively-cooled polymeric matrix composite (AC-PMC) plates. The epoxy matrix with glass fibers are used to create the 3D woven composite preform. We examine the impact of both sinusoidal-shape and straight embedded microchannels on the thermal response of the microvascular composite. The PMC plate is subjected to a heat flux that, in the absence of the active cooling, causes a high temperature gradient in the thickness direction and a high surface temperature, well beyond the maximum sustainable temperature of this material. Relevant novel applications include the design of lightweight skin materials for hypersonic aircrafts, where active cooling is needed to cope with high thermal loads caused by aerodynamic heating. The objective of this work is to determine the optimal configuration of the embedded microchannels and develop required guidelines and charts that facilitate the design of the AC-PMC plate used in hypersonic aircrafts.

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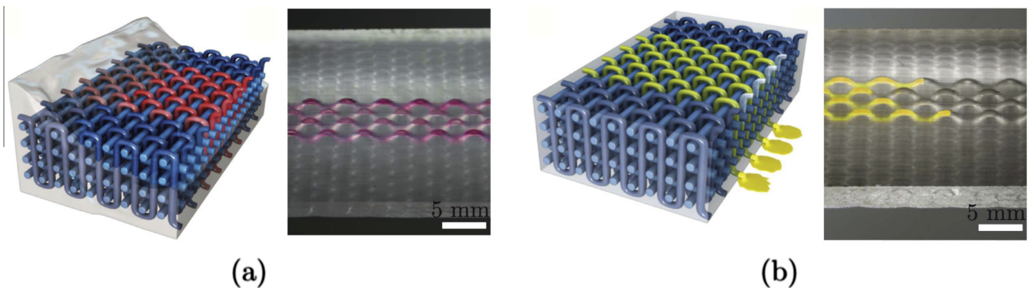

Fig. 1. Schematic and optical images of (a) sacrificial PLA fibers (shown in pink) embedded in a 3D woven glass/epoxy composite specimen and (b) hollow microchannels formed after evacuating the fibers, filled with a yellow fluid. (Adapted from [12]).

Actively-cooled materials with embedded networks of microchannels have been used for other high heat flux applications [13–15]. Due to manufacturing constraints, straight microchannels with or without branching are often employed for active cooling, as this configuration yields a high heat transfer efficiency even in the laminar regime [16]. Some studies have shown that introducing waviness in the microchannels leads to a better heat transfer performance at higher Reynolds numbers [17]. The impact of other geometric features on the thermal efficiency of the system, including the number, spacing, and cross-sectional porosity of microchannels and the arrangement of inlets and outlets, are also widely investigated [18–21]. In addition to their heat transfer performance, embedded networks are characterized by the inherent cost associated with the pressure drop needed to circulate the coolant through the microchannels [22,23]. Various techniques such as parametric studies and evolutionary algorithms are also used to determine the optimal configuration of microchannel heat sinks based on these parameters [24–26].

In the current study, which relies on a parametric design approach, the optimal configuration of the microchannels is determined such that it minimizes (i) the maximum temperature of the plate, (ii) the microchannel volume fraction, and (iii) the pressure head required to circulate the coolant in the microchannels. In addition to the microchannels configuration, we study the impact of a variety of other design parameters on the thermal response of the system, including the dimensions of the plate, microchannels spacing, applied thermal loads, boundary conditions (BCs), and the type and flow rate of the coolant. The greatest challenge in evaluating the thermal response of the AC-PMC plate with the standard Finite Element Method (FEM) is the need to create meshes that conform to the microchannels geometry. This becomes especially cumbersome in the design process, where one needs to create a new virtual model of the microvasculature for multiple microchannels configurations and domain dimensions. In this work, an Interface-enriched Generalized Finite Element Method (IGFEM) recently introduced by Soghrati et al. [27,28] is adopted to compute the temperature field. The IGFEM simplifies the design process as it uses finite element meshes that are independent of the problem morphology without affecting the accuracy of the solution. More details regarding the IGFEM thermal solver and its validation based on experiments conducted on an actively-cooled microvascular fin with sinusoidal microchannels can be found in [29].

It has been long shown that the Galerkin FEM (including the IGFEM) applied to convection-dominated flow problems suffers from spurious oscillations [30]. To address this issue, several stabilization methods including the Streamline Upwind Petrov–Galerkin (SUPG) [31,32], the Galerkin Least-Squares (GLS) [33,34], the variational multiscale (VMS) [35], and the residual-free bubble functions [36,37] methods have been proposed. In this work, the SUPG technique is adopted to stabilize the IGFEM and reduce the spurious oscillations in the temperature field. It should be noted that, for steady convective heat transfer problems, all the aforementioned schemes add a similar stabilization term to the discretized form of the governing equations [38]. For a review of different stabilization techniques and their applications in other flow problems, please refer to [39–41].

The remainder of this manuscript is structured as follows: Section 2 introduces the geometry and BCs of the AC-PMC plate of interest together with the associated design parameters studied in this work. In Section 3, we present the governing equations for the convective heat transfer in actively-cooled microvascular materials and introduce the corresponding SUPG-stabilized IGFEM approximation. Finally, the impact of varied design parameters on the optimal microchannels configuration and the cooling efficiency of the PMC plate is investigated in Sections 4 and 5.

2. Problem description and design objectives

The schematic of the 3D woven glass fiber/epoxy matrix composite plate studied in this work is illustrated in Fig. 2. Fig. 3 shows the microvascular domain, where the parallel embedded sinusoidal microchannels (defined by the amplitude A and wavelength λ) have a diameter of $D = 500\ \mu\text{m}$. The minimum distance between the microchannels centerline and the bottom surface of the plate is chosen to be 500 μm. The coolant enters the microchannels with a flow rate of Q and an entrance temperature of $T_{in} = 20\ ^\circ\text{C}$. Unless indicated otherwise, the coolant is water with the thermal conductivity, density, and specific heat of $\kappa_f = 0.6$ W/m K, $\rho_f = 1000$ kg/m^3, and $c_p = 4182.5$ J/kg K, respectively. The temperature dependence of the dynamic viscosity of water μ_f is approximated using the Seeton relation [42],

$$\mu_f(T_f) = 2.414 \times 10^{\frac{247.8}{T_f - 140}}, \tag{1}$$

where T_f is the fluid temperature in degree Kelvin.

The microvascular PMC plate shown schematically in Fig. 3(a) has a thickness of $H = 6$ mm, while its length L and width W are

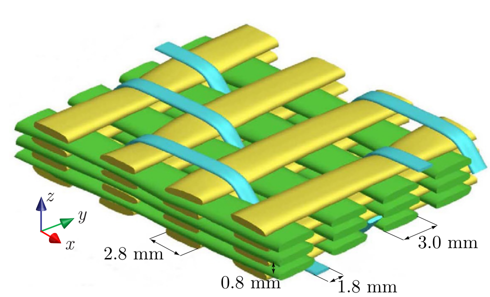

Fig. 2. Schematic of the microstructure of a unit cell of the 3D woven fiber structure of the PMC of interest. The warp (x), weft (y), and through-thickness (z) fiber tows are S2 glass and the matrix of the composite is epoxy.