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Formal Evolutionary Development of Low-Entropy Dendritic Thermal Systems

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The present work contributes to the formal evolutionary development of complex thermal physical systems by using a bioinspired evolutionary method. The bioinspired method combines Lindenmayer systems with a turtle interpretation for the modeling of the complex dendritic structures, plus a finite element method for the analysis of the structure and an evolutionary algorithm to evolve the topology of the dendritic structure. With the proposed method, the optimal planar topology of a conductive dendritic structure for draining thermal energy from a fixed-area subject to uniform heat generation, a problem originally addressed by constructal theory, is investigated. The results show that the evolutionary approach can yield complex dendritic topologies that excel in performance and robustness. Moreover, our results demonstrate that a better performance in heat removal implies an increased complexity, up to an optimal level, of the draining system. Indeed, it is shown also that there is an optimal level of complexity beyond which the performance of the system is not substantially improved, which is in agreement with results reported in the literature. Finally, the robustness of hierarchical, dendritic complex topologies for heat transfer systems is discussed and quantified.

Nomenclature

A = domain area
k = thermal conductivity
L = length scale
n = unit normal exterior-pointing vector
Q = heat source
q''' = heat source
S = entropy
T = temperature
ε = thermal conductivity ratio, k_0/k_f
ξ = dimensionless heat generation
Φ = area ratio, A_f/A

Subscripts

f = fin
0 = root

Superscript

$*$ = nondimensional quantity

I. Introduction

THE thermodynamic process of heat and mass transport from a source point to an area using a limited amount of material is encountered in a variety of natural and engineered systems, from cardiovascular and respiratory networks to the transport structure of plants and leaves and from heat and mass exchangers in thermal systems to circuits [1–9]. Although such systems vary in shape and structure, the efficiency of their designs can be generally measured by the reversibility of the cascading processes involved for obtaining the same output. For a given transport gradient, the higher the complexity of the system, the lower the entropy generated in each of the stages that make up the system. Thus, a complex internal combustion engine has a number of cascading processes that operate between the extreme temperature levels (e.g., between the adiabatic flame and the ambient temperatures). The higher the number of intermediate cascading processes involved, the higher the complexity of the system and the lower the entropy generated for a given energy potential available [9].

For engineered systems, incremental gains in efficiency are possible with the increased complexity or reversible stages, but these may result in large increments of complexity that are not currently commercially viable. Similarly, natural systems take advantage of threshold levels of complexity with cutoff scales beyond which any additional structure adds little to the overall performance [1–3,9]. In this work, the formal evolutionary process that naturally selects optimal levels of complexity for a simple transport problem is studied. The results show that there is a drive for complex structures until of the point of diminishing returns limits the complexity of systems from developing into a runaway cascade of infinite smaller scales.

Dendritic structures and their inherent advantages in channeling flows of mass and energy in natural systems have been addressed in many previous studies [3,7,10–14]. Optimal geometrical features for a variety of applications have been identified as a result of such studies, with constructal theory being the most prominent method used in this area (e.g., [7]). Recently, a series of studies employed evolutionary processes similar to those observed in nature to propose a new generation of high-performance engineering devices [10–14].

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