International Communications in Heat and Mass Transfer xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Generating optimal heat conduction paths based on bionic growth simulation

Baotong Li, Jun Hong *, Suna Yan, Honglei Liu, Liuhua Ge

State Key Laboratory for Manufacturing Systems Engineering, School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, P.R. China

ARTICLE INFO

Available online xxxx

Keywords:
Heat conduction paths
Growth simulation
Topology optimization
Conductivity spreading approach
Volume-point problem

ABSTRACT

This paper proposes a novel topology optimization method for designing the best-possible heat conduction paths. The design idea is originated from the natural observation that plant roots or leaf veins care by self-adaptive growth to minimize the flow resistance through the whole networks. Based on the analogy between fluid flow and heat flow problems, the natural growth rule is systematically transformed into a mathematical model and written as an algorithm, where the high conductivity material is treated as being alive and the topology optimization process is viewed as plant morphogenesis process. Specifically, a new treatment called 'conductivity spreading approach (CSA)' is proposed to transform nodal temperatures of cooling channels into those of the background mesh, by which cooling channels can be separated from the underlying grid so that they can branch and extend freely along any direction. The growth method is used to construct the heat conduction paths for a fundamental 'volume-to-point' problem. Unlike other methods, layout solution produced by the suggested method is favorable to practical problems because it provides clear information about the location, orientation and dimensions of each cooling channel. In addition, the growth method requires little of human involvement and is easily delegated to computers, offering great advantage of automated design for large-scale cooling channel layouts in heat conduction systems.

1. Introduction

With the miniaturization and high capacity of the electronic equipment, like the computer, LED screen or light, how to collect the generated heat and channel it out of the package becomes a very challenging work faced by thermal engineers because the space that cooling channels would occupy is too valuable not to be allocated to electronic. For this reason, heat conduction path is no doubt a design priority, and is likely to become more and more important [1–3].

In most of the cases, the determination of heat conduction paths is dependent on engineers' knowledge and experiences. Under the conventional wisdom, such design is a task that fully needs human's involvement, and usually implemented in a time-consuming trial-and-error process. In this regard, an efficient approach for flexible design of heat conduction paths is definitely desired. Topology optimization is considered as the most flexible deign method because it allows for changes in both topology and shape. Using topology optimization, engineers can quickly find the best-possible solution at a relatively low cost. In the past decades, heat conduction topology optimization has been done through the use of different techniques based on the homogenization design method (HDM) [4,5], the solid isotropic microstructures with penalization (SIMP) method [6,7], the evolutionary structural optimization (ESO) method [8,9], the bidirectional ESO (BESO) method [10], the level set (LST) method [11,12], the cellular automation (CA) method [13]. More details about this subject can be found in the review paper of [14].

Although the optimization principles employed in these reported methods are different, they have a common feature that the computation output is represented by a certain kind of material distribution, which may not form a distinct channel-like pattern, especially when the amount of cooling channels is large and the layout pattern is complicated. To improve the design efficiency and commonality, we need a new method that can produce accurate information about the location, orientation and dimensions of each calculated cooling channel. Inspired from the adaptive growth of plant roots in nature, Ding and Yamazaki [15] extended the growth simulation toward topology optimization so as to provide the easiest way for the heat to flow through the conduction domain. Although this method is straightforward to use in practice, it may not give an optimum solution because no optimality conditions were imposed in the growth simulation. For example, the growth orientation was determined by a pseudo-random number sequence rather than an optimization algorithm. In order to get the layout solution in a strict mathematical point of view, the simulation was later revised by

* Corresponding author.
E-mail address: jhong_email@163.com (J. Hong).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2017.02.016
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the author, in which a gradient-based algorithm was utilized to search for the growth orientation [16,17]. Although these previous work are of fundamental importance, they are not very helpful to get an absolute optimum solution because growing elements have always to be connected to the underlying mesh grid. As a result, the growth orientation can only be selected from a few preset discrete angles, which may not include the real optimal one.

To solve this problem, the authors developed a new growth method. The main novelty of this method is that the influence of one growing channel's conductivity is not only limited to its two nodes but also extends to the surrounding regions of the background mesh through an interpolation scheme. Based on this, sprouting points are not necessarily specified on the points of background mesh, which allows for cooling channels to grow toward an arbitrary direction in the conduction domain and therefore eliminates result dependency on the background mesh. Compared with the continuum-based topology optimization, layout solution generated from the growth simulation is favorable to practical problems because the element members are straight and have uniform cross-sectional properties. These benefits can be considered as a major advantage of the proposed method.

2. Basic principle of the growth simulation

After billions of years' natural selection, nature has evolved various exquisite topologies to solve all sorts of problems. One conspicuous type of such topologies is the branching structures existed in numerous biological systems. For example, to self-adapt to the local environment for survival, plants have to transport the water and nutrient to every part of themselves through their roots and veins as fast as possible. The evolution and function of such branched structures have fascinated and engaged researchers for decades [18–20]. During the growth process, the hydrodynamic constraints of fluid pressure (i.e., Poiseuille's law) must be satisfied, which is formulated as following.

$$Q = \frac{\pi r^4}{8v} \cdot \frac{\Delta P}{l} \tag{1}$$

where Q is the volumetric flow rate through the branching channel; ΔP is the pressure drop along the branching channel; l and r denote the length and internal radius of the branching channel; v is the dynamic viscosity of the fluid.

Furthermore, the material consumption should also be considered as a constraint in the growth procedure.

$$V = \sum_{i=1}^{n} \pi r_i^2 l_i \leq V_{max} \tag{2}$$

where V_{max} is the upper limit of material consumption, r_i, l_i are the radius and length of the i-th branching channel; and n is the total number of branching channels.

In addition, the Murray's law [21] stands for the relationship of radius between the parent branch and the daughter branches, which is

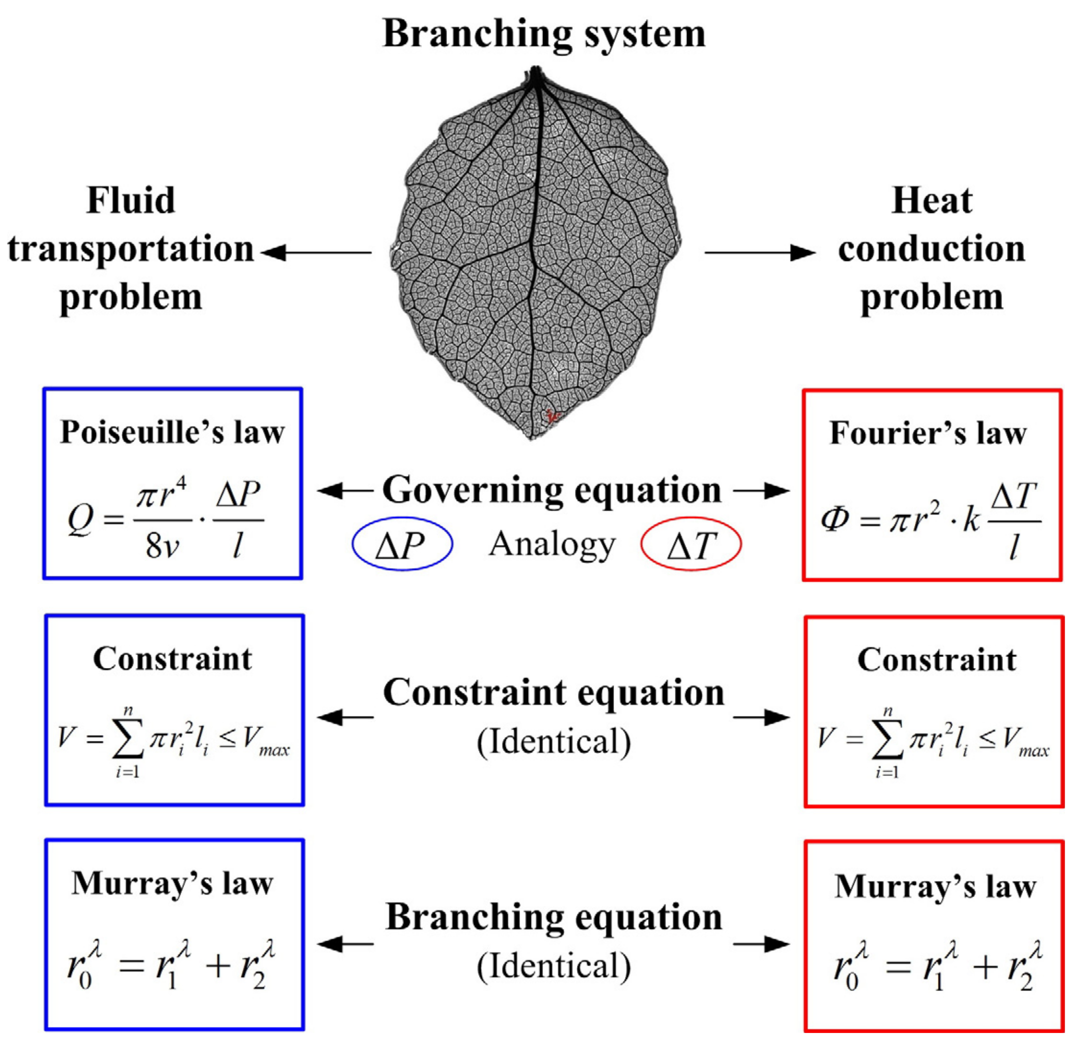

Fig. 1. Analogy between the growth principles employed in the fluid flow problem (left) and heat flow problem (right).