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Freely morphing tree structures in a conducting body

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ABSTRACT

Here we determine the tree-shaped structure that facilitates heat transfer between it and the solid body in which it is embedded. The vascular design evolves toward configurations that provide progressively greater heat transfer per unit volume. Two solid domain sizes are analyzed: a small cube where the tree structure grows to the second-level bifurcation, and a larger cube where the tree design grows to fourth-level branches. We show that when the solid domain and growing tree structure do not interfere with each other, symmetry is a beneficial feature that promotes heat transfer. When the tree structure interferes with the boundaries, asymmetry is the better design feature, and because of it the tree structure fills the available conducting medium.

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1. Introduction

The generation of flow configuration in the nature and engineering is governed by the constructal law [1]. This physics-based research on design and evolution began with formulating and solving the problem of discovering the flow architecture that facilitates flow access between a point source and a volume, and between a volume and a point sink. This growing field of research is showing that the evolutionary designs that provide greater flow access are tree-shaped (dendritic), and that this architecture unifies all point-volume flows: fluid flow and heat transfer, steady and unsteady, and animate and inanimate. Reviews of the progress made with the constructal law on design in nature and engineering are provided in Refs. [2–5].

An important contemporary application of the tree-shaped designs is in the thermal coupling of a heat pump to the ground allocated to it. This engineering challenge has been answered with classical single-pipe designs shaped as hairpins (U-shaped) and serpentines [6–15]. In this paper we propose an alternative architecture that consists of two tree-shaped sets of bifurcating pipes, which face one another line two palms pressed against each other, Fig. 1. One tree spreads the fluid from the point (heat pump) to the ground area, and the other collects the fluid from the ground and returns it to the heat pump.

We focus on only one of the trees, and seek to evolve its configuration to arrive at the best tree, with angles and branch lengths that can vary freely. This aspect of the work is essential because the usual proposal that led to tree design in fluids and heat transfer engineering is to first assume a fixed tree architecture and next to determine its performance [4]. The most frequently assumed tree design is the dichotomous tree with T-shaped branches shown in Fig. 1. The lengths of the branches are sized in the sequence

$$L_1, \quad L_2 = \frac{L_1}{2}, \quad L_3 = L_2, \quad L_4 = \frac{L_3}{2}, \quad L_5 = L_4 \tag{1}$$

In this paper we consider T-shaped design as reference (benchmark), and beginning with Fig. 2 we allow the tree geometry to morph freely. The tree architecture, with all its angles and lengths, is the unknown.

2. Numerical model and method

The tree shaped body is made of isothermal cylinders (pipes) and is buried in a solid at different temperature. The solid is shaped as a cube with the volume $V = 2L_1 \times 2L_1 \times 2L_1$, which is fixed. The boundary of this volume is insulated. The cube is initially at a higher temperature (T_1) than the tree (T_0), and in time, a cooled zone grows around the tree. The following analysis applies equally to the reverse situation where the tree structure is warmer than the solid.

The isothermal-cylinders model is a very good simplification of the configuration of pipes with heat-pump fluid buried in soil.

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Nomenclature

A	surface area, m^2
D	channel diameter, m
L	channel length, m
N	number of bifurcation levels
T	temperature, K
t	time, s
V	volume, m^3
x,y,z	coordinate, m

Greek symbols

α	thermal diffusivity, $m^2\,s^{-1}$
β	bifurcation angle
θ	dimensionless temperature
φ	composite volume fraction (porosity)

Subscripts and superscripts

avg	average
$*$	dimensionless

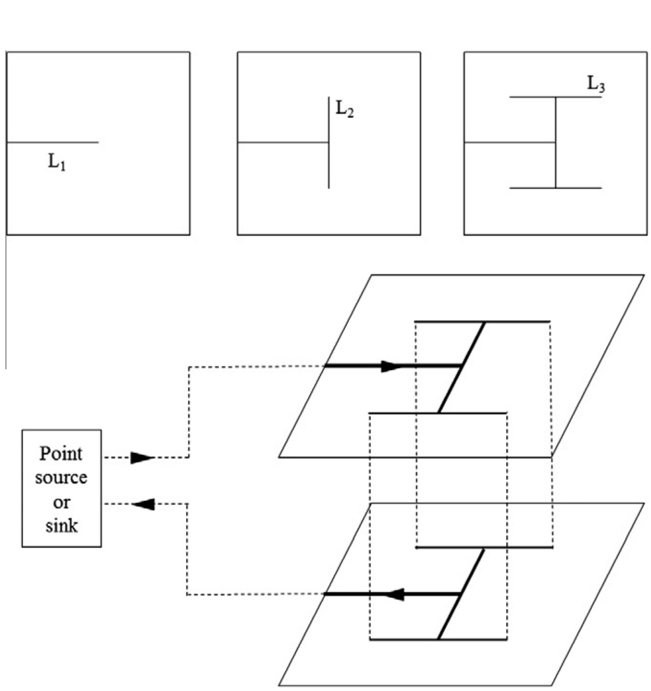

Fig. 1. Tree structures with T-shaped bifurcations. Top: view from above. Bottom: two trees in counter flow, for heat transfer between a point and a volume.

Because the residence time of the fluid in the pipes is much shorter than the diurnal or seasonal time scale of the heat transfer between the buried pipes and the soil, during most of the heat transfer process the pipes are approximately isothermal, at a temperature comparable with the inlet temperature of the fluid arriving from the heat pumps.

The tree is a sequence of Y-shaped bifurcations. The trunk has the diameter D_1 and length L_1. All the channels are round, and the diameters of the channels are sized relative to one another in accordance with the Hess-Murray law [4],

$$\frac{D_i}{D_{i+1}} = 2^{1/3} \quad (i = 1, 2, \ldots) \tag{2}$$

The lengths of the branches are the same as in the design with T-shaped bifurcations, Eq. (1). The first bifurcation angle between the trunk and the first branch is β_1. The second, third and fourth bifurcation angles are β_2, β_3, etc.

The temperature filed was simulated as time-dependent heat conduction by using a computational package [16]. The conservation of energy in the solid that surrounds tree is governed by

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \tag{3}$$

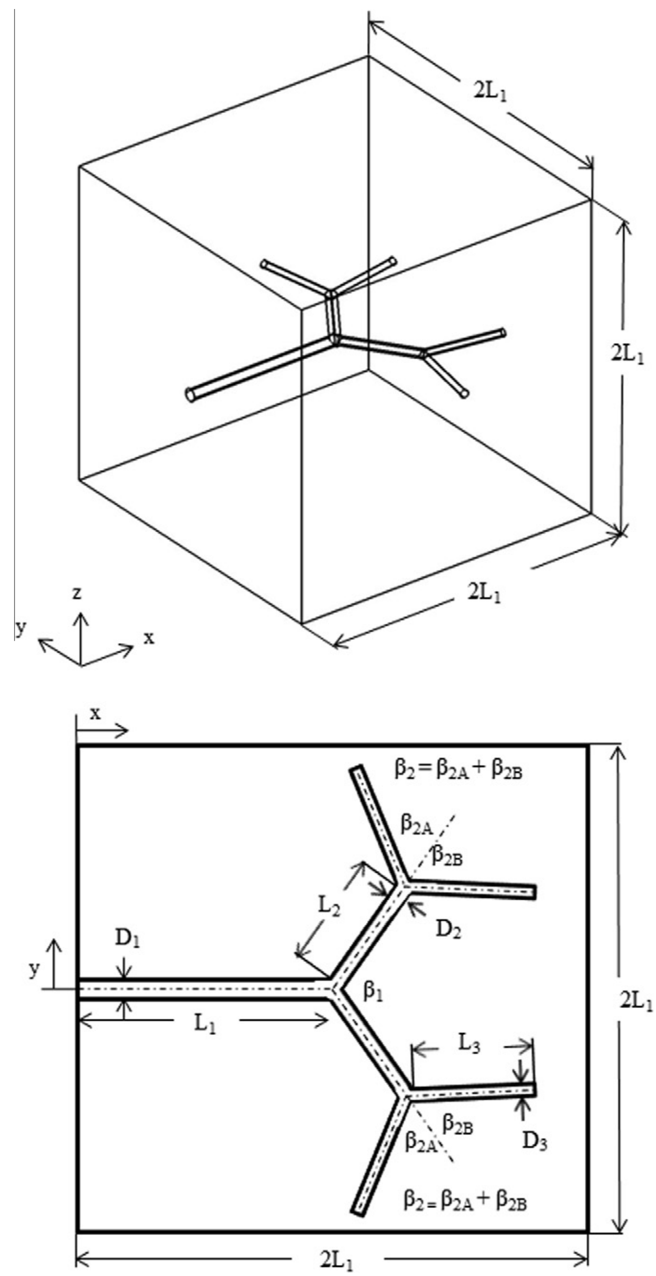

Fig. 2. Tree architecture with freely varying angles, and with lengths according to Eq. (1).

where α is thermal diffusivity of the solid, and $\nabla^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$, where x, y and z are defined in Fig. 2. For greater

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