TOPOLOGY DESIGN OPTIMIZATON FOR STUCTUES BY ADAPTVE GOWTH METHOD- LEARNING FROM BRANCH SYSTEMS IN NATURE -

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Summary The optimality and growth mechanism of branch systems in nature are studied, and a generation approach of the emergent process for branch system being considered as a material or energy transportation system is suggested. The layout design problems of the cooling channel in heat transfer system are studied as typical engineering application by the generation method based on the growth mechanism of branch systems in nature. Having the similar optimality of branch systems in nature, the constructed cooling channel can make it possible to attain a comparative uniform temperature distribution of the whole heat transfer system.

REPODUCTION OF EMERGENT PROCESS OF BRANCH SYSTES IN NATURE

It is necessary to reproduce the emergent process of branch systems in nature in order to apply the optimality of branch systems in nature to engineering design, thus a generation approach of the emergent process for a hierarchical dichotomous branch system being considered as a material or energy transportation system is studied. A certain distributed nutrition density is assigned in the perfusion space to control the growth of branches, thus the distribution of branches is dependent on the distribution of the so-called nutrition density. During the generation process of branch system, the nutrition density in the whole perfusion space decreases and its distribution tends to be uniform. The prerequisites of constructing the branch system are briefly described as follows:

i) Branching law stands for the relationship of radii between the parent branch and the daughter branches, which is adopted at every bifurcation point. For a dichotomous branch system, it is formulated as the following Eq.(1).

$$r_0^{\lambda} = r_1^{\lambda} + r_2^{\lambda} \qquad (1)$$

where r_0, r_1 and r_2 are radii of the parent branch and the daughter branches. The bifurcation exponent, λ, is physiologically reasonable when it is in the range of $2<\lambda<3$. Murray's law shows that when $\lambda=3$ the energy loss for transporting material through out the whole network can be made minimum.

ii) Growing law relates to the growing direction and growing velocity for a new branch, which is assumed to be dependent on the local nutrient distribution. A new terminal site is always positioned at the point with the highest nutrient density in the local growth space around the grown branches. If there is more than one such point in the local growth space, it is selected randomly. The hydrodynamic conditions are assumed as that each terminal branch has the same flow and pressure so as to bath the whole perfusion space evenly. Such hydrodynamic characteristics are similar to that of arterial vascular systems in human body. The branches are assumed to be cylinders. Flows in the branches are assumed as fully developed laminar flow, so they obey Poiseuille's law formulated by Eq.(2).

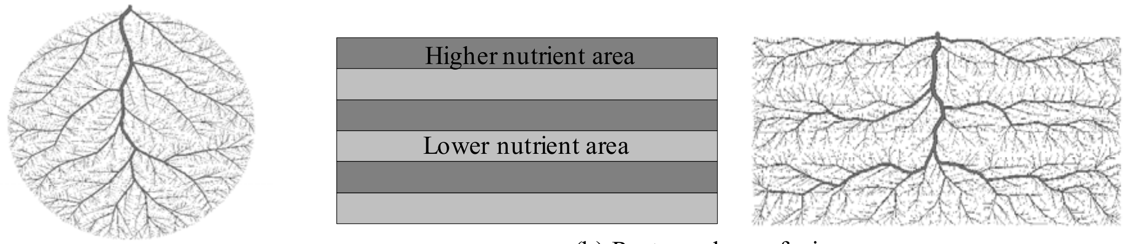
$$Q = \frac{\pi r^4}{8\nu}\frac{\Delta P}{L} \qquad (2)$$

where Q is the flow rate, ΔP is the pressure drop, r and L are radius and length of the vessel, and ν is the dynamic viscosity of the fluid. The volume of whole branch system is selected as the cost function, so the branch system is designed in such a way that the volume of it is minimized,

$$V = \sum_{i=1}^{n} r_i^2 l_i \rightarrow \min \qquad (3)$$

where r_i, l_i are radius and length of branch i, and n is the total number of branches.

According to the above prerequisites, branch systems can be generated to fill up perfusion space with any kind of shape being assigned with any complex distribution of nutrient density. Some generated branch systems are illustrated in Fig.1, where Fig.(a) shows a branch system generated on a circular perfusion area assigned with uniform nutrient density, while Fig.(b) shows a branch system generated on a rectangular perfusion area assigned with non-uniform



(a) Circular perfusion area with uniform nutrient density

(b) Rectangular perfusion area with non-uniform nutrient density

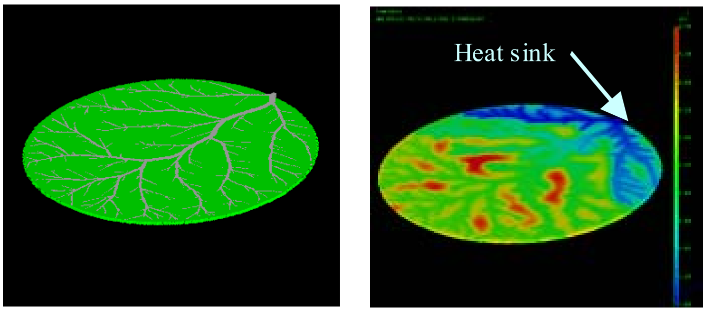
Fig.1 Some generated branch systems

nutrient density. It can be found that the distributions of branches are dependent on the distribution of nutrient densities, which can be considered being responsible for the adaptive growth of branch systems in nature, for example, the hydrotropism of root system of plant, and the phototropism of tree branch system. And the simulated branch system has both thicker and thinner size levels, which can be considered to be responsible for the characteristic of a fluid transportation branch system in nature that the thicker ones convey a long-distance material transportation, and the thinner ones exchange material with the environment. So it can be said that the essential characteristics of the simulated branch systems are qualitatively similar to that of the branch systems in nature.

LAYOUT DESGN OF HEATRANSFER SYSTEM

If the so-called nutrient density in the generation process of a branch system is referred to as the temperature in a heat transfer system, the distribution of branches can be considered being corresponding to the distribution of cooling channels. Because branch system can grow adaptively to the nutrient distribution in order to absorb the nutrition to the maximal extent, the cooling channel can be constructed adaptively by the control of the temperature so as to make it possible to achieve comparative uniform temperature distribution of the whole heat transfer system. Therefore, the generation method based on the growth mechanism of branch systems in nature can be applied to the layout design of heat transfer system.

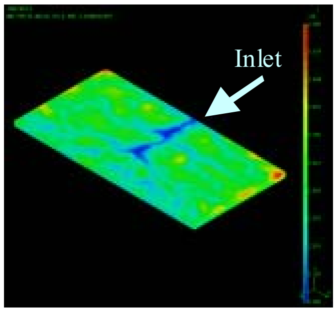
First, the layout of a conductive cooling channel in a heat transfer system is designed and its cooling performance is analyzed. The problem is stated as: “a finite-size volume is to be cooled through a small heat sink located on its boundary, in which the heat is being generated at every point. A finite amount of high conductivity (k_p) material is available. Determine the optimum distribution of material k_p through the given volume such that the temperature distribution of the whole volume is as uniform as possible.” The natural branch-like conductive cooling channel is constructed based on the corresponding original branch system. The width of the channel, however, is assumed to be the same diameter as the corresponding branch in the branch system. The ratio of thermal conductivity of the high conductivity material (k_p) to the low conductivity (k_0) is assumed as $\tilde{k} = k_p / k_0 >> 1$. A circular plate with the ratio of thickness to diameter of 0.01 is considered as the finite-size volume to be cooled, in which the heat generates at every point with the uniform volumetric heat-generating rate $q'''= 10^5 W/m^3$. The layout of the conductive cooling channel made of a high conductivity material (k_p) is based on the original branch system shown in Fig.1(a). It is noted that the distribution of heat-generating rate is identical to that of the so-called nutrient density in the generation process of the original branch system. The ratio of the thermal conductivities of the high conductivity material (k_p) to the low conductivity (k_0) is assumed to be 10^4. The temperature at the heat sink located on the boundary is set as T_{min}= 10ºC. The whole structure is insulated from the environment. Figure 2(a) shows the FEM model, in which volume rate of the cooling channel is 9.71%. Figure 2(b) shows the temperature field of the whole plate, in which the red parts stand for the hot spots, while the blue parts stands for the comparative cool spots. It is found that the hot spots are distributed over the whole volume.



(a) FEM model (Volume rate=9.71%)

(b) Temperature field T_{max}=57.55ºC

Fig.2 FEM model and temperature field for a circular plate with a natural branch-like conductive cooling channel under uniform heat-generating rate.



Temperature field T_{max}=32.55ºC

Fig.3 Heat transfer system with branch-like convective cooling channel applied non-uniformly distributed heat flux.

The layout of a convective cooling channel in a heat transfer system is designed by the generation method based on the growth mechanism of branch systems in nature. The difference from the conductive cooling channel is that the coolant flow is available to remove the heat. A branch-like convective cooling channel is constructed inside a flat plate, which is based on the corresponding original branch system. Figure 3 shows the FEM model and temperature field of a rectangular plate applied a non-uniformly distributed heat flux. The branch-like convective cooling channel is constructed based on the branch system shown in Fig.1(b), in which the volume rate is 1.26% by omitting the branches with smaller cross-sections. The heat flux is distributed on the top surface with the same distribution as the nutrient density shown in Fig.1(b), in which the stronger and the weaker heat fluxes are assumed as q_h=5x10^{5}W/m^2 and q_l=3x10^{5}W/m^2, respectively. And the volumetric flow at the inlet is assumed to be V = 6x10^{-5}m^3/s. It is found that even though the heat flux is distributed non-uniformly, good cooling performance can be achieved.