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A Robust and Efficient Cooler Design Inspired by Leaf Venation

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Abstract. After years of evolution and natural selection, leaf venation yields to a complicated pattern to achieve better transfer efficiency together with higher structure robustness. In this paper, we use the design of a cooler as an example to explore the benefits of using such venation pattern. We first utilize a bio-inspired venation generation algorithm called space colonization to generate the venation patterns, which is used as the topology of a cooler system. Numerical simulations show that, the venation-inspired design is 10% more efficient than typical cooler in heat conduction, while is about twice more robust under physical damage. These results demonstrate that plants arrange their venation in a very efficient strategy, which can be a very promising source design for both efficiency and robustness considerations.

Keywords: Bio-inspired · Leaf venation · Cooler design · Robustness

1 Introduction

The structure of leaf venation (as shown in Fig. 1a) is very complicated and has evolved over many years [1]. Several different explanations were given by biologist for the complexity of venation pattern: (1) for better efficiency in transporting water and nutrients [2–4]. The core function of the veins is fluid transportation to nourish cells, thus it is conceivable that it will tend to have high transportation efficiency. (2) supporting for the leaf weight [5–7]. It has been shown that venation can significantly increase the mechanical strength and stiffness to serve as mechanical reinforcement [5]. (3) providing redundancy [8,9]. Natural leaves are subject to all kinds of damage from insects (as shown in Fig. 1b for example), herbivore, hail and even windstorm.

Since venation has such interesting properties, researchers have started investigating the possibility to generate design configurations inspired by leaf venation patterns. For example, the branching pattern of venation has inspired people to design fuel cells [10,11], micro flow field [12], and thermal functional materials [13]. All of these venation inspired designs have shown improved efficiency over standard designs. However, the potential of venation-like pattern in achieving both high transport and high robustness to damage still hasn't been explored yet.

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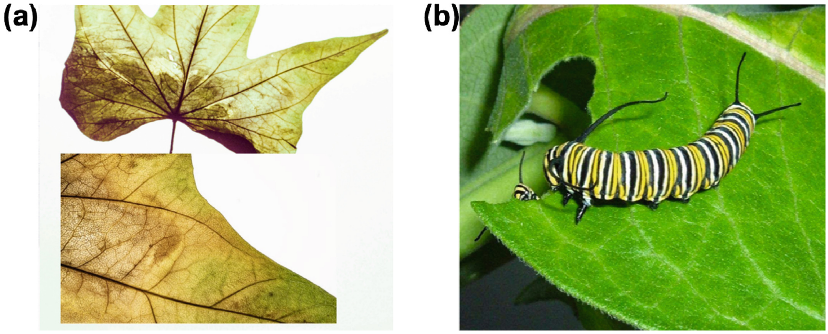

Fig. 1. Left: photograph leaf venation. Right: leaf under insect damage.

In this work, we investigate the efficiency and robustness of venation inspired design under the context of designing a cooler system based on numerical simulations. The venation structure is generated from a bio-inspired space colonization algorithm. Compared with the traditional cooler designs, the computational results corroborate that the proposed venation-inspired design can achieve a higher transportation capacity as well as processing extraordinary robustness under damage.

2 Bio-Inspired Venation Generation

In this section, we briefly review a bio-inspired algorithm called space colonization to generate the venation pattern. This generated pattern will be used to build used a cooler system in the later experiment to study both the transportation efficiency and robustness of venation based design.

The main idea of space colonization is inspired by the growth of leaves. From the biological perspective, a leaf will produce auxin (a kind of hormone) to stimulate the growth of venation, and venation will grow towards the direction with as many auxin sources as possible [14]. Once the venation is getting closer enough to an auxin source, the auxin will be depleted by the venation cells. The size of the leaf will get larger based on the span of venation, and more auxin sources will be released to further stimulate the growth of venation. This process can iterate over and over.

Space colonization is an iterative generation algorithm build on the previous described biological process. A very good illustration of this algorithm is adopted from [15] and shown in Fig. 2. The execution of the algorithm can be explained step by step as below:

- (a) Before the iteration starts, a node will be set as the beginning of venation, from where the rest of the vein (white dots) will be generated. Several auxin sources (blue dots) will be randomly initialized in the region as well.
- (b) Assign each auxin sources to different venation nodes based on the distance, as shown by the red connection.

– (c) Compute the directions for each venation node based on their associated auxin sources.
– (d) Average the directions on each venation node. Grow each venation node towards these directions.
– (e) Add newly grown venation nodes to the current venation.
– (f) Verify if the previous auxin is too close to the current venation, in other words, if it is inside the "kill distance".
– (g) Remove the auxin source if it is too close to the current venation.
– (h) Grow the size of the region of interest.
– (i) Randomly place more auxin sources in the enlarged region.
– (j) Remove the auxin sources that are close to the auxin sources in step (h).
– (k) Go back to step (b) and repeat the process.

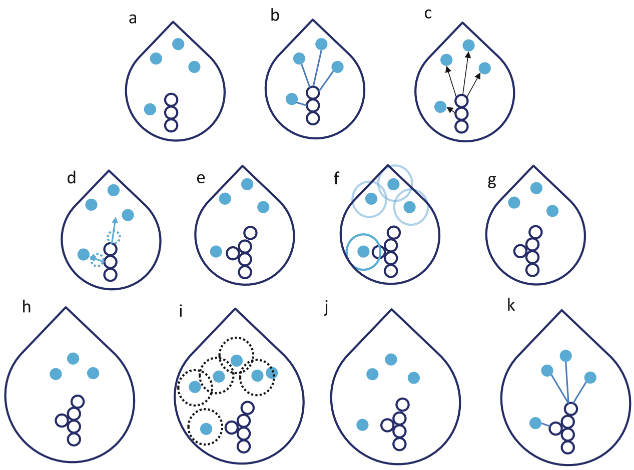

Fig. 2. Illustration of the space colonization algorithm for simulating venation growth. Figure adapted from [15]. (Color figure online)

The variables in this algorithm including the number of auxins, the kill distance, and the position of the auxin will all influence the final venation pattern. For more details on the algorithm, we encourage the readers to refer to [15].

3 Venation-Inspired Cooler Design and Analysis

In this section, a two dimensional (2D) heat conduction problem is used to demonstrate the performance of venation inspired design. The problem and configuration are defined in the first subsection, then the efficiency and robustness of venation-inspired design are investigated by the following two subsections, respectively.

3.1 Problem Setting and Design Configuration

Consider designing a cooler for the two-dimensional isotropic thermal problem in Fig. 3a. We have a uniform heat source distributed in Ω, there is zero heat conduction on Σ_N (Neumann boundary), and the temperature is fixed at zero degrees at Σ_D (Dirichlet boundary). We wish to design a cooler to cooler down the region Ω by transmitting the temperature through Σ_D.

The governing equation for the system can be written as:

$$\nabla \cdot (\kappa \nabla T) + \dot{q} = 0 \text{ on } \Omega \tag{1}$$

$$T = 0 \text{ on } \Sigma_D \tag{2}$$

$$(\kappa \nabla T) \cdot \mathbf{n} = 0 \text{ on } \Sigma_N \tag{3}$$

where T is the temperature field on region Ω, $\dot{q}$ is a heat source and κ is the material thermal conductivity. Additionally, in solving heat dissipation, the right-hand side of Eq. (1) is exchanged with a time-dependent energy term $\rho c_p \frac{\partial T}{\partial t}$, where ρ is the density and c_p is the heat capacity. The initial temperature at Ω is set at 300 °C. Other related physical parameters are set in Table 1.

Table 1. The parameters used for simulating the heat dissipation

κ_1	κ_2	$\dot{q}$	c_p	ρ
300 W/mK	0.02 W/mK	10 W/m^2	233 J/kg.K	10490 kg/m^3

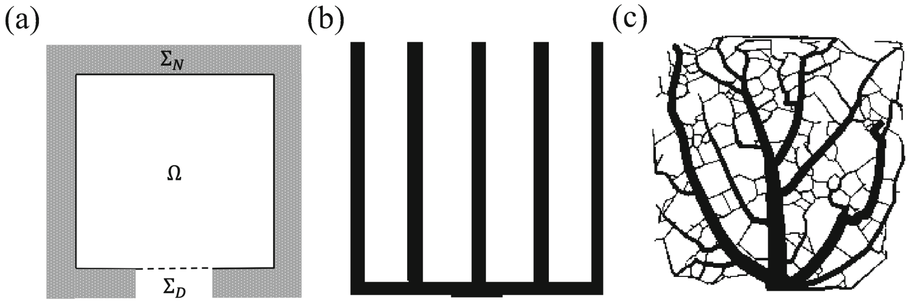

Fig. 3. (a): thermal conduction problem setting; (b): traditional conductor configuration; (c): venation-inspired conductor configuration. The coverage of conductive material for traditional and venation-inspired design is 30.7% and 30.3%, respectively.

Our objective is to reliably transfer heat from Ω through Σ_D as fast as possible. As shown in Fig. 3b and c, we tested these two different cooler configurations in the following experiments. The first configurations is a traditional design with multiple fingers, and the second one is a venation inspired design generated from the space colonization algorithm introduced in Sect. 2. We use 20 auxin sources and set kill distance to 5 to generate the venation topology. In both traditional and venation-inspired configurations, there are about 30% of the region covered by the thermal conductive material, which is marked as black. And 22.5% of one side is in contact with the external cooler, which is assumed to be at a constant temperature. The heat conductivity of the conductive material κ_1 is set to be much higher than the non-conductive base material κ_2, so that the heat conduction through venation will dominate the conduction.

3.2 Analysis of the Conductivity Efficiency

We use implicit finite difference solver to solve the heat diffusion equation Eq. 1 to obtain the temperature and heat flux distribution over the solution domain. To qualitatively compare the efficiency of different cooling configurations, we monitor the total heat flux passing through Σ_D over time. This total heat flux E can be numerically computed by summing over the heat flux over time steps:

$$E(\phi, t) = \sum_{t=0}^{t_n} q_t(\phi, x), \quad x \in \Sigma_D \tag{4}$$

where ϕ is the structure topology, and t_n is set to 800 s in the experiment. We also record the history of E over t and visualize it in Fig. 4. There is a small period at the very start (starting from initial to about 80 s) that heat conduction efficiency of traditional cooler is slightly higher resulting from more high heat conduction material around the boundary Σ_D and steady state has not reached yet. However, it can be seen that venation inspired cooler design is still able to conduct more thermal energy outside of the domain Ω for most of the time. Additionally, by the end of 800 s, the total energy conducted using venation structure is 10% higher than the traditional cooler design.

3.3 Analysis of the Structure Robustness

To investigate the robustness of the cooler design under damage, we will need to make following definitions and assumptions: We first define the robustness as how much influence an external loading will have on the performance of the cooling systems. Furthermore, following three assumptions will be made to simplify this problem:

- For a given patch of the cooler with size d, its stiffness will be proportional to the volume fraction ratio r of the venation structure.
- The patch under loading will get damaged if the deformation exceeds a certain threshold.
- If a patch is damaged, all conductive material κ_1 in this region will turn into non-conductive base material κ_2.

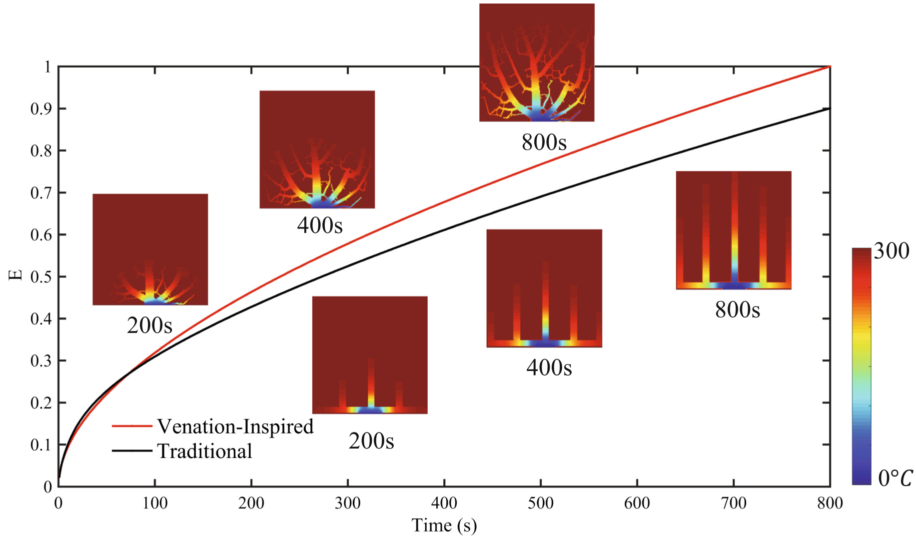

Fig. 4. Total heat conducted history. The result is normalized to be bounded in $(0, 1)$. The heatmaps above and below the curve are the temperature distribution for venation inspired cooler and traditional cooler, respectively. Captions below the heatmaps are the time stamp the heatmap is captured.

The first assumption is made reasonable because the venation structures tend to have a stronger mechanical property. Thus the more venation material exists in a patch, the harder to get this patch damaged. Based on the second assumption, we can define the "damage probability" p as the probability that a given region is likely to malfunction under a given loading magnitude. Combine these two assumptions together, we can model the relationship between p and the volume fraction ratio with a negative step function, as shown in Fig. 5a. In this experiment, we randomly pick a damaging threshold at $r = 0.4$ (we have $r \approx 0.3$ on the whole structure).

We propose to use the expectance of the drop rate of the total heat conduction E after damage as the metric to measure the robustness of a configuration ϕ. We define the expectance as ϵ, which is a function of the patch size d:

$$\epsilon(d) = \mathbb{E}_{x \in \Omega}\big(1 - E_{t_n}(\phi'(x, d))/E_{t_n}(\phi)\big) \tag{5}$$

where ϕ is the original topology, $\phi'(x, d)$ is the topology after a patch of loading with patch size d is applied at location x. As before, we still use $t_n = 800$.

We track ϵ under different damage extend d for traditional and venation-inspired cooler. The comparison is plotted in Fig. 5b with d ranging from 15% to 35% of the total region size. It can be seen that the venation-inspired design is constantly almost twice more robust than the traditional structure. This shows that plants have learned to distribute the volume of venation wisely over the leaf to achieve the maximum reliability. Firstly, it can be seen that there is a roughly linear (or piece-wise linear) relationship between d and ϵ. Furthermore, for the traditional cooler design, there exists a jump in ϵ when $d = 0.25$. This is due to the fact that the distance between the two fingers is equal to 0.25. If we reached that damage level, the transmission effect will be severely influenced. On the other hand, the venation-inspired design has constantly better performance.

In biology, it is observed that the first order veins are more influential to the conduction speed. In the meantime, first order venation will also have a stronger mechanical property that makes it unlikely to get easily damaged. Besides, there are lots of interconnections in the venation pattern and alternative heat conduction path exists if the original one is damages. This interconnection gives extra redundancy to the cooler design.

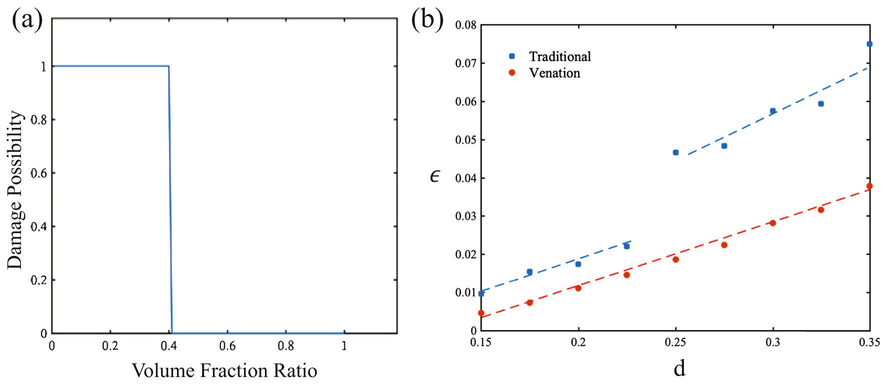

Fig. 5. (a): Illustration of the damage probability w.r.t. the volume fraction ratio. (b): Comparison of robustness under external loading.

4 Conclusions and Future Work

The thermal transportation efficiency and robustness of venation structure are explored in this paper. A bio-inspired venation generation algorithm is used to obtain the venation pattern for the conductive cooler model. An improvement of 10% in heat conduction is obtained with our venation-inspired design. What's more, the impair of the heat conduction ability due to damage in the traditional design was twice that of venation-inspired design.

Further improvements can be made in several aspects. First, a higher resolution of venation structure can be generated and fed to the numerical model. A higher level of the venation hierarchy might also improve the results. Second, different parameters in the venation generation algorithm can be optimized to obtain the most efficient network configuration. A symmetric pattern can be added to the algorithm as a constraint as well. Furthermore, designing 3D cooling systems based on venation and utilizing 3D printing techniques to fabricate these venation patterns would also be another direction worth exploring.

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