Venation-inspired channel networks for enhanced fluid transport in porous media

Caio Martins Ramos de Oliveira, Murilo Pereira de Almeida, Adriano Mesquita Alencar

caiomar@if.usp.br; murilo@fisica.ufc.br ; aalencar@if.usp.br

Abstract: *The design of improved channel networks embedded in porous media could potentially benefit multiple devices in fields such as power generation. Pursuing the construction of enhanced channel architectures, we sought similar systems in nature. Venations in leaves, with some modifications, provide the basis for the construction of improved channel networks in this work. Generation of the of the venation-inspired design was achieved via an implemented algorithm. The performance of the geometries was studied employing the Computational Fluid Dynamics (CFD) approach. The opensource CFD software OpenFOAM was used to solve the coupled momentum and mass conservation equations. Channel network properties were determined in order to identify the features that showcased strong correlations with a performance measure. Meanwhile, in order to validate the numerical results, we developed an experimental set-up, our proof-of-concept model.*

Key-Words: *channel networks ; Computational fluid dynamics ; leaf venations ; OpenFOAM ; porous media*

Introduction: There are multiple devices that employ channel networks to either distribute or to remove a solution or heat from a volume. In nature, likewise, there are many examples of systems with channel networks that perform these same functions and which are nearly optimal in their transporting task. Taking that into account, it seems reasonable that the application of nature-inspired channel architectures to human-made devices could potentially improve their performance. Indeed, recent investigations demonstrated that a proton-exchange membrane fuel cell (PEMFC) that made use of a venation-inspired channel pattern displayed a performance boost of around 20-25% when compared to conventional designs [1]. Motivated by these results, we set out to employ a myriad of channel network designs with even more realistic patterns. In order to do so, we searched the literature for an algorithm capable of generating visually realistic venations and which is consistent with the biological knowledge of venation development [2]. We then implemented our modified version of the algorithm to generate open interdigitated patterns. During the generation process, we were able quantify properties of interest of the patterns, including the Murray's law exponent, fractal dimension, vein length per area (VLA) and bifurcation number. The idea is to vary these parameters in order to identify the changes that affect the transport efficiency [3].

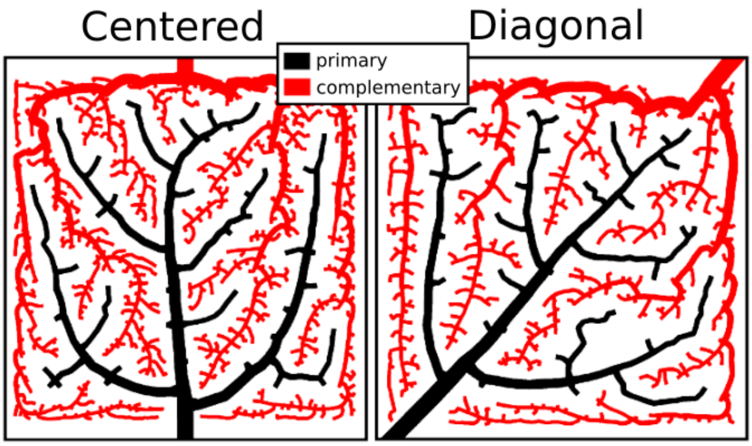

Figure 1: Computationally generated geometries.

Experimental: The first step was to create different geometries using our modified algorithm, implemented in C++, for leaf venation generation. All geometries were interdigitated, with the two disconnected networks labeled as primary and complementary venation respectively [3]. Morever, each geometry belonged to either the centered or the diagonal category, see Figure 1. In a second step, we solved the flow through some of the porous systems with the embedded interdigitated channels using OpenFOAM. The meshes were constructed using a CAD program to create the corresponding .STL files and an OpenFOAM utility, *snappyHexMesh*, to generate the final output [4]. The PIMPLE algorithm was employed to solve the coupled momentum and mass conservation equations. The porous behavior of the region outside the channels was modelled including the Darcy term in the incompressible Navier-Stokes equations. Meanwhile, the passive scalar field representing the reactant concentration was solved using a standard solver, *scalartransportfoam* [3,4]. For the generated geometries, the primary venation was first connected to the inlet while the complementary venation was associated to the outlet. Subsequently, we alternated the behavior and, thus, doubled the number of configurations for analysis, since each geometry was used twice. The results were retrieved using the post-processing tool *paraFoam* and subsequently stored for subsquent analysis using the R language. The main performance measure we employed was the volumetric coverage, defined as the volume percentage of the system that is above a given concentration threshold. Experimental models based on a photovoltaic device, a dye-sensitized solar cell (DSSC) variant [5], were also constructed with the goal of validating the numerical results. The set-ups consisted of an agar hydrogel slab sandwiched between two glass plates. The channels were formed on one of the surfaces of the hydrogel slab using a 3D printed mold with the geometry. Finally, a dye solution was introduced into the system at a constant volumetric flow rate with a microfluidic pump [3].

Results and discussion: We first observed the changes in the volume coverage performance measure with the choice of concentration threshold for each one group of the four groups of configurations. Our preliminary numerical results indicated the centered venations exhibited a better performance than the diagonal ones in the chose threshold range. Moreover, for our initial set of centered geometries, the configuration in which the primary venations were connected to the inlet displayed a better performance for low threshold values, whereas the inlet-connected complementary venation configurations had a superior performance for higher threshold values. The trend could be partly explained by the fact that most centered complementary venations have a proportianally greater volume near the inlet than the centered primary venations, although that remains to be quantified. On the other hand, most centered primary venations in our set had a lower volume difference between the extremity and the inlet channels comparatively and, thus, did not confine the solution to any specific region. A thorough analysis confirming this hypothesis must still be performed. As for our experimental line of research, which is in the initial stages, we were already able observe the evolution of dye transport throughout the our prototype, our proof-of-concept model. The time-scale of the transport observed in the numerical models is similar to the one observed in the experimental setup. For an accurate validation of the numerical results, however, some experimental challenges must be overcome.

Conclusion: Our preliminary results from CFD suggest that the inlet-connected primary centered venation configuration had a superior performance when compared to the others. This observed trend must still be confirmed for greater a large set of geometries. The correlations observed between the venation properties and the performance when investigating the flows numerically in our data set offer some possible insights on how to improve the coverage performance of the current channel networks generated with the algorithm. A convergence analysis and experimental validation of the results are also necessary to ensure the precision of the observed trends [3,6]. These validation studies as well as a more comprehensive study using more channel networks will be the subject of future work.

References and acknowledgements:

Refererences:

[1]N. Guo, M.C. Leu, U.O. Koylu, International Journal of Hydrogen Energy **39**, 21185 (2014).
[2]A. Runions, et. al, ACM Trans. Graph., **24**, 702 (2005).
[3]C.M.R. de Oliveira, Fluid distribution optimization in porous media using leaf venation patterns, Master's dissertation (2017).
[4]C.J. Greenshields, OpenFOAM user guide (2015).
[5]H.-J. Koo, O.D. Velev, Scientific Reports **3**, 2357 (2013).
[6]J.H. Ferziger, M. Peric, Computational methods for fluid dynamics, Springer Berlin Heidelberg (2001).

Acknowledgements:

C. M. R. O. acknowledges the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for support.