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Dynamics of cavitation in real and artificial trees

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Abstract

In a tree, water is transported from the roots to the leaves by the xylem structure composed of conducting elements (tracheids in gymnosperms and vessels in angiosperms). This is achieved by evaporation in the leaves which pulls the whole water column up, that is under tension (or negative pressure). Despite being a very efficient and passive way to create fluxes, this mechanism has an important drawback: water under tension is metastable and bubbles can spontaneously appear inside it, leading to embolism due to the subsequent expansion of these bubbles. This harmful process is called cavitation.

There has been a lot of effort in the past decades to understand how cavitation happens, propagate, or can be repaired. One of the main limitations to the study of cavitation is that it is virtually impossible to directly observe events in wood. As a result, most investigations use indirect techniques such as ultrasound emissions, the origin of which is still debated.

We developed a method to observe cavitation events optically, by cutting tangential slices of pinewood that are thin enough (50-100 μm) to let light pass through and to contain at least one intact tracheid in the radial direction. These wood slices are completely embedded in a hydrogel to prevent any direct air entry. Negative pressure is generated in the tracheids by drying the extremities of the samples at ambient conditions or in a controlled humidity chamber. Cavitation events can either be triggered by a laser or appear spontaneously after a sufficient drying time.

We discovered that individual cavitation bubbles have a two steps expansion process. In the first extremely fast step, a bubble appears at a microsecond timescale and reaches a transiently stable volume. The second step immediately follows: the bubble expands until filling the whole tracheid. We will show that if this filling process follows a diffusive dynamics in $t^{1/2}$, the global drying (or “embolism”) front in the wood samples grows linearly in time. We will present a simple physical modelling that explains this particular dynamics.

We will conclude by showing that we can get some insight in the previous dynamics by the study of “artificial trees” made of microfluidic channels embedded in a hydrogel. In particular, we found that the ultra-fast birth of the bubble presents volume oscillations. We expect these oscillations to play a role in the acoustic emissions detected during cavitation, and this study should help interpreting the recorded signals.

Keywords

Cavitation, Xylem, Tree, Artificial tree, Flow, Tracheid, Water, Sap, Fast Dynamics, Hydrogel