Cavitation in trees: acoustical and optical monitoring

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Abstract:

During hydric stress, the pressure of ascending sap in trees may go down to as low as \(-15\) MPa. Sap cavitation can occur, leading to the embolism within the circulation in trees. It is known that acoustic emissions are produced when trees undergo a drought. We use a device consisting of an inclusion of wood in hydrogel to create in the laboratory the same negative pressure conditions as the one found in trees. We are thus able to correlate acoustical events to optical observations and link the acoustical events features with the wood characteristics. We observe that the main source of sound is the appearance of cavitation bubbles and that the acoustical energy emitted is increasing with the volume of the cavity where the bubble appears.

Mots clefs : Cavitation; Acoustic Emission; Tree physiology

1 Introduction

The ascending sap in trees is driven by evaporation at the leaves. Due to viscous pressure drop and hydrostatic variation sap is at large negative pressure. It may reach dozens of bars in absolute value: sap in trees is in a metastable state. Water in negative pressure may cavitate, see Caupin & Herbert (2006). During high hydric stress, sap may thus cavitate, leading to the embolism of trees. The negative pressures that trees can sustain are between \(-2\) and \(-15\) MPa, depending on the species, Choat et al. (2012).

It is a common technique to use microphones in the ultrasonic range to monitor trees under hydric stress, see Tyree (1983). However the precise origin of acoustic emissions is poorly known.

Here we propose a new method to monitor both acoustically and optically wood channels. We embed wood slices in a transparent hydrogel that plays 1) the role of the leaves: water in the wood sample is under large negative pressures and then we are able to monitor wood in hydric stress both optically and acoustically and 2) prevents air from invading the wood sample.

2 Methods

To be able to monitor wood samples optically (and acoustically) we use wood slices of pine tree cut with a microtome at a thickness of 50 \(\mu\)m. Sap channels of pine tree have an average diameter of
20 μm. Thus the slices are thick enough to contain intact vessels and thin enough to be transparent to light. The length of pine sap channels is of order 500μm. With wood samples of transverse dimensions 10 × 5 mm we have enough intact sap channels to make good statistics and still have a good resolution with the camera.

To recreate the conditions of negative pressures found in trees, we include the wood slice in a hydrogel (pHEMA) developed by Wheeler & Stroock (2008), an illustration of the wood inclusion is shown on figure 1a). The protocol we use to make this inclusion has been developed by Vincent (2012). The pHEMA hydrogel has been designed to sustain large negative pressures caused by evaporation. The water potential in the hydrogel equilibrates with water potential of surrounding air. In our experiments, we place the wood inclusion in an atmosphere of relative humidity of 88%, controlled with a saturated solution of KCl. As equilibrium establishes in hydrogel, the negative pressure reaches −17 MPa, far below the pine cavitation threshold of −6 MPa approximatively.

As shown on figure 1a) we monitor the inclusion with a camera (AVT Marlin F-421B) operating at 1.875 Hz and a microphone (PICO-HF 1.2, Physical Acoustic Corporation) that records only signals of length 7000 μs when the acoustic pressure exceeds a threshold value of 0.4 mPa. With the camera we are able to follow the growth of bubbles in sap channels, figure 1b). At t = 0 s the sample is light grey, all sap channels are filled with water. At t = 1500 s cavitation events have happened and black domains appeared on the sample, corresponding to bubbles. Black domains occur because wood is a complex microfluidic system of interconnected sap channels and nucleated bubbles may spread from sap channels to another. At t = 3000 s the wood sample is totally embolised. With the microphone we record acoustical events as shown on the figure 1c). The signals last typically 50 μs and have a maximum amplitude varying from 0.4 to 5 mPa.

![Figure 1](image_url)

**Figure 1** – Experimental set up, camera and microphone recordings. a) wood inclusion undergoes negative pressure as water evaporates from the hydrogel, b) images of the wood inclusion at t = 0 s, t = 1500 s and t = 3000 s, grey and black correspond respectively to water and bubbles and c) example of an acoustic signal received on the microphone at t = 1570 s as a bubble appears.

### 3 Results

#### 3.1 Correlation of acoustics and optics

We recorded 463 optical events: nucleation or growth of bubbles. We recorded 160 acoustical events: 99.4% of them were correlated to an optical event. It means that in our experiment acoustic events are entirely due to growth of bubbles. But a great part of the optical events (65%) did not generate sound: in order to understand it, we now focus on the energy of the acoustic events.
3.2 Energy of the acoustic events

On figure 2a) we show the evolution of the acoustical energy received on the microphone with the volume of the sap channel. Round grey symbols show the measures for each sap channels whereas square blue symbols are means of groups of sap channels of close volumes. As the volume increases, the acoustical energy increases. We confirmed this trend with experiments on artificial spherical cavities with 4 orders of magnitude on the volume, figure 2b). It confirms the linearity between energy and cavity volume. On the wood experiment we see that when the sap channel volume decreases the energy falls below the microphone threshold where the microphones do not record the acoustic emissions. This contribute to the fact that 65% of the optical events did not produce sound.

The variation of acoustical energy comes from the fact that elastic energy stored in tension of water as water is at negative pressure is released into acoustical energy. This elastic energy writes $E_{\text{elastic}} = \frac{1}{2} K \left( \frac{\Delta V_l}{V_l} \right)^2 V_l = \frac{1}{2} \rho V_l$ as shown by Vincent (2012), where $K$ is the compression modulus of water ($K = 2.2 \text{GPa}$), $V_l$ the volume of the cavity, $\Delta V_l$ the variation of volume of water in the cavity and $p$ the pressure in the cavity. If the elastic energy is totally converted in acoustic energy, it explains the proportionality we have observed.

4 Conclusions

We monitored both optically and acoustically channels of wood, at a sap pressure becoming largely negative. We concluded that almost all (99.4%) acoustical events are due to the appearance of a bubble. But two thirds of the appearing bubbles did not produce acoustic events. This is partly explained by the variations of acoustic energy with the sap channels volume: if their volume is too small the energy will be too small to be heard by the microphone. However we observed bubbles appearing in large sap channels without acoustic event.

A reason could be the collapse of the sap channel when pressure becomes too negative. As the elastic channel has collapsed its volume is now too small for the appearing bubble to be heard. It is to be proved in future experiments, but has already been observed in pine needles, see Cochard (2004). The role of porosity in wood has been also enlightened by the presence of growing regions of embolism as pressure goes down: bubbles may pass from sap channels to other sap channel. This also could contribute to the apparition of bubbles without acoustic emission.
Références


