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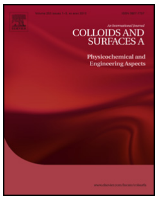


# Flow of nanofluids through porous media: Preserving timber with colloid science

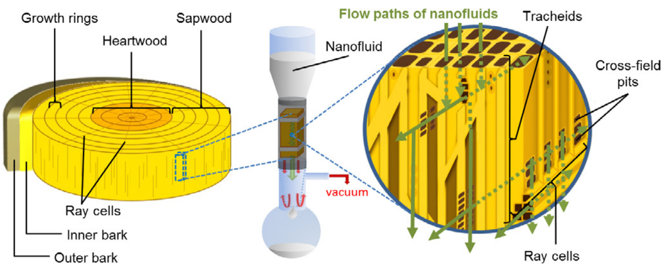
Stephen J. Uphill[a,b,*], Terence Cosgrove[b], Wuge H. Briscoe[b,*]

[a] Osmose, Fieldhouse Lane, Marlow, UK
[b] School of Chemistry, University of Bristol, Cantock's Close, Bristol BS8 1TS, UK

## HIGHLIGHTS

- Silica nanofluids of various size, charge and concentration are passed through pine.
- We find the effective pore size for flow through Scots pine to be 1.75–3.0 μm.
- Interactions of nanofluids with charged groups within the flow paths are discussed.
- Flow data and interactions are rationalised with AFM and contact angle measurements.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Understanding the flow of particles through accessible paths in timber is important to optimising the timber preservation process. In this paper, we identify inconsistencies between the previously established flow paths in timber for simple liquids, and those for particulate systems. We show that the flow paths of *nanofluids* are through the rays of *Pinus sylvestris* (Scots pine) sapwood, then into adjoining tracheids through ruptured cross-field pits with effective pore size of 1.75–3.0 μm. We then present data from a custom-designed apparatus, with which we have studied the effect of size, charge and concentration of silica nanoparticles on their flow through pine sapwood. Our results show that particles smaller than 60 nm passed well through timber irrespective of their zeta potential. The flow of positively charged particles was significantly reduced when particle diameter exceeded 100 nm; whereas negatively charged particles with diameter of 250 nm still passed through timber reasonably well, provided the concentration of particles was below 0.5% (w/w). Furthermore, we rationalise such flow data with AFM and sessile drop contact angle measurements, which gauge the interactions between the nanofluids and a functionalised silica surface as a model timber surface. Whilst negatively charged nanofluids showed better wettability on the model surface that the positive nanofluids, the wettability did not show any particle-size dependence. We suggest that such contact angle measurements, performed under quiescent conditions, could not fully predict the flow and deposition of nanofluids through timber, which would be more complex due to the presence of an applied external pressure that could affect inter-particle and particle-surface interactions.

## 1. Introduction

Since the use of wooden tools by *Homo habilis* (early man-like creatures) to build shelters and boats over two million years ago [1], timber has been used as a construction material. It is a natural resource, easily machined, and is fully sustainable. Its biggest

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* Corresponding authors. Tel.: +44 117 3318256.
*E-mail addresses:* steve.uphill@osmose.co.uk (S.J. Uphill), wuge.briscoe@bristol.ac.uk (W.H. Briscoe).

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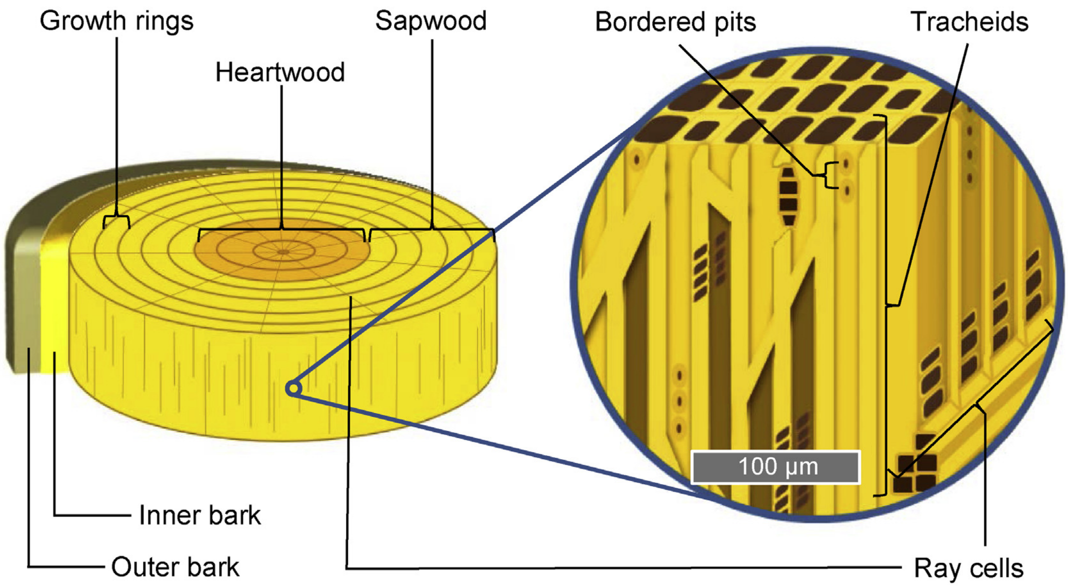

**Fig. 1.** Cross-section through a Scots pine trunk (*Source: Left, after Merriam-Webster, 2006*), with a 3D image of the structure of Scots pine. *Source*: Right, after Panshin and DeZeeuw, 1970 [5].

weakness, however, is its biodeterioration. Whether this is as a result of wood destroying fungi or insect attack, if timber is not protected against these phenomena, it may fail in service, which is likely to lead to expensive repair costs.

Wood protection is not a new science, and reference to timber preservation can be found in the bible [2]. Commercial exploitation of timber preservatives, however, was not widespread until industrial pressure treatments. The use of creosote for industrial and agricultural purposes began in the second half of the 19th century, but modern water-based preservative systems, used for domestic applications such as decking and fencing, were not commercialised until the late 1930s [3].

From the 1940s until the early 1990s, the most prevalent waterborne preservative systems were copper-chrome (CC) based. Due to their apparent toxic nature, however, the use of chromium containing preservatives was heavily restricted throughout Europe and the USA between 2003 and 2005. CC preservatives have since been replaced by amine-solubilised copper systems. With ever increasing environmental awareness and concerns, the need for more environmentally favourable preservatives is increasing. Dispersed, particulate preservatives (rather than solubilised) allow for more concentrated products, thus reducing global transport emissions and costs. Chemical emissions from treated timber into the surrounding environment can also be significantly reduced. Understanding flow of particles through timber has been identified as a crucial requirement for the development of such particulate preservatives.

## 2. Understanding particle flow through timber

### 2.1. Flow paths in Scots pine: a critical review

The liquid movement within the sapwood of living Scots pine (*Pinus sylvestris*) trees is along vertically aligned (axial) straw-like structures, called 'tracheids' which are approximately 1800–2700 μm in length. They are closed cylinders with tapered ends. Liquid travels along the hollow centres (lumina), which are approximately 20–25 μm in diameter (*cf.* Fig. 1).

Fluid moves through membranes (termed 'margo') into adjoining tracheids through 'bordered pits' [6]. Within these bordered pits, supported in the centre of the margo, is a thicker component, the 'torus', which is pulled towards either side of the pit in order to regulate water transfer between cells (*cf.* Fig. 2).

When timber is felled and dries out, the water migrates from the cell lumen of each tracheid. As the last of this 'free water' is lost from a tracheid on one side of a bordered pit, surface tension from the fluid in the adjoined tracheid will pull the torus against the cell wall and effectively close the pit [7]. Consequently, liquid flow is either severely restricted or prevented [8]. In 1972, Petty confirmed that hydrogen bonding between the torus and the secondary cell wall could occur, resulting in permanent aspiration [6].

In Scots pine, each axial tracheid is in contact with at least one 'ray' at some point along its length (*cf.* Fig. 1). Ray cells consist of ray tracheids (which show some of the features of axial tracheids: bordered pits and tapered ends) and/or ray parenchyma (which are generally undifferentiated cells) [9]. They run radially from just beneath the bark into the centre of the tree with an internal diameter of 15–20 μm. In living trees they are used to transport resins and waste materials into the heartwood at the centre of the tree. Where ray parenchyma cells and axial tracheids are in contact, there occur

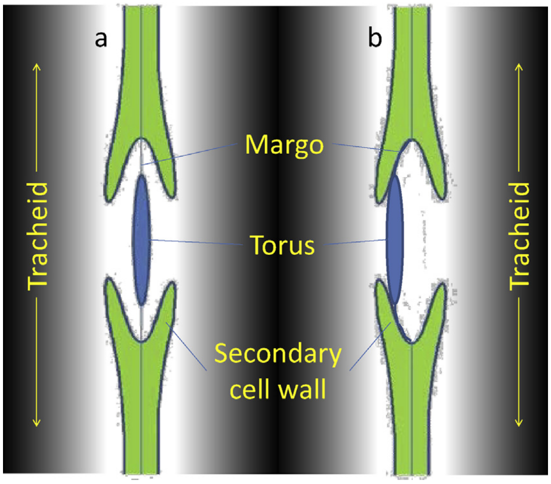

**Fig. 2.** Bordered pits (shown in unaspirated state (a) and aspirated state (b) in section transverse to the pit membrane).
*Source*: After Petty, 1972 [6].