2017 International Bionic Innovation Competition

Mathematical and experimental investigation of water migration in plant xylem

Heat pipe is a very promising heat transfer device nowadays. It involves several complex forces in the process of phase change, however, the mechanism of how coolant flow inside heat pipe is still unclear. As the flow mechanism is very similar to the water migration in plant xylem, we are hoping to find a solution to the flow and thermal management in heat pipe from the investigation of plant water migration system.

Therefore, a mathematical model is proposed considering several forces involved in plant water migration, together with a comparison with the experimental result using NMR (Nuclear Magnetic Resonance) technology.

Mathematical model

1. Cohesion-Tension theory

1)The liquid water in plant xylem system is considered as a continuous single phase flow.

2)The narrow conduit wall could enable evaporation from transpiration, but resist the entry of air at the same time.

3)Water is closely contacted to the conduit wall because of the cohesion of water molecules and tension with the wall.

2. Root pressure
3. Capillary effect
4. Gravity
5. Transpiration effect

Transpiration effect is caused by the water evaporation from plants, mainly in leaves. This is widely believed to be the critical mechanism for long distance water transportation in xylem system, especially in tall trees of over ten metres height. The simplification of transpiration effect is very difficult, and the most famous solution one proposed by Van den Honert in 1948, that consider the water flow in xylem as an analogue of the Ohm's Law.

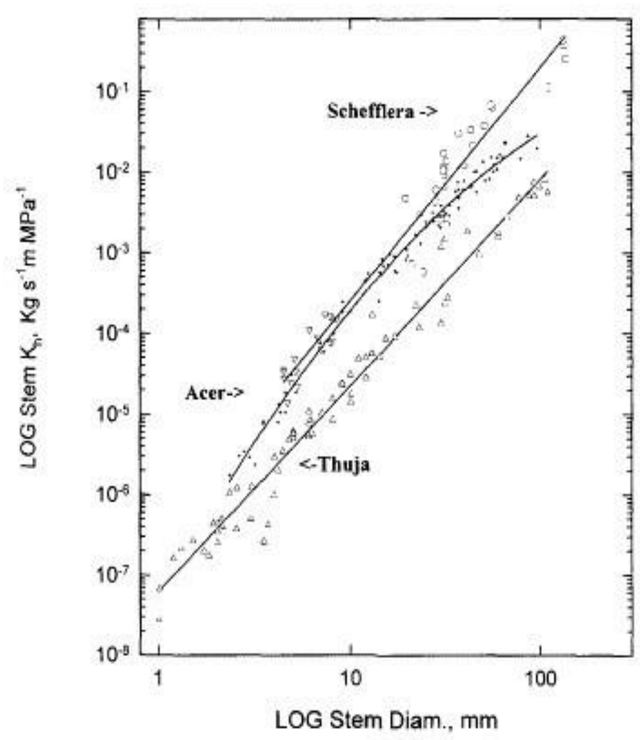
Consider the xylem conduit as a cylinder, with radius r, or diameter d, and height h. P_t is the transpiration pressure, Q is volume flow rate, ρ is density, and K_h is the hydraulic conductivity.

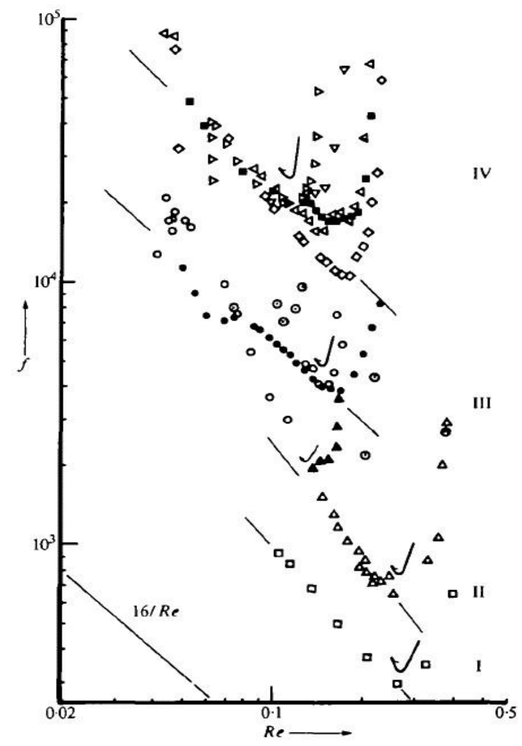
$$P_t = \rho Q h / K_h$$

6. Friction

In most researches, friction is not considered, as the extremely complex inner structure of xylem in microscale. However, there are various remarkable structures inside the xylem conduit that could be believed to be strongly affecting the friction force within the sap flow. As we are using the Darcy – Weisbach Equation to calculate the pressure loss in the water migration process due to friction, the structure details can strongly affect the friction factor, which can no longer be considered as pure laminar flow. Thus we simplify the three-dimensional structure into two dimension for calculation.

$$P_f = \rho \cdot h_f = \rho \cdot f \cdot \frac{h}{d} \cdot \frac{u^2}{2}$$





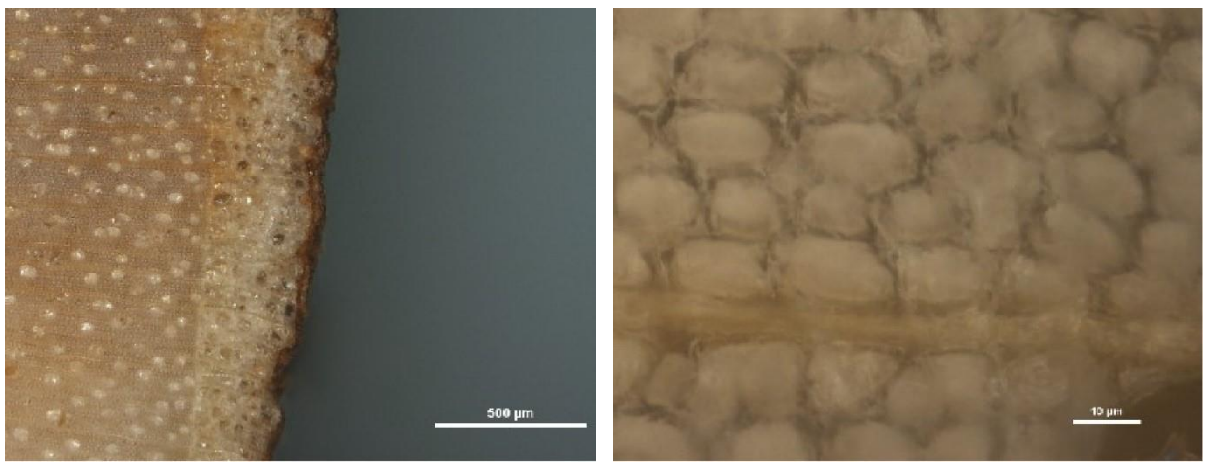
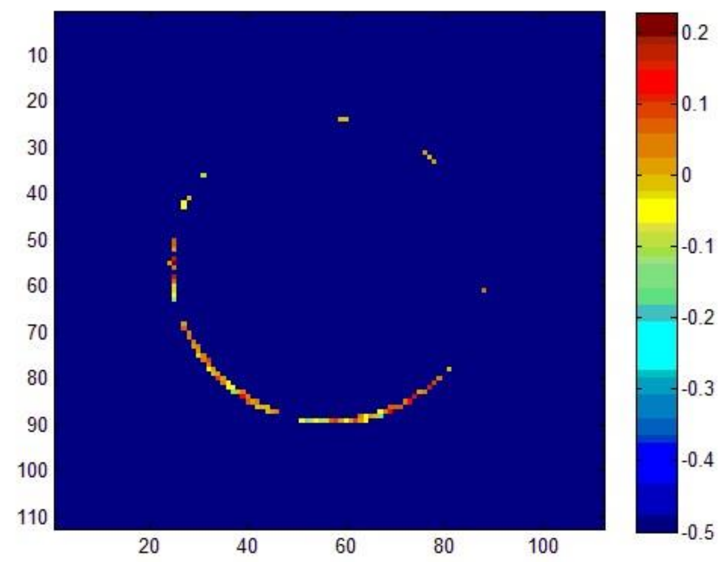


Figure: Previous researches on hydraulic conductivity (upleft) and friction factor (upright), and the stem of Salix Integra Flamingo under microscope (down)

The mathematical model is put into examination using plant Salix Integra Flamingo, and the calculation result, flow velocity inside xylem, is compared to the in vivo scanning of NMR. The flow velocity in calculation is 0.13 mm/s, while the NMR scanning shows the average velocity is 0.11 mm/s.

And the comparison shows that the our mathematical model is already very close to describing the flow pattern in plants, and possibly heat pipe as well in the following step.

Future work of this research includes reducing the error in simplification, numerical simulation and its application on heat pipe.



- Mathematical and experimental Investigation of water migration in plant xylem, Journal of Bionic Engineering, Accepted.
- Biomimetic capillary inspired heat pipe wicks, Journal of Bionic Engineering, July 2014, 11-3, 469-480