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STUDY ON A FUNCTION OF LEAF VEIN

Yoshihiro Kubota[1] and Osamu Mochizuki[2]

[1,2]*Department of Medical Engineering, Toyo University*
Kawagoe,Saitama 350-8585, JAPAN
[1]*kubota548@toyo.jp*
[2]*mochizuki@toyo.jp*

ABSTRACT : We try to explain mechanisms of a vessel flow of a plant from a fluid dynamical point of view. The necessary pressure to pump up water to stomata is estimated by using the continuity and Bernoulli's equations. The limitation of 10m related to the atmospheric pressure is nonsense because of a fault of boundary condition, so that we should be released from the spell. The pressure given indirectly by the osmotic pressure at roots is a major source of the work of pumping up. A capillary action is also possible to pump up water to a height of 20 m, if the diameter of the capillary tube is 1.5 μm. We show my latest researches on the function of leaf vein that exerts on supplying water to the whole leaf.

KEYWORDS: Sap flow, Vessel, Sieve, Xylem, Vein, Transpiration, Osmotic Pressure

INTRODUCTION

Transpiration streaming is a flow through vessel from roots to stomata. The reasons why plants can pump up water beyond the height of 10m have tried to be explained by various theories. One major concept is the water potential that is defined by Gibbs free energy (Mohr and Schopfer, 1992, and Atkins, 1998). Evaporation at stomata draws up water because of potential difference of vapor and water. Another one is osmotic pressure of cells in roots and leaves. Osmotic action is also explained by the water potential, so that this is classified as the above explanation. The capillary attraction is one of the possible reasons of water rising up to stomata. However, any ones still have not succeeded to explain the origin of the flow sufficiently. This is because of lack of data to prove the theories mentioned above.

The first mistake in the general discussions about the transpiration streaming is the limitation of 10m related to the atmospheric pressure. This story has spread widely because it seems to be plausible explanation to persuade imprudent ones. We think that this comes from the image of sucking lemonade through a straw. We make vacuum in our mouth to suck lemonade; we use the negative pressure measured from the atmospheric pressure. It means that the maximum negative pressure is -1 atm, namely, vacuum. Thus, the negative pressure at the head of water at stomata is necessary condition in the general discussion about the limitation of 10m. Is it true? No, it must be the atmospheric pressure involving partial pressure as a vapor pressure at the ambient temperature. It means that the discussion about the limit of 10m is nonsense because of a fault of the boundary condition at stomata, so that we should be released from the spell.

Many plant physiologists (Mohr and Schopfer, 1992) have introduced the concept of the water potential to explain the necessary negative pressure to suck water up to more than 10m heights as actual trees. The potential of the pure water is the maximum, so that the potential of solvent water is negative. The idea that the potential gradient from high to low is a cause of water flow is common sense between plant physiologists. This idea is possible to explain the water flow through a semipermeable membrane due to the osmotic action, too. It seems to be reasonable to explain the transpiration streaming from roots to stoma. The mechanism is as follows: 1) roots suck water from soil, 2) water flows in cells to vessel, 3) vapor phenomenon draws up water at stomata. The water potential difference between water in soil and vapor at stoma generates a driving force from a wider point of view. We need to express the water potential as pressure because energy is an ability to work but is not a force. Thus, the water potential is defined by the Gibbs free energy per a mole [J/mol] divided by volume per a mole [m^3/mol]. This is expressed by using the pressure unit [Pa]. Then osmotic flow from water to cells of roots is derived by the potential difference between pure water in soil and solvent water as plasma. Since water potential of plasma is lower than that of pure water, water flows into cells of roots. This is easy to understand according to the concept of the water potential. The problem is the second mechanism listed above, namely, the flow from cell to vessel. The liquid flowed through vessel is known as almost pure water. It means that how water flows into vessel from cells is hard to explain as the same mechanism as mentioned above since the water potential gradient is opposite. We have a question about the ability of vaporization (Hino, 2005)to have pulled water truly as related to the third mechanism listed above. Its estimation of the negative pressure is about -1000 [atm]. We cannot understand how much strong structure needs to support such a high magnitude of force at the stomata. Moreover, it is hard to make the negative pressure coincided with the atmospheric pressure as a boundary condition at the stomata from fluid dynamic point of view (Hosokawa, 2005).

We try to think this transpiration streaming by using Bernoulli's and continuity equations at first. To understand the phenomena beyond human knowledge according to fundamental principles is of first step. We assume the vessel from roots to stomata as a pipe with fine branches. We calculate the necessary conditions and requirements of supply water up to the top of high trees and evaluate the possibilities of vessel system of real trees. We show the latest our experimental researches on the function of leaf vein that exerts on supplying water to the whole leaf. It is to know the leaf function as a terminal condition.

PIPING MODEL OF VESSEL SYSTEM

Bernoulli's and continuity equations

Let's consider a main pipe with diameter d_1 and length L_1. This is regarded as a vessel of xylem in the trunk. This has n pieces of thin pipes with diameter d_2 and length L_2 connecting to the main pipe, which are regarded as veins of leaves. The velocity v, pressure p, area A of pipe and height h measured from the ground at the inlet of the main are expressed by the suffix 1, and these at the outlet of the thin pipes by the suffix 2. The Bernoulli's equation with losses is written as follows.

$$\frac{1}{2}\rho v_1^2 + p_1 + \rho g h_1 = \frac{1}{2}\rho v_2^2 + p_2 + \rho g h_2 + \zeta_v \frac{1}{2}\rho v_1^2 + n\zeta_b \frac{1}{2}\rho v_2^2 + n\zeta_t \frac{1}{2}\rho v_2^2 \qquad (1)$$

Here, $\zeta_v = \lambda_v \frac{L_1}{d_1}$, $\zeta_t = \lambda_t \frac{L_2}{d_2}$, and ζ_b are drag coefficient of the main pipe, that of the thin pipe and drag coefficient at the branch, respectively. The friction coefficient is denoted by λ_v and

λ_t for the main and thin pipes, which are calculated according to 64/Re because of low Reynolds number flow.

The continuity equation is written as follows.

$$\pi\left(\frac{d_1}{2}\right)^2 u_1 = n\pi\left(\frac{d_2}{2}\right)^2 u_2 \tag{2}$$

If $u_1=u_2$, the number n of thin pipes is obtained from eq. (2) as follows.

$$n=\left(\frac{d_1}{d_2}\right)^2 \tag{3}$$

Namely, the number n is expressed by a square of the diameter ratio. From this relation, the velocity through the thin pipe is smaller than that of the main pipe if n is more than the number calculated by a square of the diameter, and vice versa. Thus, the continuity equation gives us the relation of reasonable diameter ratio and reasonable number of branches.

Let's rewrite the eq. (1) as follows.

$$\left(1+n\zeta_b+n\zeta_t\right)\frac{1}{2}\rho v_2^2=\left(1-\zeta_v\right)\frac{1}{2}\rho v_1^2+\left(p_1-p_2\right)+\rho g\left(h_1-h_2\right) \tag{4}$$

When the flow is observed in the thin pipe, the left hand side of eq. (4) has the certain positive value. Thus, sum of each terms seen in right hand side of eq. (4) must be positive. The two terms $\left(1-\zeta_v\right)\frac{1}{2}\rho v_1^2$ and $\rho g\left(h_1-h_2\right)$ seen in the right hand side of eq. (4) are negative. If the velocity v_1 is extremely smaller than 1, this is negligible. Thus, the pressure difference (p_1-p_2) of the second term in the right hand side of eq. (4) must be larger than the potential difference $\rho g\left(h_2-h_1\right)$. In general, the pressure p_2 is the atmospheric pressure. Thus, the pressure p_1 at the root must be higher than the atmospheric pressure. In conclusion, the required gage pressure (p_1-p_2) is the pressure related to the height of plant or tree. In this conclusion, the pressure at the stomata is the atmospheric pressure. We consider that the force driving the transpiration streaming is the root pressure to push up water until the top of the tree. These are reasonable and acceptable.

Capillary action

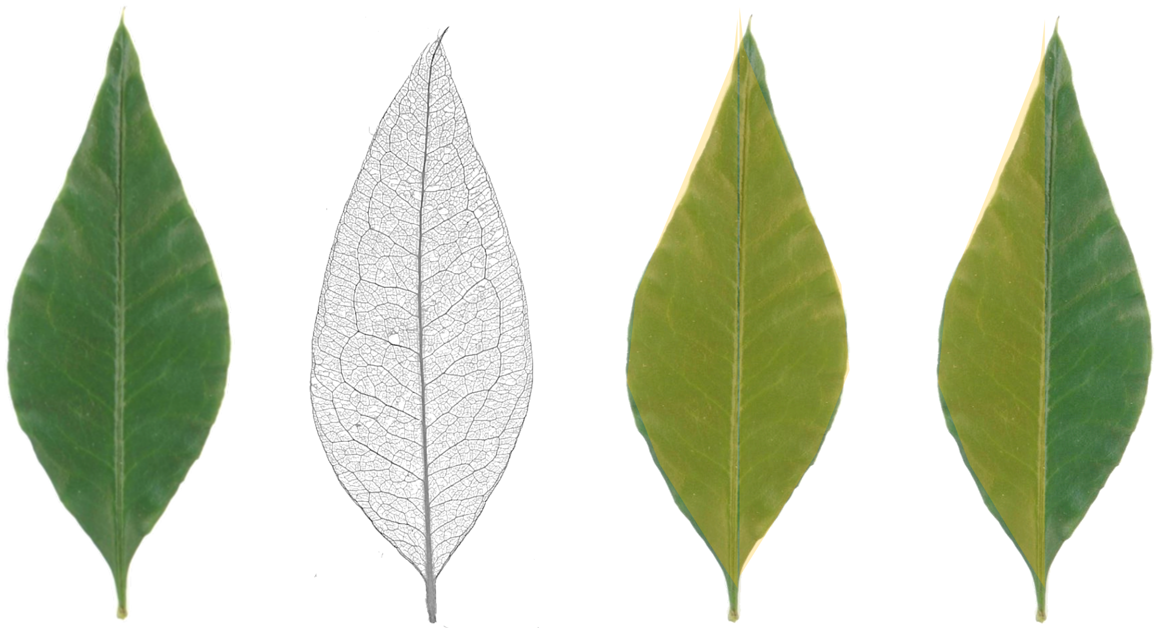
Let's consider about the effect of the capillary phenomenon on the height of a rise in water in the capillary pipe with diameter d. The height of h due to capillary action is obtained by the following well-known relation.

$$h=\frac{4\sigma\cos\theta}{\rho g d} \tag{5}$$

Here, σ is the surface tension of water, which is σ=0.073 [N/m]. The contact angle θ is about 10 degrees, so that h=0.3m if d= 100 μm, h=6m if d= 5 μm, and h=20m if d= 1.5 μm. This suggests that capillary action is also one of the possibilities to rise up water. This is an answer to the question why a cut flower also can pump up water even without roots.

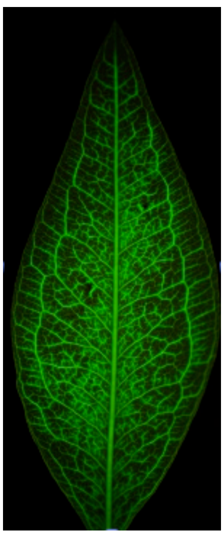
VEIN SYSTEM OF LEAVES

We study the function of leaf as the end condition of the piping system in the transpiration streaming. Three functions are considered as the uptake: 1) transpiration at stomata, 2) osmosis of cells, and 3) capillary action in veins. We think these functions are not independent but are combined with each other. To know each contribution on the uptake of leaf, we observe the flow in veins of the leaf of which we remain ingeniously only one of the three functions. Namely, we compare the visualized flow of a leaf with ones treated with following: 1) removing cells and also stomata, namely, only veins system is remained, and 2) covering all or a half stomata with wax. To separate each function, we elaborate the above treatment leaves as shown in Fig.1 that are free from root's pressure.



a) without treatment b) only vein system c) whole surface covered with wax d) a half surface covered with wax

Fig. 1: Tested treatment leaves



The leaves directly suck fluorescein solution in a plastic container. We take photos of the vein system visualized by the colored fluorescent flow at intervals of 15 seconds during 4 hours, which are illuminated by blue light with 521 nm wavelengths. We attach a high pass filter of 500nm in front of a lens of a still camera (Nikon D7100). The photos are made into a movie to see the flow spreading the whole leaf easily. One scene of the vein of a full leaf visualized by the flow is shown in Fig. 2. The straight line at the center of the leaf is a vascular bundle. This consists of not one vessel but many vessels. Each vessel of the vascular bundle connects to each veinlet. At first, water comes up through the vascular bundle. Then, water goes to each veinlet at almost the same time.

Fig.2: Vein system visualized by a sucked fluorescent flow

Spreading state toward finer veinlet is similar to the above mention. We think this is due to the fractal structure of the vein system. It is interesting that water is supplied to whole of leaf simultaneously according to the fractal structure.

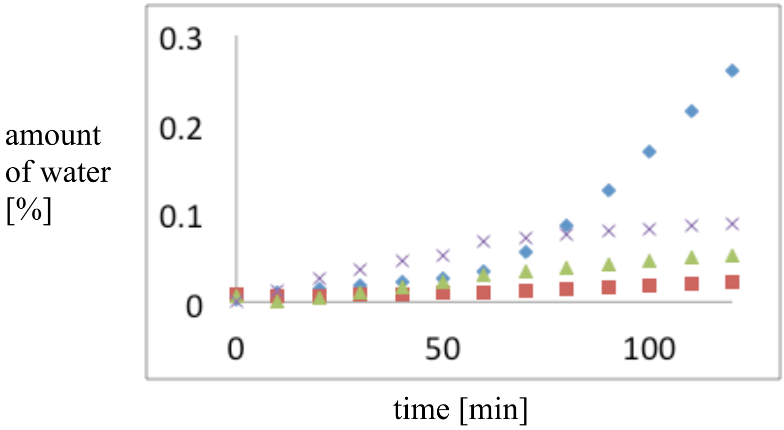


Fig. 3: Time change in sucked water. ◆: full leaf, ×: vein, ▲: a half wax, ■: whole wax.

Comparison of sucked water for each treated leaves is shown in Fig. 3. The amount of sucked water in the case of the full leaf increases abruptly 1 hour later. In the case of the treated leaves, such a sudden increase in water does not appear during observation. The change shows rather plateau after 1 hour. It seems to be hard to suck in the case of the leaf covered whole area. This means that the stomata play an important role for transpiration. The number of stomata is also important as compared with those of the leaf whose half area is covered by wax. Moreover, it is interesting that the vein leaf can suck water more than it covered by wax. This indicates that the capillary action is also important for sucking.

To know the rate of contribution on sucking for each function, we make simultaneous equations as follows.

$$Q_{v1} = Q_c + Q_s + Q_o \tag{6}$$

$$Q_{v2} = Q_c = 0.35Q_{v1} \tag{7}$$

$$Q_{v3} = Q_c + kQ_s + Q_o = 0.20Q_{v1} \tag{8}$$

$$Q_{v4} = Q_o = 0.08Q_{v1} \tag{9}$$

Here, Q_c is the flow rate due to capillary action, Q_s is that due to transpiration and Q_o is that due to osmosis. The coefficient k in eq. (8) is assumed 0.5 because the number of stomata should be a half. The total amount Q_{v1} of sucked water by the full leaf is obtained from the above observation. The Q_{v2} of sucked water by the vein leaf is 0.35 Q_{v1} as the experimental result. The Q_{v3} by the half covered leaf is 0.20 Q_{v1}. The Q_{v4} by the whole covered leaf is 0.08 Q_{v1}. Therefore, we can obtain Q_c=35 %, Q_s=57 %, and Qo=8 %. It seems transpiration is the most important function.

CONCLUSION

We discuss the transpiration streaming of tree according to the fundamental dynamics of fluid. The flow through a vessel in a vascular bundle is modeled as a flow through a main pipe with fine branches. The flow in such a piping system is considered by the Bernoulli's and continuity equations. This consideration gives us very reasonable and acceptable results. The root's pressure is a cause of pushing up water to the top of tree. We think that the limitation of a possible height to which roots push water is come from the inner pressure of root's cells. Since the inner pressure of cells is about 10 atmospheric pressure, the limit height of a tree is about 100m. The function of leaves as the end condition of the piping system of a tree is a suction due to transpiration as main contribution and capillary action as second. This is the reason why a cut flower can suck water even if there are no roots.

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REFERENCES

Mohr H. and Schopfer, P., *PFLANZENPHYSIOLOGIE*, Springer-Verlag Berlin Heidelberg, Chapter 28, 1992.

Atkins, P. W. *Physical Chemistry*, 6th edition, Oxford University Press, Chapter 4, 1998.

Hino, M., " An Essay on Transpiration from Stomata and Related Phenomena", Fluid Dynamic Research NAGARE, The Japan Society of Fluid Mechanics, vol 24, pp. 473-481, 2005. in Japanese.

Hosokawa, I., " Physics in Water-Pumping of Plants", Fluid Dynamic Research NAGARE, The Japan Society of Fluid Mechanics, vol 24, pp. 491-496, 2005. in Japanese.