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EGU2016-12635

Leaf-scale experiments reveal important omission in Penman-Monteith equation

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1 Motivation and objectives

(a) Motivation

1. A new wind tunnel enables detailed energy and mass balance evaluation of transpiring leaves.
2. Observations show substantial and unexplained underestimation of leaf transpiration (E_l) by PM-equation.
3. Re-evaluation of the PM-equation reveals an important shortcoming in the formulation

(b) Objectives

- Systematically evaluate transpiration and energy balance of artificial leaves in wind tunnel
- Propose and evaluate correction to Penman-Monteith equation

Penman-Monteith (PM) equation

$$E_l = \frac{\Delta_{eTa}(R_s - R_{ll}) + \rho_a c_{pa}(P_{was} - P_{wa})/r_a}{\Delta_{eTa} + \gamma_v \left(1 + \frac{r_s}{r_a}\right)}$$

2 PM-Equation and correction

(a) PM-Equation

Penman (1948) formulated an analytical solution for evaporation from a wet surface (E_w):

Penman equation

$$E_w = \frac{\Delta_{eTa}(R_s - R_{ll}) + f_u \gamma_v (P_{was} - P_{wa})}{\Delta_{eTa} + \gamma_v}$$

Monteith (1965) introduced an additional stomatal resistance (r_s) and formulated PM-equation for leaf transpiration (E_l).

(b) Corrected analytical solution

- Explicit consideration of 2-sided exchange of radiative and sensible heat (Fig. 1)
- Consideration of dependence of radiative exchange on leaf temperature, using linearised equation:

$$R_{ll} = 4 a_{sh} \epsilon_l \sigma T_a^3 T_l - a_{sh} \epsilon_l \sigma (T_w^4 + 3T_a^4)$$

- Following Penman (1952), but eliminating P_{wl} instead of T_l, we get latent heat flux as a function of leaf temperature and an equation for steady-state leaf temperature:

New analytical solution

$$E_l = \frac{c_H \left(\Delta_{eTa}(T_l - T_a) + P_{was} - P_{wa}\right)}{\gamma_v}$$

$$T_l = \frac{R_s + c_H T_a + c_E \left(\Delta_{eTa} T_a + P_{wa} - P_{was}\right) + a_{sh} \epsilon_l \sigma \left(3T_a^4 + T_w^4\right)}{c_H + \Delta_{eTa} + 4 a_{sh} \epsilon_l \sigma T_a^3}$$

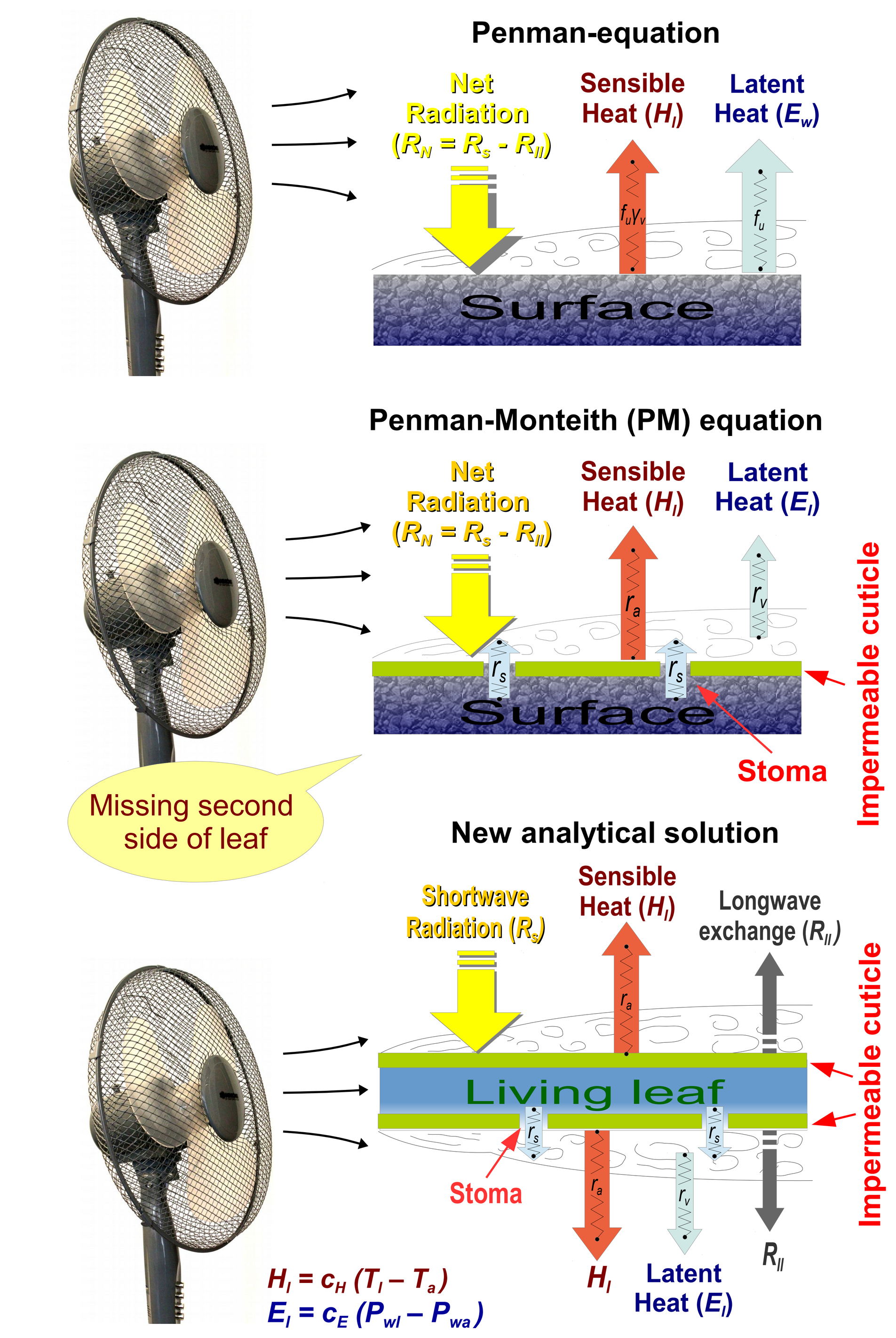

Fig. 1: Processes considered in different analytical solutions. Top: Penman equation for wet surface; middle: PM-equation with additional resistance; bottom: New analytical solution, illustrated for a hypostomatous leaf, with sensible heat exchange on both sides of the leaf, but latent heat flux only from the lower side. Here, c_H represents the two-sided sensible heat transfer coefficient, while c_E represents the one-sided total latent heat transfer coefficient, depending on both boundary layer and stomatal conductances. (Note that "latent heat" refers to the energy equivalent of transpiration.)

Symbols & Units:

- Δ_{eTa} dP_{was}/dT_a at T_a (Pa K^{-1})
- γ_v Psychrometric constant (Pa K^{-1})
- ρ_a Air density (kg m^{-3})
- c_{pa} Air heat capacity (J K^{-1} kg^{-1})
- E_w Wet surface latent heat flux (W m^{-2})
- E_l Leaf latent heat flux (W m^{-2}) (energy equivalent of transpiration)
- f_u Penman's wind function (W m^{-2} Pa^{-1})
- H_l Leaf sensible heat flux (W m^{-2})
- R_{ll} Net longwave exchange (W m^{-2})
- R_n Net radiation (W m^{-2})
- R_s Absorbed SW radiation (W m^{-2})
- P_{wa} Ambient vapour pressure (Pa)
- P_{was} Sat. vapour pressure at T_a (Pa)
- r_a Boundary layer resistance (s m^{-1})
- r_s Stomatal resistance (s m^{-1})
- T_a Air temperature (K)
- T_l Leaf temperature (K)
- T_w Temperature of chamber walls (K)

2 Experimental setup

- Insulated wind tunnel with fully controlled energy and mass exchange (Figs. 2, 3)
- Artificial leaf with laser-perforated foil ensuring constant stomatal resistance, embedded thermocouple and monitored water flow (Fig. 3)
- Stomatal conductance calculated from pore dimensions of laser perforations (Fig. 3)
- Sensible heat flux is computed from total chamber heat exchange, using monitored flow rate and temperature of incoming and outgoing chamber air (Fig. 2).

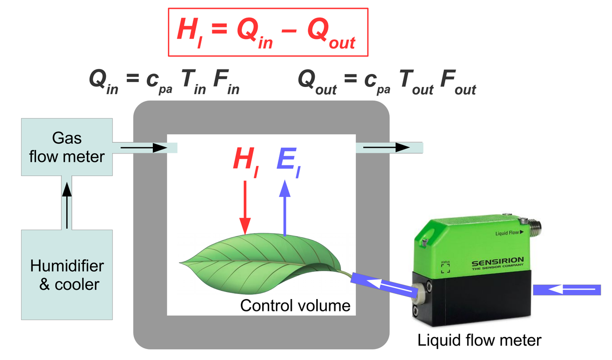

Fig. 2: Conceptual drawing of insulated leaf chamber. Latent heat flux (E_l) is calculated from liquid flow rate into leaf, sensible heat flux (H_l) is calculated from difference in heat content of incoming and outoing air.

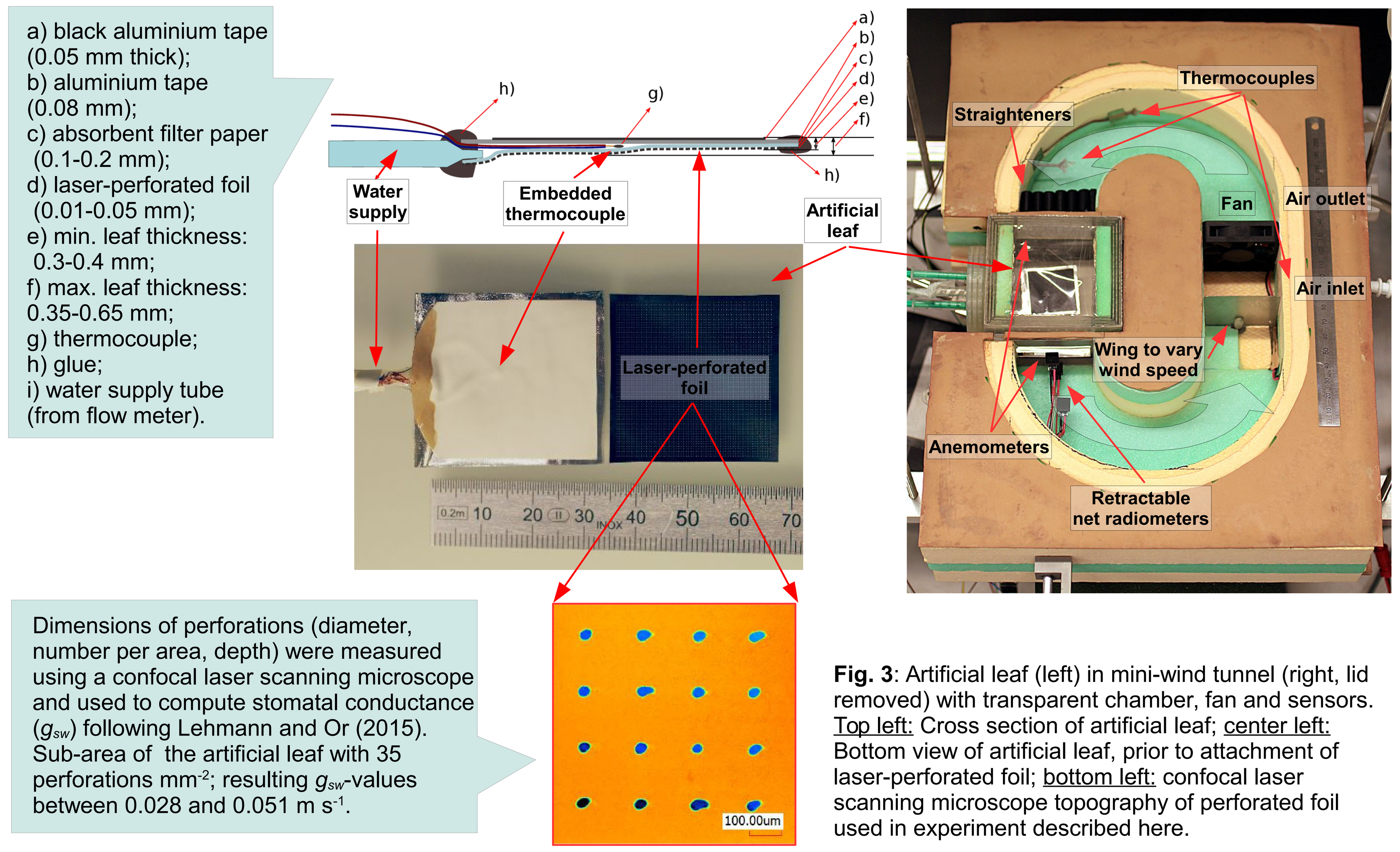

Fig. 3: Artificial leaf (left) in mini-wind tunnel (right, lid removed) with transparent chamber, fan and sensors. Top left: Cross section of artificial leaf; center left: Bottom view of artificial leaf, prior to attachment of laser-perforated foil; bottom left: confocal laser scanning microscope topography of perforated foil used in experiment described here.

3 Numerical experiment (varying T_a and R_s)

PM equation gets sensitivities wrong

New solution gets sensitivities right

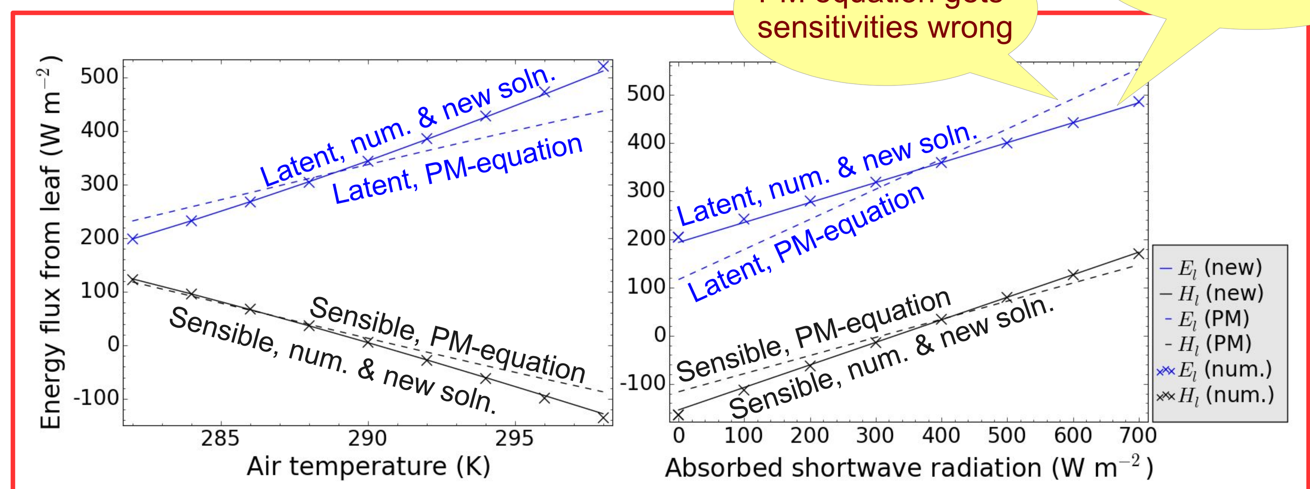

Fig. 4: Simulations of sensitivity of latent and sensible heat fluxes to air temperature (left) and absorbed shortwave radiation (right). Crosses represent numerical solutions of leaf energy balance model (Schymanski & Or, 2016), solid lines our new analytical solution (see Block 4 on the right) and dashed lines represent Penman-Monteith equation. Simulation conditions: g_{sw}=0.045 m s^{-1}, 1300 Pa vapour press., 1 m s^{-1} wind speed, 350 W m^{-2} irradiance (left) and 295 K air tempertaure (right).

4 Wind tunnel experiments (R_s = 0)

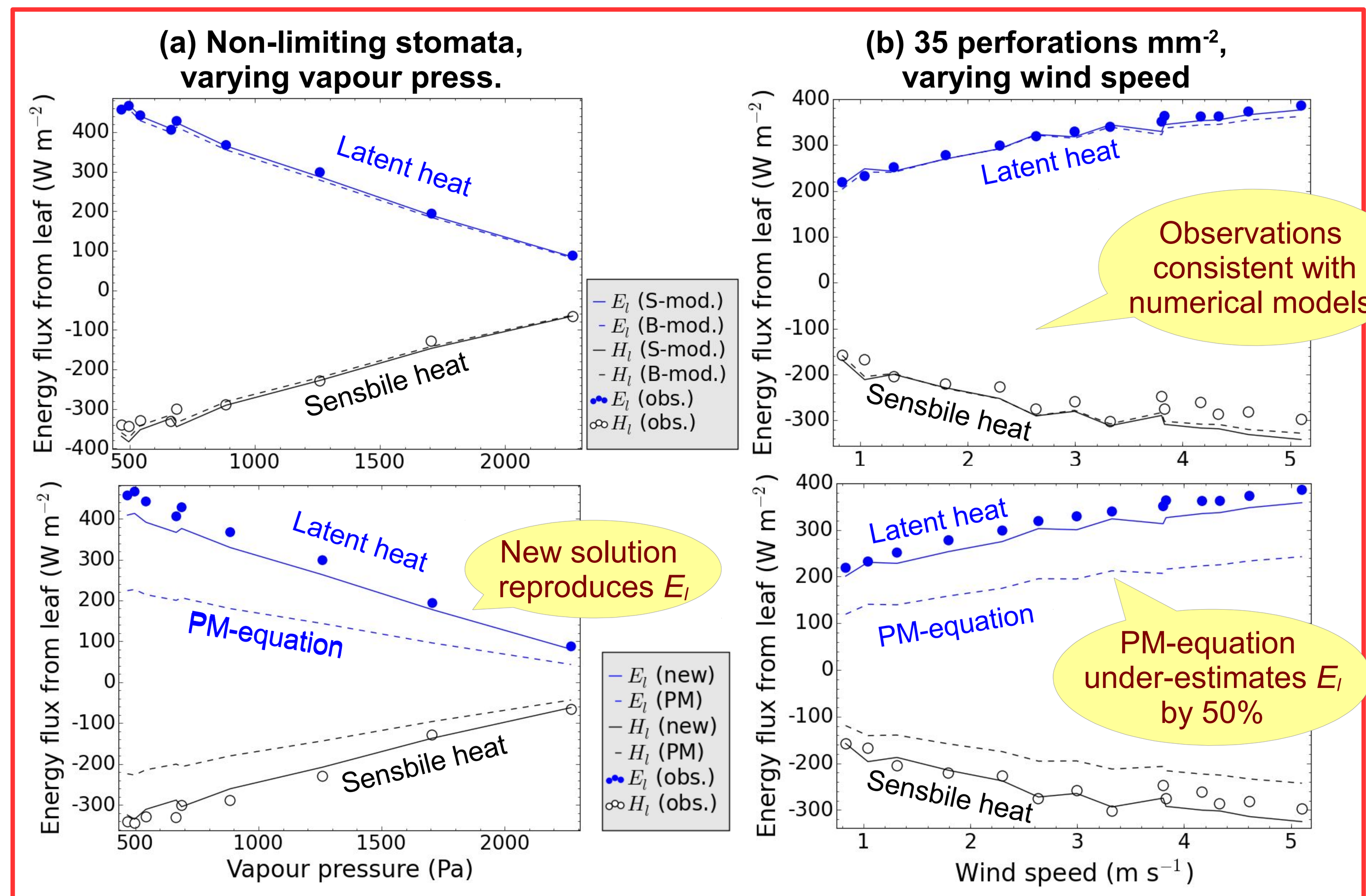

Fig. 5: Observed and simulated latent and sensible heat fluxes. Experimental data shown as symbols, simulations as lines. **Top row:** numerical models following Schymanski and Or (2016, solid lines) and Ball et al. (1988, dashed lines). **Bottom row:** Analytical solutions representing new analytical solution (solid lines) and PM-equation (dashed lines). **Left column:** Artificial leaf with wet filter paper on lower side. Exp. cond..: 1.0-1.05 m s^{-1} wind speed., 295.4-296.6 K air temp. **Right column:** Artificial leaf with 35 perforations mm^{-2}, equivalent to stomatal conductance of g_{sw} = 0.028 to 0.051 m s^{-1} (simulations for g_{sw} = 0.045 m s^{-1}). Exp. cond.: 1200-1300 Pa vapour press., 295-296.5 K air temp.

5 Conclusions

- **Experimental setup enables research on the leaf energy balance at entirely controlled conditions.**
- **Elimination of calibration need (stomatal conductance known a priori) enabled rigorous evaluation of PM-equation at the leaf scale.**
- **PM equation does not consider two-sided exchange of sensible heat and hence fails to reproduce magnitude of leaf transpiration and its sensitivity to air temperature and irradiance.**
- **New analytical solution presented here is consistent with experimental results**

6 Literature and acknowledgements

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We thank Daniel Breitenstein for help in the design and construction of the experimental setup and Roland Künzli (DMP Fehraltorf) and Hans Wunderli for technical advice and assistance.