AERODYNAMIC RESISTANCE AND WATER VAPOUR TRANSPORT IN THE FOREST STAND – ATMOSPHERE SYSTEM

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Abstract: This contribution presents the aerodynamic resistance role in the water vapour transport in the forest stand – atmosphere system. The results of the vertical wind speed profile analysis have been evaluated with the aim to determine the aerodynamic resistance in an air layer affected by a young spruce forest stand. The simple method of the aerodynamic resistance r_a determination on the basis of the wind speed profile analysis is presented. The experimental data were obtained at the locality Bílý Kříž in the highest part of the Moravian-Silesian Beskydy Mts, the Czech Republic (lat. $49^0 30'17''$ N, long. $18^0 32'28''$ E, 898-908 m a.s.l.). The experimental site consisting of two plots Fd and Fs with different trees density is created by the monoculture of a Norway spruce stand. The analysed wind speed profiles were measured in and above this spruce stand from July to October 2004 in Fd plot. During this period the 486 profiles were analysed, which fulfilled the condition $\bar{u}(h-1) > 1.0$ m s^{-1}. Then the conditions of turbulent development can be supposed. In this time the investigated forest was 23 years, and in Fd plot on the area of 2500 m^2 the stand density was 2400 trees/ha. The mean forest height h was 11.1 m, the zero-plane displacement $d = 0.76h$, and the mean roughness length $z_0 =$ 0.9 m. In presented case it was shown, that the dependence of the latent heat flux LE on the r_a values is significant only for $r_a < 100$ s m^{-1} and depends on the value of the canopy resistance r_c.

Key words: Norway spruce, aerodynamic resistance, wind speed profile, zero-plane displacement, roughness length

1. Introduction

Atmospheric factors influence significantly the growth and development of plant canopies. At the same time the plants modify the processes that take place in the atmosphere surface layer. They form their own microclimate. Forest ecosystems with respect to their area and structure have the significant role in production, modification, and microclimate protection (*Intribus*, 1977).

During the past decades, increasing attention has been paid to transpiration from forest stands as a key component of the water cycle, forest productivity, and particularly also the interaction of vegetation with the atmosphere from the aspect of global climate change (*Grelle et al.*, 1999). To estimate transpiration rates, values of the aerodynamic resistance for water vapour r_a are required. The aerodynamic resistance governs the vertical aerial transport processes. It is known, that for most tree species the transpiration rate is limited by the canopy resistance r_c, which is much greater than r_a. However, most species of trees have small r_c . Then these resistances significantly affect the evaporation rate. It is therefore more important that r_a is known accurately (*Hall,* 2002). *Daudet et al.* (1999) analysed the relationship between local boundary layer conductance g_a ($r_a = 1/g_a$) and local wind speed measured nearby the crown of 20 year old walnut trees. *Lindroth* (1993) determined r_a for willow forest as a function of the leaf area index and wind speed. His results are not applicable to different forests because the significant differences between willow and other forests in stand structure will be reflected in differences in the aerodynamic resistances.

The majority of forest ecosystems in the Czech Republic are composed of Norway spruce stands which have more than 80% share. Therefore the extensive research of the climate of the Norway spruce monoculture is carried out at the Experimental Ecological Study Site of the Institute of Systems Biology and Ecology, Academy of Sciences of the Czech Republic, in Bílý Kříž, Moravian-Silesian Beskydy Mts, Czech Republic (*Janouš, Schulzová,* 1995).

The aim of this contribution is to determine the aerodynamic resistance by the simple method on the basis of the wind speed profile analysis and to analyse its role in the water vapour transport in the spruce forest stand – atmosphere system.

2. Methods

The aerodynamic resistance to water vapour r_a is defined by (*Brutsaert,* 1982):

$$E = \rho \frac{q_s - q_a}{r_a}, \tag{1}$$

where E is the vapour mass flux density, ρ is the air density, q_s and q_a the specific humidity at the surface and the air specific humidity at the reference height z, respectively.

It follows from the definition of the integral coefficient of the turbulent diffusion D^*, which is characteristic of the turbulent transport conditions between the surface and the atmosphere surface layer. It is valid the relation $r_a = 1/D^*$. The D^* is defined as follows

$$D^* = \frac{1}{\int_{z_0}^{z-d} \left(\frac{1}{K}\right) dz}, \tag{2}$$

where z is the height above the ground, d is the zero-plane displacement, z_0 is roughness length, K is the turbulence coefficient and it can be assumed that K is the same for water and heat transfer. Within the framework of Monin-Obukhov similarity theory for K it is valid

$$K = u^* \kappa (z-d) \left(\varphi\left(\frac{z}{L}\right) \right)^{-1}. \tag{3}$$

u^* is the friction velocity, κ is the Karman constant, φ the stability correction (e.g. *Dyer and Hicks,* 1970) that allow for departures from adiabatic conditions quantified by L, the Monin-Obukhov length (*Thom,* 1975). The friction velocity can be calculated as (*Hall,* 2002)

$$u^* = \frac{\kappa\, u(z)}{\ln\left(\frac{\mathrm{z - d}}{\mathrm{z_0}}\right) - \left(1 + \beta \frac{z}{L}\right)}, \tag{4}$$

where β is the universal semiempiric constant. Then integrating the K gives the aerodynamic resistance as follows

$$r_a = \frac{\ln\left(\frac{z-d}{z_0}\right) + \frac{\beta}{L}\left[(z-d)-z_0\right]}{\kappa u*}. \tag{5}$$

The values of z_0, $u*$, and parameter β/L can be obtained from the analysis of the vertical wind speed profiles measured over an active surface under different atmosphere thermal stratification. Following from the Monin-Obukhov similarity theory each vertical wind speed profile $\bar{u}_k(z_i)$ can be approximated by the relation (*Monin, Obukhov,* 1954)

$$u_k(z_i) = A_k(\gamma + \log z_i) + C_k z_i, \tag{6}$$

where *k* is the profile number. The values of A_k, γ, and C_k parameters are calculated by the least squares method for every profile. Then the values of z_0, $u*$, and β/L are obtained from following relationships (*Monin,Obukhov,* 1954)

$$z_0 = 10^{-\gamma}, \tag{7}$$

$$u* = \frac{\kappa A_k}{\ln(10)}, \tag{8}$$

$$\frac{\beta}{L} = \frac{C_k}{A_k}\ln(10). \tag{9}$$

The value of the zero-plane displacement (*d*) was determined by processing the vertical wind speed profiles measured at the neutral thermal stratification of the atmosphere (*Brutsaert*, 1982).

The latent heat flux *LE* was determined by Penman-Montheith equation in the form (*Monteith*, 1980)

$$LE = \frac{\rho c_p D + \Delta r_a (R-G)}{\gamma(r_a + r_c) + \Delta r_a}, \tag{10}$$

where c_p is the specific heat at constant pressure *p*, Δ is the slope of vapour pressure curve, *D* is the water vapour pressure deficit, and γ is the psychrometric constant.

Above the vegetation, the roughness-sublayer extends in which surface elements directly influence the turbulence. There is some evidence that it can reach 3-8 times the stand height (*Garratt*, 1980). *Cellier and Brunet* (1992) obtained about 2 times the canopy height. In our analysis the roughness-sublayer height z_r was estimated using the relationship (*Verhoef et al.*, 1997)

$$z_r \approx 15 z_0 + h. \tag{11}$$

3. Site description and experimental data

The need experimental data were obtained at the locality Bílý Kříž (lat. $49^0 30'17''$ N, long. $18^0 32'28''$ E) in the highest part of the Moravian-Silesian Beskydy Mts (898-908 m a.s.l.). The experimental site consisting of two plots Fd and Fs with different trees density is created by the monoculture of a Norway spruce stand and it is situated on a mild slope with SW orientation (*Janouš, Schulzová,* 1995).

Bílý Kříž, by climatic classification, is a cool and humid region with abundance of precipitation. The mean annual air temperature is 4.9 ^{0}C, the mean annual precipitation total is 1100 mm, and the mean air humidity is 80% (*Rožnovský,* 1998).

The prevailing wind direction above the investigated spruce forest stand is south, in spite of this, generally in this part of the Beskydy Mts north and west airflow predominates. It is a result of the orographic broken terrain (*Havránková and Janouš*, 2000; *Havránková et al.*, 2001).

The wind speed and direction was measured continuously by the measured system InSituFlux (Sweden). It is a system to measure the fluxes of energy and substances between a surface and boundary layer of the atmosphere using the eddy-covariance method. Simultaneously the microclimatic profile measurements of the wind speed, air temperature and humidity in and above investigated forest stand were realized on 26 m height tower. The values of wind speed were continuously measured by automatic measuring equipment with data logger (DL3000, Delta-T, U.K.) and anemometers (AN1, Delta-T, U.K.) in the 10-minute intervals and records of data.

4. Results and discussion

The analysed wind speed profiles were measured in Fd plot in and above this spruce forest stand from July to October 2004. The measured levels were 8, 10, 11, 14, 18, and 26 m. During this period the 486 profiles were analysed, which fulfilled the condition $\bar{u}(h-1) > 1.0$ m s^{-1}. In this case the conditions of turbulent development can be supposed. In this time the investigated forest was 23 years, and on the area of 2500 m^2 the stand density was 2400 trees/ha. The mean forest height h was 11.1 m, the zero-plane displacement $d = 0.76h$, and the mean roughness length $z_0 =$ 0.9 m. These profiles were divided into five ranges accordance with the $u(h)$ value, Fig.1:

I $1.0 \le u(h) < 2.0$
II $2.0 \le u(h) < 3.0$
III $3.0 \le u(h) < 4.0$ (12)
IV $4.0 \le u(h) < 5.0$
V $5.0 \le u(h) < 6.0$

The most analysed profiles were measured in the range II, 53.5% of all ones.

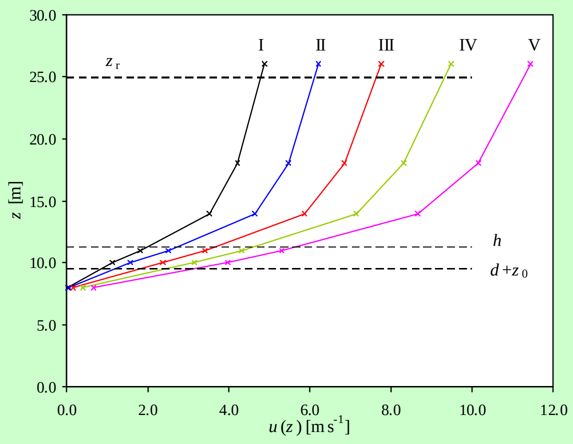

Fig. 1. Mean vertical wind speed profiles in the range of I - VI (Eqs 12) measured in and above spruce forest in the period July - October 2004. Symbol h means the mean stand height, d is the mean zero-plane displacement, z_0 the mean roughness length, and z_r the roughness sublayer height.

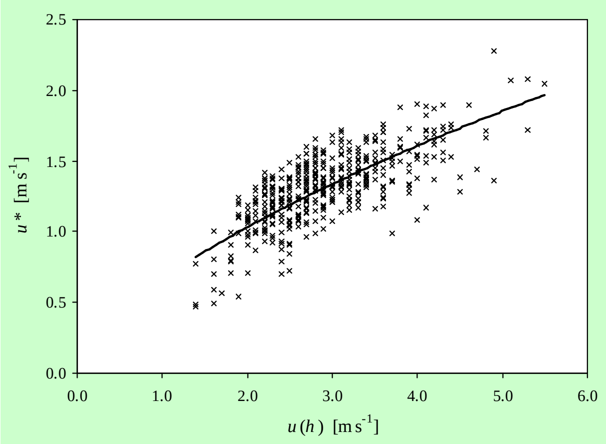

Fig. 2. Dependence of the friction velocity u^* on the wind speed $u(h)$.

First the relation between the friction velocity u^* and the wind speed $u(h)$ was analysed. It was shown, that in this investigated period this empirical relationship well approximated the analytic equation, Fig. 2:

$$u^* = 0.664[u(h)]^{0.64}. \tag{13}$$

The correlation coefficient r_{xy} between u^* values determined from wind speed profile analysis, Eq. (8), and u^* from Eq. (13) was 0.72. From this it follows that investigated spruce forest was in an aerodynamic unsteady state and the z_0 values changed systematically with the wind speed (*Hayashi*, 1983). The dependence z_0 = f(u) can be determined as the dependence ξ_0 = f(Γ), where $\xi_0 = z_0/h$ is the relative roughness length and $\Gamma = u(h)/u^*$ is the nondimensionless wind speed. In this case analytical expression of this dependence was found as follows

$$\xi_0 = 0.178\exp(-0.36\Gamma),\ r_{xy} = 0.98. \tag{14}$$

Further we analysed the dependence of r_a values on the wind speed and on the roughness length. The r_a values were calculated by Eq. (5) in the air layer from z_0 to (z-d) using the wind speed profile analysis. It means that r_a were determined in the air layer (0.9 m, 9.5 m) measured from d level. This is air layer directly affected by investigated spruce stand considering d = 8.5 m at mean stand height 11.1 m. Empirical dependence r_a = f(u^*) is in Fig. 3.

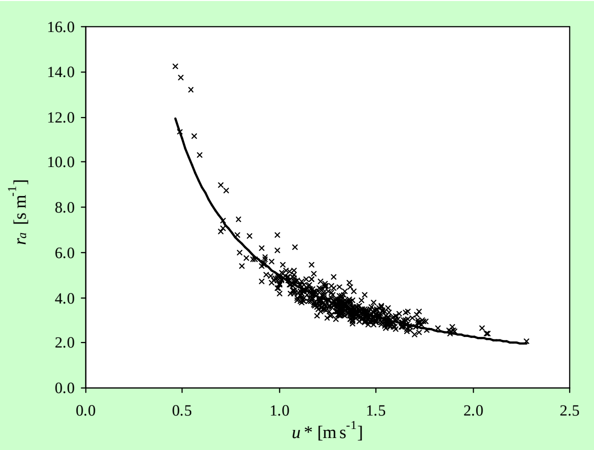

Fig. 3. Dependence of the aerodynamic resistance r_a on the friction velocity u^*.

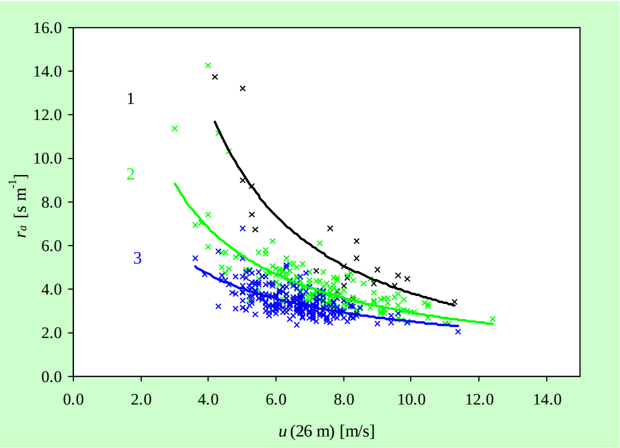

Fig. 4. Dependence of the aerodynamic resistance r_a on the wind speed u(26 m).

$0.5 \le z_0 < 0.7$ $r_a = 73.98\ u^{-1.29}$ $r_{xy} = 0.88$

$0.7 \le z_0 < 0.9$ $r_a = 24.34\ u^{-0.92}$ $r_{xy} = 0.81$

$0.9 \le z_0 < 1.2$ $r_a = 12.03\ u^{-0.68}$ $r_{xy} = 0.66$

The analytical expression of this dependence can be written as

$$r_a = 4.992(u^*)^{-1.14},\ r_{xy} = 0.93. \tag{15}$$

The dependence of the r_a values on the wind speed u(z), where z = 26 m, for different intervals of z_0 values is presented in Fig. 4.

From this it follows that a rougher surface and a stronger air flow create better conditions for the development of the turbulent exchange between investigated spruce forest stand and the lowest atmosphere layers. From the Eq. (5) it is evident, that the aerodynamic resistance is also function of the atmosphere temperature stratification, which is represented by β/L. The dispersion of experimental points in Fig. 4 can be explained by this fact.

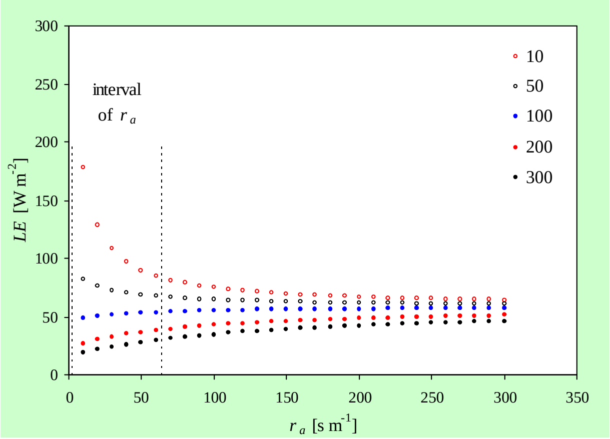

Fig. 5. Dependence of the latent heat flux *LE* on the aerodynamic resistance r_a for different values of canopy resistance r_c modelled for Ta = 12 ^{0}C, D = 250 Pa , R–G = 100 W m^{-2}.

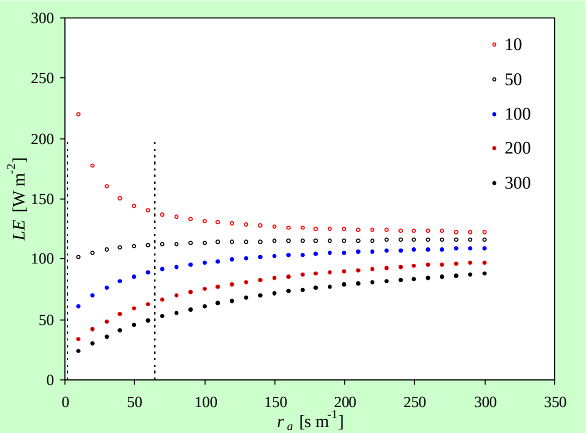

Fig. 6. Dependence of the latent heat flux *LE* on the aerodynamic resistance r_a for different values of canopy resistance r_c modelled for Ta = 12 ^{0}C, D = 250 Pa , R–G = 200 W m^{-2}.

In further the relation between the latent heat flux and aerodynamic resistance will be analysed. From Eq. (10) it follows that the *LE* values depend on the whole set of the atmosphere and canopy characteristics. So, the dependence of the latent heat flux on the aerodynamic resistance is very complicated and it is different in the dependence on the value of the canopy resistance r_c. The dependence $LE = f(r_a)$ was modelled for the mean values of air temperature Ta, the water vapour deficit D, and the difference of the net radiation flux R and the soil heat flux G. During the investigated period (July – October 2004) in Fd plot these mean values were about: $Ta \approx 12\,^0$C and $D \approx 250$ Pa. This dependence was analysed for (R–G) = 100 W m^{-2}, Fig. 5 and 200 W m^{-2}, Fig. 6. From both it follows that the dependence $LE = f(r_a)$ is significant only for $r_a < 100$ s m^{-1}. In the first case, if (R–G) = 100 W m^{-2}, the latent heat flux decrease with increasing r_a values for $r_c \leq 50$ s m^{-1} and for higher r_c values this dependence is increasing. In the second one the *LE* values decrease with increasing r_a values only for $r_c \leq 10$ s m^{-1}. In presented case the r_a values ranged in interval (2.0; 20.0) m s^{-1}.

5. Conclusions

This contribution presented the determination of the aerodynamic resistance by the simple method on the basis of the wind speed profile analysis and the analysis of its role in the water vapour transport in the spruce forest – atmosphere system.

The analysed wind speed profiles were measured in and above the spruce forest stand during growing season from July to October 2004. During this period the 486 profiles were analysed, which fulfilled the condition $\overline{u}(h-1) > 1.0$ m s^{-1}. In this case the conditions of turbulent development can be supposed. In this time the investigated forest was 23 years, and on the area of 2500 m^2 the stand density was 2400 trees/ha. The mean forest height h was 11.1 m, the zero-plane displacement $d = 0.76h$, and the mean roughness length $z_0 = 0.9$ m.

The dependence of the aerodynamic resistance on the wind speed and the dynamic roughness length confirmed, that a rougher surface and a stronger air flow create better conditions for the development of the turbulent exchange between investigated spruce forest stand and the lowest atmosphere layers. Further it was shown, that in the presented case the dependence of the latent heat flux *LE* on the r_a values is significant only for $r_a < 100$ s m^{-1}. This dependence was modelled using the Penman-Monteith relation for the mean values: $Ta = 12\ ^0$C, $D = 250$ Pa, and $(R–G) = 100$ w m^{-2} and 200 W m^{-2}, Figs. 5 and 6. From both dependences it follows that the dependence $LE = \mathrm{f}(r_a)$ is significant only for $r_a < 100$ s m^{-1}. In the first case, if (R–G) = 100 W m^{-2}, the latent heat flux decrease with increasing r_a values for $r_c \leq 50$ s m^{-1} and for higher r_c values this dependence is increasing. In the second one the *LE* values decrease with increasing r_a values only for $r_c \leq 10$ s m^{-1}. In presented case the r_a values ranged in interval (2.0; 20.0) m s^{-1}.

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