

THEORY OF EVAPOTRANSPIRATION

1. Transpiration and its quantitative description

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Basic information about the evapotranspiration and its components is presented. System of equations describing the transport of water and energy in the soil – plant continuum is analyzed. The system of five differential equations with five unknowns is proposed, describing transport of heat and water vapour within the plant canopy, including exchange processes among the leaves and the atmosphere, vertical transport of the heat, water vapour and the energy balance.

KEY WORDS: Evapotranspiration, Transpiration, Evaporation, Soil Water, Water Balance.

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Príspevok obsahuje základné informácie o evapotranspirácii a jej zložkách, výpare a transpirácii. Proces prenosu vody a energie v systéme pôda – porast je opísaný systémom piatich diferenciálnych rovníc kvantifikujúcich prenos vodnej pary a tepla medzi listami a atmosférou, ktoré umožňujú výpočet charakteristík vertikálneho prenosu vody a tepla v poraste a tiež bilanciu energie v tomto systéme.

Kľúčové slová: evapotranspirácia, transpirácia, evaporácia, pôdna voda, bilancia vody.

1. Movement of water from soil to canopy

Water movement from soil to the canopy leaves, is the most important part of the more general interdisciplinary problem – transpiration process formation – as well as of the heat and water regime of the canopies formation. Formulation of this problem was given by *Budagovskij* and *Lozinskaja* (1996).

Biophysical approach to the quantitative description of this process should be based on qualitative results of the plant physiology. It is accepted today, that the fundamental laws of physics and chemistry are base of the plant growth. But the final effect of the above mentioned laws depends on conditions of their applications. It can be considered, that plants during their evolution, depend on climate and local conditions. They were created themselves as kinds of structures, in which general laws of nature were functioning optimally. Those structures are complicated, therefore even qualitative analysis of them is rather difficult. For quantitative analysis, it seems to be reasonable, to analyze the most important laws only.

We start with short description of water transport in the soil – plant system, as it was formulated by the plant physiologists. Those ideas were developed during decades and they can be taken as the classical ones. The later results of research having fragmentary character, will be generally omitted.

Water is transported from soil to plant through the highly developed root system. Information about these systems – elaborated basically by *Dettmar*, can be found in many monographs (e.g. *Maximov*, 1958; *Peterburskij*, 1964; *Sabinin*, 1955; *Waisel* et al., 1996). Experiments were performed in wooden boxes of 1 m³ volume, with winter barley canopy. Total length of roots in those boxes was about 600 km, and the total root surface was found to be 225 m², for the earing ontogenesis phase. To those roots were joined 15 billions of root hairs, of total length of appr. 10 thousand km, and its surface was about 400 m². Every day, approximately 119 millions of the new root hairs appeared, with total length of about 80 km. Leaf area index (LAI) of the winter barley canopy was 4.5.

Soil water is extracted by plants mainly by root hairs. Typical parameters of the root hairs are given

by their length 100 – 1000 μm , diameter 8 – 12 μm , and duration of life – 1 day. It was found, however, that for fruit and forest trees, the root hairs can live longer (*Muromcev*, 1969). Plant physiologists deduced, using data of the root hairs length and of their specific surface, that not water is flowing to roots only, but root hairs are approaching soil water too, e.i. roots are hydrotropic, as well as chemotropic.

Now, it seems to be reasonable to discuss the soil water mobility. Two or three days after heavy rain on the soil profile, the soil water content corresponding to a particular soil hydrological constant is usually established. This constant is the minimum water capacity (MWC) for the deep groundwater table level, or hydrological constant field capacity (FC) for groundwater table level close to the soil surface. Soil water content corresponding to those two hydrological constants, is supposed to be upper limit of the soil water content, corresponding to optimum conditions for the plant growth. For higher values of this soil water content, the soil aeration is low, and roots function is limited. Soil is highly conductive for soil water in states containing it close to constants MWC and FC. In such state, water lost by transpiration is partially compensated. Conductivity of soil for water decreases significantly with the decrease of the soil water content, and in such a dry state, it is then reducing the soil water extraction by roots significantly. Under such condition, as it follows from evaluations, root hairs can grow more rapidly, than is the soil water transport velocity to the root hairs.

Soil water is held in soil by capillary – sorption forces. Intensity of interactions between water and its solid phase, can be characterized by the difference between chemical potential of the clear water with horizontal water table surface, and the chemical potential of water held by capillary – sorption forces. This difference (with the negative sign) is indicated as the soil water potential, and it can be expressed in pressure units. In this respect in soil physics, it is frequently expressed as the "negative pressure of the soil water". It often implies misunderstandings, even among specialists. Therefore, to simplify the term "soil and plant water potential", it should will be used preferably the wording "higher" or "lower", according to their absolute values. Of course, water in the soil – plant system, moves from points with lower water potential to those with its higher absolute values.

Cells of root hairs contain solution of high – molecular materials with its osmotic pressure between

0.1–0.2, and sometimes 0.3 MPa. Soil water potential of the irrigated soil is usually lower in absolute values. Walls of the root – hair cells can be regarded as semipermeable membranes, and therefore in the soil – root system, osmotic pressure is generated which is often assigned by plant physiologists as the root pressure. Due to this phenomenon, water flows through the root cells and through the xylem into the leaves.

Appearance of the liquid water on leaves surfaces can be observed (guttation) due to the root pressure action, when liquid phase change to vapour phase (transpiration), and it cannot be performed at the intensity equal to that of the water transport to the surface. This phenomenon can be observed for net radiation intensity close to zero, high air humidity and relatively high soil water content. Appearance of water from cutted plant stems can be observed at high soil water content too. However, root pressure is not high enough to transport water from the soil to leaves during the meteorological conditions at high net radiation (during the hot days, particularly at noon). Several flexible mechanisms have been formed during the evolution process, which enable transport of water from soil to the whole plant. Basic principles of these mechanism are the following.

In leaves, there are tissues, called parenchym. Structure of this tissues is relatively complex, therefore we can use simplified and popular description, presented by *Maximov* (1958).

Typical plant cell can be presented as a "bubble" filled up by the cell solution, outer part of which is the cellulose covering. A cover is firm enough to keep its shape, it is elastic and permeable for water. Cell solution with high osmotic potential exerts additional pressure on outer walls of such cell "bubble". Cell walls, under normal conditions, are under pressure which is called the turgor pressure (usually the word pressure is replaced by word potential). Turgor potential equals to a cell osmotic potential under the static conditions. The difference between both values is called the leaf water potential. In the past, this value was indicated also as the "suction force", which is not correct, but basically reflects its function.

In a case, when the cell losses part of its water, it can be uptaken from adjoining cells, having lower water potential than the cell mentioned. This is briefly a way, how the cells are interacting between themselves.

Dense packed epidermal cells are covered on the top by a hydrophobic cuticula. Leaf surface created

by cuticula is characterized by the low permeability for water vapour.

Leaf mesophyll is composed by parenchym cells, with a free space among them. This space has a surface covered by relatively thin specific cells, creating stomata. They are open during the full hydration of cells, and are continuously becoming closed, according to its (hydration) decrease. There are even other reasons for the stomata activity, but they are of secondary importance, and therefore not mentioned here.

Change of water from liquid to vapour phase, takes place in capillaries of the cell walls, interfacing the intra-cell space, where the water vapour moves to stomata and further on to the leaf surface, and to the atmosphere. Small part of water vapour is transported to the atmosphere through cuticula. This is called the cuticula transpiration.

In literature, there were reported "energy dependent microchanges of pressure potential of parenchym cells" (Tarcevskej, Zolkevicz (Eds.), 1989), found out by carefull experiments. This phenomenon is not involved in governing theories, but it probably influences the water transport mechanism from soil to plant leaves less significantly. Because of its significance for plant, it can probably play some role also in metabolics exchange between floem and xylem tissues. We can focus our attention to the information published in sixties and at the beginning of seventies (partial list of literature can be found in Tarcevskej, Zolkevicz (Eds.), (1989), declaring, that growth rate decrease is due to the CO₂ penetration to the leaf, which is performed because of "overfeeding" of them by the assimilation products. Result of this phenomena is decrease of the metabolic rate and transport of the metabolics to the growth areas and their retention.

Full and reliable description of water transport in this complex system – involving roots and the above ground part of plant – is complicated. Such problems should be solved in the framework of the plant canopy biophysics. This discipline is not ready to solve this problem. Complexity of those phenomena – even if they would be solved – needs to simplify them for the application purposes. Therefore, we can use relatively simple approach, supported by the currently assesed experimental material. Results of calculation, based on the presented approach, should be verified independently.

Analysis of the water transport from the soil to plant, can be started by the equation of the canopy water balance, involving both, the root system, as

well as the above ground part of canopy. This equation can be written as

$$dV/dt = v_p - E_t, \quad (1)$$

where V is the whole plant water content per unit soil surface area, v_p – water transport intensity from soil to plant, E_t – water vapour transport intensity from plant leaves to the atmosphere (transpiration).

Transpiration E_t in this chapter is a result of direct measurement. Formation of it is described in detail here. To evaluate v_p , it can be developed a relationship, taking into account the following assumptions:

- v_p should be proportional to the difference $\psi_l - \psi_r$, where ψ_l – leaf water potential, ψ_r – root hair water potential.
- active root hair (root hairs uptaking water) water potential should equal to average value of the soil water potential in the depth z .
- root pressure can be neglected, because of its small additional value to the leaf water potential.

With the above mentioned assumptions it can be written:

$$v_p = K_p (\psi_l(t) - \psi_r). \quad (2)$$

K_p is integral coefficient of the canopy hydraulic conductivity as a whole. Methods of its assessment are described later. It can be shown, that the value of ψ_r can be taken as a constant during a day.

Using (1) and (2), it can be written

$$dV/dt = K_p(\psi_l(t) - \psi_r) - E_t(t). \quad (3)$$

According to the previously stated assumptions, the right side of the Eq. (3) can be known, to calculate dV/dt . It seems to be more suitable – however – to integrate the Eq. (3) according to t , starting with $t(0)$, which should equal to the sunrise time. As a result of integration

$$V(t) - V(0) = \int_0^t [K_p(\psi_l(t) - \psi_r) - E_t(t)] dt. \quad (4)$$

Using calculated values $V(t)$ and measured $\psi_l(t)$, a linear empirical relation between them can be estimated as

$$\psi_l(t) = \beta_p (V(t) - (V(0))). \quad (5)$$

Parameter β_p estimation technics is simple and needs no further description.

Differentiating (5) according to t and substituting dV/dt to (3), after the following simple tranformation, the equation can be derived

$$d\psi_l/dt + K_p \beta_p [\psi_l(t) - \psi_r(0)] - \beta_p E_t = 0. \quad (6)$$

Leaf water potential is of sine function shape during the sunny days – its maximum is usually 30 to 50 minutes after noon (according to the local sun time). For this case, from the Eq. (6), for $d\psi_l/dt = 0$ it can be written

$$K_p = E_t / (\psi_l \text{ max} - \psi_r(0)) \quad (7)$$

Because $\psi_r(0) = \psi_s$, daily course of the soil water content, and the soil water potential as well, are not so distinctive in comparison to the leaf water potential. Therefore, it can be supposed for a day, that $\psi_r(0) = \psi_s = \text{const}$.

Table 1. Parameters K_p [$\text{mm h}^{-1} \text{MPa}^{-1}$] and β_p [MPa mm^{-1}].

Crop	Number of events	\bar{K}_p	$K_p \text{ max}$	$K_p \text{ min}$	$\bar{\beta}_p$	$\beta_p \text{ max}$	$\beta_p \text{ min}$
Maize	7	0.37	0.57	0.13	1.44	2.40	0.76
Wheat	6	0.78	0.97	0.55	1.28	2.30	0.36
Buckwheat	2	3.87	4.55	3.08	0.16	0.18	0.13

Coming back to the differential Eq. (6), its solution under condition of $\psi_l(0) = \psi_s$, can be presented as

$$\psi_l(t) = \psi_l(0) + \beta_p e^{-K_p \beta_p t} \int_0^t E_t(t) e^{K_p \beta_p t} dt. \quad (8)$$

To estimate $\psi_l(t)$ using Eq. (8), values of E_t and $\psi_l(0)$ must be known from the measurements. Suitable methods for the E_t estimation are described later. Modification of the "isotonic solution" was used to estimate $\psi_l(t)$, (Budagovskij, 1964). Measurements were performed in the three hourly intervals, starting from 1 pm, according to the local sun-time. Parameters K_p and β_p were estimated from Tab. 1. Calculations were performed in two ways: first one was the estimation, using individual parameters derived for any arbitrary day; in the second case, the average values of parameters for all the time intervals under consideration were taken.

On the graphs of these relationships, their values of the measured and calculated values of $\psi_l(t)$, are grouped well around the line of symmetry. Correlation coefficient for the first case of calculation was 0.99, for the second case it was 0.98. This means, that both relatively simple methods are well suitable for the use. Important is, that dispersion of the parameters K_p and β_p is not critical, for calculation of $\psi_l(t)$.

By combination of Eqs. (2) and (8) it can be written

Estimation of K_p starts with preliminary evaluation of the maximum $\psi_l(t)$, according to the course of $\psi_l = f(t)$. Next step is estimation of the $E_t = v_s \text{ max}$, using daily course of the $E_t = f(t)$. Then, using $\psi_l(t)$ course, the value of $\psi_l(0) = \psi_s$ can be estimated, corresponding to the time of dawn. Then, value of the K_p can be calculated, using Eq. (7). For potentials expressed in Pa and E_t in mm h^{-1} parameters K_p and β_p are shown in Tab. 1. They are results of the field measurements. Because of relatively low number of such results, the statistical parameters of the measured values are not shown there, but only the average and limiting values as well.

$$v_p(t) = K_p \beta_p e^{-K_p \beta_p t} \int_0^t E_t(t) e^{K_p \beta_p t} dt. \quad (9)$$

Fig. 1 demonstrates daily course of the measured transpiration values, as well as of the estimated water flow rate values from soil to leaves, using Eq. (9). The area between both courses demonstrates decrease of the water content in a canopy, during the first half of the day, and its rehabilitation during its second half. Replenishment of the canopy water starts soon after sunrise and its restoring begins soon after the noon. It is shown, that often used condition $E_t = v_p$, is an approximation only.

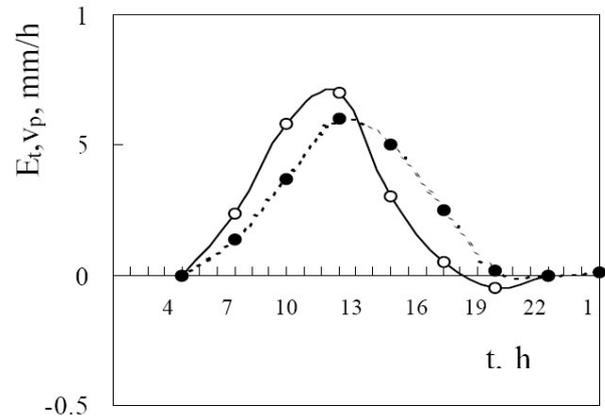


Fig. 1. Transpiration E_t daily course (empty circles) and water flow rate to the plant leaves v_p (full circles).

It was demonstrated, that quantitative description of the transpiration presented here is relatively simple, and results of calculation are close to the measured data. The next step is estimation of the water vapour transport from leaves to the atmosphere.

1.1 Leaf transpiration analysis

Leaf is a basic transpiring element of a plant. Therefore, it seems to be meaningful to start transpiration analysis from a single leaf – or detached part of it. Such a part of the leaf can be taken as a flat membrane. In this case, it can be reasonable to start with application of some basic rules of the heat and energy transport theory on the leaf transpiration.

At the very beginning, the equation of energy balance can be written:

$$R = LE + P, \quad (10)$$

where R – net radiation, L – latent heat of evaporation, E – water vapour flux (term LE is often noted as the latent heat flux), P – sensible heat flux.

Equations for LE and P can be written as:

$$LE = \rho L D_l (q_l - q); \quad D_l = \frac{D_t}{1 + D_t / D_y}, \quad (11)$$

$$P = \rho c_p D_t (T_l - T), \quad (12)$$

where ρ – air density, q – absolute humidity, T – air temperature near the leaf, T_l – leaf temperature, q_l – saturated air humidity in inter-cells leaf space, c_p – specific heat capacity at the constant air pressure, L – latent heat of evaporation, D_l and D_t – coefficients of water and heat transport between the leaf and its environment, respectively, D_y – stomata conductivity.

Relationship between D_t and environment properties can be developed within the framework of the mass and energy transport theory. The theory is usually using dimensionless numbers of Nusselt $Nu = D_t l / \varepsilon$, and of Reynolds $Re = ul / \nu$, Schmidt number $Sc = \nu / \varepsilon$ for the mass transport, and Prandtl number $Pr = \nu / a_t$. For the heat transport, the following interrelation is used

$$Nu = 0.664 Sc^{1/3} Re^{0.5}, \quad (13)$$

where ε – molecular diffusion coefficient of water vapour in the air, ν – air kinematic viscosity coefficient, l – length of an element under study in the direction of wind velocity u . In such a way, the

problem of D_t estimation for leaf element can be solved.

Substituting terms Nu , Sc and Re into (13), the resulting equation for D_t is

$$D_t = c_t (u / l)^{0.5}. \quad (14)$$

In this equation c_t contains terms ε , ν and the constant 0.664. Formula (14) is valid for the forced convection, due to wind blowing around the leaf. Free convection can be developed, when wind velocity is close to zero, due to air density differences at the leaf surface and nearby. Mixed convection comes into action, under small Reynolds numbers, which is not well understood. Mixed regime of convection will not be analysed later. Therefore, in our case it is quite acceptable to use the simplest correction rewriting (14) into

$$D_t = c_t (\xi + u / l)^{0.5}. \quad (14a)$$

According to preliminary evaluation, ξ values can be found within the interval 0.2–0.3 m s⁻¹.

To complete the system of equations described, it needs a complementary relationship between q_l and T_l . Dynamic meteorology is using usually the Magnus formula

$$q_l = q_m(0) \exp\left(\frac{17.1T_l}{235+T_l}\right), \quad (15)$$

where q_l – saturated air humidity in intercellular space of leaf, $q_m(0)$ – saturated air humidity for $T = 0$ °C.

Substituting (15) into (11), follows then the equation for LE , in which the saturated air humidity $q_l(T_l)$ is not more involved.

$$LE = \rho L \frac{D_t}{1 + D_t / D_y} \left[q_m(0) \exp\left(\frac{17.1T_l}{235+T_l}\right) - q \right]. \quad (16)$$

By substitution (16) and (12) into (10), it follows the Eq. (17)

$$R = \rho L \frac{D_t}{1 + D_t / D_y} \left[q_m(0) \exp\left(\frac{17.1T_l}{235+T_l}\right) - q \right] + \rho c_p D_t (T_l - T) \quad (17)$$

Transcendent Eq. (17) can be solved by iteration. Value of T_l is evaluated, using (15), and q_l is estimated. LE and P can be estimated by (11) and (12).

The Eq. (17), together with the other relationships described above, can be used to estimate coefficients D_t and D_y . Measuring LE independently, evaluation is relatively easy and does not need specific comment. To analyze the transpiration process, relatively simple equation is needed. This equation can be developed, by using the Magnus equation in a form of exponential series, and by taking into account its first two terms. After some rearrangement, these two terms can be taken as

$$q = q_m + \phi' (T_l - T); \quad \phi' = \frac{dq_m}{dT}, \quad (18)$$

where q_m – saturated air humidity, T – temperature of the air around the leaf.

By the following substitution of (18) into (11), and by expressing $(T_l - T)$ according to (12), and after rearrangements, the following equations are developed

$$LE = \frac{1}{1 + b_1 p_l} (L \rho b_1 D_t d + b_2 R), \quad (19)$$

$$b_1 = 1 / \left(1 + \frac{L}{c_p} \phi' \right); \quad b_2 = 1 - b_1; \quad p_l = D_t / D_y.$$

Errors, introduced into Eq. (19), due to development of Magnus equation into the exponential series, were evaluated by *Lozinskaja* (1981). Results of errors evaluation were presented as a comparison of ratios LE/R , in which LE was evaluated by (19), (11) and (17). On the graph, values LE/R of the interval 0.4–1.6 can be seen, determined by the accurate and by the approximate methods. Points lower than $LE/R = 1.3$, can be approximated by the line of symmetry. For values $LE/R > 1.3$, the points are continuously declining of it, at $LE = 1.5$ the difference is about 3%. Value $LE/R = 1.3$ can be reached even in the field conditions in particular cases only. Values LE/R , higher than 1.3, can be observed during the evening and the night time only, when transpiration ceased and condensation (dew formation) starts. From it follows, that the Eq. (19), is fully acceptable approximation, which in the field fully corresponds to the reality.

As a base of approximative and accurate description of the transpiration process, there are two basic equations: the energy balance equation and the transport equations for water vapour and heat. The state of art, does not allow to change this approach. It should be noted, that the first modern approach using the above mentioned equations, was made in

1948 by *Penman* (1948). At that time, this approach was formulated in a simple way and its weak points can be revealed by a careful analysis only. The outstanding studies on the evapotranspiration process were performed using this approach. Extension of the results achieved by such approach, can be made by experimental analysis of the evapotranspiration process. Here, our analysis will be limited to the extent of experiments, done by the Institute of Water Problems, Russian Academy of Sciences, Moscow (IVP RAS).

The basic experiments were performed using small aerodynamic tunnel. Cross-section of it was 0.22 x 0.22 m, length – 1.2 m. In the intake part of the wind tunnel, the aerodynamic screen was located to homogenize the air flow velocity in it. At the distance of 20 cm from the exhaust end, the highly sensitive anemometer was located, to measure the air flow rate. Intake part of the tunnel was equipped with the ventilator, allowing to keep the air velocity at the range of 0.2 – 3.2 m s⁻¹. Analytical scale with electronic registration was established above the tunnel, allowing to record weight changes of the leaf in the tunnel, up to 10⁻⁴ g. Wind tunnel body was made of plexiglass. Long-wave radiation coming from the lamp with the output of 400W was eliminated by the screen.

The scale was connected to the leaf (or to its part) in the tunnel through a tiny opening in the tunnel wall. This equipment was designed in a way not to disturb neither the scale function, nor that of the tunnel. Short-wave radiation was measured by pyranometer, before and after the experiment, assuming stable conditions inside of the tunnel. Long wave radiation was evaluated, using difference between the leaf and the air temperature. Air humidity was measured by the aspiration psychrometer as well, as the air temperature. In such a way, all the necessary information was acquired in course of the experiments.

The described apparatus was relatively simple and lightweight, to be established in the field conditions, nearby fields under study.

The first aim of this experimental work was to describe the relationship between leaf transpiration and its water content v_l , in full range of their realistic values, starting with saturation water content of the leaf, up to its wilting point.

To reach full saturation of the leaves, plants were extracted from the soil in the evening. Stems were dipped down into water, in which plants were preserved until the next day. During the day they were

covered and periodically sprinkled with water, thus simulating rain. Leaves or their parts were used in the equipment described above. Duration of the experiment was usually 30–40 minutes. During it, mass change of the leaf (or of its part) was recorded and then recalculated to water content of the unit leaf area, as it changed in time $v_l = f(t)$. Differentiating it numerically, according to v_l and t , transpiration of the leaf surface area was calculated $E_l = dv_l/dt = f(t)$. Assigning leaf water content to the given time, relationship between the transpiration and the leaf water content $E_l = f(v_l)$ was estimated. All these relationships seem to be similar.

To generalize them, it is necessary to focus on horizontal section of the relationship $E_l = f(v_l)$, and on change of its slope when approaching the low leaf water contents.

Change of the relationship $E_l = f(v_l)$ slope, behaves in a narrow range of the leaf water contents v_l . Therefore, the leaf water content corresponding to this change can be taken as a characteristic. As it will be shown, its meaning is crucial and can be noted as v_{kr} . Even continuity of the slope change from the first sloped curve to the second one, is experimentally supported well in the range of the leaf water contents v_l , and error of measurements δE_l , due to approximation of the $E_l = f(v_l)$ relationship, is very small too. The second characteristic point on the horizontal coordinate axis can be estimated, noted as v_{kt} . For $v_l < v_{kt}$, the leaf stomata are probably fully closed, and the cuticular transpiration is taking place only. Now it is clear, how to construct generalized relationship $E_l = f(v_l)$. It can be used the ratio $E_l/E_{l0} = \Phi_l$, in which E_{l0} – transpiration at optimum leaf water content, corresponding to the horizontal section of the relationship $E_l = f(v_l)$. On horizontal axis, the dimensionless leaf water content $v_l^* = (v_{kr} - v_l)/(v_{kr} - v_{kt})$ is interpreted. Leaf water content v_l is related closely enough to the leaf water potential ψ_l , which can be taken here as linear. Therefore, instead v_l^* dimen-

sionless leaf water potential ψ_l^* can be used in the form $(\psi_l - \psi_{kr})/(\psi_{kt} - \psi_{kr})$. Subscripts "kr" and "kt" for ψ have the same meaning as for v . Note, that $\psi_l^* = -v_l^*$. Relationship $\Phi_l = f(\psi_l^*)$ is presented in Fig. 2.

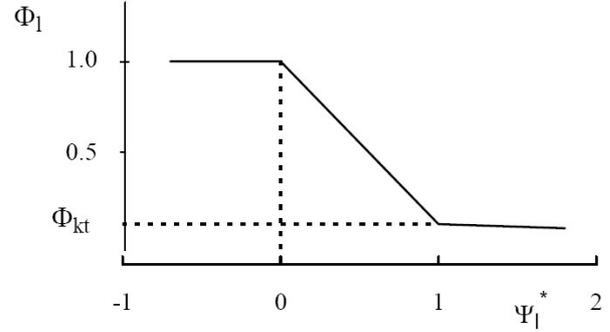


Fig. 2. Scheme of the actual and potential transpiration ratio Φ_l , depending upon dimensionless leaf water potential Ψ_l^* .

Relationship $\Phi_l = f(\psi_l^*)$ is accurate enough for purposes of this analysis. But values of parameters like v_{kr} , v_{kt} , and ψ_{kr} , ψ_{kt} are changing in wide ranges as it is typical for biostructures, particularly for leaves. Tab. 2 contains data illustrating these findings.

Relationships in Fig. 2, can be expressed by the following analytical equation, using the dimensionless water content v_l^* and the leaf water potential ψ_l^* .

$$\Phi_l = \begin{cases} 1 & \text{for } \psi_l^* \leq 0 & (20) \\ 1 - (1 - \Phi_{kt})\psi_l^* & \text{for } 1 \geq \psi_l^* \geq 0 & (21) \\ \Phi_{kt} = (\psi_l^* - 1)\eta & \text{for } \psi_l^* > 1 & (22) \end{cases}$$

Table 2. Characteristics of the leaf water regime. Mean values are in numerator, coefficients of variation are in denominator.

Plant type	Number of experiments	v_{kr} [mm]	v_{kt} [mm]	Φ_{kt}	η
Corn	57	0.12	0.10	0.17	0.14
		0.10	0.12	0.36	0.38
Wheat	20	0.09	0.06	0.21	0.16
		0.12	0.24	0.26	0.34
Sunflower	20	0.16	0.12	0.18	0.18
		0.12	0.24	0.29	0.36

Study of the D_t/D_y ratio, is the second important problem which can be solved using the described wind tunnel. It is necessary to solve this second problem experimentally, because value of the D_y can be estimated even theoretically, but based on abstraction of the molecular transport mechanism. But, the molecular diffusion coefficient of water vapour in the air is approximately constant with weak relation to the air temperature. Therefore, it seems to be reasonable to expect, that the ratio $p_l = D_t/D_y$ depends upon the air velocity. If it is so, the leaf transpiration as described by the Eq. (19), should decrease with the wind velocity increasing, especially for net radiation high values. Even in some publications, e.g. (Bichele, Moldau, Ross, 1980), and others, categoric conclusions about decreasing of transpiration with the wind velocity increasing, could be found. Experimentally estimated facts are in contrary to those opinions. Therefore, it is necessary to perform experiments confirming or denying those conclusions. And of course, it is also necessary to find out reasons of those erroneous opinions.

To perform such experiments, it is necessary to use leaf water contents interval in which transpiration is of the constant rate, when the outer conditions are stable. It seems, that water imbibition by the leaf section can be successfully used. It was also shown, that after at about one hour of transpiration, its ratio is decreasing. The reason of it is probably the assimilates concentration in the leaf. Usually, they are moving in phloem, from which they cannot penetrate to water.

Plants with leaves located close to the soil surface should be used in such experiments. Those plants can be extracted from the soil, together with part of their roots together with the soil. Then, transport of assimilants to the roots and to the leaves will be preserved, because of the low radiation level in the experimental device.

Extracted part of roots and soil was irrigated, then located into small plastic container. This part, together with the leaf, was connected to the analytical scale, using the above described arrangement. Nineteen experiments were performed with leaves of plantain, sorrel, maize and wheat (first fully developed leaf from the beginning of vegetation). 5 to 7 measurements were conducted in every experiment, necessary for evaluation of D_y . Later, the graph $D_y = f(u^{1/2})$ was derived. To understand the process better, closer to the leaf a segment of the wet blotting paper was located, to estimate the D_t .

Results of these measurements were drawn, to express the relationship $D_t = f(u^{1/2})$. Because there were differences between the fixed wind velocities for experiments with the leaves, and with the paper (wet body), $D_t = f(u^{1/2})$ were used to estimate D_t values, corresponding to those wind velocities at which D_y were measured.

Evaluation of the experiments has shown, that the ratio D_t/D_y was constant but it changed at repeated experiments with the same plant. Even more, it changed for different plants and different stages of their development. The reason is probably resulting from the natural variability of their biological parameters. Nevertheless, for any leaf the value of this difference was the same, do not depending on the air velocity around the leaf. This is illustrated in Fig. 3, where on the vertical axis are values of D_y , and on the horizontal one are those of the $D_t C$, where C is the proportionality coefficient.

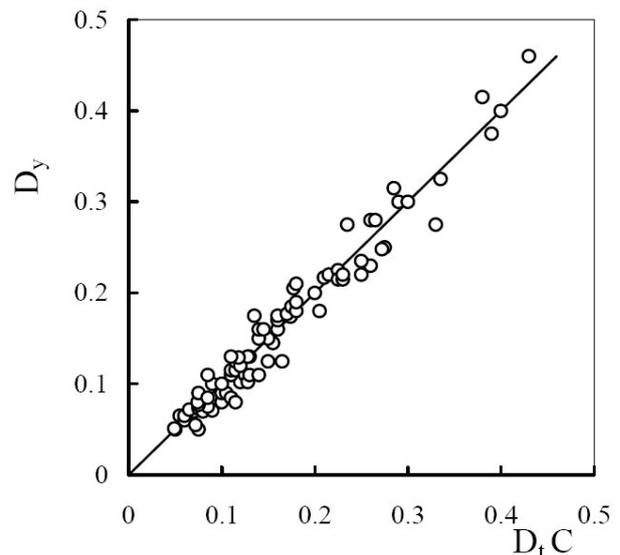


Fig. 3. Relationship between coefficient of stomatal conductivity D_y and the heat and water vapour transport coefficient, between leaf and the atmosphere $D_t C$.

By this way it was established, that the ratio D_t/D_y does not depend on the wind velocity. Qualitative type of explanation can be given only until now. Pressure pulsations of the turbulent flow and of the air around the leaf are generated. Orthogonal component of the flow velocity penetrates through thin air boundary layer. Probably, with the wind velocity increase at identical conditions, stomata conductivity can increase too, leading to the transpiration increase as well.

It is interesting, that *Morozov* (1938) raised the hypothesis, according to which the orthogonal pressure pulsation component of the surface air layer leads to the increase of the atmospheric upper layer diffusion coefficient, which is significantly higher, than that of the molecular diffusion. Therefore, the above mentioned independence of the ratio D_i/D_y upon the wind velocity, can be taken as a generalisation of the *Morozov* hypothesis, for case of the plant leaves stomatal conductivity.

The influence of function b_1 (depending on the air temperature) upon the term $b_1 D_i/D_y$, is the third problem which can be solved, using experimental equipment described above. For this purposes equipment should be modified as to establish the equal air temperatures outside as well as in inside of the wind tunnel. This appeared to be a fairly difficult problem. Therefore, results of the field measurements with transpiration rates and all necessary meteorological characteristics were used. This problem will be discussed later, here are presented some results only. It was estimated, that the ratio $b_1 D_i/D_y$ is nearly constant, for the broad range of the function b_1 values between 0.15 and 0.34, and of the air temperatures between 38 °C and 17 °C, at the relatively high soil water content values. That means, the term $1+b_1 p_l$ in Eq. (19), containing b_1 , which is a function of the air temperature and wind velocity, depends on D_y only. In such a way, simple answer of question related to the influence of stomata conductivity upon the leaf transpiration was estimated.

This result is basic for the transpiration process quantitative description. It seems to be reasonable to analyze briefly state of the art of this problem.

Bichele, Moldau, Ross (1980), presented state of the art of the stomata resistance values r_s ($r_s = 1/D_y$) evaluation. Empirical relations between the r_s and the photosynthetically active radiation (PAR), leaf water potential, leaf temperature, and the CO₂ concentration, were evaluated in the intercellular leaf area. Influence of the air water vapour pressure gradient, between the intercellular and around the leaf area upon r_s was also taken into account.

Estimation of the PAR influence upon r_s , can be accepted in principle. But its importance is limited to the early morning and to the late evening periods, when condensation starts according to the actual meteorological conditions. For the last case, the value of r_s does not influence the condensation. Therefore, this problem is not considered here.

Family of formulae was presented, expressing relationship between r_s and the leaf water potential ψ_l , containing not less than three empirical parameters. In this chapter, formula for D_y estimation is presented, (better for Φ_l estimation, which depends upon the D_y), as it follows from the Eq. (21). It contains three parameters too, but they have full physical meaning – ψ_{kr} , ψ_{kt} and Φ_{kt} .

Another family of formulae describing relation between r_s and the air temperature, gives quite different results. Any of them contains at least three empirical parameters too. Conclusions derived from the analysis of this type of formulae, disagree with the conclusions from the term $b_1 p_l$ analysis, estimated from a large number of the field measurement results.

Relationship between r_s and concentration of the CO₂, is based upon the measurements misinterpretation. Extensive scale research of *Kursanov* (1976) has shown, that inappropriate plant water regime lead to assimilates accumulation in leaves, and in the CO₂ concentration increase, respectively. In this case, this formal relationship is not properly interpreted in the plant physiology.

Similarly, the same can be told about the influence of water vapour pressure gradient upon the r_s . In this case, probably leaves were kept at the constant temperature, and natural energy balance of the leaf was changed. This resulted in all the non-natural changes.

To discuss influence of the wind velocity upon r_s/r_a , where $r_a = 1/D_t$, this problem was supposed to be of a small importance, and has not been studied.

1.2 Equations of the heat and water transport in the canopy and their solution

A canopy can be taken as an active layer, in which the heat and water are transported in its radiation and convection modes. This process is complex, therefore even its qualitative description is complicated. Nevertheless, a short and schematic description of the process is presented here.

Basic source of energy for transpiration is the solar radiation, in direct and/or transformed form. The main its components are the direct solar radiation (S_*), and the Sun's diffusion radiation – (s_*). The term $S_* + s_*$ is used to indicate the total short-wave radiation. The major part of it is absorbed by the soil surface and by the plant canopy. Its second part forms the so called reflected radiation. Ratio of the reflected short-wave radiation to its total, is denoted

as albedo (A_*). The value $A_*(S_*+s_*)$ is often noted as the short-wave radiation balance

$$B_k = A_*(S_* + s_*). \quad (23)$$

Any body on the Earth, also the soil and the plant canopy, is radiating in the long-wave range. Its value can be estimated using the Stefan – Boltzmann formula

$$I_l = \sigma_* a_* T^4, \quad (24)$$

where I_l – long-wave radiation of the body, T – its absolute temperature, σ_* – Stefan – Boltzmann constant, a_* – radiation coefficient, its value for black body is unity. It is often noted as the "coefficient of grey", by which it is stressing the difference between radiation of the particular body and the black one. Atmosphere, better its gaseous components, are radiating too. It is predominantly the water vapour and CO_2 . Other gases have minor influence upon the radiation. This term, sometimes indicated as radiation of the atmosphere, can be noted as I_a .

Effective radiation I_e is the sum of I_l and I_a . It is accepted, that radiation fluxes directed downward are used to be indicated as positive, upward fluxes are the negative ones. The effective radiation, which is the long-wave radiation balance, can be expressed as

$$I_e = I_a - I_l. \quad (25)$$

The algebraic sum of all radiation fluxes is used to be indicated as the net radiation R .

$$R = (1 - A_*)(S_* + s_*) + I_a - I_e. \quad (26)$$

Now, there is a variety of instruments, suitable to measure the long-wave, as well as the short-wave radiation fluxes. Empirical formulae for calculation of the both types of these fluxes, need standard meteorological parameters only. Limitation of those formulae is, that they are suitable for bare soils and for canopy surfaces only. In a canopy, complex radiation fluxes are taking place, playing decisive role in the transpiration process formation. This problem is attracting a considerable attention of researchers, but by now we are far from the acceptable solution to it. The plant canopy radiation regime is very well presented in the monograph by Ross (1975), which was published already many years ago.

Results presented in this monograph (Ross, 1975), do not contain the information necessary to analyze transpiration process in the full scale.

Therefore, the net radiation will be used as a basic term in the transpiration analysis.

Part of radiation flux approaching the plant canopy surface, reaches the soil surface in proportion given by the plant canopy properties. Radiation flux absorbed by the phytomass elements, is transformed to convective fluxes of the latent (LE) and the sensible (P) heat among the leaves and the air. Transport of the heat and of the water vapour between air in the canopy and the adjacent air layer, is taking part. This is a qualitative picture of the heat and water vapour fluxes in and around the plant canopy, which will be used also to describe the transpiration process quantitatively.

Plant canopy is not a real continuum, but the discrete body. All its characteristics used for its description, are supposed to be averaged in the horizontal plane xy , for any co-ordinate z from the soil surface.

To describe heat and water transport in the leaf-air space, the following equations can be used

$$\frac{dP}{dz} = \rho c_p d\omega / dz D_t(z)(T_l(z) - T(z)), \quad (27)$$

$$L \frac{dE}{dz} = \rho L d\omega / dz D_l(z)(q_l(z) - q(z)), \quad (28)$$

$$D_l = D_t / (1 + p_l); p_l = D_t / D_y.$$

where z – vertical co-ordinate, with its zero value starting from the soil surface upward.

To describe latent and sensible heat fluxes directed vertically from the phytomass surface (mainly leaves) to the interleaves space, formally the same equations are used as those describing transport in the air boundary layer:

$$LE = -\frac{\rho L k}{h} dq / dz, \quad (29)$$

$$P = -\frac{\rho e_p k}{h} dT / dz, \quad (30)$$

where k – coefficient of the turbulent transport, h – height of the plant canopy.

To the Eqs. (27)–(30) should be added the above mentioned Magnus formula and the energy balance equation, which can be presented as

$$dR / dz = L dE / dz + dP / dz. \quad (31)$$

In such a way, system of the six independent equations contains with the six unknowns – q , q_l , T , T_l , LE and P , is used. In principle it can be solved.

But, the above mentioned system contains two transport functions $D_t(z)$, $k(z)$, which can be estimated using experimental data only. For $k(z)$, analytical relationships $k = k(z)$ were developed, involving some non-acceptable assumptions. These are too complicated and cannot be used for analytical solution of the equation system presented. The most important characteristic is the net radiation R , which is changing with the height too. Generalized quantitative description of the relationship between R and height above the soil surface is not available. However, it can be evaluated using results of the field measurements. The above mentioned three relationships yield much better results, if instead of independent variable z , the leaf area index ω is used. Use of the dimensionless ratio $x = \omega/\omega_0$, where ω_0 is ω value at the plant canopy surface, seems to be suitable.

Therefore, substituting variable z for x , and transforming system of equations, functions $R = R(x)$, $D_t = D_t(x)$ and $k = k(x)$ can be expressed by the exponential functions, used in the next sections:

$$\frac{dP}{dx} = \rho c_p \omega D_t(x) (T_l - T(x)), \quad (32)$$

$$L \frac{dE}{dx} = \rho L \omega D_t(x) (q_l - q(x)), \quad (33)$$

$$P = - \frac{\rho c_p \eta k}{h} \frac{dT}{dx}, \quad (34)$$

$$LE = - \frac{\rho L \eta k}{h} \frac{dq}{dx}. \quad (35)$$

Here $\eta = dx/dy$, $y = z/h$, where h – height of the plant canopy above the soil surface. It can be seen, that η equals to ratio of the normalised leaf area index and the normalised height. Subscript “s” indicates the soil surface, i.e. $x = 0$, subscript “0” – is related to the plant canopy surface ($x = 1$), subscript “2” – to some fixed height above it, which is usually conveniently taken 2 m, height of the standard meteorological observations. Derivatives according

$$LE' = \frac{1}{1 + b_1 p_l} \left[\rho L \omega D_t(x) d - \rho L \omega D_t(x) (q(x) - q_0) + R' + \frac{n D_t(x)}{k_0} \int_0^x \frac{(R(x) - B)}{k^*(x)} \right] \quad (39)$$

$$k^*(x) = k(x) / k_0.$$

Partial differential equations were developed, using two approaches. The first of them was published already and it will be presented briefly

to x are indicated by superscript “comma” (‘). Empirical relationships for $R(x)$, $D_t(x)$ and $k(x)$ can be expressed as:

$$\begin{aligned} R(x) &= R_0 e^{n\omega(x-1)} \\ D_t(x) &= D_{t0} e^{m_t \omega(x-1)} \\ k(x) &= k_0 e^{m_k \omega(x-1)}. \end{aligned} \quad (36)$$

To make future transformations more comfortable, let us integrate Eq. (31), taking into consideration changes of values x from $x = 0$ to x , where for $x = 0$ (soil surface) is $R(0) = LE(0) + P(0) + B$, where B – soil heat flux.

After some rearrangements

$$R(x) = LE(x) + P(x) + B. \quad (37)$$

The next rearrangement is suitable to start with Eq. (33), expressing q_l by series limited into its two first terms. Then to add and take from the left side of the equation q_0 , (in a case, when meteorological conditions are to be used on the plant canopy surface), or q_2 , (for the fixed height z_2). For that case, we limit ourselves on the first case. It should be noted, that difference between saturated water vapour humidity at $x = 1$, and that at the same height q_0 , equals to the air saturation deficit. Resulting equation is

$$LE' = \frac{\rho L \omega D_t(x)}{1 + b_1 p_l} \left[d - (q(x) - q_0) + \phi'(T_l - T_0) \right]. \quad (38)$$

Omitting description of this simple rearrangements, some basic further steps can be mentioned briefly. At first, there is $T(x)$ added and taken to right side of the Eq. (38), subtracting the difference $T_l - T(x)$ according to (32), and then Eq. (31) will be applied.

here. The second approach is presented for the first time and therefore it will be given in details.

Using first approach, the equation for $q(x)$ will be developed. Differentiating Eq. (35), then evaluating LE from (35), and the variable $U(x) =$

$$U'' + m_k \omega U' + \frac{1}{1 + b_1 p_l} \frac{L \rho \omega_0 D_l(x) U}{k(x)} = \frac{1}{1 + b_1 p_l} k(x) \left[n \omega_0 R(x) + \frac{D_l(x)}{k_0} \left[R_0 \left(e^{n - m_k \omega(x-1)} - 1 \right) - B \left(e^{-m_k \omega(x-1)} - 1 \right) \right] \right]. \quad (40)$$

Boundary conditions for solution of the Eq. (40) are: for $x = 1$ $U = 0$; for $x = 0$ $U = U_s$.

It can be seen, that the coefficient at U is not constant, because $n \neq m_k$, and therefore, the equation can be solved numerically. Neglecting the relation between x and the coefficient, solution of the equation can be performed without difficulties, even if its form seems to be complicated. To present solution in a simple way, it can be written, using Φ_1 , Φ_2 , Φ_3 functions for terms standing at d_0 , R and B . Those functions contain even meteorological quasi constant, like L , ρ , c_p , and other characteristics, which can be taken as constants. Then,

$$U(x) = \Phi_1(x) d_0 + \Phi_2(x) R_0 - \Phi_3(x) B. \quad (41)$$

Differentiating the solution of the equation according to x and to multiply it by $\rho L k(x)$,

$$LE(x) = (1/(1+b_1 p_l)) [\Phi_1(x) d_0 + \Phi_2(x) R_0 - \Phi_3(x) B] \quad (42)$$

Simplifications were used to solve Eqs. (41), (42). To confirm its acceptability, it is necessary to compare values of $U(x)$ and $LE(x)$, calculated according to above mentioned solution with those measured in the field.

Results of those estimations are presented on Fig. 4. The comparison was performed in two ways. In the first case, parameters n , m_l and m_k , were used, for the situation in which values $q(x)$ and $LE(x)$ were estimated. For the second case, averaged values of them were used. Coefficients of correlation for both cases were estimated, and the necessary errors of measurements were taken into account. They are evaluated relatively high, their average value is 0.985. Evaluation performed indicates development and solution of equations as fully acceptable. Functions Φ_i are expressed in a complicated form and contain expression $1/(1+b_1 p_l)$, which complicated analysis of the re-

$= q(x) - q_0$ will be used instead the $q(x)$. After some rearrangements we obtain the linear partial differential equation of the second order for U :

sulting solution. Therefore, finding of other approaches becomes actual, to find new form of the analysed problem solution.

In the next part of this presentation, some partial results of *Monin* and *Obukhov* (1953, 1954) will be used, based on similarity concept of turbulent regime of the temperature stratified atmosphere, accepted world-wide. Relations between vertical profiles of air temperature and air humidity can be taken as linear. As a result of this, the well known Bowen ratio

$$Bo = P / LE = c_p dT / L dq$$

will be linear with maximum at the soil surface adjacent layer. The profile

$$\theta(x) = q(x) + \frac{c_p}{L} T(x)$$

is suitable for use in this case, and then to write relationship

$$LE / (R - B) = dq(x) / d\theta(x).$$

Analogous relation can be written even for

$$\frac{P}{R - B} = c_p dT / d\theta.$$

The sum of those two relations equals to unity. These relationships are constant along elevation in boundary layer of the atmosphere too. Therefore, the question arises, whether those relations can be generalised even for the homogeneous plant canopy. Answer can be obtained using results of experiments, containing air temperatures and air humidity profiles in the canopy, for different values of x . The generalised graph presented in Fig. 5 was designed using those results. On axis of ordinates there are values $q(x) - q_0$, and on axis of abscissas $Bu(\theta(x) - \theta_0)$ values, where $Bu = dq / d\theta = LE(x) / (R(x) - B)$. To design a chart,

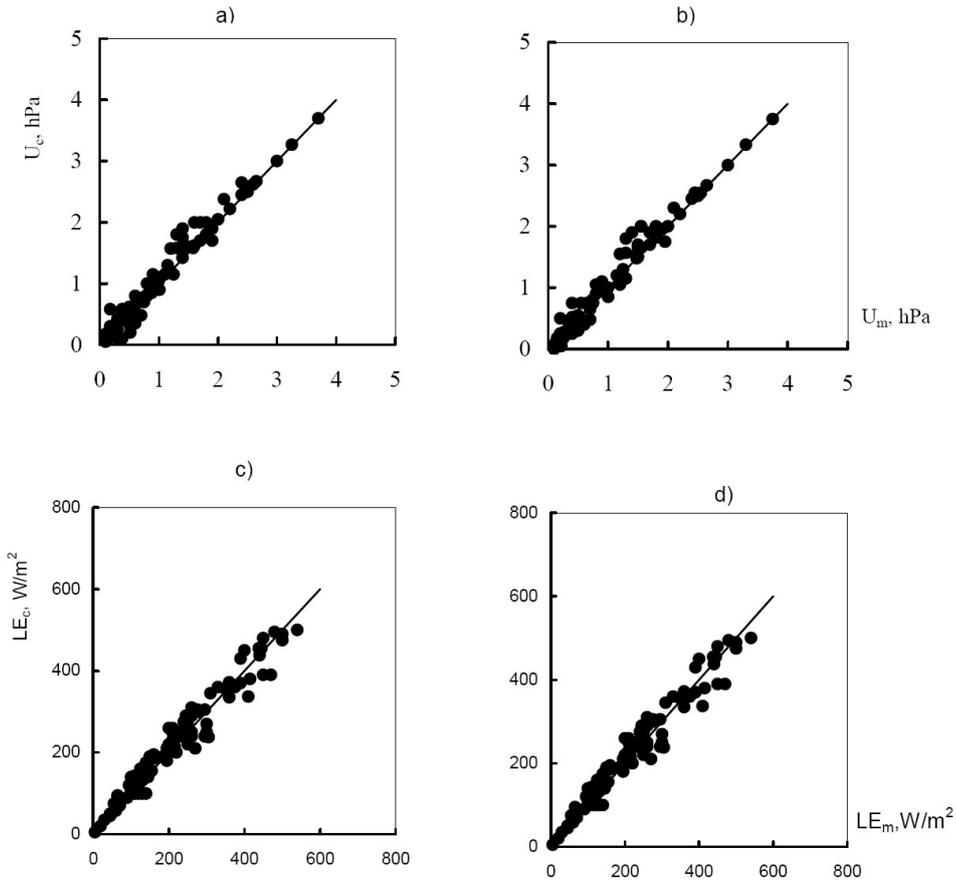


Fig. 4. Comparison of the calculated and the measured values of $U(x)$ – (a, b), and $LE(x)$ – (c, d) – Eqs. (41) and (42). Figs. a) and c) were calculated using individual values of m_k and m_r , b) and d) were calculated with the “average” values of m_k and m_r . Subscripts c and m mean calculated and measured values.

the numerous results of measurements were used, acquired by measurements on canopies of maize, wheat and cotton in Estonia, Moldova, Tadjikistan and Russia (Kursk Experimental Station). Mean quadratic errors are shown, not higher than measurement errors of $q(x)$ and $T(x)$, and $\theta(x)$ values as well, while mean quadratic errors are not larger than those above the canopy. Linearity of the relationship discussed means constancy of the Bu with height of the plant canopy. Some differences were found in the layer close to the soil surface, which can be characterised by the air layer roughness, close to the bare soil surface.

Using this approach and after transformation of q_l to series, and using first two terms of the series $q(z_2)$ and $T(z_2)$ measured at the standard height $z_2 = 2 \text{ m}$, because this is the height of standard meteorological observations, in basic Eq. (38), two new terms will appear. Rewriting this equation including the variable $\theta(x)$

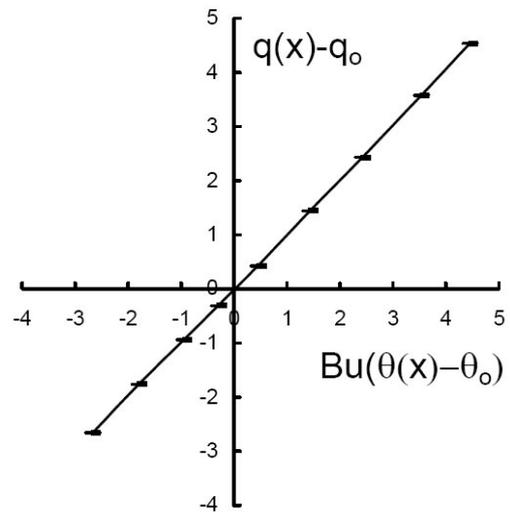


Fig. 5. Relationship between $q(x) - q_0$, and $Bu(\theta(x) - \theta_0)$. Figure was designed using vertical profiles of $q(x)$ and $\theta(x)$.

$$LE'(x) = \frac{1}{1+b_1p_l} [\rho L b_1 \omega_0 D_t(x) d - \rho L \omega_0 D_t(x) (q(x) - q_0) + \rho L \omega_0 b_2 (\theta(x) - \theta_0) - \rho L \omega_0 D_t(x) (q_1 - q_2) - \rho L \omega_0 D_t(x) b_2 (\theta_1 - \theta_2) + b_2 R'] \quad (43)$$

Subscripts “1” and “2” at q and θ mean, that those are the values for the level of plant canopy, and of the z_2 height, respectively.

To separate terms $q_1 - q_2$ and $\theta_1 - \theta_2$ from Eq. (43), the following equations are used:

$$LE = \rho L D_0 (q_1 - q_2), \quad (44)$$

$$(R_0 - B) = \rho L D_0 (\theta_1 - \theta_2), \quad (45)$$

where D_0 – integral coefficient of turbulent conductivity of the air, between levels z_1 (plant canopy surface) and z_2 .

Eqs. (34) and (35), will be used, to separate term containing $\theta(x) - \theta_0$, to join the energy balance equation, which leads to the relationship

$$R(x) - B = \frac{\rho L k(x)}{h} \frac{d\theta}{dx}. \quad (46)$$

Integrating this equation according to x , from $x = 1$ to x , and multiplying both parts of this equation by ω_0 , we can take

$$LE' = \frac{1}{1+b_1p_l} \left\{ \rho L \omega_0 b_1 D_{t0}(x) d - LE_0 \frac{D_{t0} h \omega_0 e^{m_t \omega_0 (x-1)} \int_1^x \frac{(R(x)-B)}{k^*(x)} dx}{k_0 (R_0 - B)} - \frac{D_{t0} e^{m_t \omega_0 (x-1)} LE_0}{D_0} + b_2 \left[R' + \frac{D_{t0} (R_0 - B)}{D_0} + \frac{D_{t0} h \omega_0 e^{m_t \omega_0 (x-1)} \int_1^x \frac{(R(x)-B)}{k^*(x)} dx \right] \right\} \quad (49)$$

Eq. (49) is a simple differential equation, which can be solved by integration only. It will be done for boundaries from “1” (plant canopy surface) to “0” (soil surface), without consideration of the thin air layer adjacent to soil surface. It was estimated, as a result of numerous measurements discussed before. But how to apply this knowledge it is not known so far. It can be stated and accepted, that the equations describing the relationships $k(x)$ and $D_t(x)$ are valid up to $x = 0$. Accepting this assumption, and multiplying both sides of the Eq. (49) by -1 , it is obtained:

$$\rho L \omega_0 (\theta(x) - \theta_0) = \frac{\omega_0 k_0}{h} \int_1^x \frac{R(x) - B}{k^*(x)} dx. \quad (47)$$

To eliminate the difference $q(x) - q_0$, the above mentioned linear relationship between $q(x)$ and $\theta(x)$ can be used. Then, the following equation can be developed

$$\frac{q(x) - q_0}{\theta(x) - \theta_0} = \frac{LE'}{R'} = \frac{LE(x)}{R(x) - B} = \frac{LE_0}{R_0 - B}. \quad (48)$$

To apply the approach presented, for development of the differential equation describing the transpiration process, in principle, any of the three possibilities of the right side of the Eq. (48) can be used. Nevertheless, the final form of this equation depends upon this choice.

The simplest and the most comfortable solution can be obtained, by using the term

$$(q(x) - q_0) / (\theta(x) - \theta_0) = LE_0 / (R_0 - B).$$

According to the above mentioned, the expression (43) can be rewritten as follows:

$$LE_{tp} = \frac{1}{1+b_1p_l} [\rho L b_1 D_{t0} dy_1 - LE_s (y_1 + y_3) + (R - B)(y_2 + A_1 y_1 + A_2 y_3) - LE_{tp} (A_1 y_1 + A_2 y_3) - \delta B A_2 (y_3 - y_4)] \quad (50)$$

$$A_1 = D_{t0} / D_0; \quad A_2 = h D_{t0} / k_0$$

$$y_1 = (1 - e^{-m_t \omega_0}) / m_t; \quad y_2 = 1 - e^{-n \omega_0};$$

$$y_3 = \frac{1 - e^{-(m_t+n-m_k)\omega_0}}{(m_k - n)(m_t + n - m_k)\omega_0} - \frac{1 - e^{-m_t\omega_0}}{(m_k - n)m_t\omega_0},$$

$$y_4 = - \left[\frac{e^{(m_t-m_k)\omega_0} - 1}{m_k(m_t - m_k)\omega_0} + \frac{e^{-m_t\omega_0} - 1}{m_k m_t \omega_0} \right].$$

For the above mentioned rearrangements, the validity of the equation $LE_p = LE_s + LE_{ip}$ is accepted. Here E_s – soil evaporation rate below canopy, in principle it can influence transpiration rate. For potential rate of E_s , air humidity in plant canopy is slightly increasing and its temperature is decreasing. This leads to corresponding transpiration decrease. For $E_s \rightarrow 0$ the turbulent heat transport is increasing too, which leads to air temperature increase, and correspondingly, to increase of the transpiration rate.

There are basic ideas describing the influence of E_s on transpiration rate. Quantitative description of this phenomenon was probably given for the first time by *Budagovskij* (1964). Quantitative evaluation of this phenomenon indicates, that the influence of E_s on transpiration rate can be neglected in practice, for a detailed analysis of the transpiration process. Keeping this in mind, terms containing E_s will be neglected in further rearrangements of the Eq. (50).

The last term of the Eq. (50) can be neglected too. It appeared, because integrals containing $R(x)$ and B , will be expressed by a single term. Therefore, the last term can be neglected as negligibly small.

It should be noted, that heat fluxes should be involved in the calculation, when studying daily courses of transpiration fluxes only. The differences between daily totals of heat fluxes in soil, usually falls within errors of its estimation.

Coming back to the solution of Eq. (50), the term LE_{ip} , will be transferred from the right to the left side of it. After some simple rearrangements, the term of the right side of the equation $1/(1+b_1p_l)$ can be expressed as

$$\Phi_0 = 1/(1+b_1p_l + A_1y_1 + A_2y_3). \quad (51)$$

The right side of the Eq. (51) will be divided by the expression $1/(1+b_1p_{l0} + A_1y_1 + A_2y_3)$, which corresponds to the optimal soil water content for transpiration. Resulting equation is

$$\Phi_0 = \frac{1 + b_1p_{l0} + A_1y_1 + A_2y_3}{1 + b_1p_l + A_1y_1 + A_2y_3}. \quad (52)$$

To simplify the expression, numerator and denominator of this equation have to be divided by $M = 1 + A_1y_1 + A_2y_3$. It can be written then

$$\Phi_0 = \frac{1 + b_1p_{l0}^*}{1 + b_1p_l^*}; \quad p_{l0}^* = p_{l0}/M; \quad p_l^* = p_l/M. \quad (52')$$

It seems to be suitable to introduce into denominator of the Eq. (52') such a term $b_1p_l^*$, which equals to the value of this term for particular canopy, under condition of optimally hydrated soil. Then, the value of Φ_0 will represent the ratio of the given canopy transpiration, and transpiration of the canopy chosen as typical. Let it be expressed as Φ_{01} . In this way, the differences in different kinds of plant canopies transpiration can be evaluated.

The influence of stomata conductivity coefficient – and Φ_0 – on transpiration is decreasing before the end of vegetation period. To describe the transpiration process of this period, it is suitable to introduce coefficient $\Phi_{02}(t)$. Its value can be estimated by transpiration of the plant canopy measurements only. To evaluate material of the measurements, it is suitable to use dimensionless time $\tau = (t - t_i)/(t_k - t_i)$, where t – time, t_i – initial time, and t_k – final time of the constant transpiration rate period.

At the end, the coefficient Φ_{03} should be involved, characterising transpiration at sub-optimal soil water content. The way of its estimation, will be described later.

Now, the part of the Eq. (50) will be analysed. First, the term at the expression $(R - B)$, will be noted as Φ_2 .

$$\Phi_2(\omega_0) = y_2 + A_1y_1 + A_2y_3. \quad (53)$$

The second function – Φ_1 is much more complicated, because it depends not on ω_0 only, but also upon linear leaf dimension in the wind direction – l . Therefore, Φ_1 can be expressed as

$$\Phi_1 = C_p \cdot l^{0.5} y_1, \quad (54)$$

where C_p – proportionality coefficient in the relationship $D_t = C_p (u/l)^{0.5}$. It can be mentioned, that u is not involved in Φ_1 , but it is in equation with superscript not 0.5, but 2/3. Correspondingly, the wind velocity in this solution is not given for canopy surface, but for the standard $z_2 = 2$ m.

Taking into consideration the above mentioned comment, the Eq. (50) can be expressed in the form

$$LE_{tp} = \Phi_0 \left[\rho L b_1 u^{2/3} d \Phi_1 + b_2 (R_0 - B) \Phi_2 \right]. \quad (55)$$

The Eq. (55) is suitable for evaluation of Φ_1 and Φ_2 functions, having results of measurements LE_{tp} , and R_0 , B , d , u_2 . To be able to do that, it seems to be reasonable to divide the equation by $\rho L b_1 u_2^{2/3}$. Resulting is the simple equation

$$Y = \Phi_1 + \Phi_2 \bar{X}$$

$$Y = LE_{tp} \rho L b_1 u_2^{2/3} d; \quad X = \frac{b_2 (R_0 - B)}{\rho L b_1 u_2^{2/3} d}. \quad (56)$$

Data, used to estimate functions Φ_1 and Φ_2 , should fulfil at least the following criteria: the first is – measurements should be conducted above the dense canopy ($\omega_0 \geq 4$), to neglect the soil evaporation. The second condition which should be met is – the canopy should be hydrated optimally and its growth should be optimal too. In other case, results of the measurement will be nonhomogeneous, and values of the functions Φ_1 and Φ_2 will be inaccurate and incorrect.

Table of Φ_1 , Φ_2 and functions value was calculated using results of our measurements, as well as materials of other research institutes. Types of canopies are arranged according to their values of function Φ_1 , starting with their lowest one.

T a b l e 3. Functions Φ_1 , Φ_2 and Φ_0 values, estimated from experimental data.

Vegetation type	Φ_1	Φ_2	Φ_0
Beets	0.15	1.16	0.98
Cotton	0.20	1.21	1.00
Corn	0.20	1.18	0.98
Alpine meadows	0.30	0.96	0.80
Birch-aspen forest	0.30	1.24	1.03
Alfalfa	0.40	1.17	1.00
Camel thorn	0.40	1.21	1.00
Oats	0.40	1.19	0.99
Wheat	0.45	1.22	1.02
Barley	0.45	1.20	0.99
Rice	0.45	1.22	1.02
Pine-tree planting	0.75	1.10	0.91

It can be mentioned, that in 10 of 12 cases, values of the function Φ_2 are very close. Their maximum deviations from the mean value $\bar{\Phi}_2 \equiv 1.2$ are not higher than $\pm 3\%$, what is within the interval of systematic errors due to the measuring

equipment quality, skill of the personnel, and homogeneity of the experimental field. Therefore, the value $\Phi_2 = 1.2$ can be taken as typical, up to the time, when more experimental material will be collected.

Remembering, that function Φ_0 is ratio of the actual transpiration and the potential one, the first value was estimated by dense canopy transpiration measurements, the second one was evaluated using Eq. (55).

The strong influence of the effective leaf diameter l_1 on function Φ_1 can be found easily from Tab. 3. It can be recalled, that independent measurements of the l_1 is impossible in principle. Therefore, for LE calculation it is necessary to utilise Φ_1 classification, evaluated by the above mentioned method, using the measurement data. This fact cannot be the necessary limitation of the method presented, because the term in the Eq. (55) containing the function Φ_1 , is not higher – even under extraordinary conditions – then 15–20% of LE_{tp} . The last term was evaluated using $\Phi_0 = 1$, Φ_0 was evaluated by the method described before, results of which are presented in Tab. 3. Values Φ_0 in Tab. 3 can be taken – according to the above discussed method – as values Φ_{01} .

From the Tab. 3 it follows, that values of Φ_{01} for the 10 analysed plant canopies are close too. Minor differences in function values are within the range of evapotranspiration estimation systematic errors.

Analysing the Tab. 3, another important conclusion can be made. It can be concluded, that at the "typical" cases Φ_2 and the $b_1 p_{i0}^*$ does not depend upon Φ_1 , but on the effective leaf dimension – l_1 .

It was shown in the previous part based on results of laboratory measurements, that the above mentioned term does not depend on wind velocity. Now, this conclusion can be expressed in more general form. It means practically constancy of the ratio $p_{i0} = D_{i0}/D_{i0}$, for any type of plant. It can change for different plant types. It is not clear so far, what is role of the air temperature in this term. This problem is discussed in detail by *Budagovskij* (1989), therefore our presentation here will be limited to his results.

Those conclusions were based on the analysis of results of four years of field measurements with the cotton canopy, in Central Asia. The air temperature during the field measurements changed within the range from 38 to 17 °C, and function b_1

changed from 0.15 to 0.30, correspondingly, i.e. twofold. Analysis of measurement results has shown, that the differences of evaluated function Φ_2 were not higher than ± 0.02 – 0.03 , using values b_1 from 1.2. Such a differences are within the stochastic errors of transpiration measurements. That means, the independence of the term $b_1 p_{10}^*$ does not depend on b_1 for the particular plant type.

The significant deviation of function Φ_{01} from the value 1.0 of Alpine meadows and Pine trees will be discussed. Alpine meadows observations were conducted in Armenia, close to Aragac peak at the elevation around 3200 m a.s.l. Typical for this site is high intensity of the solar radiation, and the low air temperatures. Only those kinds of plants can adapt to those conditions during their evolution – which productivity was the highest. But it basically depends on the leaf temperature, especially at relatively low air temperature. The leaf temperature increase is possible – during the high solar radiation intensity – but it is connected to decrease transpiration intensity. This can occur by partial stomata closing, which leads to limiting CO_2 inflow to the substomatal cavities. This is the price for growth under such conditions.

Pine tree behaviour is incomparable to Alpine meadows. Pine trees of different kinds are distributed in wide ranges of altitudes between the subtropic and polar latitudes. The pine leaves, represented by long, thin needles, are covered by the relatively thick cuticle. The relatively high value of heat transport coefficient and relatively thick cuticle is preserving leaf protoplasm to be overheated. Value of the ratio $p_{10} = D_{i0}/D_{010}$ is lower than that for other plants, due to the anatomical differences of the pine tree.

Analytical form of function $\Phi_2(\omega_0)$ was presented – in brief – before, but to analyse it comfortably, it is written here too

$$\Phi_2 = y_2(\omega_0) + A_1 y_1(\omega_0) + A_2 y_3(\omega_0), \quad (57)$$

where $A_1 = D_{i0}/D_0$, $A_2 = D_{i0}h/k_0$. Terms D_{i0} , D_0 , and k_0 are correlated and therefore a value of A_1 and A_2 , are varying in a wide range. Their values can be estimated experimentally. As it was shown, for dense canopy the value of Φ_2 is nearly constant and equals to 1.2. The above mentioned equation for $\Phi_2(\omega_0) = 1.2$ can be used, to estimate A_1 and A_2 . The Eq. (57) can be expressed in the form

$$Y^* = A_1 + A_2 \bar{X}^* \quad (58)$$

$$Y^* = (1.2 - y_2) / y_1; \quad \bar{X}^* = y_3 / y_1.$$

Functions y_1 , y_2 and y_3 are characterized by the above presented relationships, and the parameters n , m_t and m_k are evaluated independently, using specific field experiments.

Values of the estimated parameters are presented in Tab. 4.

Table 4. Parameters n , m_t and m_k values.

	n	m_t	m_k
Number of measurements	90	19	16
Mean value	0.31	0.40	0.52
Mean quadratic deviation	0.11	0.18	0.07
Coefficient of variation [%]	35	45	13

Dispersion of all parameters in the Tab. 4 is significant. Dispersion of parameter n is maximal, particularly because the influence of Sun elevation on its value was neglected. This problem – which seems not to be very important – was discussed in details by *Budagovskij* (1981). Probably the most important is to establish the correlation between different parameters. To find out those interrelations among parameters is extremely difficult, because parameters are evaluated for different time intervals, due to technical reasons. Mutual measurements of characteristics family is needed to establish interrelations among them.

The most probable values of parameters should be used for evaluation of A_1 and A_2 using the Eq. (57). Parameters, presented in Tab. 4 were not evaluated under the same conditions, therefore the average values of them should be used. As it was shown, values $A_1 = 0.1$ and $A_2 = 0.15$, are close to the mean values, but calculation of Φ_2 has shown, that results were not of acceptable values.

To increase the accuracy of relationships $\Phi_2 = \Phi_2(\omega_0)$ estimate, additional field measurements are needed, in which synchronised evaluation of parameters n , m_t and m_k would be performed. Experimentally estimated data acquired so far, are not satisfactory to evaluate function $\Phi_2(\omega_0)$, by a currently used method. It seems to be reasonable to use other methods, e.g. relationship $E_t/E_{tp} = f(\omega_0)$ seems to be a useful tool for it. For $\omega_0 \geq 4$ $\Phi_2 = 1.2$, from which it follows that the term E_t/E_{tp} in this relationship can be multiplied by 1.2. To do that, the analysis made by *Novak* (1981) can be used, who used data of different authors. The generalised relationship $E_t/E_{tp} = f(\omega_0)$ was expressed

analytically, using his chart, with multiplying of E_t/E_{t0} by 1.2. Co-ordinates of points of the relationship $\Phi_2 = f(\omega_0)$ were evaluated there. Graphical representation of this relationship is on Fig. 6.

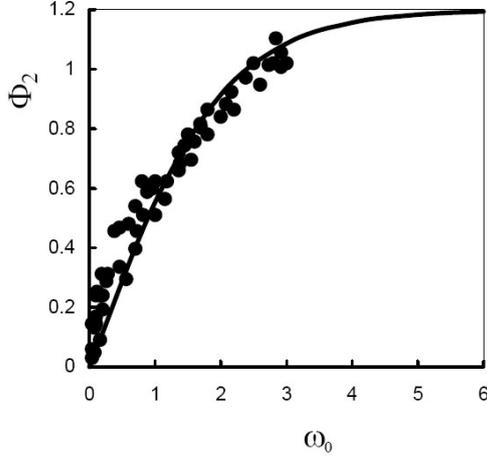


Fig. 6. Function Φ_2 and leaf area index ω_0 . Points were estimated by Novák (1981), the curve was calculated by Eq. (59).

There are some values of function Φ_2 , in the Tab. 3, which were not used in the figure, because the leaf area index for them was not estimated. According to visual evaluation, leaf area index is changing within the range 4 – (6–7). From it follows, that within this range of ω_0 value, function Φ_2 will be nearly constant, with the mean value 1.2. Using the previously mentioned results, quite simple relationship can be proposed, between Φ_2 and the leaf area index

$$\Phi_2 = 1.2th(0.5 \omega_0). \quad (59)$$

It can be expected, that function $\Phi_1(\omega_0, l_l)$, for increasing ω_0 is converging to the limit, in the same way, as it is with $\Phi_2(\omega_0)$. In this case it can be approximated by the same type of expression like that for Φ_2 . The basic difference is, however, in Eq. (59), where instead of factor 1.2, the function Φ_1^* should be applied, in analogy to those, introduced in Tab. 3, or the proposal described above should be used,

$$\Phi_1(\omega_0, l_l) = \Phi_1^* th(0.5 \omega_0). \quad (60)$$

As a result, the relationship $\Phi_1(\omega_0)$ will be presented by the family of curves, any of them for particular value of the effective leaf dimension. Those should not be – as it was accented before – estimated independently. Therefore, there is not alternative way of its estimation, instead of using

the Eq. (60). It can be noted, that some differences in evaluation of Φ_1 , using different mentioned approaches, are not critical for transpiration calculation.

Function Φ_{01} can be estimated experimentally in the same way, as it was shown before. Classification of this function in relation to its sensitivity to environment would be made, or if necessary, experimental data should be collected.

Parameter $\Phi_{02} = \Phi_{01}$, depends on plant type only for the optimum soil water content. Its value is decreasing at the plant maturity stage. This period for cereals starts just before stage of the wax maturity up to full maturity of the grains. During this stage the lowest leaves are becoming yellow and partially falling down as a result of plastic stuff extraction from them, and its transport into reproductive organs, probably due to decreasing of the D_y coefficient. The reason of it is probably biological.

Evaluation of function Φ_{02} can be made by using the measured values of E_t and the calculated ones E_{tp} , for given type of plant. The soil water content must be optimal during the measurements. Changing soil water content, as well as the soil water potential during measurements, would lead to data which reflect the influence by those changes. Data, suitable for estimate of Φ_{02} are not available at that time, therefore we can discuss the problem qualitatively. It should be noted, that the time interval of transpiration during this phase is relatively short.

To evaluate the Φ_{03} function, first of all the Eq. (6) in dimensionless form will be used. To simplify the final form of the equation, leaf water potential ψ_l , introduced by the difference $\psi_{kt} - \psi_{kr}$, can be expressed by $\psi_z - \psi_{kr}$, where ψ_z is the leaf water potential, corresponding to the wilting point. Term $E_t = \Phi_{03}E_{tp}$ will be used, to rewrite Eq. (6) in the form

$$\frac{d\psi_l^*}{dt} + K_p \beta_p \psi_l(t) - K_p \beta_p \psi_l(0) - \frac{\beta}{(\psi_z - \psi_{kr}) \Phi_{03} E_{tp}} = 0, \quad (61)$$

where $\psi_l^* = (\psi_l - \psi_{kt}) / (\psi_z - \psi_{kr})$.

To solve this problem, a simplified form of the Eq. (21) will be introduced, which can be – using some simplifications – written as

$$\Phi_{03}(t) = 1 - \psi_l^*(t), \quad (62)$$

where $\psi_l^*(t)$ is of the same meaning as it is in Eq. (61).

Differentiating (62) according to time, and expressing $\frac{d\psi_l^*}{dt}$ from (61), the differential equation for Φ_{03} can be developed as

$$\frac{d\Phi_{03}}{dt} + M_t(t)\Phi_{03}(t) - K_p\beta_p\Phi_{03}(0) = 0 \quad (63)$$

$$M_t(t) = \frac{\beta_p}{\psi_z - \psi_{kr}} E_{tp}(t) - K_p\beta_p.$$

Solution of the Eq. (63) can be expressed as

$$\Phi_{03}(t) = e^{-\int_0^t M_t(t)dt} \left[-\Phi_{03}(0) + K_p\beta_p\Phi_{03}(0) \int_0^t e^{M_t(t)dt} \right] \quad (64)$$

Form of the Eq. (64) is complex, not very suitable for an analysis. Therefore, numerical experiment was performed, result of which is shown in Fig. 7. Time t is there expressed in the solar time. Numbers at particular curves correspond to the initial dimensionless leaf water potential. Recalling the last one correspond to soil root zone water potential, typical by its slow change in time, in comparison to its significant daily changes. Therefore, these daily changes of soil root zone water potential should be neglected in this analysis.

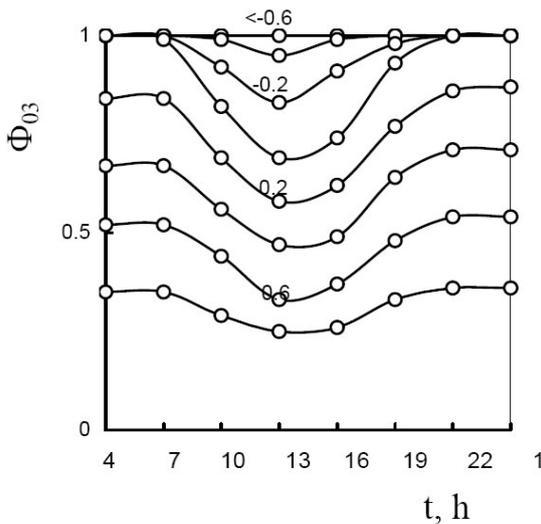


Fig.7. Daily course of functions Φ_{03} for its different initial values.

Typical daily course of the relationship $\Phi_{03}(t)$ is shown. Daily minimum of this term appears just after noon, when $\psi_l^*(t)$ reaches its maximum under stable weather condition. It can be noted, that by biophysicists it was found the mid-day transpiration depression due to non-specified biological properties of plants.

Results of our analysis are demonstrating clearly the noon transpiration depression, which is result of the potential transpiration daily course, and of the term $\psi_l^*(t)$ initial value.

The relationship $\Phi_{10}(t) = f(\Phi_{10}(0), E_{tp}(t))$ evaluated from data of the numerical experiments should be presented. Difficulties with estimation of the involved parameters are due to lack of systematic observation results of the K_p , β_p , ψ_{kr} and ψ_z coefficients, needed to evaluate the Eq. (64).

It is necessary to use the soil water content instead of the leaf water potential. It can be mentioned, that $\psi_l(0)$ equals to the soil water potential, which can be used as proportional to the soil water content, in the range between the wilting point and the field capacity. $\Phi_{03} = E_t/E_{tp}$ relationship can be used as directly proportional to the soil water content too, for the constant value of E_{tp} . Then, it can be presented

$$\Phi_{03} = E_t / E_{tp} = \theta / \theta_{kr} \quad (65)$$

$$\theta_{kr}(t) = \zeta_1 + \zeta_2 E_{tp}(t)$$

where ζ_1 and ζ_2 are parameters evaluated using directly measured data $W(t)$, $E_t(t)$, and meteorological data necessary to calculate E_{tp} . Fig. 8 presents the relationship (65). Soil water content θ is expressed in volumetric units. Potential transpiration is expressed in mm h^{-1} . Then, there the following values were obtained: $\zeta_1 = 6.0$; $\zeta_2 = 4.6$.

It could be mentioned, that the Eq. (65) is a good approximation of the Eq. (64), and can be used to estimate the influence of the soil water content on transpiration. This can be demonstrated simply. Knowing course of the $E_{tp}(t)$, θ_{kr} can be calculated according to formula (65), for maximum value of the E_{tp} . Different values of $\theta/\theta_{kr} \approx \Phi_{03}$, are shown on horizontal axis, on vertical axis there are the $E_{tp} = f(t)$ values.

Then, values of $\Phi_{03} = f(E_{tp})$, can be calculated according to formula (65), for any chosen initial value of the θ/θ_{kr} . Results of those estimations are giving the picture close to those, as in Fig. 7, closely approximating the numerical experiment.

It means that this approximation is acceptable and additionally, a simple one.

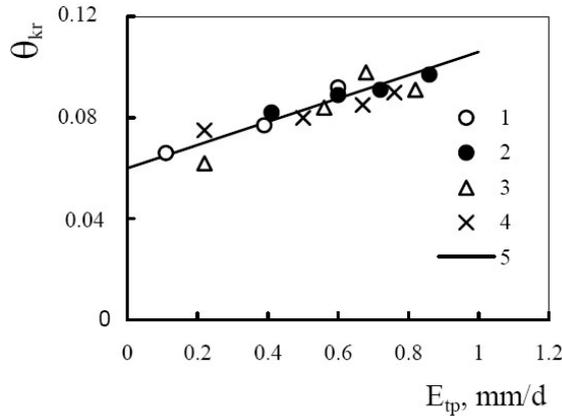


Fig. 8. Critical soil water content θ_{cr} versus potential transpiration E_{tp} ; 1 – barley, 2 – pearl millet, 3 – polygonum sativa, 4 – maize. Linear approximation (5) is according to the Eq. (65).

Third stage of the transpiration starts at $\psi_l^* > 1$ and at $\Phi_{03} \leq 0.2$, respectively. This stage, in fact practically is not covered by the field experiments.

Referring to this, we will limit our discussion to a qualitative level. Cultural plants – under condition of the third stage of transpiration – usually die away, or their ontogenesis is not leading to the production of economically valuable part of plant (grain, fruit). The third stage of transpiration during the later stages of ontogenesis (milk ripeness, etc.), usually ends in basic decrease of the yield and biomass production. Xerophytes and xeromorphous plants are adapted to withstand drought. As it was shown by Maximov (1950) – one of the leading plant physiologist – xerophytes under conditions of optimal soil water content are transpiring at the same rate like mezophytes – plants grown usually in conditions with optimum or slightly decreased soil water content.

At the end of this part, an important interval $0 < \psi_l^* < 1$ should be mentioned here. In it, the relative transpiration is decreasing slower, than the biomass production intensity (Budagovskij, Golubas, 1994).

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List of symbols

- A – area, [L²],
- B – soil heat flux [L² M T⁻²],
- C_s^* – specific heat capacity of a wet soil [L² T⁻² K⁻¹],
- C_w – water specific heat capacity [L² T⁻² K⁻¹],
- C_s – specific heat capacity of the solid fraction of soil [L² T⁻² K⁻¹],
- D_l – water vapour conductivity between leaf and its environment [L T⁻¹],
- D_t – heat conductivity between leaf and its environment [L T⁻¹],
- D_y – stomata conductivity [L T⁻¹],
- D_0 – turbulent conductivity of air layer between levels z_1 (the top of the canopy) and z_2 [L T⁻¹],
- E_t – transpiration rate [L³ L⁻² T⁻¹],
- E_{tp} – potential transpiration rate [L³ L⁻² T⁻¹],
- E – evapotranspiration rate [L³ L⁻² T⁻¹],
- E_{lp} – leaf transpiration at optimal leaf water content (potential transpiration) [L³ L⁻² T⁻¹],
- E_l – transpiration from the unit of leaf area [L³ L⁻² T⁻¹],
- E_p – potential evapotranspiration rate [L³ L⁻² T⁻¹],
- E_{sp} – potential evaporation rate [L³ L⁻² T⁻¹],
- E_s – soil evaporation rate [L³ L⁻² T⁻¹],
- H – precipitation [L³ L⁻²],
- I_a – long-wave radiation of the atmosphere [L² M T⁻²],
- I_e – long-wave radiation balance [L² M T⁻²],
- I_l – long-wave emission of the land surface [L² M T⁻²],
- K_p – integral hydraulic conductivity of a canopy [L³ L⁻² T⁻¹],
- L – latent heat of evaporation [L² T⁻²],
- P – sensible heat flux [L² M T⁻²],
- R – net radiation [L² M T⁻²],
- R_0 – net radiation at the top canopy level [L² M T⁻²],
- T – air temperature [°C],
- T^* – scaling parameter for air temperature,
- T_l – leaf temperature [°C],
- T_2 – air temperature at height z_2 [°C],
- V – volume [L³],
- c_p – specific heat capacity of air at constant pressure [L² M T⁻² K⁻¹],
- d – air humidity deficit [-],
- h – hydraulic head [L],
- k – coefficient of turbulent transport [M² T⁻¹],
- l – length of an element under study in the direction of wind speed [L],
- q – absolute air humidity [-],
- q^* – scaling parameter for absolute air humidity,
- q' – instantaneous fluctuations of absolute air humidity [-],
- q_l – saturated absolute air humidity in inter-cells leaf space [-],
- r_a – canopy aerodynamic resistance [T L⁻¹],
- r_s – stomata resistance [T L⁻¹],
- v_l^* – dimensionless leaf water content [-],
- v_l – water content per unit leaf area [L⁻²],
- v_p – rate of water flow from soil to the plant leaves [L³ L⁻² T⁻¹],
- w' – instantaneous fluctuations of the vertical component of wind speed [L T⁻¹],
- z – vertical coordinate [L],
- α – albedo [-],
- ε – thermal emissivity [-],
- ρ – air density [M L⁻³],

- ρ_s – dry soil density [$M L^{-3}$],
 σ – Stefan – Boltzmann constant [$M T^{-3} K^{-4}$],
 χ – von Kármán constant [–],
 ψ_l – leaf water potential [L],
 ψ_r – water potential at the surface of root hairs [L],
 ψ_w – soil water potential [L],
 $\omega(z)$ – leaf area index as a function of z [–],
 ω_0 – leaf area index [–].

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