Aerodynamic characteristics of wind disaster area in High Tatra Mts

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Abstract: The 19 November 2004 windstorm caused significant forest damage in High Tatra Mts. when about 12000 ha of forest stand was totally destroyed during this devastating windstorm effect. The vegetation type was dramatically changed when closed forest stands with age of 40–110 years were replaced by low vegetation. One part of this locality was also fire-stricken in July 2005. The extensive research and monitoring of meteorological and microclimatological characteristics is carried out on 4 windstorm-stricken sites. In this contribution an analysis of the airflow and wind speed profiles measured above one of them, the research fired site (FIRE site, 49° 08′ N, 20° 12′ E), is presented. This site is situated at a slope of 5–10% with SE orientation in the height 1000–1200 m a.s.l. The analysed wind direction and wind speed profiles were measured continuously by the wind speed and direction sensor WindSonic on 4 m high measured stand in four levels: 0.5, 1.0, 2.0, and 4.0 m from May 15 to July 17, 2007. The roughness length and aerodynamic resistance values were determined using this wind speed profile analysis. Dependencies of aerodynamic resistance on the roughness length and wind speed were analysed.

Key words: windstorm, wind speed profile, friction velocity, roughness length, aerodynamic resistance

1. Introduction

The land surface characteristics have the potential to make a critical impact on dynamics of meteorological elements in the surface layer of the atmosphere what results in creating characteristics of the microclimate. Forest ecosystems with respect to their area and structure play a significant role in production, modification, and microclimate protection (*Intribus, 1977*). Therefore the study of the interactions between the forest stand and the

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atmosphere was one of the objectives of several international experiments (*Halldin et al., 1999; Amoriello and Constantini, 2002*).

Almost no information is currently available as to the microclimate of the windthrow, neither in the domestic nor in the foreign literature. The authors touch only marginally on the microclimate of the windthrow. *Flesch and Wilson (1999a, 1999b)* determined aerodynamic characteristics of unharvested forest strips which provide wind shelter in harvest cutblocks and reduce windthrow for remnant trees, and found out that the spatial pattern of wind statistics over landscape, if known, arguably maps the relative risk of windthrow. *Venäläinen et al. (2004)* found out that, under conditions of high wind velocity, the change in surface roughness caused a locally significant increase in the windthrow risk. *Pellikka and Järvenpää (2003)* studied the meteorological characteristics and the impact of windstorm in boreal forest in western Finland. However, it is a surprising lack of information on the microclimate of the windthrow.

More then 40% of the Slovak territory is covered by forest stands. The 19 November 2004 windstorm caused significant forest damage in High Tatras when about 12 000 ha of forest stand was totally destroyed during this windstorm with devastating effect. The vegetation type was dramatically changed when closed forest stands with age of 40–110 years were replaced by low vegetation. In July 2005 the largest fire since 1949, when the Tatra National Park was founded, broke out. About 250 ha of the area, including forests, were burned to ashes. Damage to the forests caused by the fire was estimated at 16 million Slovak crowns. The environmental damage, however, is much greater. It evokes occurring of completely new airflow conditions above this area and then changes of the aerodynamic characteristics. Therefore the extensive research and monitoring of meteorological and microclimatological characteristics is performed on 4 windstorm-stricken localities: REF – reference, intact forest, EXT – extracted forest, wood removed site planted, FIRE – burnt forest, wood partly removed, and NEX – non-extracted forest, unmanaged (*Fleischer and Koreň, 2007*). Implementation and application of soil-vegetation-atmosphere transport models require knowledge of aerodynamic properties of the exchanging surface. Therefore, one needs to specify several parameters, such as the zero plane displacement (d), the roughness length (z_0), and additional parameters describing the roughness layer (*Graefe, 2004*). Aerodynamic resistance is an important parameter in bulk resistance models of energy exchange between the active surface and the atmosphere. The aerodynamic resistance is the time for unit volume of air to exchange heat or water vapour with unit area of surface. This time depends partly on the wind speed of the air-stream and partly on the geometry of the surface (*Monteith, 1965*).

The aim of this contribution is an analysis of the airflow and wind speed profiles measured above the FIRE site in High Tatras. Closed form analytical expressions are given for the wind speed profile ($u(z)$), the friction velocity (u^*), the roughness length (z_0), and the aerodynamic resistance (r_a). Dependencies of r_a on the z_0 values and wind speed were analysed.

2. Experimental site and methods

As mentioned before, the experimental data used for the analysis of airflow and determination of aerodynamic characteristics of windstorm-stricken locality were obtained by measurement at the FIRE site, High Tatras (49° 08′ N, 20° 12′). This research site is situated at a slope of 5–10% with SE orientation at the height of 1000–1200 m a.s.l. with tree representation, before windfall: spruce 70%, larch 30%, and stand age 80 years (*Fleischer and Giorgi, 2007; Fleischer and Koreň, 2007*). The vegetation type and surface cover was dramatically changed after windstorm and fire. At the beginning of the investigated period, in May, the surface was formed by burnt forest, wood partly removed and clusters of short grass. This surface in June and July was formed also by new vegetation, Lythrum salicaria, with mean height of about 0.9 m during July.

The field of airflow in the surface atmospheric layer generated by general atmospheric circulation is extremely influenced by terrain morphology. High-mountain massif of the High Tatras highly impacts the on wind field deformation because the massif represents a topographical barrier, especially for the northern components of general atmospheric circulation. Therefore the High Tatras in the Western Carpathian system are the region with the most expressive fall-winds. Fall-winds are created under certain weather situations with the topographical intensification of wind in their leeward regions. From the point of view of suitable meteorological conditions the occurrence of the severe fall-winds at the southern part of the

Tatra Mts. is the most probable at the beginning, as well as at the end of the cold half-year (*Otruba and Wiszniewski, 1974*). Extreme situation with the windstorm occurred in November 19, 2004.

The analysed wind direction and wind speed profiles were measured continuously by the wind speed and direction sensor WindSonic (GILL Instruments, UK). Analysed measurements carried out on 4 m high measured stand in four levels: 0.5, 1.0, 2.0, and 4.0 m measured from the soil surface from May 15 to July 17, 2007.

The aerodynamic characteristics of the investigated surface can be described using parameters like the roughness length (z_0) and the zero plane displacement height (d). The aerodynamic resistance values (r_a) were also determined from the wind speed profile analysis.

The d values were determined by processing the vertical wind speed profiles measured at the neutral thermal stratification of the atmosphere (*Brutsaert, 1982*). This parameter describes the effective aerodynamic origin of a rough surface. A physical interpretation was given by *Thom (1971)* as d being the height of the centre of pressure of the drag forces acting on surface including the drag on the soil surface. It is known, that $d > 0$ if the surface is formed by vegetation with the height more than 0.3 m.

The values of z_0 can be obtained from the analysis of the vertical wind speed profiles measured above a surface under different atmosphere thermal stratification (*Monin and Obukhov, 1954; Hurtalová and Matejka, 1999*). Following from the Monin-Obukhov similarity theory each vertical wind speed profile $\bar{u}_k(z_i)$ can be approximated by the relation

$$u_k(z_i) = A_k(\gamma + \log z_i) + C_k z_i, \tag{1}$$

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 are obtained from following relationship (*Monin and Obukhov, 1954*)

$$z_0 = 10^{-\gamma}. \tag{2}$$

Using the known values of A_k, C_k for each profile the friction velocity u^* and β/L, where β is the Monin-Obukhov‘s universal constant and L is the Obukhov‘s stability length, can be determined (*Monin and Obukhov, 1954*)

$$u^* = \frac{\kappa A_k}{\ln(10)}, \tag{3}$$

$$\frac{\beta}{L} = \frac{C_k}{A_k} \ln(10). \tag{4}$$

Based upon Eqs. (3) and (4), the physical sense of A_k and C_k parameters can be seen.

Aerodynamic resistance r_a was determined taking into account the thermal stratification using the relationship (*Hurtalová et al., 2003*):

$$r_a = \frac{\ln(z/z_0) + \frac{\beta}{L}(z - z_0)}{\kappa u^*}, \tag{5}$$

where z is the vertical coordinate of the reference level.

3. Results and discussion

As mentioned above the analysed wind speed profiles were measured above the investigated FIRE site on 4 m high measured stand in four levels: 0.5, 1.0, 2.0, and 4.0 m measured from the soil surface from May 15 to July 17, 2007.

At the beginning of the investigated period, in May, the surface was formed by burnt forest, wood party removed and clusters of short grass. The zero plane displacement height: $d \sim 0$ in this case. The analysed wind speed profile set during 15–31 May contained 398 profiles (mean hourly values). From these profiles 49.5% were in range $0.0 \leq u(1.0 \text{ m}) < 1.0 \text{ m s}^{-1}$ and 37.4% ones in range $1.0 \leq u(1.0 \text{ m}) < 2.0 \text{ m s}^{-1}$. During June 710 wind speed profiles were analysing and 81.3% of these ones were in range $0.0 \leq u(1.0 \text{ m}) < 1.0 \text{ m s}^{-1}$ and 18.3% in range $1.0 \leq u(1.0 \text{ m}) < 2.0 \text{ m s}^{-1}$. Investigated surface in June was formed by new vegetation Lythrum salicaria with mean height about 0.5–0.7 m and $d \sim 0.3 - 0.4$ m. It happend so that most of the analysed profiles were in range $0.0 \leq u(1.0 \text{ m}) < 1.0 \text{ m s}^{-1}$. But in the 4 m level the airflow was stronger then in May. Similar conditions for airflow above the investigated surface were also in July, when the mean plant height was about 0.9 m, but this vegetation was not closed around measured stand. The analysed wind speed profile set during 1–17 July contained 408 profiles and 88% of these were in range $0.0 \leq u(1.0 \text{ m}) < 1.0 \text{ m s}^{-1}$ and 12% in range $1.0 \leq u(1.0 \text{ m}) < 2.0 \text{ m s}^{-1}$.

Daily variability of the wind speed in the high-mountain zones of the High Tatras is due to the daily course of the turbulent exchange between the surface and higher levels of the free atmosphere, as well as between lower and higher parts of the massif. The wind speed at FIRE site has an expressive daily course characterized by one maximum and one minimum, Fig. 1. Such daily course is typical for the sites in the slope positions in the High Tatras. To a certain extent it can be compared with the course in the near meteorological station Stará Lesná (*Ostrožlík, 2007*). During the day, with the sunrise and by the development of thermal convection, the wind speed increases. In addition, Fig. 1, the highest values of the wind speed occur at noon and extreme values are round the 13 and 14 h. According to expectation the lowest values of wind speed are in the evening and above all in the morning hours (6 and 7 h). Stable atmospheric stratification causes a deceleration of air exchange in evening and morning hours.

The wind direction above FIRE site was measured at the same levels as the wind speed. During the investigated period, in May and June, the prevailing wind direction was WNW-NW at all levels (*Ostrožlík et al., 2008*). In July wind direction raged in the larger interval of SWS-NW except 0.5 m level. At this level the airflow was light.

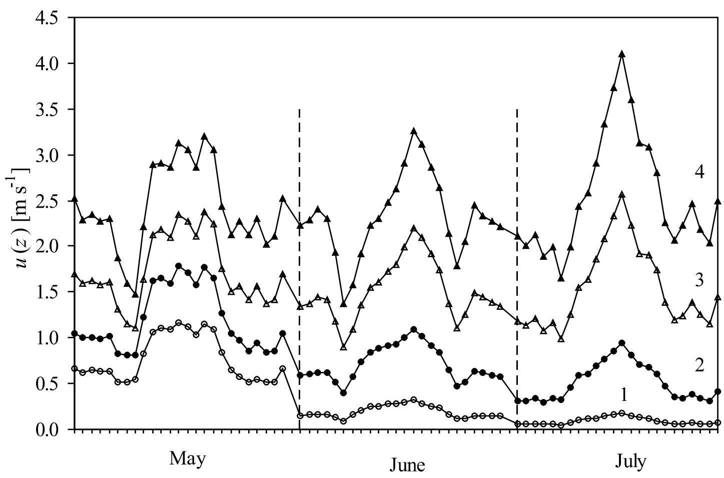

Fig. 1. Daily course of wind speed mean hourly values ($u(z)$) in four levels in May, June, and July at FIRE site. 1 – $z = 0.5$ m, 2 – $z = 1.0$ m, 3 – $z = 2.0$ m, 4 – $z = 4.0$ m.

The values of z_0 were obtained from the analysis of the vertical wind speed profiles measured above the investigated FIRE site surface under different atmospheric thermal stratification (*Monin and Obukhov, 1954; Hurtalová and Matejka, 1999*). Fluctuation of the mean daily z_0 values from 15 May to 17 July is presented in Fig. 2. It can be seen that z_0 values increased systematically with changing cover surface. The dispersion of z_0 values in July was caused by the dependence of these values on airflow above the investigated surface covered by vegetation. It was mentioned before that in July the surface was formed by Lythrum salicaria plants with the mean height (h) about 0.9 m. The surface characteristics were expressively changed. In this case the dependence of the friction velocity (u^*) on the wind speed measured approximately at the mean plant height level (u(1.0 m)) was analysed, Fig. 3. Assuming z_0 and d are constant with the wind speed, then from the log law the linear equation follows $u^* = a\,u(h)$, where a is constant. In this case the vegetation is in an aerodynamic steady state, the friction velocity is in the direct proportion to the wind speed. From experiment it follows that in a lot of cases above the flexible vegetation the u^* value settles down and deviates from the linear relation. Accordingly, the relation $u^* = f(u(h))$ is fitted as follows, $u^* = a[u(h)]^b$, a, b are constant. Then the vegetation is in an aerodynamic unsteady state and z_0 and d vary with the wind speed (*Brutsaert, 1982; Hayashi, 1983; Hurtalová and Matejka, 1999*). In this case the dependence u^* on $u(z)$, $z = 1.0$ m was analyzed and it can be approximated by the relationship

$$u^* = 0.485[u(z)]^{0.93}. \tag{6}$$

The correlation coefficient between u^* values determined from wind speed profile analysis, Eq. (3) and u^* values calculated using relationship (6) was 0.98. The b value is near to 1, but it was shown that z_0 values were strongly dependent mainly on small wind speed measured at 1.0 m level. It was shown, that 88% of these analysed wind speed profiles were measured in range $0.0 \leq u(1.0\text{ m}) < 1.0\text{ m}\,s^{-1}$. The mean monthly z_0 value in May was 0.15 m, in June 0.46 m, and in July 0.72 m.

The aerodynamic resistance r_a values were determined using results of the wind speed profile analysis by the Eq. (5). Fluctuation of the mean daily r_a values from 15 May to 17 July is presented in Fig. 4. Dispersion of r_a values can be explained by the dependence of r_a values on the wind speed, roughness length, and also on the atmosphere thermal stratification. It is evident from Eq. (5), where the atmosphere stratification is characterized by parameter β/L. As written before, the analysed wind speed profiles

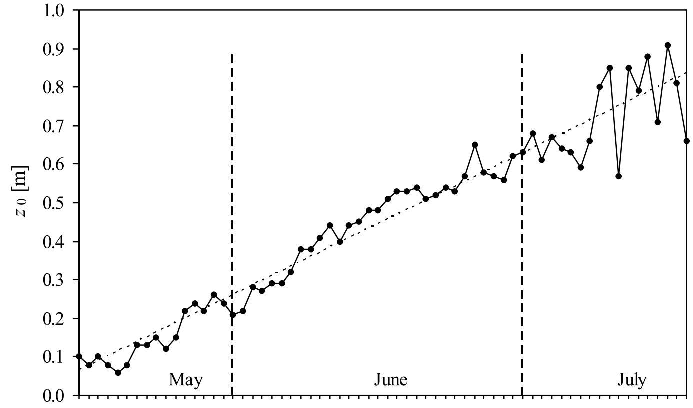

Fig. 2. Fluctuation of the roughness length mean daily values (z_0) at FIRE site from 15 May to 17 July 2007.

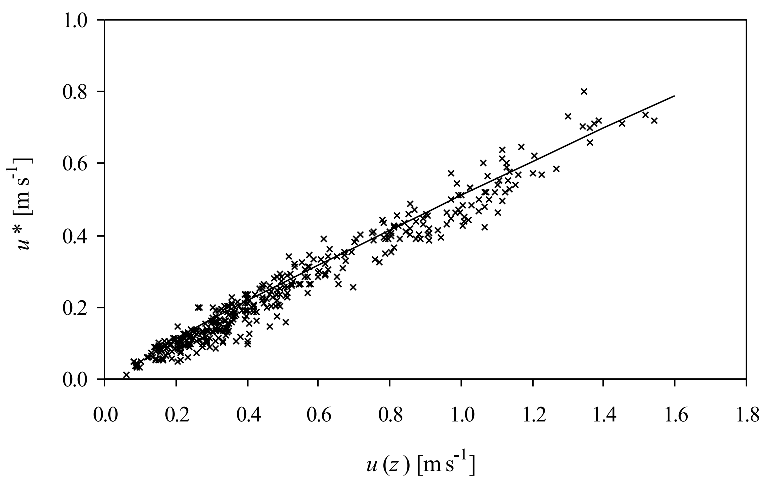

Fig. 3. Dependence of the friction velocity (u^*) on the wind speed mean hourly values ($u(z)$), where $z = 1.0$ m, in July 2007.

were measured under different atmospheric thermal stratification. The dependence of r_a values on z_0 mean daily values is presented in Fig. 5. This dependence can be fitted by a relation in the form

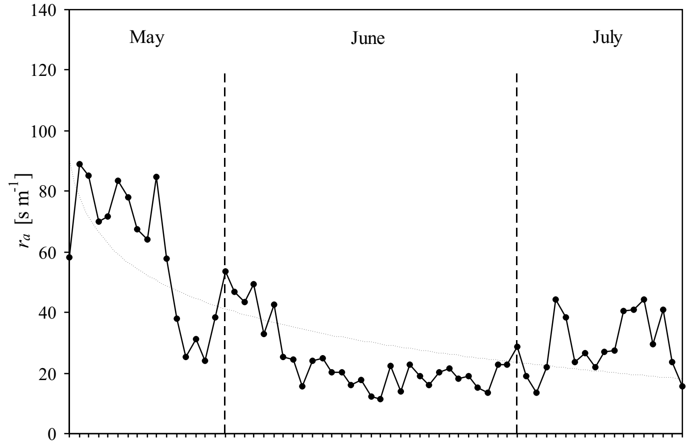

Fig. 4. Fluctuation of the aerodynamic resistance mean daily values (r_a) at FIRE site from 15 May to 17 July 2007.

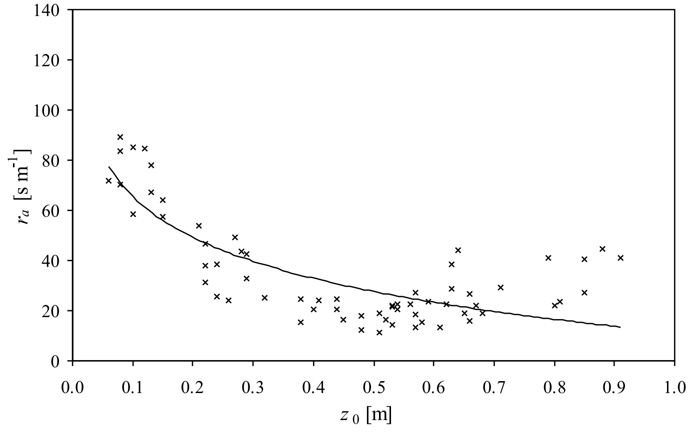

Fig. 5. Dependence of the aerodynamic resistance (r_a) on the roughness length mean daily values (z_0) during investigated period.

$$r_a = -23.58 \ln(z_0) + 11.30, \tag{7}$$

the correlation coefficient between r_a values being determined by Eq. (5) and Eq. (7) was 0.80.

The dependence of aerodynamic resistance on wind speed is more complicated. Therefore the dependence $r_a = f(u(z))$, where $z = 1.0$ m, was analysed for different z_0 values, Fig. 6. For interval 0.2 m $\leq z_0 <$ 0.4 m this dependence can be fitted by logarithmic equation in the form

$$r_a = -25.15 \ln(u(z)) + 30.56, \tag{8}$$

the correlation coefficient was 0.69. For larger interval of z_0 values: 0.6 m $\leq z_0 <$ 0.9 m

$$r_a = -24.45 \ln(u(z)) + 10.97, \tag{9}$$

the correlation coefficient being 0.83. It confirmed the fact that aerodynamic resistance decreases with increasing wind speed and dynamic roughness length. From this it follows that suitable conditions for increasing turbulence in the atmosphere boundary layer are created over roughness

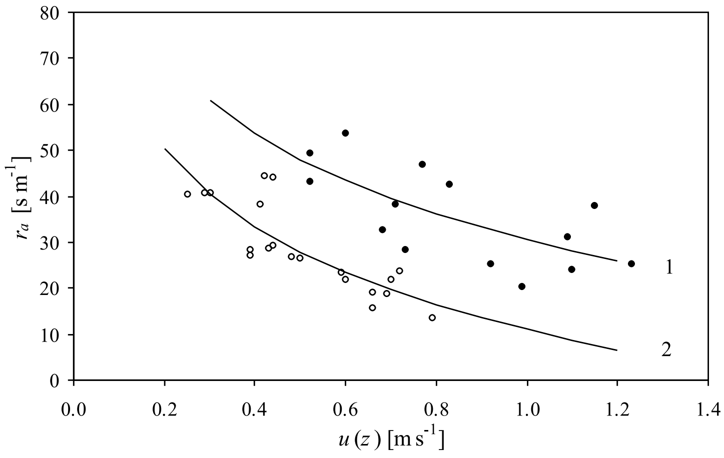

Fig. 6. Dependence of the aerodynamic resistance (r_a) on the wind speed mean daily values ($u(z)$), where $z = 1.0$ m, for different z_0 values.
1 0.2 m $\leq z_0 <$ 0.4 m
2 0.6 m $\leq z_0 <$ 0.9 m

surface at strong airflow. This is in good conformity with the experimental results published for example by *Hall (2002)* and *Smith et al. (1997).*

4. Conclusions

Forest damage caused by wind and fire is a serious economical problem concerning forestry in Europe (*Pellikka and Järvenpää, 2003*). The environmental damage is much greater. The windstorm in November 2004 and fire in July 2005 caused significant forest damage in High Tatra Mts. and dramatically changed conditions and factors affecting the microclimate in this stricken region. The vegetation type was changed when closed forest stands with age of 40–110 years were replaced by low vegetation. It evokes occurring of completely new airflow conditions above this area and then changes of the aerodynamic characteristics of the surface and of air layer affected by this surface. Implementation and application of soil-vegetation-atmosphere transport models require knowledge of aerodynamic properties of this system. Therefore the extensive research of meteorological and microclimatological characteristics is realized in this windstorm-stricken region, which forms a large natural laboratory.

In this paper the analysis of the airflow and wind speed profiles measured above one of 4 experimental disaster sites - FIRE site - was presented. The wind direction and wind speed profiles were measured continuously at 0.5, 1.0, 2.0, and 4.0 m levels from 15 May to 17 July 2007. The analysed set contained 398 wind speed profiles in May, 710 in June, and 408 profiles in July. From these profiles 49.5% were in range $0.0 \leq u(1.0\ \mathrm{m}) < 1.0\mathrm{m\,s^{-1}}$ and 37.4% ones in range $1.0 \leq u(1.0\ \mathrm{m}) < 2.0\ \mathrm{m\,s^{-1}}$ in May. During June and July, when the surface was covered also by new vegetation (Lythrum salicaria), 81.3% in June and 88.0% from analysed profiles in July were in range $0.0 \leq u(1.0\ \mathrm{m}) < 1.0\ \mathrm{m\,s^{-1}}$. The aerodynamic characteristics of the investigated surface can be described using parameters like the roughness length (z_0) and the zero plane displacement height (d). In May $d \sim 0$ and mean z_0 - value was 0.15 m. During June mean daily z_0 - value increased systematically from 0.22 m to 0.63 m and in July these values ranged in the interval $< 0.57, 0.91 >$ m. It is the result of surface characteristic changes. On the basis of experimental dependence $u^* = f[u(1.0\ \mathrm{m})]$ in July, Eq. (6), it was shown that vegetation covering the investigated surface was in aerodynamic unsteady state. It means that z_0 values vary also with the wind speed.

The prevailing wind direction in May and June was WNW-NW at all levels. In July wind direction raged in the larger interval of SWS-NW except 0.5 m level. In this level airflow was light. It is result of the local orographicaly broken terrain in High Tatras (*Ostrožlík et al., 2008*).

It is known that aerodynamic resistance is an important parameter in bulk resistance models of energy exchange in the surface – atmosphere system. Therefore r_a values were also determined using wind speed profile analysis. Dependencies $r_a = f(z_0)$ and $r_a = f(u(1.0\text{ m})$ were found, Figs. 5–6, and analytically expressed by Eqs. (7), (8), and (9). So, u^* values decrease with increasing wind speed and dynamic roughness length. From this it follows that suitable conditions for increasing turbulence in the atmosphere boundary layer are created over roughness surface at strong airflow.

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