AERODYNAMIC RESISTANCE OF THE LAYER OF ENERGY WOODEN CHIPS*

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Aerodynamic resistance of the layer of energy wooden chips in the process of drying is an important characteristic parameter of a material allowing dimensioning of the size of drying fans. It is presupposed that existing high-capacity haylofts equipped by drying grates and fans would be used for drying and storage of these materials. To determine aerodynamic resistance of the layer of a material, measuring device was designed in the shape of cylinder, in which the layer of material is aerated supplied by fan of a varied pressure conveyed under the grate. Aerodynamic resistance was determined for the layer of chips from plantation management of woody species and for energy wooden chips of different structure. Chipped material manifests aerodynamic resistance of air comparable with hay or similar stemmed materials.

aerodynamic resistance; energy wooden chips; high-capacity haylofts

INTRODUCTION

For drying of bio-energy materials it is necessary to know their ability to pass drying air through the heaped layer. It is assumed that high-capacity haylofts equipped with routine technology can be used for drying of these materials, e.g. energy wooden chips from thinnings, plantation management or plantations of fast-growing woody species. The possibility of the usage of existing fans is limited by condition that heaped layer of a drying material has comparable aerodynamic resistance with hay, for which these technologies were originally designed. The possibilities of drying of some materials were tested in experiments (Hutla, Sladký, 1998, 1999). Some differences appear when comparing with drying of forage during drying of energy materials. During forage drying this has to be done relatively quickly to prevent the loss of nutrients and depreciation of hay. In energy materials the first is minimization of electric energy consumption.

When determining resistance of airflow it can be started from the general theory of passage of gas through the layer of particles. The aerodynamic resistance represents certain integral characteristics of the layer of material including a set of partial phenomena of relatively complex flow of gas among the particles randomly created through the through-flow routes. Regions with uneven aerodynamic resistance may exist in the layer, through which the gas can flow sometimes by very different velocities. Gradual irregular by-passing of particles in the layer results in formation of whirls in gaps and leads to certain degree of mixing of the gas flow as in the direction of passage as in the direction perpendicular to it. For characteristics of the material a concept of hydraulic diameter of the layer d_h given by the following equation (Hlavačka et al., 1980) can be introduced:

$$d_h = \frac{4\varepsilon}{a_s} = \frac{2}{3}\frac{\varepsilon}{1-\varepsilon}d \qquad (1)$$

where: d – characteristic size of a particle
a_s – specific surface of particles (related to the volume of the system)
ε – porosity ($\varepsilon = \frac{1}{V}\iiint_V \mu(x)dV$, where $\mu(x) = 0$ for points particles are present, somewhere else $\mu(x) = 1$)

It follows from the dimensional analysis that the aerodynamic resistance characterized by the pressure decrease Δp in the layer is proportional to the product of powers determining physical quantities (Hlavačka et al., 1980).

$$\frac{\Delta p}{L} \approx \eta_g^{2-n} v^n l^{n-3} \rho_g^{n-1} \qquad (2)$$

where: L – height of layer
η_g – dynamic viscosity of air
ρ_g – density of air
l – characteristic dimension
v – characteristic velocity of gas

If a characteristic velocity of gas in the layer is substituted by out of layer velocity of gas w_o and porosity, then after the insertion of d_h according to the relation (1) for l follows the dependence

$$\frac{\Delta p}{L} \approx \eta_g^{2-n} w_o^n d^{n-3} \rho_g^{n-1} \frac{(1-\varepsilon)^{3-n}}{\varepsilon^3} \qquad (3)$$

Exponent n in equations (2) and (3) reaches the values from 1 to 2 depending on the character of flowing (Hlavačka et al., 1980). In laminar region $n = 1$, in developed turbulent flowing $n = 2$.

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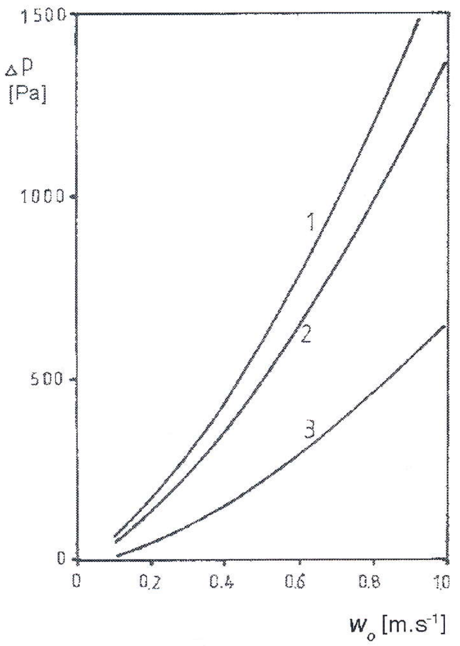

Fig.1. Aerodynamic resistance of 10 mm thick of the grain layer as depended on velocity of airflow (Pěkný et al., 1963):
1 – rye, 2 – wheat, barley, 3 – maize

For aerodynamic resistance of air in the passage through the layer of some grains Shedd (1953) reported the similar relation but in a simplified form:

$$\frac{\Delta p}{L} = A \cdot w_o^B \qquad (4)$$

where: A, B – experimentally found coefficients for the given testing conditions

Hukill and Ives (1955) reported other model used later in recommendation ASAE D272.3 MAR 96 (ASAE, 1997)

$$\frac{\Delta p}{L} = \frac{a \cdot w_o^2}{\ln(1 + b \cdot w_o)} \qquad (5)$$

where: a, b – experimentally found coefficients for the given testing conditions

However, it is typical for some agricultural materials that the air aerodynamic resistance is dependent on the direction of passage. Mathematical model was developed for these cases that is suitable for passage of air through anisotropic medium (Jayas, Muir, 1991).

When applying aerodynamic conditions in drying agricultural materials some general dependencies of aerodynamic resistance are referred to (Figs. 1, 2; Pěkný et al., 1963). The data of aerodynamic resistance in dependence on the type of drying material, material water content and velocity of flow for withered herbage (FMZV, 1984) correspond to these values (Tables 1 to 3).

For practical utilization of hay after-drying is considered that the airflow velocity in the material should not exceed value of 0,1 m/s. The working pressures at this velocity are ranging from 30 to 100 Pa per 1 m of height in dependence on forage type and stage of its after-drying.

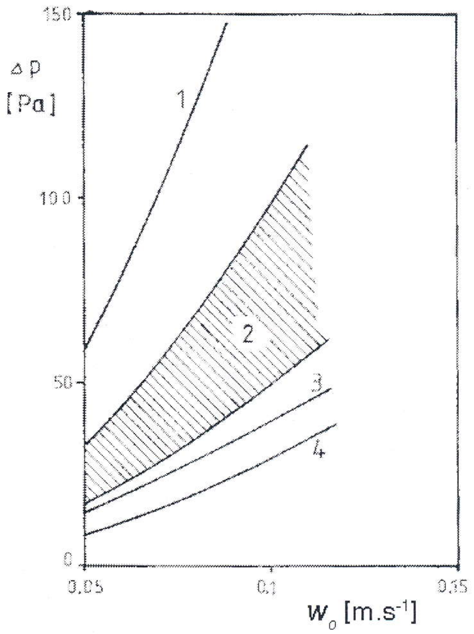

Fig. 2. Aerodynamic resistance of 1 m thick herbage layer as depended on the velocity of airflow (Pěkný et al., 1963):
1 – alfalfa cut to 50 mm, 2 – meadow hay cut to 50 mm – range given in section lining part contains the material of different moisture and density, 3 – long meadow hay, 4 – long alfalfa

Table 1. The range of air aerodynamic resistance in the dried forage of water content (w.b.) from 35% to 40% in hayloft in dependence on the type of forage in conversion per 1 m of the layer (FMZV, 1984)

Forage, species, condition	Relative pressure decrease (Pa/m)	Note
Young, richly leaved grass	60 to 100	cut
Older, stemmed grass	30 to 60	not cut
Young, richly leaved alfalfa	40 to 80	cut
Older, stemmed alfalfa	20 to 50	not cut

Table 2. Dependence of aerodynamic resistance in forage on the water content (w.b.) (FMZV, 1984)

Water content in material w.b. (%)	Relative pressure decrease (Pa/m of grass height)	Note
20	40	dry
30	70	semi-dry
40	110	very wilted for drying
50	150	wilted
60	200	slightly wilted for drying by heated air

Scheuermann (1996) studied aerodynamic resistance of air for strongly pressed meadow hay. The values of pressure decrease ranging between 500 and 100 Pa/m as depended on water content from 18 to 16.5% were reported for the velocity of airflow 0.1 m/s. The material used is compressed to the density from 140 to 170 kg/m^3.

Table 3. Dependence of air pressure and power of fans on the velocity of flow of drying air through the wilted forage in hayloft (FMZV, 1984)

Velocity of airflow through forage	Drying grate area	Height of layer	Working pressure of fan	Airflow passing through the dryed material	Engine power	
$m.s^{-1}$	m^2	m	Pa	$m^3.s^{-1}$	kW	%
0.1	108	5	460	10	7.5	100
0.2	54	5	1200	10	19.6	260
0.3	36	5	2000	10	32.0	426

Note: With higher permeable velocities the fan works inefficiently, it makes itself a useless resistance.

Aerodynamic resistance of the layer of material is also determined in other agricultural materials. Irvine (1993) studied the effect of different factors during storage of potatoes on pressure decrease during passage of the air through their layer. In big potato tubers these values reached only 41 % of the data obtained for small ones. In addition, e.g. the variety Rłlusset Burbank with elongated tubers, had lower pressure decrease with horizontal flow compared with vertical direction. Soil admixtures were increasing this value during vertical flowing.

Neale and Messner (1976) found that the value of aerodynamic resistance in onion, carrot and potatoes is more affected by soil admixtures and other materials than physical properties of the crops themselves. Tabil et al. (1999) studied the effect of the size of sugar beet roots, soil admixtures and direction of airflow on aerodynamic resistance of flowing air. The highest values were found in small sugar beet roots, where soil admixtures were further increasing significantly this value. These soil admixtures had a greater effect on increasing of pressure decrease values of flowing air in vertical direction of flow compared with horizontal one. Coefficients A and B were determined for taken values of dependence of pressure decrease on the velocity of airflow according to equation (4).

Kumar, Muir (1986) studied the airflow resistance during passage through cleaned and non-cleaned grains of wheat and barley as depended on direction of airflow, method of container filling and volume of filled container. It follows from the results that pressure decrease values in horizontal direction of airflow through the layer of grains are much lower than those taken in vertical direction and the same time, the method of filling.

ASAE Standards (1997) present characteristics of aerodynamic resistance for different agricultural materials, for which drying and storing systems are designed. Aerodynamic resistance of the layer of material showed horizontally 60–70% of the values of vertical aerodynamic resistance. In experiments with grains contaminated by other admixtures it was found that the aerodynamic resistance is rising if the structure of admixture is softener than grains and on the contrary, it is dropping, if admixture is of harder structure than grains.

This study is aimed at determining of the aerodynamic resistance of the layer of energy wooden chips of a different structure.

MATERIAL AND METHODS

The device presented in Fig. 3 was designed to determine aerodynamic resistance. It is composed of transparent cylinder of brightness 0.29 m and length of 1.5 m. The cylinder is attached to the over-pressure part of the same material into which the air is conveyed through the flexible air pipe. The source of pressure air is a radial fan.

Grates of different perforation can be placed in the lower part of the main cylinder. The studied material is on the grate. Revolutions of the fan are controlled by the value of conducted voltage and allow creation of over-pressure under the grate up to 400 Pa. The air pressure is measured under the grate and above the dried material. The measuring instrument DIGIMA LPU – Model 250 (manufactured by Special Instruments) takes the difference of these pressures. The velocity of airflow is measured in reduction outlet adapter of conical shape.

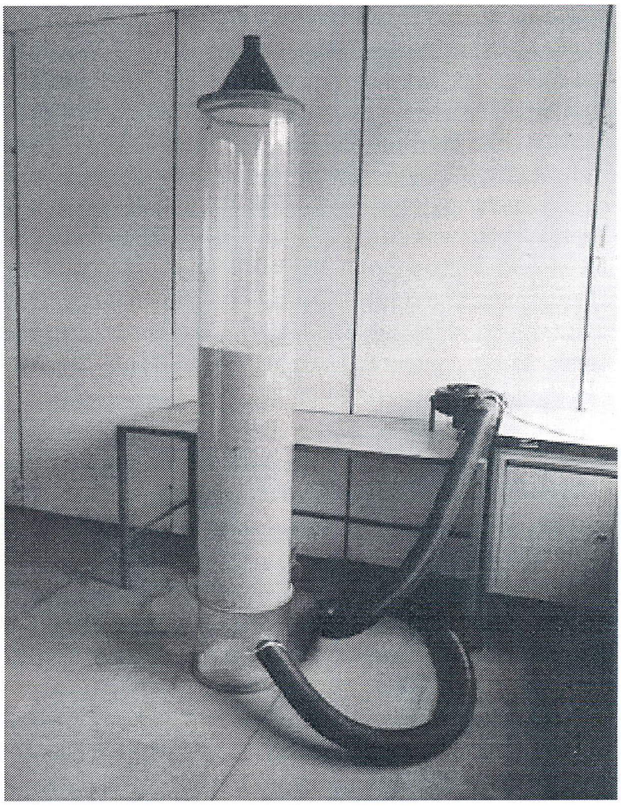

Fig. 3. The device measuring pressure decrease in dried layer of material

The area of cross section of the main cylinder is here reduced to the circular cross section of the diameter 0.039 m. Propeller anemometer, type 1416 U10 manufactured by Wilhelm Lambrecht GmbH is used for measurement. Diameter of measuring propeller of this device is 15 mm.

The equation of continuity can be applied for conversion of the measured value to the values of the rate in cross section of the main cylinder, i.e. to the rate w_0 according to equation (3). The coefficient of cross section change, that is also in ratio of velocities in the main cylinder (outside the material) and outlet part is as follows:

$$K_r = \frac{S_v}{S_n} = \left(\frac{d_v}{d_n}\right)^2 = 0{,}018 \qquad (6)$$

where: S_v – area of outlet part
S_n – area of cross section in measuring cylinder
d_v – diameter of outlet part
d_n – diameter of measuring cylinder

Dependencies of pressure decrease values were measured in the above measuring device for the layer of wooden chips. They are chips from plantation management of woody species and chips from poplar energy plantation. The material was loosely heaped and not compressed in all cases.

The chips from plantation management

The source of the chips is thinning of fruit trees. The device manufactured by the company Pötinger was used for chipping, at which the specified size of the chip 2 cm was set. The structure of the chips is in Table 4.

The chips from the poplar plantation

The source of the chips is the plantation of energy poplars from the farm Peklov of Hospodářské družstvo Unhošť (Agricultural Enterprise). The trees were 4 years old, diameter of stems was up to 12 cm. It is a hybrid Populus maximoviczii x Populus nigra, the clone No. J-104 and J-105. Drum chipping machine 4 HM 40 (Tomahawk M-P-350) driven by the tractor Zetor 7711 was used for chipping. The material was earlier dried on grates. Water content (w.b.) in the material is 10.1%. The structure of the material is in Table 5.

The presented material was further separated into fractions according to the size of particles and pressure decrease of such material of different structure was measured.

RESULTS AND DISCUSSION

The chips from plantation management

The material was measured at two values of water content (w.b.), i.e. 40.4% and 22.1%. In the first case the layer of the material was 0.9 m. In the second case, the layer of the material was 0.85 m. Graphs in Fig. 4 present dependencies $\Delta p = \Delta p\ (w_o)$ for calculated values of the height of the material 1 m and for the velocity of airflow in profile of cylinder of measuring device. Dependencies are also given in analytical expression, for which power function was applied.

Table 4. Chip size from plantation management

Size x (mm)	Proportional amount (% of weight)
$x > 40$	3.1
$40 > x > 25$	5.3
$25 > x > 20$	7.3
$20 > x > 15$	24.5
$15 > x > 10$	29.4
$x < 10$	30.4

Table 5. Chip size from poplar plantation

Size x (mm)	Proportional amount (% of weight)
$x > 80$	0
$80 > x > 40$	2.4
$40 > x > 25$	10.9
$25 > x > 20$	11.2
$20 > x > 15$	19.4
$15 > x > 10$	24.6
$x < 10$	31.5

It is evident from Fig. 4 that the material shows decrease in pressure decrease with falling water content for passing air. It corresponds also to experience with drying of other plant materials when porosity is growing with falling water content (FMZV, 1984) (Table 2).

The chips from the poplar plantation

This material was measured in the layer of 0.9 m. Water content (w.b.) in material was 11%. This value was obtained by drying and subsequent longer persisting storage on dry place. Moreover, the values were measured for different fractions of the size of particles of poplar chips. More detailed definition of some fractions is in Table 6.

Graphs in Fig. 5 present dependencies $\Delta p = \Delta p\ (w_o)$ for calculated values of the layer of height 1 m and for the velocity of flowing in profile of cylinder of measuring device. The dependencies can also be given in analytical expression using the power function $\Delta p = A \cdot w_o^B$. The coefficients A and B for different dependencies were determined by the method of the least squares (Table 7).

The expected fact, i.e. increasing aerodynamic resistance is with decreasing structure of the material, is evident from Fig. 5. However, the founding is interesting that the fraction with content of the least particles, i.e. smaller than 10 mm, including not classified material show all aerodynamic resistance exceeding fractions without the least particles. The highest aerodynamic resistance has the fraction with particles < 10 mm. On the

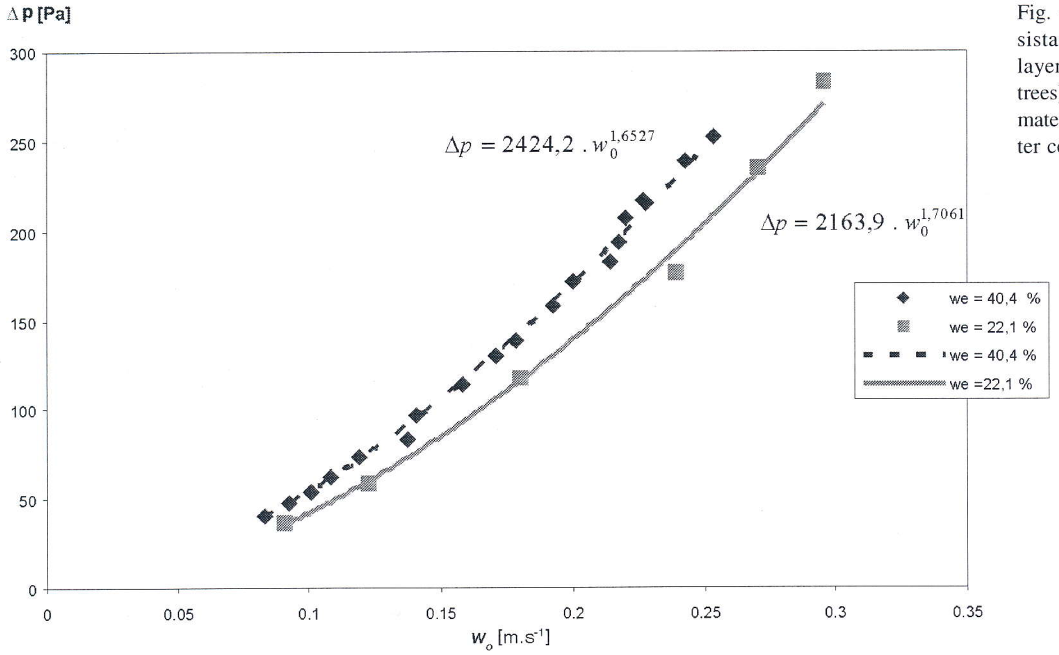

Fig. 4. Aerodynamic resistance of the chips layer (thinning of fruit trees) 1 m thick for the material of different water content (w.b.) (w_e)

contrary, in the mixture of the least particles with greater particles, i.e. with fractions in intervals (10, 15) mm and (15, 20) mm aerodynamic resistance is significantly decreasing, by more than a half.

Moreover, Table 7 presents for all dependencies from Fig. 5 for all types of measured materials transparently among the coefficients *A* and *B* according to the equation (4) and relevant correlation indicators (Kába, 1977).

In additions, Figs 6 and 7 present the dependence of coefficients *A* and *B* on medium size of particle of poplar chips.

From both these graphs a typical falling dependence of coefficient *A* is evident on medium size of particles to the increasing value of coefficient *B*. It remains to compare the data found with the values given in the literature. Available are data for wheat and barley (Kumar, Muir, 1986) and for sugar beet roots (Tabil et al., 1999). These literary data are in Table 8.

The size of the material given in Table 8 is not quoted in literature. Therefore, these agricultural materials were measured and mean dimensions are presented in Table 9.

For the values of mean size of materials according to Table 9 coefficients *A* and *B* from graphs in Figs 6 and 7 can be subtracted. Despite the fact that graphs in these figures are applied for the structure of material particles of wood chips, it can be presupposed hypothetically that

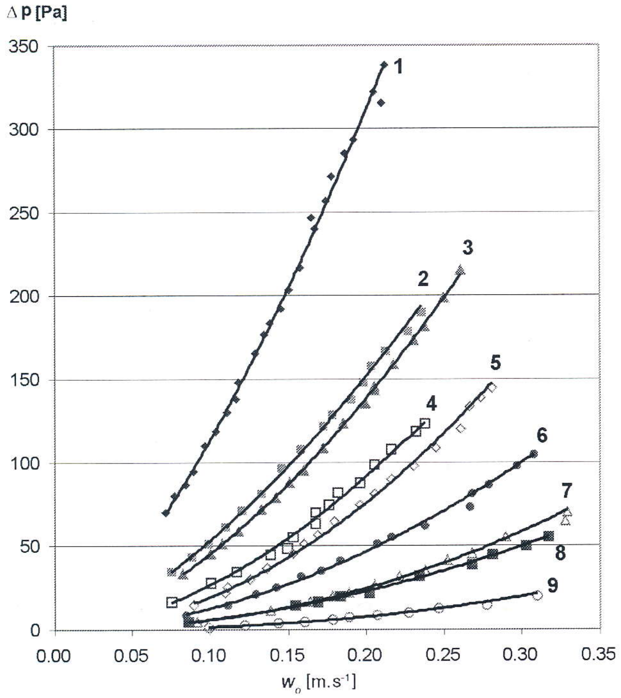

Fig. 5. Aerodynamic resistance of the layer of poplar chips 1 m thick with different size of particles. Numbers of samples, characteristics of the sizes of a material as well as calculated parameters of regression equations are in Table 7

Table 6. Chip size of some fractions of poplar chips

Denotation of materials (size x in mm)	Structure according to mesh sieve analysis	
	Size x (mm)	Proportional amount (% of weight)
20 > x > 0	20 > x > 15	15.7%
	15 > x > 10	32.7%
	x < 10	41.6%
15 > x > 15	15 > x > 10	44.0%
	x < 10	56.0%

Table 7. Characteristics of samples of poplar chips and parameters of regression equations for different samples

Sample 1	Processed data		Non-linear regression		
	Fraction	Medium size	Regression equation $\Delta p = A \cdot w_o^B$		
	d (mm)	d_s (mm)	A	B	I_{yx}
1	0–10	5.0	3,237.25	1.45791	0.9979
2	0–15	8.29	1,729.62	1.51453	0.9991
3	0–20	10.66	1,870.30	1.61907	0.9998
4	0–80	15.39	1,622.59	1.78758	0.9963
5	10–15	12.70	1,791.78	1.96619	0.9980
6	15–20	17.50	960.95	1.87997	0.9976
7	20–25	22.50	758.18	2.12805	0.9955
8	25–40	32.50	508.13	1.92614	0.9989
9	40–80	53.33	330.77	2.33653	0.9919
Statistics of correlation indicator I_{yx}			mean value		0.9972
			standard deviation		0.0024
			minimum		0.9919
			maximum		0.9998

Table 8. Coefficients of power functions of characteristics of aerodynamic resistance of some material (Kumar, Muir, 1986; Tabil et al., 1999; ASAE, 1997)

Material	A	B
Wheat	6690	1.11
Wheat*	8680	1.30
Barley	7540	1.23
Barley*	6480	1.42
Sugar beet roots	159.83	1.94
Sugar beet roots with soil admixture 8.53%	426.92	1.98
Sugar beet roots < 1.2 kg	228.94	1.85
Sugar beet roots < 1.2 kg with soil admixture 4.44%	603.28	1.91
Sugar beet roots > 1.2 kg	116.69	1.82
Sugar beet roots > 1.2 kg with soil admixture 4.57%	275.3	1.9

* by the ASAE standard

Table 9. Characteristic dimensions of some agricultural materials

Material	Length (mm)	Width (mm)
Wheat – grain	6.5	3.5
Barley – grain	7	2.7
Sugar beet root 1.2 kg	200	120

above all the size of particles can significantly affect the aerodynamic resistance. Comparison of read values with literary data according to Table 8 is in Table 10.

It is evident from the above comparison that the values of coefficient A are higher for particles in the shape of grains or roots and the values of coefficient B are lower than it corresponds to the values for chips.

Consequently, these agricultural materials manifest in the layer aerodynamic resistance corresponding to smaller dimensions, however, in the shape of particles characteristic for particles of wooden chips. Both the values are close enough and can be easily explained by completely different shape of particles. To find the suitability of drying fans that are originally designed for finishing drying of fodder plants, for purposes of drying of energy wooden chips, aerodynamic resistance can be compared for both these materials. From Fig. 2 and Tables 1 to 3 pressure decrease of the layer of material about 30 to 200 Pa/m can be read for a usual velocity of airflow 0.1 m/s. Pressure decrease 42 and 54 Pa/m can be subtracted for the chips from plantation management for the same velocity of airflow (Fig. 4). In energy wooden chips from poplar plantation (Fig. 5) pressure decrease is 27 Pa/m. For fraction of the smallest particles this value is 112 Pa/m, for the greatest particles (40–80 mm) it is 1.5 Pa. It is apparent from the mentioned comparison that the values of aerodynamic resistance of the layer of fodder plants and wooden chips presented in this study are similar and the same drying fans can be used for both these materials.

CONCLUSION

The dependencies of aerodynamic resistance in the heaped layer of wooden chips allow judgement of possibilities to use existing fans, installed in high-capacity haylofts for finishing drying of these bio-energy materials. At the same time it is possible to estimate energy demandingness during drying or optimal size of particles of drying material.

The chipped material of the structure, as it was used for the given measurement, shows aerodynamic resistance comparable with hay or similar materials that were devoted for drying in existing high-capacity haylofts. Therefore, it can be concluded from this aspect on suit-

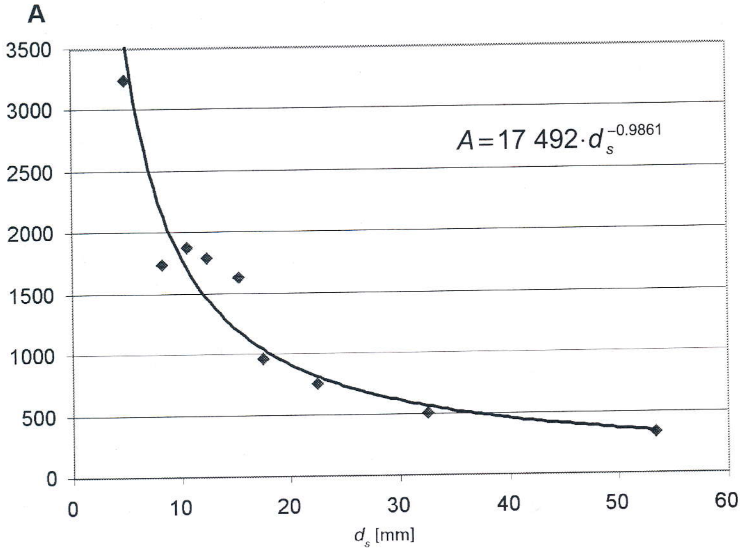

Fig. 6. Dependence of parameter *A* of regression equation on the medium size of particles of poplar chips

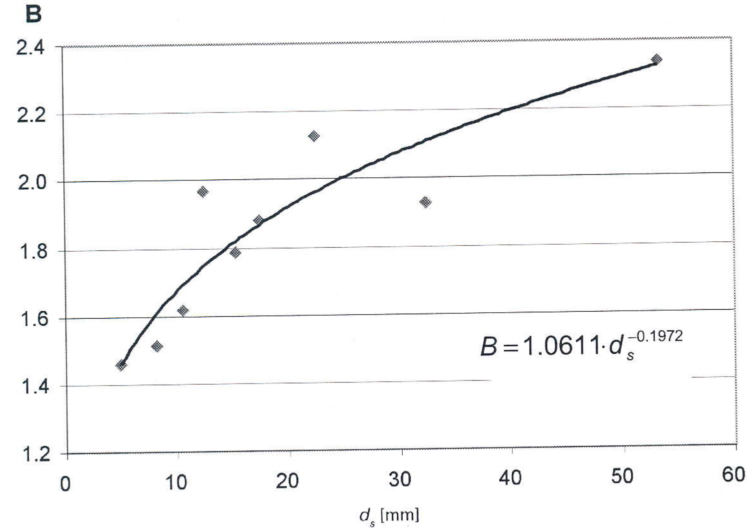

Fig. 7. Dependence of parameter *B* of regression equation on medium size of particles of poplar chips

Table 10. Coefficients of power functions of characteristics of aerodynamic resistance for the values of dimensions of some agricultural materials and comparison with literary data

Material	Coefficient *A* after Fig. 6	Coefficient *A* after Table 8	Coefficient *B* after Fig. 7	Coefficient *B* after Table 8
Wheat – grain	3580	6690 ÷ 8680	1.46	1.11 ÷ 1.30
Barley – grain	3690	6480 ÷ 7540	1.45	1.23 ÷ 1.42
Sugar beet roots	117[1)]	116 ÷ 229	2.89[1)]	1.82 ÷ 1.85

[1)] sugar beet roots of weight 1.2 kg

ability of usability of existing fans that are installed in high-capacity stocks of hay as well as for finish of drying of wooden chipped materials.

The size of particles significantly affects the value of aerodynamic resistance. It is evident from Fig. 5 that when bigger particles are removed from the mixture, aerodynamic resistance increase almost twice in fractions 8 and 9 and four times in the fraction with the smallest structure ($x < 10$ mm). Aerodynamic resistance during finishing of drying are thus one of prerequisites for determining of requirements for the structure of wooden chipped material.

The list of used symbols

d_h – hydraulic diameter of the layer of material (m)
d – characteristic size of particles of layered material (m)
a_s – specific surface of particles ($m^2.m^{-3}$)
ε – porosity (–)
Δp – pressure decrease (Pa)
L – height of layer of material (m)
η_g – dynamic viscosity of air ($N.s.m^{-2}$)
ρ_g – density of air ($kg.m^{-3}$)
l – characteristic dimension of flow channels (m)
v – characteristic velocity of gas ($m.s^{-1}$)
w_o – out of lyer velocity of gas ($m.s^{-1}$)
K_r – coefficient of the change of cross-section of measuring device (–)

S_v – area of outlet part of measuring device (m^2)
S_n – area of cross-section in measuring cylinder (m^2)
d_v – diameter of outlet part of measuring device (m)
d_n – diameter of measuring cylinder (m)
A, B, a, b – experimentally found coefficients for the given testing conditions in equations to calculation of aerodynamic resistance
d_s – mean size of particles in the sample (mm)
I_{yx} – correlation indicator of random variables X, Y
w_e – water content of material (%)

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Scientia Agric. Bohem., *36*, 2005: 113–120.

Schopnost materiálu propouštět sušící vzduch je důležitým parametrem, jehož znalost je třeba pro navrhování sušicích roštových zařízení. Předpokládá se, že pro sušení a skladování bioenergetických materiálů mohou být využity stávající velkokapacitní seníky, které jsou v současnosti z velké části nevyužity. Jejich technologické vybavení, tj. rošty a sušicí ventilátory, jsou dimenzovány pro sušení sena a jiných stébelnatých materiálů.

V této práci jsou zjišťovány tlakové ztráty při průchodu vzduchu vrstvou energetické štěpky s různou strukturou částic. Jsou uvedeny teoretické podklady pro závislosti tlakových ztrát na rychlosti proudění vzduchu v pevné vrstvě a známé naměřené závislosti pro některé zemědělské materiály. Pro měření tlakových ztrát energetické štěpky bylo vyvinuto a dále použito měřicí zařízení, sestávající z válce, v němž je na roštu vrstva měřeného materiálu. Pod rošt je přiváděn ventilátorem vzduch s regulovaným tlakem. Měří se tlakový rozdíl na vrstvě materiálu a mimovrstvová rychlost proudění vzduchu. Měřenými materiály jsou štěpka ze sadových úprav s definovanou strukturou, štěpka z topolové energetické plantáže a frakce téhož materiálu rozděleného podle velikosti částic. Naměřené závislosti tlakových ztrát vykazují podobnost se stébelnatými materiály. Lze proto odvodit vhodnost použití stávajících seníkových technologií pro dosoušení bioenergetických materiálů na bázi dřevní štěpky.

aerodynamický odpor; energetická štěpka; velkokapacitní seník

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