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Influence of shape of cutting tool on pressure conditions in workspace of mulcher with vertical axis of rotation

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Abstract. Nowadays there is laid great insistence on work efficiency improvement. This effort also affects the construction of mowers such as mulchers. Mulching with a vertical axis of rotation is very energy demanding work operation mainly, due to high energy losses. These energy losses, but also the quality of work, are influenced by the airflow and associated conditions of pressure inside the workspace of mulcher. Airflow in the workspace ensures repetitious contact of the truncated forage crops with the cutting edge tool and thus ensures crushing of aboveground parts of plants. The paper deals with the influence of the cutting tool shape on the mulcher's inside workspace pressure conditions with the vertical axis of rotation. The influence of the trailing edge angle and rake angle on the pressure profile in the mulcher's workspace with dependence on the rotor speed was examined. Measurements were performed on a laboratory single rotor mulcher model. It was found that in the mulcher's workspace the vacuum is formed by virtue of the rotary movement of the cutting tools wherein the vacuum increases with rotor speed. The maximum measured vacuum was about 2.4 kPa and from the centre of the rotor towards its circumference almost linearly decreases. Furthermore, it was found that with decreasing trailing edge angle and with increasing rake angle the maximum vacuum decreases. When reducing the angle of the trailing edge from 45° to 25° led to reduction of vacuum of about 0.3 kPa (12.6%).

Key words: mulcher, pressure, airflow, cutting tool.

INTRODUCTION

Mulching is a technological process during which crushed plant residues are left on the soil surface. It is primarily used for cutting and crushing green plant residues, old grass on permanent grasslands and for treatment of fallow lands. Mulching can also be used for crushing crop residues on the arable land (Mayer & Vlášková, 2007; Syrový et al., 2013).

Mulchers with vertical axis of rotation in its principle rank among rotational mowers. Power requirement of rotational mowers can be dependent according to work conditions, method of use and its construction. Literature deals with power requirement in range of 3.53.5–23 kW m^{-1} (kW per meter of the working width of the machine) (McRandal & McNulty, 1978; Tuck et al., 1991; Srivastava et al., 2006; Syrový et al., 2008; ASABE D497.7, 2011; Čedík et al., 2015; Kumhála et al., 2016) while the mulchers reach a very high values of power requirement. Air flow and associated pressure conditions inside the workspace of mulcher (ie. ventilation effect) is very important for the energy demands and quality of work of mulcher (Chon et al., 1999a; 1999b). Direction and speed of air flow have an influence on relative speed of air and tool and thus influences aerodynamic resistance and also repeated contact of plant matter with tool, which lead to the perfect crushing of plant matter. Air flow and pressure conditions in workspace of mulcher also influence uniform dispersion of crushed plant matter in the whole working width of machine (Čedík, 2016; Čedík et al., 2016a; 2016b).

Direction and speed of the air flow are influenced by cutting speed. The mower's cutting speed is normally in range of 71–84 m s^{-1} (O'Dogherty, 1982; Jun et al., 2006). Srivastava et al. (2006) stated that in dependence on the cutting tool sharpness the cutting speed should be in the range of 50–75 m s^{-1} for reliable function. From the results of other authors (Hosseini & Shamsi, 2012; Kakahy et al., 2014) it is evident that the optimization of the cutting speed and the cutting tool shape can significantly reduce the power consumption.

The cutting tool shape, primarily the trailing edge angle (Fig. 1), is important factor influencing the pressure conditions and air flow inside the mulcher's workspace. Chon & Amano (2004) with the aid of a mathematical model found that high pressure is formed in the space above the cutting tool, whereas low pressure is formed in the area below the cutting tool. The highest pressure is then generated on the front edge of the cutting tool. Steady flow in the workspace and reduced power consumption can be achieved by optimization of cutting tool in terms of aerodynamics (Zu et al., 2011). Jun et al. (2008) concluded that for reliable function of side-discharge of mower is required a minimum trailing edge angle of 20°. Hagen et al. (2002) stated that the shape of the cutting tool has equal importance as the shape of the covering of mulcher in terms of air flow. Another important parameter of the cutting tool shape is the rake angle. In the literature the rake angle have been studied mainly from viewpoint of its effect on energy of cut in the range 0–50°. The most effective cut was found within the range 15°–30° (O'Dogherty & Gale, 1986; O'Dogherty & Gale, 1991; Kakahy et al., 2012; Kakahy et al., 2013). McRandal & McNulty (1980) states that the blade rake angle is significant for the resistance to penetration of both stem and leaf. Hoseinzadeh et al. (2009) reached the lowest shearing energy of wheat with the rake angle of 25°.

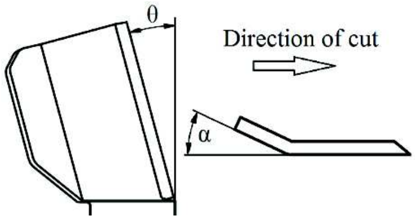

Figure 1. Schematically ilustrated angles on the cutting tool – rake angle (θ) and trailing edge angle (α).

The aim of this paper is to experimentally determine the effect of the cutting tool shape, in particular, the rake angle and the trailing edge angle on the pressure conditions inside the workspace of mulcher with vertical axis of rotation.

MATERIALS AND METHODS

The measurement was carried out under laboratory conditions at the Department of Agricultural Machines at Czech University of Life Sciences Prague. In order to determine the influence of the cutting tool shape on the pressure conditions inside the workspace of the mulcher, a laboratory model of a single mulcher rotor was used. This model was based on the working mechanism of three-rotor mulchers MZ 6000 produced by the BEDNAR FMT, Ltd company. The working speed of the mulcher's MZ 6000 rotors is 1,000 rpm. To drive the rotor with a diameter of 2 m an asynchronous electromotor MEZ with output of 22 kW was used. The speed of the electromotor was controlled by a frequency converter (Siemens). The laboratory model of the mulcher is shown in Fig. 2.

Figure 2. Laboratory model of one mulcher rotor with highlited position of the pressure sensors by dotted line.

In order to determine the influence of cutting tool shape, tools with different rake angles of 0°, 15° and 25° (Fig. 3) and a trailing edge angle of 35° and 25° were produced. The values of the rake angle were chosen based on the literature review. The values of trailing edge angles were chosen lower than original in order to lower aerodynamics resistance of the tools (Čedík et al, 2016b). Tools were made of carbon steel. As a reference, the original cutting tool (rake angle = 0°, the trailing edge angle = 45°) was used. Tools are referred to as rake angle X trailing edge angle (e.g 15X25 – rake angle of 15° and a trailing edge angle of 25°).

To measure the pressure conditions in the workspace of mulcher the strain gauge pressure sensors were used. The sensors in the form of strips were installed radially to the axis of rotation on the upper covering of mulcher model (Figs 2 and 4). On the strips the individual measuring elements are located with spacing of 10 mm. The sensors were produced by Association for Research and Education, Ltd. Three strips placed in series were used for measurement. Parameters of the sensors, provided by the manufacturer, are shown in Table 1. Data from the pressure sensors were stored on the PC's hard drive with a frequency of 2.5 Hz. Between the measurements the zeroing of the sensors was done by means of external pressure sensor, provided by manufacturer.

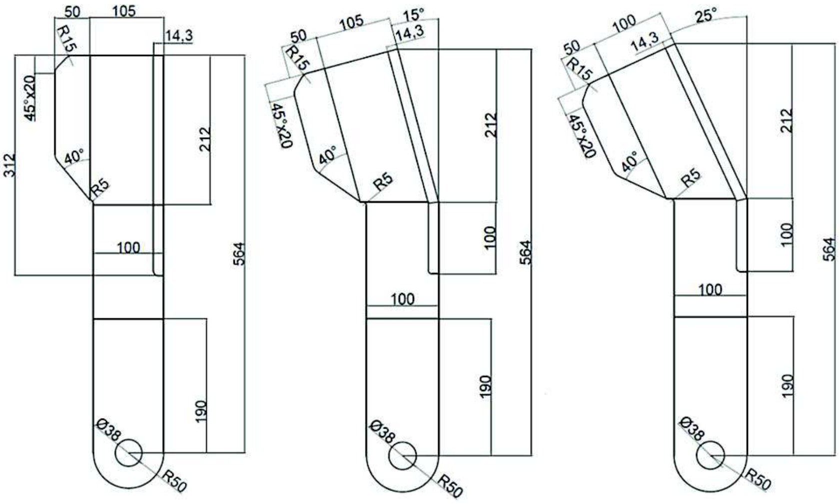

Figure 3. Proposed cutting tools with different rake angle (from left: 0°, 15°, 25°; dimensions in mm).

Figure 4. Pressure sensors in the form of strips.

Measurements were carried out at rotor speeds of 200, 400, 600, 800 and 1,000 rpm which correspond to cutting speeds of 21, 42, 63, 84 and 105 m s^{-1} respectively. For safety reasons it was not possible to reach 1,000 rpm (105 m s^{-1}) for all measured variants because the vibration acceleration of the frame's central part of the rotor reached up to 12 g.

Table 1. Parameters of the used pressure sensors

Pressure range	93–107 kPa
Temperature range	15–40 °C
Sampling frequency	10 Hz
Accuracy	< 10 Pa
Nonlinearity and hysteresis	< 8 Pa
Noise	± 5 Pa

RESULTS AND DISCUSSION

Fig. 5 shows the dependence of the average values of the pressure inside the workspace of mulcher on the distance from the rotation axis of the rotor for the original cutting tools (0X45).

From Fig. 5 it is clear that the pressure in dependence on speed decreases from the periphery towards the centre of the rotor almost linearly. This phenomenon occurs most likely due to centrifugal forces of the rotating air volume. The pressure values may also to some extent be influenced by the position of the sensors, which are always on the inside of the top cover. Chon & Amano (2004) also measured the lowest pressure at the centre of the rotor of municipal mower, caused by centrifugal forces. This result also agrees with Chon & Amano (2003) who stated that the air flow velocity increases from the rotor centre to its periphery.

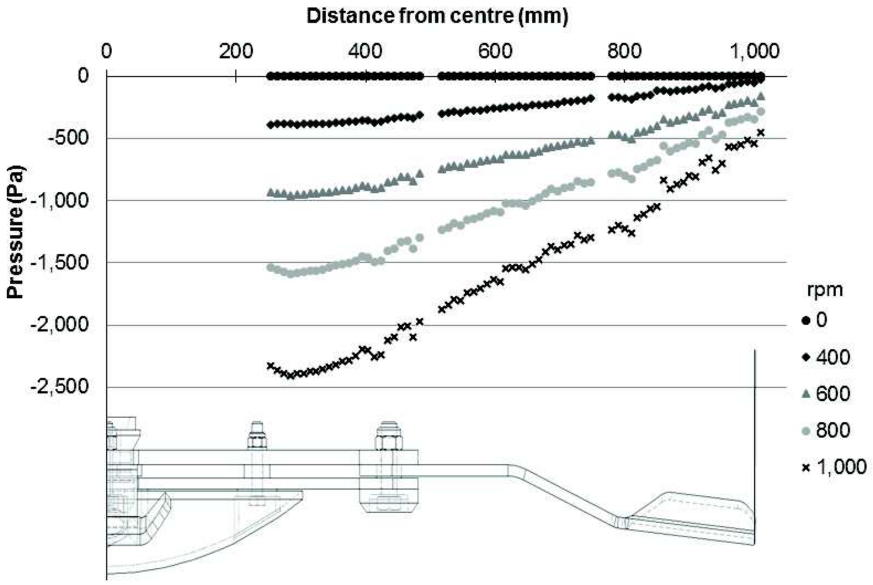

Figure 5. The course of pressure inside the workspace for original cutting tool (0X45).

When comparing the pressure curves with the drawing of cutting tool disposed below the graph it is possible to see the influence of various elements of the cutting tool on the course of pressure, e.g., cranked parts of the tool, trailing edge, retaining screw, etc. Further, it can be seen that the shape of the average pressure curves for each rotation speed are for the same cutting tool very similar and differ only in absolute pressure. Fig. 6 shows the course of pressure in the workspace of model of mulcher for different rotation speed of rotor with 0X25 cutting tool.

The course of pressure of the individual cutting tools are very similar as can be seen in Figs 5 and 6. For all the measured tools the highest vacuum was always measured by a sensor positioned of 284 mm from the centre of the rotor. Further from the centre of rotation (about 414–424 mm) it is evident the effect of retaining screw of the cutting tool which is similar for all variants. Pressure then increases linearly up to cranked part of the cutting tool, which was the same for all variants. Here, the noticeable pressure stagnation ranged between values of 627–657 mm from the centre of rotation can be seen. Further, significant deviation from linearity occurs at the second cranked part of the cutting tools, its trailing edge and rake angle. Despite differences in the shape of the tip of the cutting tools the pressure trends between 780 mm and 1,010 mm from the centre were again very similar to each other. At 810 mm a pressure drop occurred which was followed by its increase between 860–870 mm from the axis of rotation. This effect was stronger for the proposed cutting tools with zero rake angles 0X25 and 0X35. The trend of pressure around the tip of the blade is in good agreement with Chon & Amano (2005). They claimed that in the area around the tip of the blade the level of turbulent kinetic energy is higher than in the rest of the workspace.

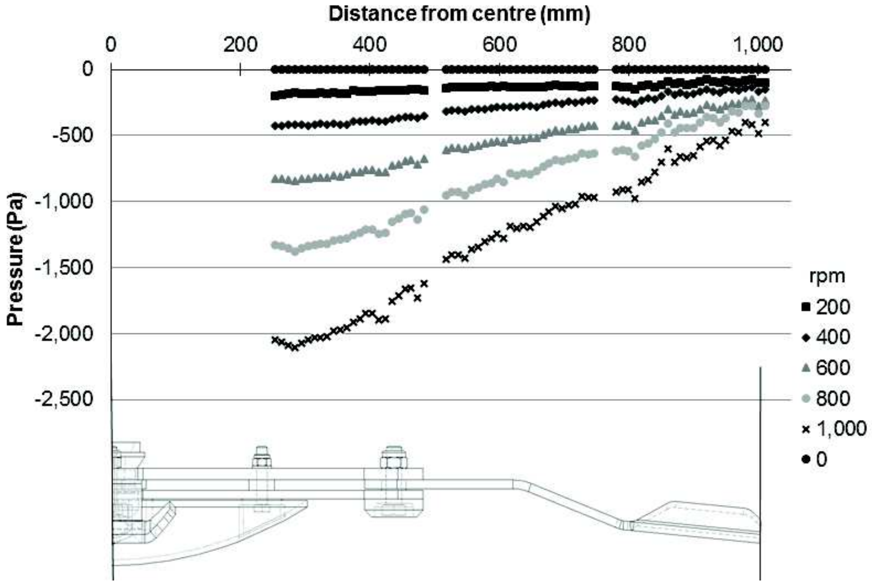

Figure 6. The course of pressure inside the workspace for cutting tool 0X25.

Since the pressure profile for all variations was very similar and under given conditions of measurement the differences were at the limit of the measurement accuracy the main criterion of comparison was the absolute value of achieved vacuum. Fig. 7 shows the maximum vacuum achieved in the workspace due to movement of the cutting tools. The maximum measured vacuum was 2.41 kPa and it was achieved with the original cutting tools. The analysis of variance of measured maximum vacuum values showed the statistically significant difference among all measured tool shapes at 800 min^{-1} and 1,000 min^{-1} at significance level $\alpha = 0.05$. The analysis of variance for 1,000 min^{-1}, complemented with Tukey HSD post-hoc test is shown in the Table 2. From Fig. 7 it is evident that at the zero rake angle of the cutting tool the decreasing value of achieved maximum vacuum can be observed as a result of the decreasing cutting tool's trailing edge angle. This effect is evident both at 800 min^{-1} for instruments 0X45, 0X35 and 0X25, and at 1,000 min^{-1} for instruments and 0X45 0X25. Decrease of the trailing edge angle from 45° to 25° can reduce maximum reached vacuum at 1,000 min^{-1} by approx. 0.3 kPa (12.6%). Further, it may be noted that when rake angle is reaching a non-zero values the increase of the maximum vacuum in the workspace can be observed as a result of decreasing trailing edge angle. This effect was reflected for both rake angle of 15° (15X35 and 15X25) and 25° (25X35 and 25X25) at the rotation speed of 800 min^{-1}. For the rake angle of 15° and 25° the decrease of the pressure at 800 min^{-1} was approx. 0.15 kPa (10.2%). This effect requires further analysis based on the air flow velocities measurement in the workspace by means of Laser Doppler Velocimetry.

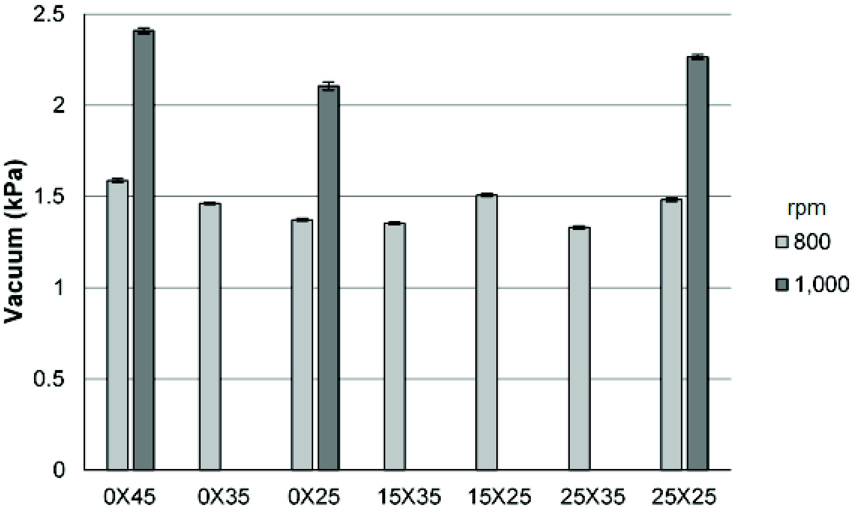

Figure 7. The maximum reached underpressure with original and proposed tools.

Table 2. Analysis of variance, complemented with Tukey post-hoc test for different tools at 1,000 min-1 (105 m s^{-1})

ANOVA

α = 0.05	Sum of squares	Degrees of freedom	Variance	F
Between groups	8.6411	2	4.3205	16,872.185
Within groups	0.1857	725	0.0003	
Total	8.8267	727		

Tukey HSD Post-hoc Test
Group 1 vs Group 2: Diff = -0.3043, 95%CI = -0.3083 to -0.3003, p = 0.0000
Group 1 vs Group 3: Diff = -0.1445, 95%CI = -0.1502 to -0.1388, p = 0.0000
Group 2 vs Group 3: Diff = 0.1598, 95%CI = 0.1532 to 0.1664, p = 0.0000

The difference between maximal and minimal pressure values is also important in the terms of quality of work. According to Chon & Amano (2004) the low pressure near to the centre of the rotor helps to create better air circulation and higher upward velocity at the tip of the blade. On the contrary, Čedík et al. (2016a) and Čedík (2016) claims that vacuum in the centre of rotor could cause a suction of higher quantity of grass matter under the rotor centre and thus it can reduce the work quality. Table 3 gives the values of maximum pressure difference measured for individual cutting tools. It is obvious that the highest difference (approx. of 2 kPa) was achieved with the original cutting tools.

The lowest difference was achieved, as expected, with the cutting tools 0X25. As an interesting cutting tool appears variant 25X35 which has shown the second lowest difference in pressure, but in field trials, conducted by Čedík (2016), showed the best work quality from the proposed instruments. However, due to unfavourable measuring conditions these results are not fully conclusive and require additional measurements.

Table 3. Pressure differences

Cutting speed	Pressure difference (kPa)						
(m s^{-1})	0X45	0X35	0X25	15X35	15X25	25X35	25X25
84	1.31	1.18	1.10	1.15	1.24	1.13	1.24
105	1.95	-	1.71	-	-	-	1.91

Chon & Amano (2005) performed measurement with a double-blade mower with side-discharge and co-rotating blades. They reached the maximum pressure difference of 3 kPa at a cutting speed of 82 m s^{-1}, but at 2,700 rpm, which produces a higher centrifugal force and therefore the higher pressure difference.

CONCLUSIONS

During the measurement of the pressure conditions inside the mulcher's workspace the following conclusions were made:

- The movement of cutting tools creates the vacuum (under pressure) within the workspace. This vacuum decreases almost linearly from the centre of the rotor towards to its periphery. Maximum reached vacuum was 2.41 kPa with original shape of cutting tools. Other sources (Chon & Amano, 2003; Chon & Amano, 2005) with use of mathematical model also found the highest vacuum in the centre of rotor of municipal mower.
- The maximum pressure difference in the workspace was measured 1.95 kPa at cutting speed 105 m s^{-1}. Chon & Amano (2005) reported the pressure difference 3 kPa at municipal double rotor mower with rotor diameter approx. 0.6 m with cutting speed 82 m s^{-1}.
- Proposed shapes of the cutting tools generally lowered the maximum reached vacuum in comparison with the original cutting tool. Also, proposed shapes of the cutting tools have only a negligible effect on the course of pressure.
- At zero rake angle of cutting tool the maximum achieved vacuum was reduced by decreased trailing edge angle. For the rake angle of 15° and 25° it was found that decrease of the trailing edge angle conversely increases the maximum vacuum.

Lower vacuum has resulted in a smaller power requirements for creating and maintaining of vacuum. But too low vacuum could significantly impair the quality of mulcher work since there would be no sufficient disruption of the plants structure by repeated contact with blades of the cutting tools.

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