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Effect of rake angle and cutting speed on energy demands of mulcher with vertical axis of rotation

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Abstract. The contribution deals with the reduction of agriculture energy demands. For maintenance and treatment of permanent grassland areas, areas left fallow and put to rest the mulching in combination with other workflows (mowing, grazing) is advantageous procedure. As conventional impact grass cutting and chopping is energy demanding procedure, it is proper to reduce the energy demands of such device. In the paper the effect of shape of cutting tool, particularly the rake angle, on energy demands of mulcher with vertical axis of rotation is studied. The effect of cutting speed on energy demands is also verified. The measurement was performed using mulcher MZ 6000 made by Bednar FMT Ltd. with working width of 6 m and three rotors. During the measurement the test rides using the cutting tools with different rake angle and cutting speeds of 105m s^{-1}, 89 m s^{-1} and 79 m s^{-1} were performed. The rake angle of cutting tools were chosen 0°, 15° and 25°. The test area was pasture with permanent grassland. During the measurement the torque and power, transferred through PTO to the machine, fuel consumption and GPS coordinates were measured. From each test ride the samples of grass matter were taken in order to determine the yield and moisture content. It was found that increase of the rake angle up to 25° and decrease of the cutting speed resulted in decrease of the power requirement of the mulcher.

Key words: mulcher, permanent grassland, energy demands, cutting tool, rake angle, cutting speed.

INTRODUCTION

At the present time there is put ever increasing emphasis on reducing the energy demands of individual operations in agriculture. Mulching with vertical axis of rotation belongs to the energy demanding agricultural operations. Mulching with use of vertical axis of rotation causes the impact cutting, which is in principle much more energy demanding than mowing with a support.

For the rotary mowers, to which belong also a mulcher with vertical axis of rotation, the sources of scientific literature mention very different values of energy demands (Table 1).

Table 1. Results of energy demands of rotation mowers, measured at different conditions

Source	Performance requirement ($kW\ m^{-1}$)	Conditions
Čedík et al. (2015)	10–23	Mulcher working with mass performance of 10–35 $t\ h^{-1}$
	5	Mower
	8	Mower with conditioner
	6.67	Mower with the average mass performance 120 $t\ h^{-1}$ and blunt blades
	5.67	Mower with the average mass performance 120 $t\ h^{-1}$ and sharp blades
Srivastava et al. (2006)	11–16	Mower at a speed of 15 $km\ h^{-1}$
	8–10	Mower with sharp blade
	10–12	Mower with worn blade
	5	Mower
	3.5–6.5	Mower with conditioner

During the impact cutting the reaction to the cutting force is represented by structural stiffness or inertia of plants. From this reason a plant can be cut only in case, when these resistance forces of plant exceed the force delivered by tool (Johnson, 2012). It is obvious, that the stiffness and mass of plant stem represent very important factor, to which must be adapted cutting conditions, in particular cutting speed. Therefore, cutting speed plays very important role in terms of energy demands and quality of work. The effect of cutting speed on cutting parameters of mowers has been examined in numerous studies (McRandal & McNulty, 1978a; O'Dogherty & Gale, 1991a; Tuck et al., 1991b; Chattopadhyay & Pandey, 1999; Chattopadhyay & Pandey, 2001; Hagen et al., 2002; Yiljep & Mohammed, 2005; Hosseini & Shamsi, 2012; Kakahy et al., 2012; Kakahy et al., 2013; Kakahy et al., 2014). The results of most of these studies mention the lowest energy needed for impact cutting at cutting speeds in the range of 60–90 $m\ s^{-1}$. O’Dogherty (1982) mentions typical cutting speed for disc and rotary mowers in range of 71–84 $m\ s^{-1}$.

Species and the condition of processed plants, especially its moisture, has also a significant effect on energy demands during the mowing (Chen et al., 2004; Shahbazi et al., 2011; Kronbergs et al., 2013).

Another important factor related to the energy demands is the geometry of tool, sharpening angle and rake angle (Fig. 1). In case of sharpening angle the sources of scientific literature mention the most advantageous range of values from 20° up to 30° (O'Dogherty & Gale, 1991b; Tuck et al., 1991b; Chattopadhyay & Pandey, 2001; Hoseinzadeh et al., 2009). Owing to the higher degree of wear of cutting blades during the mulching as a result of repeated contact of cutting tool with material and soil, the rake angle of tool appears as more significant.

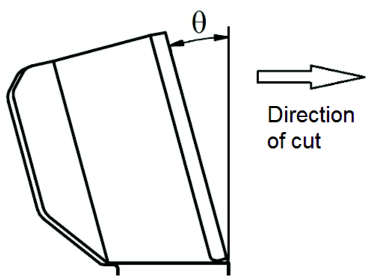

Figure 1. Schematically illustrated rake angle θ.

In the literature the rake angle have been studied in the range 0–50°. The most effective cut was found within the range 15°–30° (O'Dogherty & Gale, 1986; O'Dogherty & Gale, 1991b; 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°.

The disruption of plant structure by repeated contact with tool blade is important when mulching with vertical axis of rotation in order to facilitate the decomposition of the plants and as well as its distribution in the entire width of machine. Fulfillment of this requirement ensures ventilation effect and the associated negative pressure in the workspace (Čedík et al., 2016a). This fact however means considerably higher losses due to the air resistance.

Identified energy losses of rotary mowers are the following: acceleration of the material to the output speed, overcoming friction forces between the material and the cover of the mower mechanism while the material is still pressed by the cutting device, overcoming friction forces between the blade and the stubble/soil, continuous movement of the air in the cut area (so called ventilation effect), overcoming mechanical friction forces of the drive mechanism and other parasitic losses. Total losses may be greater than the real cutting performance (Persson, 1987; O'Dogherty & Gale, 1991b). The experiments with mowing machines with vertical axis of rotation proved that 50% of the input energy is used for 'transport' of the plants while only 3% of the input energy is used for cutting the plant stems (McRandal & McNulty, 1978a).

This contribution is aimed at determination of effect of the changes of cutting tool rake angle and cutting speed on energy demands of mulcher with a vertical axis of rotation in field conditions.

MATERIALS AND METHODS

For the measurement the mulcher with vertical axis of rotation Mulcher MZ 6000 produced by the company Bednar FMT, Ltd. in the set with tractor FENDT 818 were used (Fig. 2). Both machines were rented from collective farm Agro Liboměřice, joint-stock company. The area, on which the mentioned mulcher was used during the period of its operation didn´t exceed 200 ha.

Figure 2. Working set – tractor Fendt 818 with connected Mulcher MZ 6000.

In order to verify the effect of change of rake angle there have been designed and manufactured the tools with rake angle 0°, 15° a 25° from carbon steel. The values of the rake angle were chosen based on the literature review. Sharpening angle of the blades was 40° according to the original cutting tools. The drawings of semifinished tools are shown in the Fig. 3.

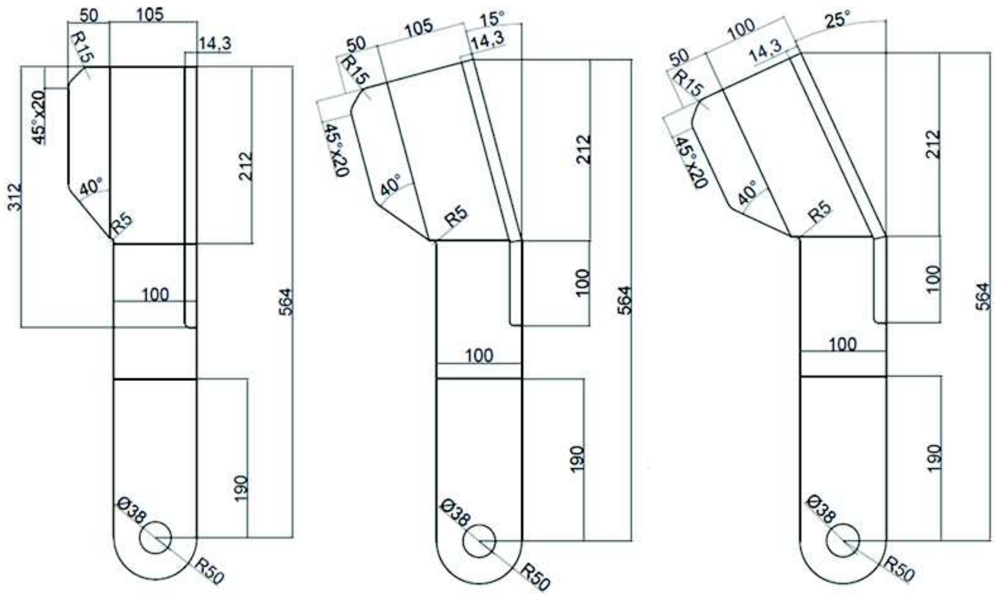

Figure 3. Cutting tools with different rake angle.

In order to determine the energy demands a torque sensor Manner Mfi 2500Nm_2000U min^{-1} (accuracy 0.25%), mounted on the tractor PTO shaft was used and for the determination of position of the working set and its speed the GPS receiver Qstarz BT-Q1000XT was placed on the tractor roof. All sensors were connected by means of analog-digital converter LabJack U6 (resolution 18 bit) to the measuring computer HP mini 5103, which was placed in tractor cab. Data were recorded at frequency of 2 Hz.

On the measuring plot there have been carried out the test drives with designed tools at the PTO 1,000 rpm (cutting speed 105 m s^{-1}), 850 rpm (cutting speed 89 m s^{-1}) and 750 rpm (cutting speed 79 m s^{-1}). The speed of set was chosen 9 km h^{-1}. For each shape of the tool and cutting speed there were carried out two drives. In order to evaluate and compare the energy demands there were used only these drives, at which the comparable mass performance was achieved. As there was already published (Čedík et al., 2015; Kumhála et al., 2016), energy demands and efficiency of mulcher itself depend strongly on achieved mass performance.

The measuring plot was pasture area at village of Bojanov, near to Chrudim in the Czech Republic (49.430567°N, 15.7102258°E). This plot is flat and it is situated approximately 420 m above sea level. Mulched plant stand has been mostly formed by grasses (cocksfoot, perennial ryegrass) with dry undergrowth, where the faded stalks of sorrel were represented to the greatest extent.

For the determination of measurement conditions two samples were taken for each shape of cutting tool blades in order to determine the proportion of moisture content. The moisture content had average value 67%w.b. with standard deviation 7.3%w.b. The data has been also used to determine the average yield of grass matter from each measuring section by means of a laboratory scales Vibra AJ 6200 (range 6,200 g, resolution 0.01 g, accuracy 0.1 g).

The power requirement and specific energy consumption were evaluated parameters of energy demands. Specific energy consumption is energy needed to process 1 ton of the material and thus reflects the efficiency of the machine. The power requirement was calculated according to Eq. (1) and the specific energy consumption was calculated according to Eq. 2:

$$PR = \frac{\overline{P}}{B} \quad (1)$$

where PR – power requirement (kW m^{-1}), P – mean input power of the mulcher for the test ride (kW); B – working width of mulcher (m)

$$SEC = \frac{\sum_{i=1}^{n}(P_i \cdot t_i)}{360 \cdot \omega \cdot L \cdot B} \quad (2)$$

where SEC – specific energy consumption (kWh t^{-1}); P_i – measured input power of the mulcher at i index of data-set (kW); t_i – measuring interval of i index of data-set (ms); ω – yield per hectare of grass cover (t ha^{-1}); L – length of test ride (m); B – working width of mulcher (m)

RESULTS AND DISCUSSION

From the measured data only drives with comparable mass performance were selected for the comparison. For determination of the effect of rake angle there have been selected drives, in which it was attained mass performance approx. 7–8 t h^{-1} (Fig. 4). In order to determine the effect of cutting speed there were chosen the drives with achieved mass performance approx. 3–4 t h^{-1} (Fig. 5).

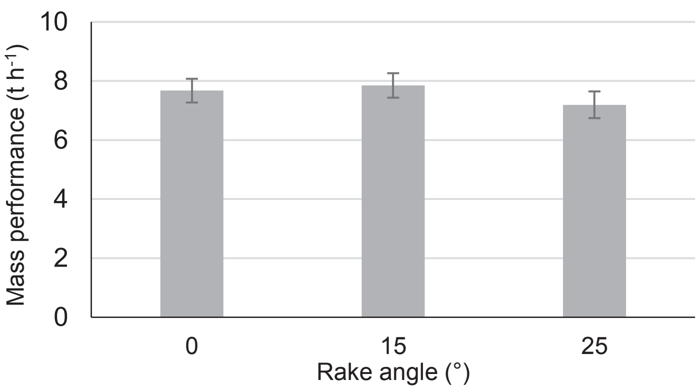

Figure 4. Achieved mass performance for tools with different rake angle.

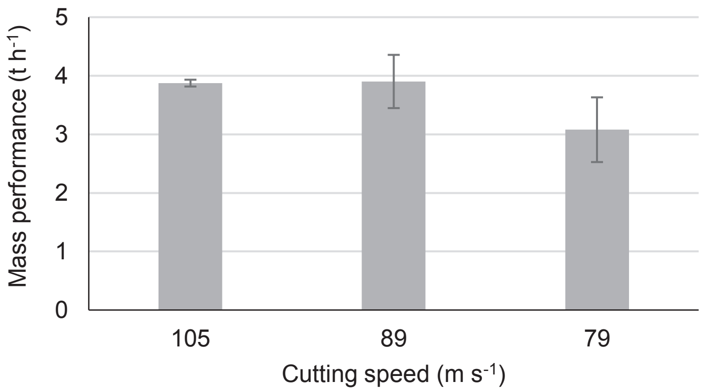

Figure 5. Achieved mass performance for different cutting speeds (rake angle = 0°).

Determination of rake angle effect

The Fig. 6 shows the effect of rake angle on power requirement and specific energy consumption. As can be seen from the figure, increasing rake angle results in a reduction of energy demands of mulcher during the working operation in the field conditions. By increase the rake angle from 0° to 25° the specific energy consumption has been reduced by 21.4% and power requirement by 26.3%. The results of this measurement have a high explanatory value, because during the measurement it was achieved very similar mass performance in all drives. Such a finding is consistent with other publications (Hoseinzadeh et al. 2009; Kakahy et al., 2012; Kakahy et al., 2013), however other sources (Chattopadhyay & Pandey, 2001) mention, that the lowest level of consumed energy is reached with a significantly higher rake angle (40°).

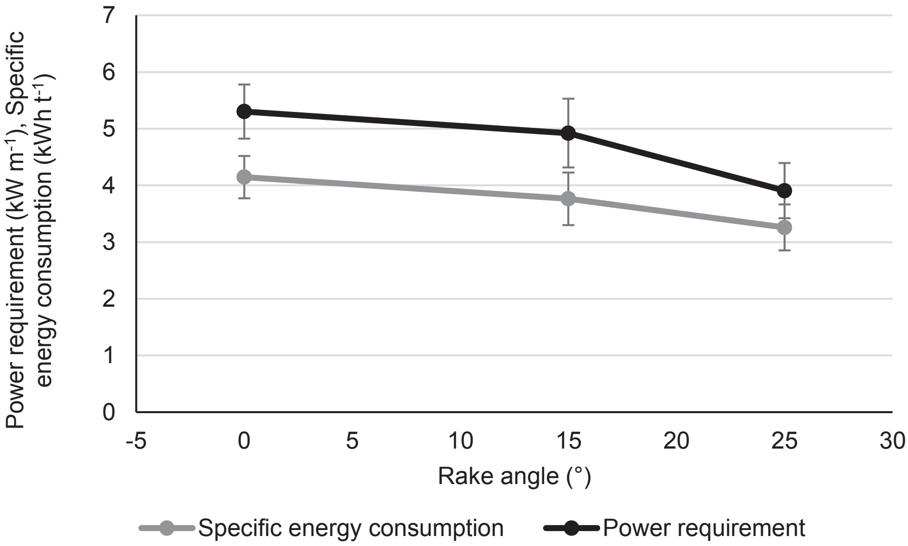

Figure 6. Power requirement and specific energy consumption for tools with different rake angle.

In the Table 2 there is shown an analysis of variance of measured values destined for evaluation of the effect of rake angle on power requirement, complemented with Tukey HSD post-hoc test. The results show, that among all the variants there is statistically significant difference at significance level $\alpha = 0.05$.

Table 2. Power requirement analysis of variance, complemented with Tukey post-hoc test for tools with different rake angle

ANOVA				
α = 0.05	Sum of squares	Degrees of freedom	Variance	F
Between groups	92.9084	2	46.4542	42.3345
Within groups	297.3718	271	1.0973	
Total	390.2802	273		
Tukey HSD Post-hoc Test				
Group 1 vs Group 2: Diff = -0.3790, 95%CI=-0.7372 to -0.0208, p = 0.0352				
Group 1 vs Group 3: Diff = -1.3938, 95%CI = -1.7568 to -1.0308, p = 0.0000				
Group 2 vs Group 3: Diff = -1.0148, 95%CI = -1.3958 to -0.6338, p = 0.0000				

Determination of cutting speed effect

In the Fig. 7 the power requirement and specific energy consumption for various cutting speeds when using the tool with zero rake angle is shown. It is evident, that with decreasing cutting speed the power requirement also decreases and the greatest difference can be seen between 105 m s^{-1} and 89 m s^{-1}.

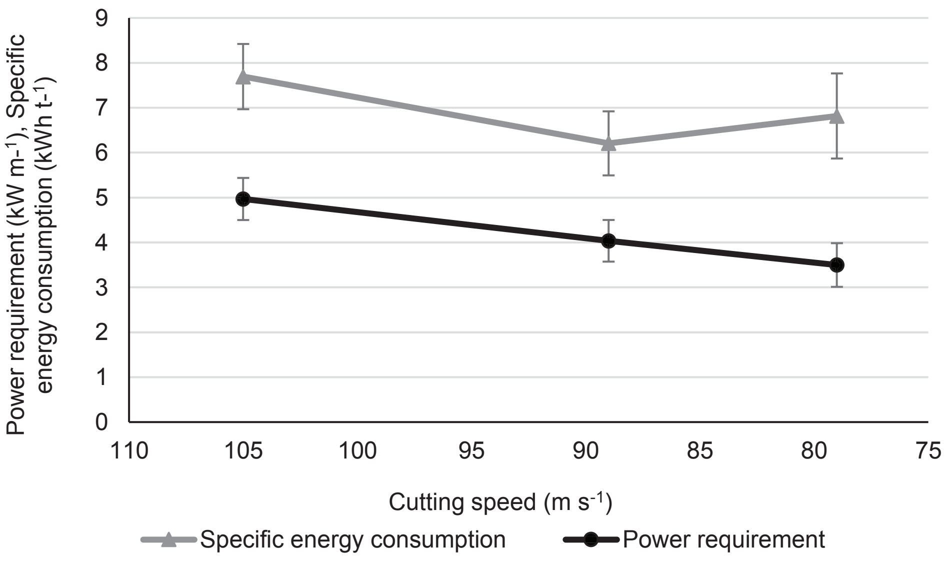

Figure 7. Power requirement and specific energy consumption for different cutting speeds (rake angle = 0°).

By reduction of cutting speed from 105 m s^{-1} to 89 m s^{-1} it is possible to decrease the specific energy consumption by 19.3% and power requirement by 18.7%. By reducing the cutting speed from 105 m s^{-1} to 79 m s^{-1} it was achieved the decrease of specific energy consumption by 11.4% and power requirement by 29.6%. This reduction was achieved mainly due to lower aerodynamic losses of the cutting tools in the workspace, which is in good agreement with previous results (Čedík et al., 2016a; 2016b). The value of specific energy consumption for cutting speed of 79 m s^{-1} was affected by lower mass performance achieved in the measuring section.

In the Table 3 there is analysis of variance of the measured values complemented by Tukey HSD post-hoc test in order to compare the influence of cutting speed on power requirement. From the results it is obvious, that among all variants there is statistically significant difference at significance level $\alpha = 0.05$.

Table 3. Power requirement analysis of variance, complemented with Tukey post-hoc test for different cutting speeds

ANOVA				
α = 0.05	Sum of squares	Degrees of freedom	Variance	F
Between groups	104.1988	2	52.0994	58.2416
Within groups	229.8965	257	0.8945	
Total	334.0953	259		
Tukey HSD Post-hoc Test				
Group 1 vs Group 2: Diff = -0.9313, 95%CI = -1.2688 to -0.5937, p = 0.0000				
Group 1 vs Group 3: Diff = -1.4703, 95%CI = -1.8010 to -1.1396, p = 0.0000				
Group 2 vs Group 3: Diff = -0.5391, 95%CI = -0.9070 to -0.1711, p = 0.0018				

CONCLUSIONS

From the measurement results it is obvious, that by increasing the rake angle of cutting tool up to 25° the power requirement was reduced by more than a quarter. This result is in good agreement with results of other authors obtained with mowers of lower dimensions in different cutting speed (Kakahy et al., 2012; Kakahy et al., 2013) or in laboratory conditions (Hoseinzadeh et al., 2009; O'Dogherty & Gale, 1986). On the contrary O'Dogherty & Gale (1991b) reported statistically insignificant lowest cutting energy at rake angle of 15°.

The decrease of energy demands is above all caused by lower energy of cut, because it has been already previously demonstrated in laboratory and field conditions (Čedík et al., 2016b), that the rake angle has only minimal effect on energy losses of mulcher. These losses occur mainly due to the air resistance.

By reducing the cutting speed to the value of 79 m s^{-1} it was achieved the decrease of power requirement almost by 30%. This result is in good agreement with results of other authors, achieved in different conditions (O'Dogherty, 1982; Chattopadhyay & Pandey, 1999; Kakahy et al., 2013; Tuck et al., 1991b).

The decrease of energy demands was reached mainly due to lower aerodynamic losses of mulcher blades, because the cutting speed highly influences relative speed of cutting tool and airflow inside the mulcher workspace (Čedík 2016a, 2016b). The energy losses of the mulcher can consume most of the energy supplied depending on conditions.

However, the reduction of cutting speed has also a negative influence on ventilation effect, which ensures good quality of machine work. Cutting speed must be high enough so that the movement of machinery had as a consequence sufficient number of repeated contacts of cut plant matter with cutting edges of cutting tools and the structure of plant matter was disrupted, which enables its easier decomposition.

Increase of rake angle influences as well as the pressure conditions and air flow in workspace of mulcher. This phenomenon will be further studied.

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