Technical Sciences 16(3), 2013, 234–247

A THEORETICAL ANALYSIS OF CEREAL SEED SCREENING IN A STRING SIEVE

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Received 22 June 2013, accepted: 23 October 2013, available on line 23 October 2013

Key words: string sieve, modelling, seeds, angle of inclination.

Abstract

The conditions of the screening process in a fixed string sieve designed by the author have been formulated. The string sieve was designed for separating seeds of 5 cereal species (wheat, rye, barley, oats and triticale). The width of the separating groove was set at 1 mm at the beginning of the screen and 5 mm at the end of the screen. It has been assumed that seeds have a spheroidal shape and that their motion is initiated by positioning the string sieve at an appropriate angle. The results of a theoretical analysis revealed that at the given parameters of a string sieve, the above angle is determined only by the thickness and width of separated seeds. The sieve's angle of inclination should be set at 45° to propel seeds into motion and at 50° to ensure the continuity of the screening process. Such a large setting angle is not recommended because it increases the sieve's height and deteriorates the quality of the separation process. The problem can be solved by setting the separator bucket into motion and separating seeds at a small inclination angle of the string sieve.

Symbols:
a, b – seeds thickness and width, mm,
d – equivalent diameter of seed width and thickness, mm
D_s – string diameter, mm,
e – distance from the beginning of the screen, mm,
g – gravitational acceleration, $m \cdot s^{-2}$,
G, G_y, G_{y1}, G_{y2}, G_z – gravity force and gravity force components, N,
L_s – screen length, mm,
m – seed weight, kg,
N_1, N_2, N_{1x}, N_{1z}, N_{2x} – the string's normal ground reaction forces and normal ground reaction force components, N,
R_s – string spacing, mm,
s – width of groove at distance a from the beginning of the screen, mm,
s_k – width of separating groove at the end of the screen, mm,
s_p – width of separating groove at the beginning of the screen, mm,

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s_1 – width of groove at distance $^3/_4$ e from the beginning of the screen, mm
T_1, T_2 – frictional force components, N,
x, SD – average value and standard deviation of trait,
x_{min}, x_{max} – minimum and maximum value of trait,
α – angle of inclination of a string sieve, °,
γ – opening angle between strings in bottom rows, °,
μ_k – coefficient of sliding friction of a cereal seed,
μ_s – coefficient of static friction of a cereal seed,
φ – included angle between the seeds' gravity force component and a string's normal ground reaction force, °.

Introduction

Seed mixtures are cleaned and sorted with the involvement of separators that rely on the aerodynamic and geometric characteristics of processed material (BERLAGE et al. 1984, CĂSĂNDROIU et al. 2009, GROCHOWICZ 1994, LI et al. 2002, RAWA 1992, RAWA et al. 1990, SIMONYAN, YILJEP 2008, VOICU, CĂSĂNDROIU 2004, WANG et al. 1994, WIERZBICKI et al. 1991). This group of separators includes string sieves which should be equipped with a set of wire and/or mesh screens with differently shaped and/or sized openings to maximize the effectiveness of the separation process. Several mesh screens appropriate for the separated mixture are selected and placed in the separator bucket. The screens available from the machine supplier generally have fixed mesh openings, which limits the separation effectiveness of seeds that belong to the same species and variety but differ in plumpness.

A string sieve is a solution that flexibly adapts to variations in the parameters of the separated seed mixture (KALINIEWICZ 2011, 2013a). Strings are stretched between two horizontal bars (Fig. 1). This arrangement creates a separating groove along the screen, and the size of the separating groove changes gradually with distance from the beginning of the screen in the range of s_p to s_k. At the beginning of the screen, the width of the openings between strings is smaller than the thickness of the finest seeds, and the openings at the end of the screen are larger than the thickness of the largest seeds of the principal species. In view of the average size of farm-produced seeds, the width of the separating groove should be set at 1 mm at the beginning of the screen and 11 mm at the end of the screen. In sieves not designed for grading large seeds or vetch seeds, the width of the separating groove can be set at 1 mm and 5 mm, respectively. Seeds are sorted into various size fractions by changing the position of collecting buckets under the screen (KALINIEWICZ 2013a).

The angle of inclination of a separator screen is also an important consideration which determines the effectiveness and continuity of the separation process.

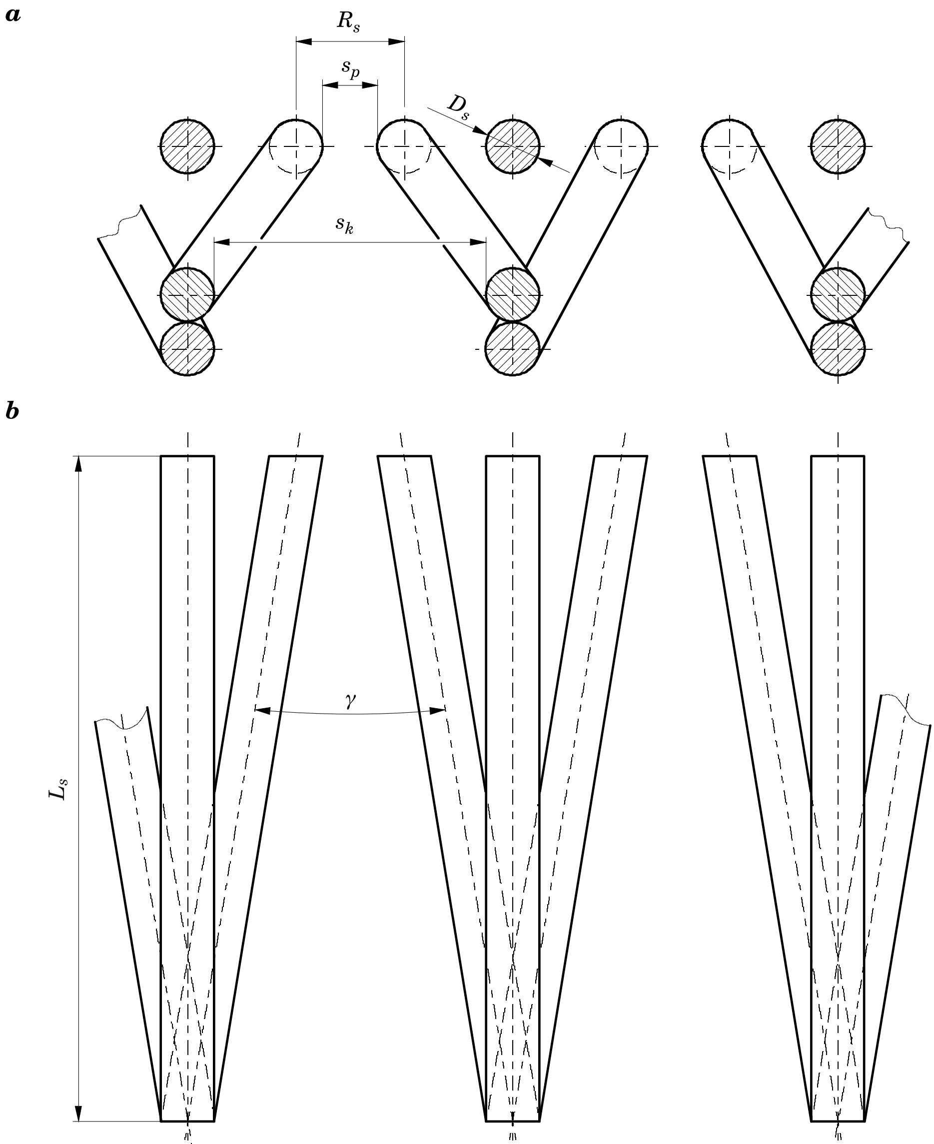

Fig. 1. String arrangement in a string sieve: *a* – rear view, *b* – top view
Source: KALINIEWICZ (2013a).

This paper analyzes the movement of grain seeds on a fixed string sieve with the aim of determining the screen's angle of inclination that guarantees maximum separation effectiveness.

Theoretical analysis

It was assumed that the string sieve is made of wires, rods or strings with circular cross-section. Strings are made of steel, and they may be additionally coated with plastic or rubber. A narrow stream of seeds is fed from the seed container to the initial section of the string sieve with the smallest width of separating grooves. The surface of the string sieve is set at angle α relative to the horizontal plane (Fig. 2). Since seeds are not fed into the sieve individually, some of them are blocked by other seeds, and their motion is initiated with a certain delay. Therefore, it was assumed that the initial velocity of seeds equals zero and that seeds are set into motion by the force of gravity. It was also assumed that the motion of each seed is self-initiated and it is not affected by other seeds. For the sake of simplicity, the following angles were disregarded: opening angle between strings in bottom rows, angle of inclination of bottom strings in the first row relative to top strings, and angle of inclination of bottom strings in the second row relative to top strings. The observed angles are small, and they do not exceed 1.5° even in the shortest screens with the widest separating grooves at the end of the screen (KALINIEWICZ 2013a).

In line with the models proposed by other authors (GASTÓN et al. 2002, GROCHOWICZ 1994, HEBDA, MICEK 2005, 2007, ZDYBEL et al. 2009, ŻABIŃSKI,

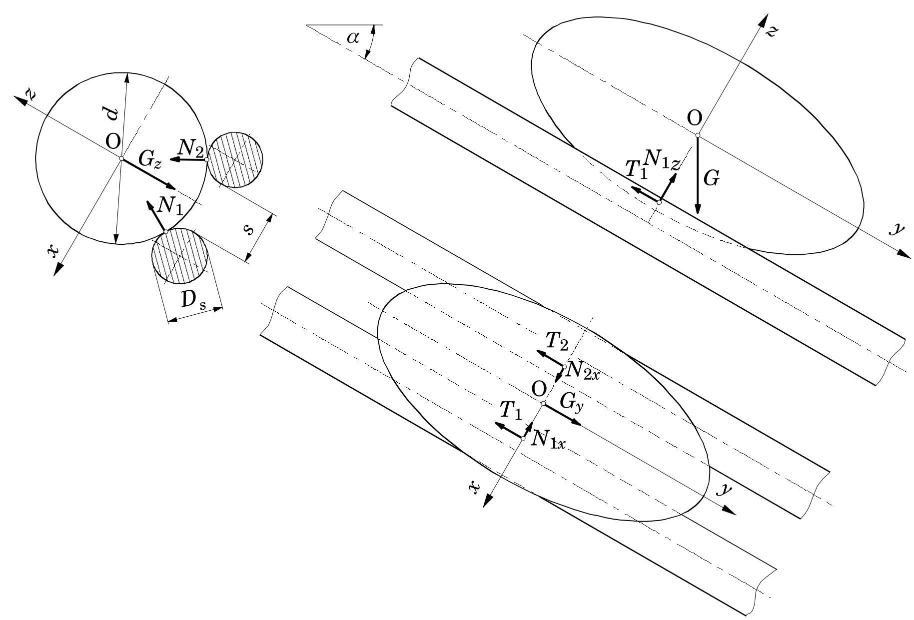

Fig. 2. Forces acting upon cereal seeds at the beginning of a string sieve

SADOWSKA 2010), the geometrical model of the analyzed seeds was adopted in the form of a rotating ellipsoid whose major axis was seed length and minor axis was the average of seed thickness and width, calculated based on the following formula:

$$d = \frac{a + b}{2} \tag{1}$$

In the first stage of the analysis, a seed was placed on the surface of a string sieve with its longitudinal axis parallel to the strings, i.e. the string was supported by two adjacent strings (Fig. 2). In line with the principles of classical mechanics, it was assumed that the only external force acting upon the seed was the force of gravity G. In view of the sieve's angle of inclination, the force of gravity can be separated into two components: the force parallel to the strings G_y (which causes seeds to slide down the strings) and the force perpendicular to the strings G_z. Gravity force components can be expressed with the use of the below formula:

$$G_y = mg \sin\alpha \tag{2}$$

$$G_z = mg \cos\alpha \tag{3}$$

Component G_z can be decomposed into directions of the strings' normal ground reaction forces (Fig. 3):

$$G_{y1} = G_{y2} = \frac{G_z}{2 \cos\varphi} = \frac{mg \cos\alpha}{2 \cos\varphi} = N_1 = N_2 \tag{4}$$

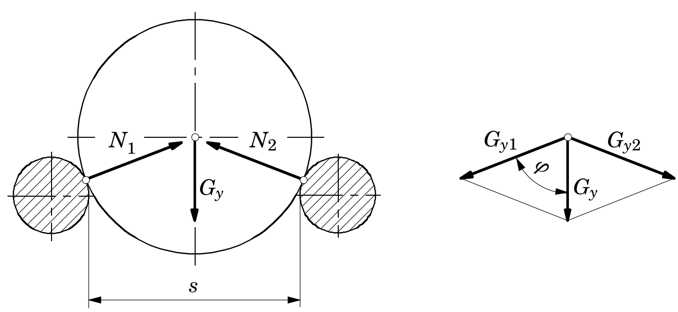

Fig. 3. Distribution of gravity force components and a normal ground reaction forces at a terminal point of the distance traveled by a seed on a string sieve

where angle φ is determined from a simple trigonometric function:

$$\sin\varphi = \frac{\frac{s}{2} + \frac{D_s}{2}}{\frac{d}{2} + \frac{D_s}{2}} = \frac{s + D_s}{d + D_s} \tag{5}$$

which is transformed to:

$$\varphi = \arcsin\frac{s + D_s}{d + D_s} \tag{6}$$

When seeds are immobile, the friction force between a seed and a string can reach:

$$T_1 = \mu_s \cdot N_1 = \mu_s \cdot N_2 = T_2 \tag{7}$$

For a seed to slide down the strings, gravity force component G_y has to be greater than the net friction force:

$$G_y > 2T_1 \tag{8}$$

Equations (2), (4) and (7) were substituted into the above formula to produce:

$$mg \sin\alpha > 2 \cdot \mu_s \cdot \frac{mg \cos\alpha}{2 \cos\varphi} \tag{9}$$

which was transformed to:

$$\tan\alpha > \frac{\mu_s}{\cos\varphi} \tag{10}$$

The above inequality was used to determine a sieve's critical angle of inclination which, when exceeded, will propel seeds into sliding motion:

$$\alpha = \arctan\frac{\mu_s}{\cos\varphi} \tag{11}$$

In accordance with formula (6), at given parameters of a string sieve, the critical angle of inclination will be determined only by the equivalent diameter of seed width and thickness.

When a sieve string is set at an angle that propels all seeds into motion, seeds will initially slide in uniformly accelerated motion. Angle φ will increase with an increase in the width of the separating groove, which increases normal force and friction force. Seed motion is inhibited (changed to uniformly retarded motion) as of the moment force component G_y becomes equal to friction:

$$mg \sin\alpha = \mu_k \cdot \frac{mg \cos\alpha}{\cos\varphi} \tag{12}$$

The angle between the direction of a normal force and the gravity force component at which the above forces are equalized can be determined by transforming formula (12) as follows:

$$\varphi = \text{arc cos} \frac{\mu_k}{\tan\alpha} \tag{13}$$

Angle φ is directly proportional to a seed's coefficient of sliding friction and inversely proportional to a string sieve's inclination angle.

As seeds continue to move down the sieve where the width of the separating grove gradually increases, their center of mass will be gradually lowered relative to the strings. The normal force of sieve strings will continue to increase, thus increasing friction. Those forces will not reach infinitely large values at the location where a seed passes through the screen because strings will deflect despite their initial pull tension. In view of the rapid increase in normal force at the final stage of seed motion along the screen, it was assumed that seeds should accelerate across minimum $^3/_4$ of the traveled distance and that their motion should be inhibited across maximum $^1/_4$ of the traveled distance to avoid mesh blockage. The above also applies to seeds characterized by the smallest equivalent diameter of width and thickness and the highest sliding friction coefficients which, in principle, ensures the continuity of the screening process. To fulfill the above condition, a string sieve's angle of inclination can be determined by transforming formula (12):

$$\alpha = \text{arc tan} \frac{\mu_k}{\cos\varphi} \tag{14}$$

Angle φ can be tied to the equivalent diameter of seed width and thickness based on the principle of similar triangles (KALINIEWICZ 2013a). In line with the above principle:

$$\frac{s_1 - s_p}{\frac{3}{4}e} = \frac{d - s_p}{e} \tag{15}$$

Formula (15) can be transformed to:

$$s_1 = \frac{3d + s_p}{4} \tag{16}$$

When the above formula is substituted into equation (6), the correlation with angle φ can be expressed as:

$$\varphi = \text{arc sin}\,\frac{3d + s_p + 4D_s}{4(d + D_s)} \tag{17}$$

At given parameters of a string sieve, angle φ will be determined only by the equivalent diameter of seed width and thickness.

Materials and methods

The experimental material consisted of 120 seeds of every analyzed principal cereal species (wheat, rye, barley, oats and triticale). The physical parameters of the analyzed seeds have been described by KALINIEWICZ (2013b). For the needs of this experiment, only the results of seed thickness and seed width measurements and the coefficients of sliding and static friction of seeds are presented in Table 1. Seed thickness was determined with a special apparatus comprising a dial indicator, and seed width was measured under the MWM 2325 workshop microscope. Coefficients of sliding and static friction were determined with a special device for measuring the frictional properties of seeds.

Table 1

Statistical distribution of the physical parameters of seeds

Parameter	Cereal species				
	wheat $x \pm SD$	rye $x \pm SD$	barley $x \pm SD$	oats $x \pm SD$	triticale $x \pm SD$
a	2.87 ± 0.21	2.39 ± 0.25	2.87 ± 0.22	2.55 ± 0.15	2.70 ± 0.33
b	3.29 ± 0.31	2.65 ± 0.28	3.84 ± 0.30	3.15 ± 0.25	3.23 ± 0.38
μ_s	0.31 ± 0.03	0.30 ± 0.05	0.31 ± 0.03	0.35 ± 0.06	0.38 ± 0.06
μ_k	0.22 ± 0.03	0.19 ± 0.04	0.23 ± 0.03	0.16 ± 0.05	0.19 ± 0.06

Source: KALINIEWICZ (2013b).

The equivalent diameter of seed width and thickness was determined for each seed based on formula (1). The correlations between the equivalent diameter and the coefficients of sliding friction were analyzed. The range of variation in seed thickness and width was expanded by including the values determined for various cereal species by CHOSZCZ et al. (2010), GEODECKI and GRUNDAS (2003), GROCHOWICZ (1994), HEBDA and MICEK (2005, 2007), KALKAN and KARA (2011), KUSIŃSKA (2004), KUSIŃSKA et al. (2010), SADOWSKA and ŻABIŃSKI (2009), SEGIT et al. (2003) and SOLOGUBIK et al. (2013). The minimum and maximum values of the examined parameters were used to determine the range of variation in the equivalent diameter of seed thickness and width.

Calculations were performed for a string sieve variant equipped with steel strings where the width of the separating groove equaled $s_p=1$ mm at the beginning of the screen and $s_k=5$ mm at the end of the screen. String diameter was $D_s=1$ mm and string spacing was $R_s=2$ mm at the beginning of the screen (KALINIEWICZ 2013a).

Results and discussion

The analyzed seeds were arranged in the following descending order based on the average values of the equivalent diameter of seed width and thickness: barley, wheat, triticale, oats and rye (Tab. 2). The equivalent diameter was determined in the range of 1.79 mm (rye) to 3.81 (barley).

Table 2

Statistical distribution of the equivalent diameters of seed width and thickness

Cereal species	x_{min}	x_{max}	x	SD
Wheat	2.52	3.55	3.08	0.24
Rye	1.79	3.08	2.52	0.24
Barley	2.60	3.81	3.35	0.24
Oats	2.25	3.23	2.85	0.18
Triticale	1.99	3.57	2.97	0.34

KALINIEWICZ (2013b) demonstrated that physical dimensions (length, width, thickness), weight, volume, density and shape of cereal seeds do not significantly affect their frictional properties. Similar results were reported during attempts to determine correlations between the equivalent diameter of seed width and thickness and the seeds' coefficients of external friction (Tab. 3). Practically significant correlations, i.e. situations in which the coefficient of correlation exceeded 0.4, were not observed. A very weak correlation was noted only between the equivalent diameter and the coefficient of static friction of barley seeds on a steel surface. In the remaining cases, correlation coefficients were below critical value. Every analyzed seed can be thus assigned a coefficient of sliding friction from the entire range of values determined for a given cereal species.

Table 3

Coefficients of linear correlation between the equivalent diameter of seed width and thickness and the coefficients of external friction of seeds

Cereal species	Coefficient of external friction	
	μ_s	μ_k
Wheat	-0.061	-0.048
Rye	-0.120	0.017
Barley	**-0.198**	-0.027
Oats	0.047	0.106
Triticale	-0.012	0.017

Bold font indicates that the correlation coefficient has exceeded critical value

HEBDA and MICEK (2005, 2007) demonstrated very strong correlations between physical dimensions of cereal grains. In line with the determined sign of the correlation coefficient, it was assumed that the observed correlations were directly proportional, e.g. low thickness corresponded to low width of cereal seeds. When the range of variability in physical dimensions was expanded, the equivalent diameter of seed width and thickness was determined in the range of 1.3 to 4.9 mm (Tab. 4). When the adopted parameters of a string sieve, i.e. $s=s_p=1$ mm and $d_s=1$ mm, were substituted into formula (6), the result was:

$$\varphi = \arc \sin \frac{2}{d+1} \tag{18}$$

Table 4

Equivalent diameters of seed width and thickness

Cereal species	d [mm]
Wheat	1.5–4.2
Rye	1.3–3.5
Barley	1.7–4.9
Oats	1.3–3.6
Triticale	1.8–4.2

The above equation and Figure 4 indicate that angle *o* decreases with an increase in the equivalent diameter of seed width and thickness. Subject to the seed's plumpness, angle φ can range from 19.8° (barley) to 60.4° (rye and wheat). The values of angle φ and the values of static friction coefficients were substituted into equation (11) to obtain a range of sieve angles at which seeds are propelled into motion (Fig. 5). The plumper the seeds, the smaller the angle of inclination. The following ranges of sieve angles were determined for the analyzed cereal species:
– wheat – 14.1–34.0°,
– rye – 14.5–40.1°,
– barley – 14.6–31.2°,
– oats – 14.2–44.0°,
– triticale – 16.0–38.1°.

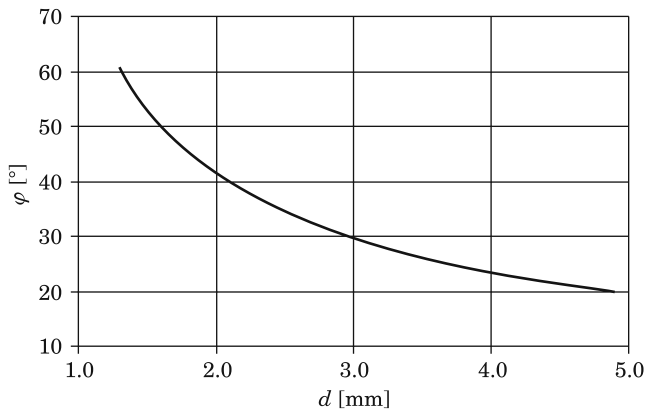

Fig. 4. Interrelation between the equivalent diameter of seed width and thickness and the angle of a string's normal ground reaction force relative to the gravity component (beginning of sieve)

The above indicates that seeds are propelled into motion when a string sieve is set at an estimated angle of 45°. The sieve's parameters were substituted into equation (17) to produce:

$$\varphi = \text{arc sin} \frac{3d + 5}{4d + 4} \tag{19}$$

The values of angle φ were substituted into formula (14) to produce a range of sieve angles at which the ratio of the distance traveled by accelerating seeds and the distance traveled by slowing down seeds was 3:1. The above angle can assume the following range of values, subject to the equivalent diameter of seed width and thickness and the coefficient of sliding friction:

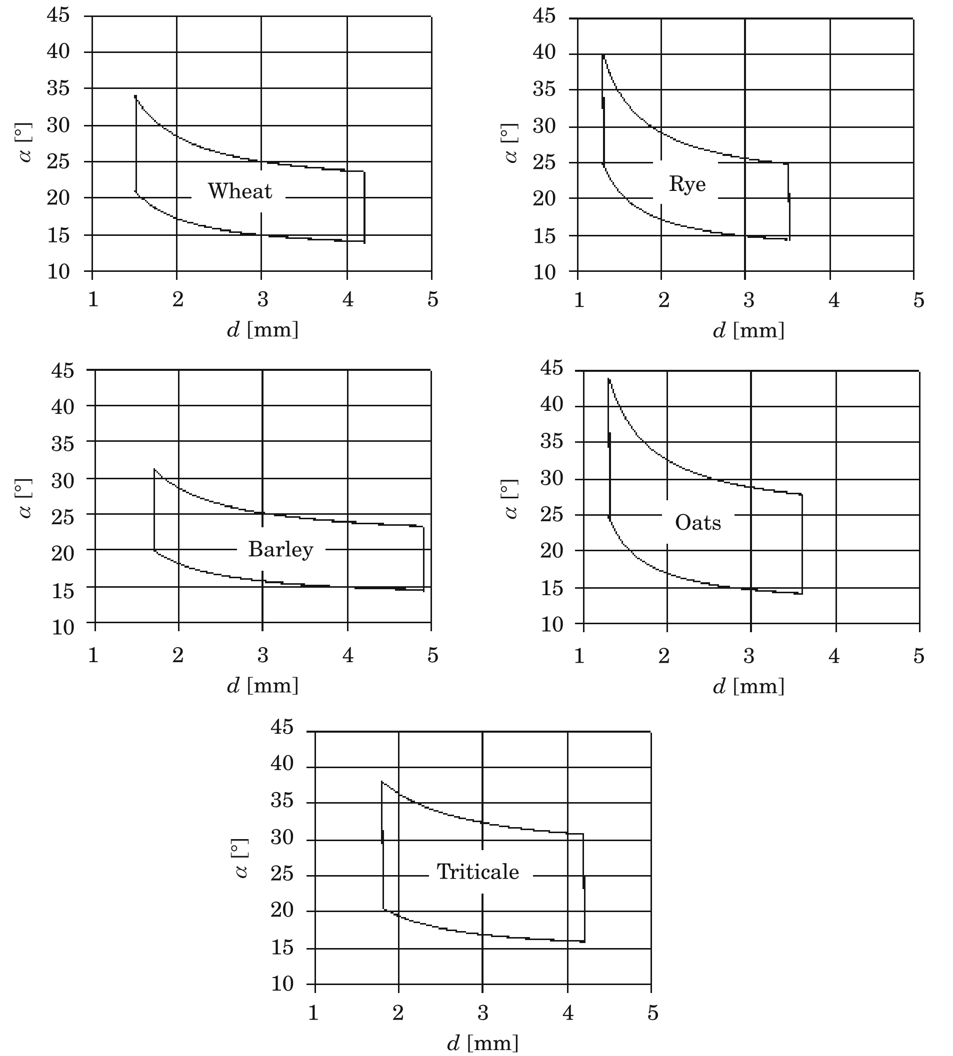

Fig. 5. Range of inclination angles of a string sieve at which cereal seeds are propelled into motion

- wheat – 13.9–41.9°,
- rye – 12.1–44.0°,
- barley – 12.4–39.9°,
- oats – 7.4–48.5°,
- triticale – 5.1–41.3°.

The range of variation is relatively broad, in particular for triticale seeds. Seed movement should satisfy the previously formulated conclusion to ensure the continuity of the separation process and to avoid mesh blockage. For this

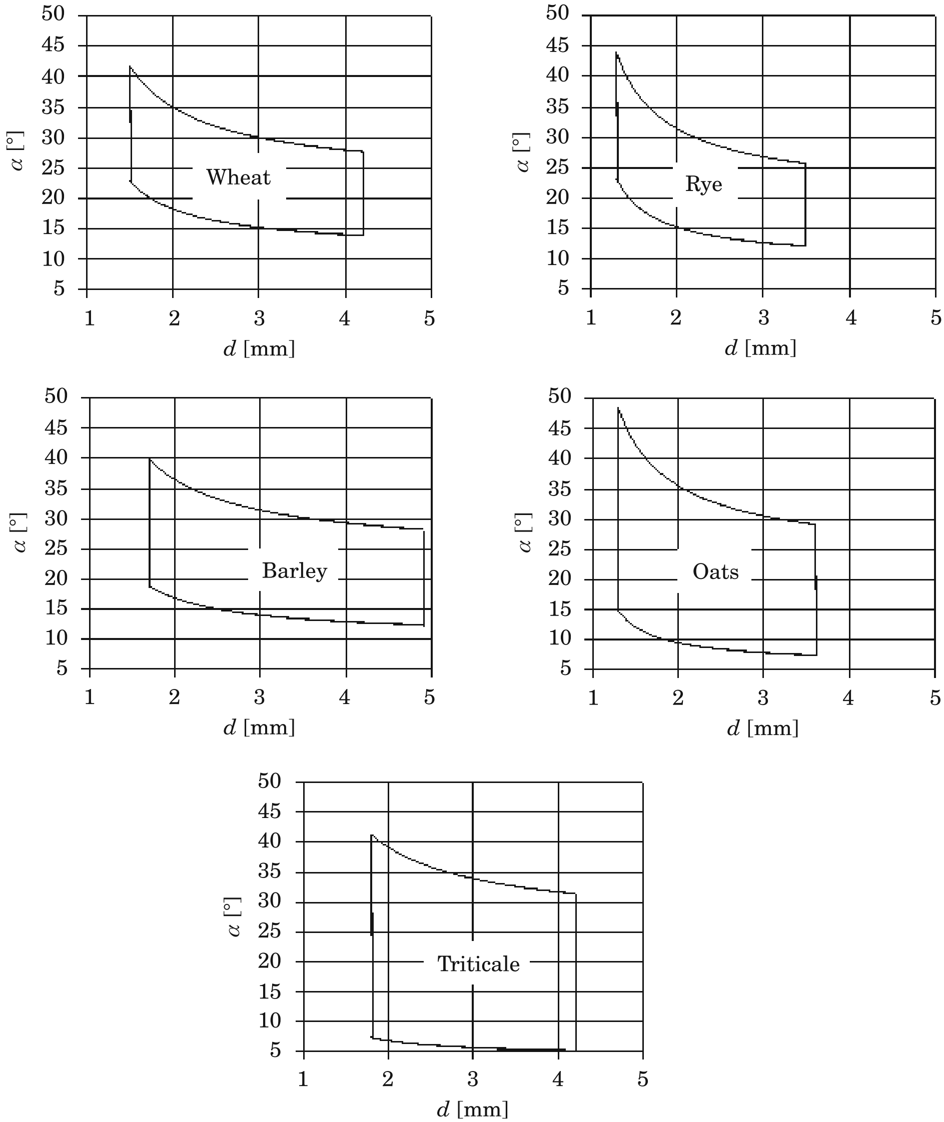

Fig. 6. Range of inclination angles of a string sieve which ensure the continuity of the separation process

reason, a string sieve should be set at the greatest angle. Oat seeds can be separated effectively at the angle of approximately 40°, whereas wheat, barley and triticale seeds require a greater angle of around 45°. To separate a mixture of the analyzed seed species, the inclination angle of a string sieve should be set at approximately 50°. According to GROCHOWICZ (1994), the angle of inclination in modern separating devices rarely exceeds 8°. In this experiment, the choice of such a large inclination angle seems to be irrational, and it leads to an adverse increase in sieve height. In the discussed solution, the height of the sieve is increased by approximately 77% of its length to ensure the effective separation of all cereal seed species. To appropriately position a string sieve with the length of 1.2 m, its height has to be increased by 0.92 m. Large inclination angles are also undesirable because they prevent seed mixtures from being separated with the required precision. A mixture contains large seeds with relatively low coefficients of friction. Such seeds can attain high speeds, and they will fly over the location where they should theoretically pass through the screen. They will reach seed fractions characterized by significantly larger dimensions and higher coefficients of friction. To avoid the above scenario, the inclination angle of a string sieve should not exceed 10°, and seeds should be propelled into motion on the surface of the screen with the use of power brushes or by setting the entire separator bucket into motion.

Conclusions

1. In the presented solution which relies solely on the force of gravity, a string sieve has to be set at the angle of 50° to ensure the continuity of the separation process and avoid mesh blockage. At such a large angle, large seeds with a small coefficient of friction will attain excessive speeds, thus decreasing separation effectiveness.

2. The designed string sieve relies only on the force of gravity, and further research is needed to find more effective solutions. The effectiveness of the separation process can be enhanced by decreasing the inclination angle of the sieve to maximum 10° and propelling seeds into motion with the use of power brushes or by setting the entire separator bucket into reciprocating motion.

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