

## ANALYSIS OF THE PNEUMATIC SEPARATION PROCESS OF AGRICULTURAL MATERIALS\*

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**A b s t r a c t.** In the process of pneumatic separation we use as separating characteristics aerodynamic properties of particles, their critical velocity being the characteristic value. The investigations were carried out on a pneumatic separator whose design enabled a wide range of regulations of parameters. Based on the study results the essential factors that affected the course of the process were identified and the theoretical correlation between them, deciding about the efficacy of pneumatic separation, were determined.

The main aim of the study was to analyse the separation process in an air stream of broken-up lupine seeds, chiefly involving theoretical considerations of movement and behaviour of mixture particles in a pneumatic canal. Investigations and observations gave ground for an attempt at determining a deriving a movement equation of particles in an unrestrained, uniform air stream.

The equations obtained can be used for calculating the parameters of particle movement in pneumatic canals. The velocities of air stream, then, can be a few times higher than the critical velocity /convection/ of individual particles. While working out the above problems there were considered, on the one hand possibilities of obtaining the greatest effectiveness of the separation process, and on the other, the smallest possible losses of valuable material in the discarded lot.

**K e y w o r d s:** crushed mixes of lupine, the analysis of the process pneumatic separation

### INTRODUCTION

The utilization of protein in lupine seeds involves numerous processes, the primary objective of which is to separate effectively the

high-protein material through processing raw material [1,2,4]. In this respect the selection of measures improving the nutritional properties of the product is highly important, as is the composition of machinery and apparatus of strictly defined operational parameters [1,3,5]. Such measures include the processes of husking and husk fraction separation. It should be added that the process of separation of the mentioned lupine mixture has its own specific character, determined by numerous untypical and not fully understood physical properties of the mixture, and related to a number of technical and operational parameters determining the choice of optimum method of separation.

### OBJECTIVE AND SCOPE

The process of air separation of crushed lupine mixtures has a certain specific character, determined by the degree of diminution, moisture content, and the airflow velocity in the aspiration duct of the separator. Therefore, a working hypothesis was adopted, to the effect that the above technical parameters and physical properties of mixtures have a decisive influence on the course and quality of the process of air separation of protein from any mixture of crushed lupine seeds.

The primary objective of the study was to determine the effect of selected parameters and properties of crushed lupine mixtures on obtaining the maximum possible amount of the cotyledon fraction. Moreover, an attempt was made at the determination of the relationship between the conditions under which the shelling process was conducted, and the effectiveness of separation of the seed cover fraction in air at various air flow velocities.

Description equation of particle motion in an unrestricted, uniform air stream.

The effectiveness of the process of air separation was assessed by determining the separation effectiveness index.

#### METHODS

The study was conducted for three air flow velocities, for all the varieties involved, using a laboratory air separation system.

The study was conducted on Mediterranean lupine which includes the annual multi-seed lupines grown in Poland. Out of each group of lupines, one variety, representative for the species, was selected for the study. The varieties used in the study were the following:

- yellow lupine - Amulet variety,
- blue lupine - Emir variety,
- white lupine - Bardo variety.

The object of the study were mixtures obtained through the crushing of seeds of three lupine varieties using a cone crusher. The wor-

king slot width was  $a_1=2.5$  mm,  $a_2=3.0$  mm and  $a_3=4.1$  mm, respectively. Out of the grain material, 20 samples of 100 g each were weighed. Samples of moisture content of  $W_1=10.1\%$ ,  $W_2=12.3\%$ ,  $W_3=13.8\%$  and  $W_4=15.7\%$  were subjected to air separation in the aspiration duct of the separator. The fraction separated by the air flow was then hand sifted to separate the cotyledon fraction from the fraction of seed covers with cotyledon fragments. The two fractions were weighed with an accuracy of 0.01 g using an electronic balance.

In the next stage of the study the results obtained were used as a basis for the calculation of the index of separation effectiveness. The index  $\eta$  was determined on the basis of the following equation:

$$\eta = \frac{b}{b_0} 100\%$$

were  $\eta$  - separation effectiveness index (%),  $b$  - content of contaminant (seed cover fraction) in the fraction separated in air flow (kg),  $b_0$  - content of contaminant in the input material (kg).

The calculated values of index  $\eta$  permitted the assessment of the effectiveness of the process of air separation of crushed grain mixture in relation to its moisture content, degree of diminution, and air flow velocity.

The samples of all the grain mixtures were tested in the laboratory air separator (Fig. 1).

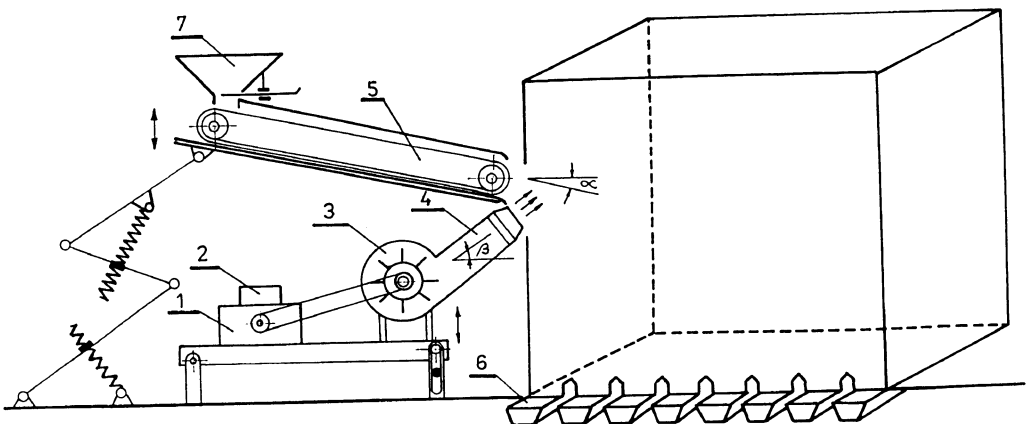


Fig. 1. Scheme of investigation stand: 1 - engine, 2 - wave-maker, 3 - ventilator, 4 - ventilator nozzle, 5 - conveyor loader 6 - collective chutes, 7 - loading basket.

## RESULTS AND ANALYSIS

On the basis of the tests conducted by means of the air separator and through manual separation of crushed seed mixture into cotyledon and seed cover fractions, the authors determined the index of separation effectiveness  $\eta$ . The calculated values of the index permitted the assessment of the effectiveness of the process of air separation of lupine seed mixture in relation to its moisture content, degree of diminution, and air flow velocity in the separator duct.

Figure 2 presents the values of the separation effectiveness index  $\eta$  obtained in the course of the air separation process of crushed mixtures of three lupine varieties, in relation to the moisture content and the degree of diminution of the seeds.

Analysis of the values of the separation effectiveness index  $\eta$  obtained indicates a relatively complex correlation describing the relations among the effects of the particular parameters on the effectiveness of the process of air separation. A change in one of the parameters (even a slight one) leads to a considerable disturbance and deterioration of the process of separation, making it difficult to determine the optimum conditions for air separation.

And thus, the highest values of the separation effectiveness index were obtained in the process of air separation of crushed mixtures of Amulet yellow lupine. Its values were varied in relation to the moisture content of the samples, the degree of diminution, and the air flow velocity in the separator duct. The highest value, 87.2%, was obtained for a grainy mixture of a moisture content of  $W_1=10.1\%$ , at working slot width  $a_1=2.5$  mm and air flow velocity  $V_3=12.8$  m/s. As the moisture content of the mixture increased, the effectiveness of air separation of the seed cover fraction deteriorated distinctly. At a moisture content  $W_4=15.7\%$  and a working slot width  $a_3=4.1$  mm, the value of the index  $\eta$  was only 33.1%.

The values of the index  $\eta$  for mixtures of the Emir lupine variety were somewhat different. In this case the highest value, 58.2%, was obtained at working slot width  $a_2=3.0$  mm, air

flow velocity in the aspiration duct of the separator  $V_3=12.8$  m/s, and grain moisture content  $W_1=10.1\%$ . It should be noted that a change in any single parameter of the separation process caused a decrease in the value of the separation effectiveness index. This also held true for an increase in the air flow velocity above the limit value of 12-13 m/s. While higher air flow velocities did result in an increase in the effectiveness of seed cover fraction separation from the cotyledon fraction, it was at the cost of increased amounts of the valuable fraction in the refuse. As follows from the above, the upper value of air flow velocity of  $V_3=12.8$  m/s is the optimum value for crushed lupine seed mixtures.

In the course of air separation of mixtures of the Bardo white lupine variety an increase in the air flow velocity from  $V_1=7.8$  m/s to  $V_2=10.5$  m/s resulted in an average increase in the value of the separation effectiveness index by 17-21%. An increase in the velocity from  $V_2=0.5$  m/s to  $V_3=12.8$  m/s the value of  $h$  increased more slowly, the average gain being 10-15%. It should be added here that in this case, like for the other lupine varieties, the working slot width had a distinctly lower effect on the effectiveness of separation than the air flow velocity. And thus, a change in the working slot width from  $a_3=4.1$  mm to  $a_1=2.5$  mm resulted in a 3-16% increase in the separation effectiveness, depending on the air flow velocity and the moisture content of the mixture. In the case of this lupine variety, as for the other varieties, the lowest increases in the value of the effectiveness index  $\eta$  occurred for samples of moisture content  $W_4=15.7\%$ .

Analysis of the values of the separation effectiveness index confirmed that the moisture content of the crushed lupine seed mixture has a considerable effect on the effectiveness and on the course of the process of air separation. The highest values of the index, for all the lupine varieties tested, were obtained at moisture content  $W_1=10.1\%$  and working slot width  $a_1=2.5$  mm. And thus, the index  $\eta$  attained the highest values for the Amulet lupine mixture -87.2, while for the Emir and Bardo varieties the highest values

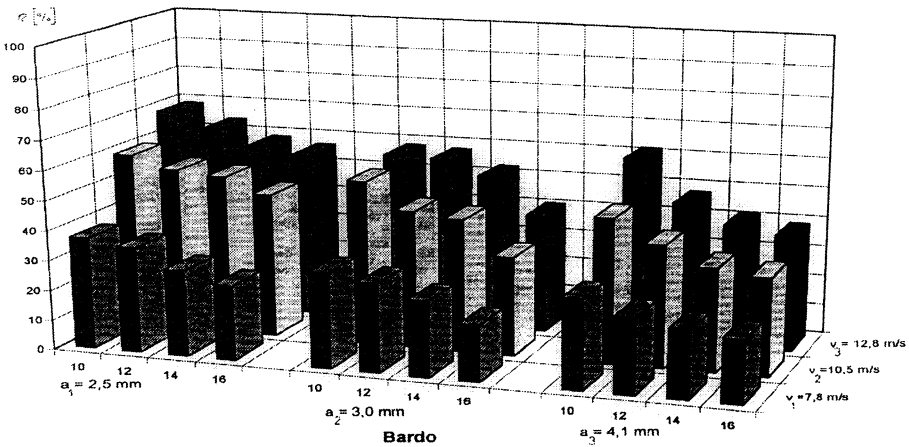
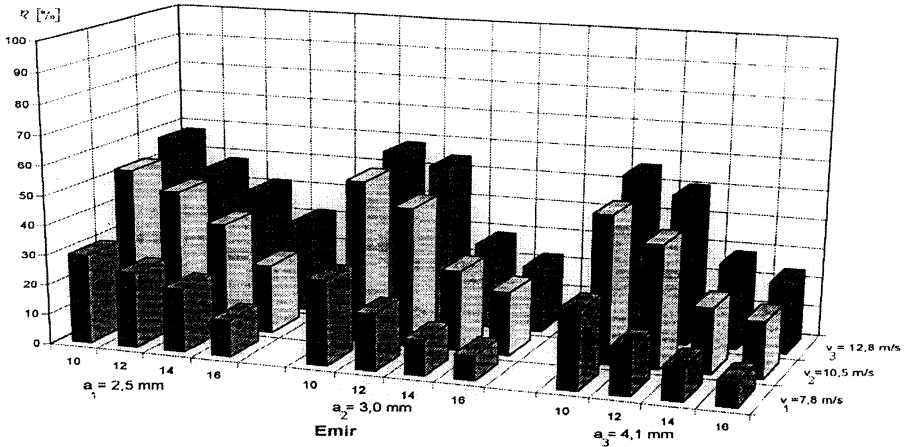
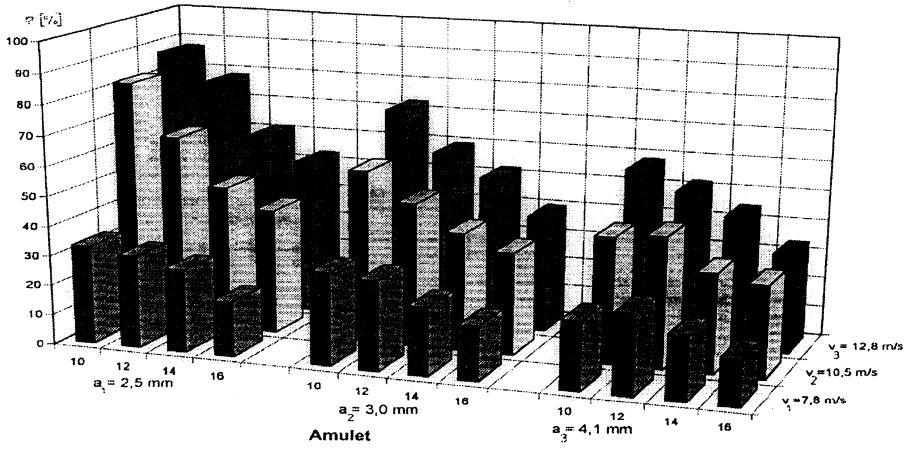


Fig. 2. Values of the separation effectiveness index obtained in the course of air separation of crushed mixtures of three lupine varieties.

of the index were 58.2% and 68.4%, respectively. Increasing moisture content of the mixtures brought about a noticeable decrease in the effectiveness of the process of air separation, irrespective of the degree of diminution of the mixtures and of the air flow velocity.

THEORETICAL DESCRIPTION OF STUDY RESULTS

Equation of particle motion in an unrestricted, uniform air stream

On the basis of the study results an attempt was undertaken to analyse the particle motion habitat of the granular mixture in an area of air stream interaction. This refers to the course of the pneumatic separation process made in the investigation stand presented in (Fig. 1).

During separation, a particle of mass  $m$  is introduced with given initial velocity  $W$  and angle  $\alpha$  into the area of air stream affection. The stream moves at velocity  $u$  and it is directed at angle  $\theta$  in relation to horizontal plane (Fig. 3).

Let us take the case of particle motion in air stream under gravity force  $mg$  directed parallel to the vertical axis and to head resistance force  $R$ . The resistance force direction is opposite to the moment relative velocity  $v$ , and its value is proportional to the second power of velocity  $kv^2$ . When the particle comes into the stream, it moves at relative velocity  $v$ , value and direction of which are described as the resultant of parallelogram constructed using vectors -  $\bar{u}$  and  $\bar{w}$ .

From Fig. (3b) it follows that:

$$v_o = \sqrt{u + \omega^2 - 2u\omega \cos(\alpha - \beta)}. \quad (1)$$

Taking into account the sinus theory, it can be obtained that:

$$\theta = \beta - \arcsin \left[ \frac{\omega}{v_o} \sin(\alpha - \beta) \right]. \quad (2)$$

Let us consider the relative motion of particle assuming that axes of Cartesian co-ordinates system move along with the air stream. The equations of relative motion shape:

$$\frac{dv}{dt} = g \sin \theta - kv^2, \quad (3)$$

$$\frac{v^2}{r} = g \cos \theta, \quad (4)$$

where:  $r$  - radius of trajectory curvature,  $\theta$  - angle between  $x^y$  axis and tangent to relative velocity  $v$ .

Dividing Eq. (3) by (4) and taking into account that  $v dt = r d\theta$ , we obtain the equations of velocity hodograph:

$$\frac{dv}{v^3 dv} = \frac{\operatorname{tg} \theta}{v^2} - \frac{k}{g \cos \theta} - \frac{2dv}{v^3 \cos^2 \theta} - \frac{2 \operatorname{tg} \theta d\theta}{v^2 \cos^2 \theta} = \frac{k}{g} \left( \frac{2d\theta}{\cos^3 \theta} \right), \quad (5)$$

where  $k$  - volatility coefficient.

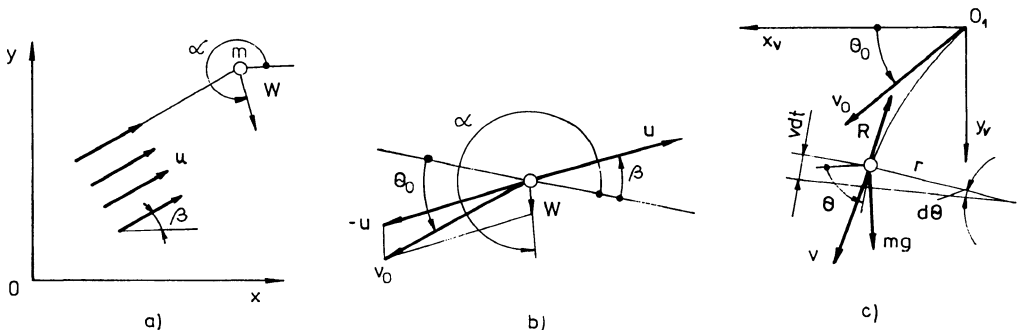


Fig. 3. Scheme of particle motion in an uniform air stream: a) introducing the particle into the air stream interaction area, b) estimation of the relative velocity at the moment of particle introducing into the stream affection area, c) effect of stream and particle interaction on its trajectory in relative motion.

For air stream velocity equalled to particle critical velocity we may accept that  $k = \text{const}$ . The left side Eq.(5) is full derivative of expression  $\frac{1}{v^2 \cos^2 \theta}$ , and part of equation between brackets is a derivative of expression:

$$\frac{\sin \theta}{\cos^2 \theta} + \ln \text{tg} \left( \frac{\theta}{2} + \frac{\pi}{4} \right).$$

Integrating the equation (5) we obtain:

$$\frac{1}{v^2 \cos^2 \theta} + c_2 = \frac{k}{g} \left[ \frac{\sin \theta}{\cos^2 \theta} + \ln \text{tg} \left( \frac{\theta}{2} + \frac{\pi}{4} \right) \right]. \tag{6}$$

Constant  $c_2$  meaning can be found on a base of initial conditions that are:  $t=0, V=V_o, \theta = \theta_o$ :

$$c^2 = \frac{k}{g} \left[ \frac{\sin \theta_o}{\cos^2 \theta_o} + \ln \text{tg} \left( \frac{\theta_o}{2} + \frac{\pi}{4} \right) \right] - \frac{1}{v_o^2 \cos^2 \theta_o}. \tag{7}$$

From Eqs (6) and (7) we obtain an expression that helps to calculate the relative velocity referring to angle  $\theta$ :

$$v = \frac{1}{\cos \theta \sqrt{\frac{k}{g} \left[ \frac{\sin \theta}{\cos^2 \theta} + \ln \text{tg} \left( \frac{\theta}{2} + \frac{\pi}{4} \right) \right] - c_2}}. \tag{8}$$

From equation  $v^2 = r g \cos \theta$  we find

$$v \frac{d\theta}{\cos \theta} = g dt \text{ and then } t = \frac{1}{g} \int_{\theta_o}^{\theta} \frac{v d\theta}{\cos \theta}.$$

Because  $v$  is known quantity of function  $\theta$  thus:

$$t = \int_{\theta_o}^{\theta} \frac{d\theta}{g \cos^2 \theta \sqrt{\frac{k}{g} \left[ \frac{\sin \theta}{\cos^2 \theta} + \ln \text{tg} \left( \frac{\theta}{2} + \frac{\pi}{4} \right) \right] - c_2}}. \tag{9}$$

The relative particle shift is described by expression:

$$S_v = \int v dt = \frac{1}{2k} \ln$$

$$\left\{ \frac{k}{g} \left[ \frac{\sin \theta}{\cos^2 \theta} + \ln \text{tg} \left( \frac{\theta}{2} + \frac{\pi}{4} \right) \right] - c_2 \right\} - c_3, \tag{10}$$

where:

$$c_3 = \frac{1}{2k} \ln \frac{1}{v_o^2 \cos^2 \theta_o}. \tag{11}$$

At this stage we may estimate the particle transaction during relative motion referring to Cartesian co-ordinates system:

$$x_v = \int v \cos \theta dt =$$

$$\int_{\theta_o}^{\theta} \frac{d\theta}{g \cos^2 \theta \left\{ \frac{k}{g} \left[ \frac{\sin \theta}{\cos^2 \theta} + \ln \text{tg} \left( \frac{\theta}{2} + \frac{\pi}{4} \right) \right] - c_2 \right\}}, \tag{12}$$

$$y_v = \int v \sin \theta dt =$$

$$\int_{\theta_o}^{\theta} \frac{\text{tg} \theta d\theta}{g \cos^2 \theta \left\{ \frac{k}{g} \left[ \frac{\sin \theta}{\cos^2 \theta} + \ln \text{tg} \left( \frac{\theta}{2} + \frac{\pi}{4} \right) \right] - c_2 \right\}}. \tag{13}$$

Thus the equations of particle relative motion under conditions of unrestricted air stream and resistance forces may be written as follows:

$$\frac{dv}{dt} = -kv^2, \tag{14}$$

$$\frac{v^2}{r} = 0. \tag{15}$$

From Eq. (14), after integrating we obtain the expression for  $v$ :

$$v = \frac{v_o}{1 + v_o kt}, \tag{16}$$

but,  $v_o$  value has to be calculated from Eq. (1).

From Eq. (15) it follows that  $r = \infty$  and it means that  $\theta = \text{const.}$ , and the trajectory of particle relative motion is a straight line. In a case when the volatility coefficient  $k = \text{const.}$ , we can easily obtain the expression estimating the projections of particle motion in absolute motion:

$$\frac{dx}{dt} = u \cos \beta - \frac{v_o \cos \theta}{1 + v_o kt}, \quad (17)$$

$$\frac{dy}{dt} = u \sin \beta - \frac{v_o \sin \theta}{1 + v_o kt}, \quad (18)$$

where:  $\theta = \beta - \arcsin \left[ \frac{\omega}{v_o} \sin(\alpha - \beta) \right]$ .

Integrating Eqs (17) and (18) we obtain:

$$x = ut \cos \beta - \frac{\cos \theta}{k} \ln |1 + v_o kt|, \quad (19)$$

$$y = ut \sin \beta - \frac{\sin \theta}{k} \ln |1 + v_o kt|. \quad (20)$$

The equation obtained can be used in pneumoseparation processes, especially during calculations of motion parameters of various components of initial mixture, although the air stream velocity may be several times higher than the critical velocity of particles being separated. It should be stressed that those equations have non-linear interdependencies and finding the precious analytical solution is practically impossible. Thus, in order to practically solve them, their transformations to computer modelling is very necessary.

#### CONCLUSIONS

1. An increase in the moisture content of crushed lupine seeds caused a considerable decrease in the value of the separation effective-

ness index  $\eta$ . With a 2% increase in moisture content the average decrease observed in the separation effectiveness was 8.1% for yellow lupine, 7.9% blue lupine and 2.9% for white lupine.

2. A decrease in the working slot width of the crusher from  $a_1=4.1$  mm to  $a_1=2.5$  mm permitted an increase in the effectiveness of the cotyledon fraction separation from the seed cover fraction by 2.1% -7.7% at moisture content  $W_1=10.1\%$  and by 5.5% -11.6% at moisture content  $W_4=15.7\%$ , depending on the lupine variety.

3. With increasing air flow velocity the separation effectiveness index increased, but its increase was accompanied by an increase in the amount of valuable fraction carried away by the air flow. With an increase in the air flow velocity above  $V_1=7.8$  m/s (for moisture contents within the range from  $W_1=10.1\%$  to  $W_4=15.7\%$ ), the highest increase in the value of the separation effectiveness index was recorded for the yellow lupines - from 16.1% to 38.2% corresponding increase values for the blue and white lupines being from 11.3% to 22.2% and from 9.0% to 23.9%, respectively.

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