ANALYSIS OF THE SEPARATION OF STRAW AND CHAFF FROM WHEAT BY AN AIR BLAST

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Grain losses in an aerodynamic pre-cleaner for a grain combine are affected by air velocity and direction. In this study, a mathematical model of particle motion was solved numerically to simulate the motion paths of grain and straw particles in an air stream. Furthermore, laboratory experiments were conducted to observe the grain loss in the apparatus using different jet angles and fan inlets. The results were analyzed by regression analysis and compared with the theoretical results. A low grain loss was obtained by selecting appropriate velocities and directions of the air stream over the pre-cleaner sieve.

INTRODUCTION

Aerodynamic forces play an important part in grain separation and cleaning. The cleaning efficiency is very sensitive to air velocity since the drag force caused by the air stream is proportional to the second power of the air velocity. Numerous authors have studied the effect of air velocity on the efficiency of grain separation and cleaning (Uhl and Lamp 1961; MacAulay and Lee 1969; Rumble and Lee 1970; Misener and Lee 1973; Freye 1980). On the other hand, the direction of the air stream introduced to the material has been realized as another important factor affecting cleaning efficiency (Misener and Lee 1973). Consequently, the manner in which the combination of these two factors affects separation and cleaning efficiency is of interest in our study of incorporating a pre-cleaner into the combine cleaning system.

This pre-cleaner would replace the traditional oscillating grain pan. The threshed material mixture would be transported pneumatically to the cleaning sieves by an air blast. Can. Agric. Eng. 26: 181-187.

One end had the highest terminal velocity (4.9 m/sec).

Jet angles of the pre-cleaner. The results from both theoretical and laboratory studies are discussed and compared. The best jet angles and fan inlet diameters of the pre-cleaner were thus determined.

LITERATURE REVIEW

The aerodynamic drag force $F_d$ acting upon a particle moving through air is a function of particle frontal area $A_p$, air density $\rho_a$, air viscosity $\eta$, elastic modulus of air $E$ and the relative velocity between the air and the particle $V_r$ (Mohsenin 1970):

$$F_d = f(A_p, \rho_a, \eta, E, V_r)$$

The general form of $F_d$ determined with the Buckingham $\pi$ theorem is:

$$F_d = 1/2 C \times A_p \times \rho_a \times V_r^2$$

where $C$ is a dimensionless quantity related to Reynolds number and is called the drag coefficient.

A few methods were developed to determine the drag coefficient $C$, the particle front area $A_p$, and the Reynolds number $N_r$ (Bilanski et al. 1962; Garrer and Brooker 1965; Hawke et al. 1966; Shellard and MacMillan 1978).

Rumble and Lee (1968) developed the differential equations of particle motion in an air stream by assuming that the drag coefficient remained constant as the particle was accelerated from zero to terminal velocity.

In 1963, Bilanski et al. determined the terminal velocities of wheat grain to be between 8.8 and 9.2 m/sec. In like manner, Bilanski and Lal (1965) determined the terminal velocities of wheat straws of various lengths. The results showed that straws less than 6 mm long with a node at one end had the highest terminal velocity (4.9 m/sec).

The possibility of aerodynamically separating the grain from straw and chaff was studied by Uhl and Lamp (1961). They found that all chaff-like portions could readily be separated without grain loss, and approximately 94% of the straw could be removed from the wheat grain without grain loss.

Several authors (MacAulay and Lee 1969; Rumble and Lee 1970; Misener and Lee 1973) studied the aerodynamic action by introducing an auxiliary air stream to the entrance of the upper sieve. MacAulay and Lee (1970) pointed out in their study the need for a device that could disperse the material mat completely before it reached the sieves. The results of Misener and Lee’s work showed that the best angle of the duct used to direct air over the sieve is around 40 to 45 degrees.

THEORETICAL STUDY

The principle of this study is based on the aerodynamic properties of grain, chaff and straw. The forces acting upon a particle moving in an air stream are the gravitational force, $F_g$, and the drag force caused by the air stream, $F_d$.

According to Newton’s second law $F = ma$, the equations of particle motion in vertical and horizontal directions are, respectively,

$$ma = F_e - F_d$$

$$ma = F_e$$

To simplify the theoretical analysis, the assumptions used in Rumble and Lee’s study (1968) are adopted here. In addition, it is assumed that the velocity and direction of the air all over the multiple-air-jet sieve are constant (do not change with the position).

The drag forces in the $Y$ and $X$ directions obtained by Rumble and Lee are...
\( F_d = mg \left( \frac{V_y}{V_z} \right) \)  \( F_d = mg \left( \frac{V_x}{V_z} \right) \)

where, \( V_y \) and \( V_x \) are the relative velocities in the \( Y \) and \( X \) directions, respectively.

By substituting the component forces of \( F_d \) into the equations of particle motion and noticing that \( a_y = \ddot{Y} \), \( a_x = \ddot{X} \), the basic differential equations for pure aerodynamic separation are:

\[ \ddot{Y} = g \left( \frac{V_y}{V_z} \right) \]  \( \ddot{X} = g \left( \frac{V_x}{V_z} \right) \)

Substitution of the relative velocities

\[ V_y = V_{yw} - V_{yw} = V_{yu} - \dot{Y} \]  \( V_x = V_{xw} - V_{wx} = V_{wu} - \dot{X} \)

into Eqs. 6 and 7, yields the differential equations of particle motion:

\[ \ddot{Y} = \left( \frac{gV_y}{V_z} \right) \frac{Y}{Y} + \left( \frac{2gV_y}{V_z^2} \right) Y \]  \[ \ddot{X} = \left( \frac{gV_x}{V_z} \right) \frac{X}{X} + \left( \frac{2gV_x}{V_z^2} \right) X \]

A FORTRAN program using the Runge-Kutta method was developed to solve the equations under four different initial conditions. The respective results are shown in Figs. 1 to 4. The particle initial velocity used in the \( Y \) direction was zero and in the \( X \) direction was 0.35 m/sec. The angles were the air flow direction angles which were equal to arc tan \( \left( \frac{V_y}{V_x} \right) \). The grain terminal velocity used was 9.0 m/sec (Bilanski et al. 1963). The paths of grain particles are plotted in solid lines. The straw terminal velocity used was 4.9 m/sec (Bilanski and Lal 1965). The paths of the straw particles are plotted in dotted lines. The respective position of the sieve is shown in the figures.

Figures 1 and 2 show the motion paths of the grain and straw particles at the air flow direction angles of 20°, 30°, 40°, 50° and 90° at an air velocity of 10.5 m/sec and 6.4 m/sec, respectively. It can be seen from Fig. 1 that at the higher air velocity the straw and grain particles are blown more upward and rearward as the air flow direction angle increases. At angles greater than 30° the straw particles are moved quickly upward since the vertical component of air velocity far exceeds the straw terminal velocity. As the air flow direction angle increases, the vertical component air velocity increases and the horizontal air velocity decreases. This slows down the particle velocities in both the vertical and horizontal directions when the vertical component of air velocity is not greater than the particle terminal velocity. Depending on the relative magnitude of components of air velocity changed, two possible cases are:

1. If the decrease of the particle velocity in the vertical direction is greater than that of particle velocity in the horizontal direction, the particle will be transported more rearward.
2. If the decrease in particle velocity in the horizontal direction is greater than in the vertical direction, the particle will not be transported as far rearward.

At a high air velocity (i.e. 10.5 m/sec) the vertical component air velocity is close to the grain terminal velocity at high angles, thus case 1 occurs. From the curves it can be seen that if a 90° angle is used, theoretically the grain would be blown upward shortly after it entered the air stream.
The grain could not be transported rearward since there is no horizontal component of air velocity.

From Fig. 2, it can be seen that the straw would be transported more rearward and the grain would be transported relatively less as the air flow direction angle increases at an air velocity of 6.4 m/sec. At high angles, the vertical component air velocities are close to or slightly exceed the straw terminal velocity. Thus the straw is transported more upward and rearward as the air flow direction angle is increased. The grain, however, is transported less since the vertical component air velocities are still far from the grain terminal velocity, causing a case 2 example. From the above results, it may be hypothesized that in a high air velocity region, the straw and the grain will be transported more rearward as the air flow direction angle increases; and in a low air velocity region, the straw will be transported more rearward but the grain will be transported less rearward as the direction angle increases. Hence, it is possible to obtain a satisfactory separation efficiency by properly selecting air velocities for certain air flow direction angles.

In step two of the theoretical work, the particle motion paths for different combinations of air velocity and air direction were solved and plotted in Fig. 3. The air flow direction angles used in this step were 20°, 25°, 30°, 40° and 50°. The air velocities used for each angle are 9.9, 8.6, 7.6, 7.2, and 6.0 m/sec, respectively. These values were obtained from the actual measurement when a fan inlet diameter of 330 mm was used in the pre-cleaner (see Table I). From the curves it can be seen that as the air direction angle increases both grain and straw particles are transported less rearward for all the combinations, the only exception being at the angle 40°. At the angle of 40°, the grain is moved less than the 30°, 25° and 20° angles, but the straw is moved more rearward than at these angles. This may result in a good separation. For the angle of 50°, the grain motion path is steep, which may not be good for the purpose of grain transport. It was hypothesized that with this fan inlet, a good separation may be obtained at the angle of 40°.

In step three of the study, the particle motion paths for different air velocities at an air direction of 20° are solved and plotted in Fig. 4. The air velocities are the mean values of the measured data when using 305-, 330- and 355-mm diameter fan inlets (See Table I). The curves presented show that the grain and straw will be transported more rearward as the air velocity
increases. This is due to the simultaneous increase of air velocities in the vertical and horizontal directions. Thus, reducing air velocity may reduce the grain loss and at the same time increase the MOG content in the grain.

**EQUIPMENT AND METHOD**

When the grain drops onto the sieve surface, it will either slide, bounce or stay on the sieve surface depending on the air and other conditions. In practice, particles in a material mat interact with each other and a large number of variables affect particle motion in an air stream. It is impossible to determine the proper air velocities and directions theoretically; hence, this was done experimentally.

The apparatus used in this experiment included a pre-cleaner consisting of a multiple-air-jet sieve, an air chamber and a fan; a belt conveyor; and a collecting container. The collecting container was divided into four boxes. The first three boxes (total 1.05 m long) correspond to the cleaning sieve in a combine. Figure 5 shows a schematic layout of the functional components of the equipment in their respective positions.

The multiple-air-jet sieve, 1.0 m in length and 0.576 m in width was made by using a number of steel straps with dimensions of 3.2 x 50.8 x 597 mm. Both ends of the strap were set in the slots of a wood frame at constant intervals of 4.8 mm, giving a 60% open area of the sieve. Five sets of sieve frames provided five different jet angles of 20°, 25°, 30°, 40° and 50° to control the air flow direction over the sieve.

The air velocity over the multiple-air-jet sieve was very difficult to control since it was affected by both variables of jet angle and air flow rate. Therefore, the experiment was conducted on the base of the control of the air flow rate. Since the fan speed was constant, three fan inlets with 305-mm, 330-mm and 355-mm diameters were used to control the air flow rate. The air velocities across the fan entrance pipe were measured at 15 equi-distance points for different fan inlet diameters to determine the air flow rates.

The static pressure below the sieve was measured at three equi-distance points along the sieve, and the average values for different jet angles and fan inlet diameters were plotted in Fig 6. Air velocities were also measured inside the sieve jets at 14 points across the sieve length. Figure 7 shows the velocity profiles when using the 330-mm-diameter fan inlet. The average values of air velocities for different jet angles and fan inlet diameters are listed in Table I. The air velocities ranged from 5.4 m/sec to 10.5 m/sec for the angles and fan inlets tested. This range was roughly determined from the theoretical results, in which a dramatic change of the motion paths occurred from 6.4 m/sec to 10.5 m/sec.

The test material was delivered by belt conveyor and dropped onto the front area of the pre-cleaner sieve. It was then carried to the collecting container by an air stream. The material caught by the four collecting boxes was weighed, cleaned and reweighed. The grain collected in the fourth box was considered to be the grain loss as this grain would not be deposited on a cleaning sieve or sieve extension of a normal length sieve in a combine cleaning system. The amount of grain loss was expressed as a percentage of the total grain caught. Three feed rates of 1.5, 2.0, 2.5 kg/sec-metre (kilogram per second per metre width) were tested.

**MATERIAL**

Winter Hard Wheat was used for this experiment. The straw and chaff were obtained from the Harvesting Laboratory, Massey-Ferguson Company Limited. The moisture content of the grain and the MOG were 11-12% (WB) and 6% (WB), respectively. The bulk density of grain was 1.074 kg/L and of MOG was 0.036 kg/L. The MOG to grain ratio was fixed at 0.5 by weight.
The percent grain loss with different jet angles and fan inlet diameters are shown in Table II.

The best results with a fan inlet diameter of 355 mm (air flow rate 2.3 m³/sec) seemed to be around 40°–50° angles at low feed rates. At a feed rate of 2.5 kg/sec-m the grain losses were high for all of the angles tested.

Reducing air flow rate to 2.1 m³/sec by using a smaller fan inlet diameter (330 mm) decreased the grain loss considerably. A good separation was obtained at 30° and 40° angles for all the feed rates tested. At 25°, the results were quite good for feed rates of 1.5 kg/sec-m and 2.0 kg/sec-m. At 50° the grain was observed to stagnate on the sieve surface during the separation. Only a very even feeding of material at the 1.5 kg/sec-m feed rate avoided grain piling up at this jet angle.

When the 305-mm fan inlet was used (air flow rate 1.9 m³/sec), the grain loss at 20° angle was greatly reduced. With the same fan inlet diameter, the grain piled up on the sieve seriously for the 25° to 50° angles. The sieve could not function at these situations.

Comparing the above results, the best separation for the different fan inlets tested are shown in Table III. The loss curves of these conditions are presented in Fig 9.

The MOG content in the grain collected from the first three boxes increased with the increase of the jet angle and the decrease of the fan inlet diameter; but the variation was small and of no practical significance for a pre-cleaner.

The most efficient separation with low grain loss and low MOG content occurred at a jet angle of 40° with a 330-mm-diameter fan inlet. This agreed with the theoretical hypothesis. The efficient separation also occurred at jet angles of 20° and 30° with a 305-mm- and a 330-mm-diameter fan inlet, respectively. At these jet angles, the grain was observed to stagnate on the sieve surface during the separation. Only a very even feeding of material at the 1.5 kg/sec-m feed rate avoided grain piling up at this jet angle.

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angles and up to a feed rate of 2.5 kg/sec-m, the material mixture was dispersed as soon as it entered the air stream over the sieve. The grain was observed to be fluidized and flowed gently into the collecting container as the straw and chaff were blown out, resulting in good separation of the grain from the straw and chaff with a low percent of grain loss.

An interesting phenomenon was observed here. Though the air velocity when using a 20° angle with a fan inlet of 305 mm was higher than many other cases (e.g. a 35° angle with a 330-mm fan inlet, or a 30° or 40° angle with a 355-mm fan inlet), the percent grain loss was lower than in those other cases. Results show that the grain loss is not only related to the resultant air velocity, but must be a quantity related to the air directions and, consequently, to jet angles. On the other hand, the change in air direction mainly changed the horizontal and vertical component velocities. In order to study the influence of the vertical and horizontal air velocities, respectively, the resultant velocity inside the sieve jets was resolved into two components: the vertical velocity and the horizontal velocity. Denoting the grain loss as $Y$, two linear regression models are set under the normal assumptions:

**Model 1:**
$$Y = a_0 + a_1 X$$

**Model 2:**
$$Y = b_0 + b_1 X_1 + b_2 X_2$$

where $X$ represents the resultant air velocity inside the sieve jets, and $X_1$ and $X_2$ represent the vertical and horizontal component air velocities respectively. A Statistic Analysis System (SAS) program was used to conduct the regression. The results obtained from the computer output are:

**Model 1:**
$$Y = -1.1578 + 0.2240 X$$

**Model 2:**
$$Y = -4.4899 + 0.6868 X_1 + 0.3426 X_2$$

The $F$-test showed both models to be significant at the 95% confidence level. The multiple correlation coefficient $R^2$-Square, which is equal to 52.06% in Model 1, was significantly improved in Model 2, where it equalled 76.77%, meaning that grain loss $Y$ is more closely correlated with the linear combination of the two component air velocities than with the resultant air velocity alone. If the jet angle remains the same, an increase in air flow rate will result in an increase in resultant air velocity $X$. Since the component air velocity $X_1 = X \sin \beta$ and $X_2 = X \cos \beta$, the $X_1$ and $X_2$ will increase simultaneously. The increase in air velocity will cause grain loss increase. This is similar to the results in the third step of the theoretical study and can be seen from both models. If the resultant air velocity is kept the same and the jet angle increases, the component air velocity $X_1$ will increase and $X_2$ will decrease; hence, the grain loss will depend on the magnitude of change in each component velocity. This has been hypothesized in step one of the theoretical work from Figs. 1 and 2. The regression Model 2 took this into account but Model 1 did not. Thus, we may conclude that the regression Model 2 better explains the grain loss. As can be seen from Model 2, if the vertical air velocity increases, the horizontal air velocity needs to be reduced to meet the same grain loss requirement, and vice versa. This agrees with the work done by Harrison (1969) and Rumble and Lee (1970).

**CONCLUSIONS**

The grain loss decreased as the fan inlet diameter decreased or as the sieve jet angle increased. However, higher angles and smaller fan inlet diameters are liable to cause the grain to pile up on the sieve surface.

Both theoretical and experimental results showed that the grain loss was dependent upon the velocity and direction of the air stream over the multiple-air-jet sieve. The regression analysis indicated that the grain loss is related to the linear combination of the horizontal and vertical component air velocities. When one of the component air velocities increased, the other needed to be reduced to maintain the
same separation efficiency. By properly selecting the air velocities, a low grain loss can be obtained for the tested angles. From the experimental results, the grain losses for jet angles of 20°, 30° and 40° with air velocities of 8.7, 7.6 and 7.2 m/sec, respectively, were not greater than 0.5%, which was considered satisfactory for a pre-cleaner. The most efficient separation was obtained at 40°.

Since the device removed a large portion of MOG (80% and up) from the material mixture in every test conducted, the MOG content in the output grain was not considered as an important evaluation criterion. In general, it is possible to greatly reduce the MOG content while maintaining an acceptable grain loss for a combine cleaning system by aerodynamically transporting the threshed wheat material.

REFERENCES


