Philippine Engineering Journal (1995) XVI (2): 77-97

A REVIEW OF OSCILLATING SCREEN-BLOWER CLEANERS FOR GRAINS

Melchor C. Pasikatan
Senior Research Assistant

Graeme R. Quick
Head

Agricultural Engineering Division
International Rice Research Institute (IRRI)
Los Baños, Laguna, Philippines

ABSTRACT

The literature concerned with grain or seed cleaners using blower and linearly oscillating screens, and related machines and mechanisms was reviewed. Attempts in developing the theory and mechanics of cleaners was discussed. Grain, straw and chaff aerodynamic and mechanical properties which affect separation were assessed. The potentials and limits of pure aerodynamic separation, effects of design, operating and material parameters on cleaning performance were critically examined.

The available information may be limited, but sufficient to provide rough parameters for design under different operating conditions. Researches show that to achieve good cleaning performance at high material capacity in wheat and paddy, air velocity of 7.2-9.2 m/s, air direction of 40-45°, height of drop of 70-102 mm, and hanger angles of 15-25° should be used.

Attemps to relate cleaning performance with two or more influencing factors are rare in the literature. Results derived with wheat and based on straw walker and shoe assembly of combines need to be validated for rice, rice threshers and cleaners. Further studies that will lead to a universal cleaning equation and a good understanding of particle motion as influenced by several variables are needed.

INTRODUCTION

The air-screen cleaner is the basic machine in almost all seed processing facility. Practically all seed is cleaned by air-screen cleaner before other separators can be used properly, and air-screen cleaners can satisfactorily clean many seed lots (Hall, 1963). The oscillating screen-blower cleaners (horizontal or inclined) are widely used in Western agriculture. In Asia they are employed as cleaning units for mobile threshers (as in IRRI designed threshers) and grain combines. About half a million threshers and combines in Asia are equipped with these oscillating screen-blower cleaning units. The advantages of such cleaning mechanism are simplicity, compactness, low cost, ease of fabrication and operation, and high reliability in cleaning different seeds (Diestro et. al, 1981; Hu Hexing, 1989).

The basic design of oscillating screen-blower cleaners consists of two eccentric-agitated screens, and a fan. The top screen is basically a scalping screen and the bottom a grading screen. Variations of this design may use up to eight screens and four different fans in one cleaner (Hall, 1963). Multiple screens give higher capacities and increase versatility for separation (Gregg, 1970). Several designs provide the following adjustments: fan speed air directional shutters, screen vibration, pitch or slope of the screen, and interchangeable screens for different materials. Accessories used for improving capacity and cleaning efficiency are: clog preventing brushes under the fine screen, screen dams to retard seed flow for more thorough sifting, triangular bottom screens for elongated seeds, oil cloth covers for long seeds, and clay crushing rolls (Hall, 1963; Gregg, 1970).

This review was undertaken to gather all available studies on aeromechanical cleaning of granular seeds through linearly oscillating screen-blower units and related machines, to correlate and integrate their results in order to serve as a design guide for improved grain cleaners. Another aim was to identify areas for further research on this type of grain cleaners.

AERODYNAMIC PROPERTIES OF GRAIN AND NON-GRAIN MATERIALS

Separation of a mixture of particles utilizes difference in aerodynamic properties, important among these are the terminal velocity and drag coefficient.

Terminal (Suspension or Critical) Velocity

Terminal velocity of the particle is the most important aerodynamic property in pneumatic separation and conveying of particles. It is defined as the air velocity required to support the particle against the action of gravity in a vertical air stream. Terminal velocity, V_t, may be expressed as

$$V_t = (2mg / C_d A p)^{1/2} \tag{1}$$

where *m* is mass, *g* is acceleration due to gravity, C_d is the drag coefficient, *A* is frontal area and *p* is density. Cooper (1966) stated that there is greater difference between terminal velocities of wheat kernels and wheat straw, hence, they are easier to clean than other grains. When terminal velocities overlap, as in the case of corn, cobs and stover, complete pneumatic separation is not possible (Uhl and Lamp, 1966). For wheat, they concluded that if straw were reduced to shorter lengths such as less than 5 cm (to decrease terminal velocity), complete separation from grains would be quite probable.

Tiwari, cited by Goryal (1990) reported that actual terminal velocities for individual beans were found to be less than calculated values. He attributed this to the effects of spinning and rotation of the beans in the air stream (which changes the frontal area). Rotation of particles in an airstream caused a higher drag and lower terminal velocity (Bilanski and Lal, 1965). Goryal (1990) observed that straws with node at one end, which tend to align themselves vertically in an airstream, have higher terminal velocity than nodeless, or middle-node straw, which tend to orient horizontally in a vertical airstream.

Drag Coefficient and Shape Factors

When materials (as particles) move relative to the airflow in a vertical wind tunnel, the airflow will exert a force on the materials called drag force. It is a function of frontal area, A, air density, p, relative between the air and the particle, V_r and drag coefficient, C_d. The aerodynamic drag force, F_d, acting upon a particle moving through air has been expressed as

$$F_d = 1/2\,C_d A p V_r^2 \qquad (2)$$

The drag coefficient includes both skin friction and pressure drag. The measurement of drag coefficient for various grains has been the subject of many studies, whose results varied mainly because of the differences in the assumption of the frontal area (Mohsenin 1970). In most cases particles have been assumed to be spherical, the diameter of the particle being taken as the diameter of the sphere of the same volume as the particle. Uhl and Lamp (1966), using equivalent spheres as frontal area, obtained drag coefficient for oats, wheat, corn and soybeans. Bilanski and Lal (1965) reported lower drag coefficient for the same grains used by Uhl and Lamp. Goryal (1990) measured drag coefficients for various grains and noted an array of C_d in the range of spheres and cylinders (C_d=0.44-1.0). Wheat, beans rye, maize and rice were grouped together with average C_d of 0.8. C_d for straw was 1.0 corresponding to the value of cylinders. Table 1 shows the terminal velocity, drag coefficient, Reynolds number, sphericity and coefficient of friction for selected grains as reported by several authors.

PARTICLE MOTION (TRAJECTORY) STUDIES

Jiang et al (1984) derived differential equations of particle motion for pure aerodynamic separation using the assumption of constant velocity and direction of air. The acceleration in the x and y direction, a_y and a_x is a function of terminal velocity, V_t, relative velocity between the air and the particle, V_{rx} and V_{ry}, component of air velocity in the x and y direction, V_{ax}, V_{ay}, and acceleration due to gravity, g. These were expressed as

$$a_y = \left[\left(g / V^2{}_t\right)\left(V^2{}_{ry}\right)\right] + \left[\left(2gV_{ay} / V^2{}_t\right)V^2{}_{ry}\right] + \left[\left(gV^2{}_{ay} / V^2{}_t\right) - g\right] \qquad (3)$$

$$a_x = \left[\left(g / V^2{}_t\right)\left(V^2{}_{rx}\right)\right] - \left[\left(2gV_{ax} / V^2{}_t\right)V^2{}_{rx}\right] + \left(gV^2{}_{ax} / V^2{}_t\right) \qquad (4)$$

Using a FORTRAN program, an assumed particle initial velocity, grain and straw terminal velocity, they were able to predict the path of motion of straw and grain at air flow direction angles of 20°, 30°, 40°, 50° and 90° at air velocities of 6.4 and 10.5 m/s, respectively. They observed that it is possible to get low grain loss by properly selecting air velocities and jet angles. They found that at an angle of 40°, the grain is moved less rearward, but the straw is moved more rearward than at the 30°, 25° and 20° angles. This resulted in good separation (Figure 1). To validate these results experimentally, they designed a pre-cleaner consisting of a multiple-air-jet sieve, an air chamber and a fan, a belt conveyor, and a collecting container (Figure 2). Five sets of sieve frames provided five different jet angles of 20°, 25°, 30°, 40° and 50° to control air flow direction over the sieve. Three fan inlets with 305 mm, 330 mm and 355 mm fan diameters were used to control the air flow rate.

The most efficient separation with low grain loss and low materials other than grain (MOG) content occurred at a jet angle of 40° and velocity of 7.2 m/s with a 330 mm diameter fan inlet. These agreed with the hypothesis. This study proved the possibility of greatly reducing the MOG content while maintaining an acceptable grain loss for a cleaning system by aerodynamically transporting the threshed wheat material.

Goryal (1991) derived a model of particle motion using numerical method. From the point of feeding, the displacement *S*, of a particle in the x and y direction, respectively, are:

$$S_x = V_a t + \left(V_t^2 / g\right) \ln\left[C / \left(C + \left(gt / V_t\right)\right)\right] \qquad (5)$$

$$S_y = \left(V_t^2 / g\right) \ln \cosh\left(gt / V_t\right) \qquad (6)$$

where C is a constant equal to $1/(V_a - V_p)$, V_p is particle initial velocity, and *t* is time. These equations were solved to simulate the paths of grain and straw in a horizontal air stream using an assumed horizontal air velocity, V_{px}, and V_{py} of 6, 0.23, and 0 m/s, respectively, and assumed terminal velocity for straw, white caps, chaff and wheat grain. The trajectories of these particles followed different paths and deposited particles at different distances from the point of injection, depending on their terminal velocity. Without whitecaps in the mixture there was a distinct point of separation between straw and wheat grains.

EFFECTS OF MECHANICAL DESIGN PARAMETERS

Screen Parameters

Screen Theoretical Considerations

A sieve separates a material mixture into two parts by means of difference in particle size. It is generally displaced horizontally and a little vertically by oscillating motion to transport the material along its length and to spread out the mixture evenly and thin enough to allow penetration of the mat by a rapidly moving airstream. Goryachkin (1973) stated that the force F, necessary to accelerate grain movement should be equal to the screen accelerated motion, that is

$$F = fmg \tag{7}$$

where *f* is the coefficient of friction, *m* is mass, and *g* is acceleration due to gravity. When *fg* is less than the accelerated motion of the screen, the grain cannot move up the screen. However, when *fg* is greater than the accelerated motion of the screen, the grain begin to rise on the screen with a constant acceleration *fg*. This intermittent loss of contact between sieve and material facilitates better aerodynamic separation (Joshi, 1981). To make grains jump on the screen or cause the straw to be tossed up, oscillating motion must be transmitted with the acceleration of gravity *g* (Goryachkin, 1973) such that $w^2r = g$. (*w* is the angular velocity of the crankshaft, and *r* is the crank radius).

Using Goryachkin's assumptions Diestro et. al(1981) derived the relationship of crankshaft speed *n*, maximum screen acceleration *a*, and crank radius *r*, based on the slider crank mechanism as

$$n = (30/\pi)(a/r)^{1/2} \tag{8}$$

Considering hanger angle Θ, and coefficient of friction *f*, they further derived

$$n = (30/\pi)(fg/r\sin\theta)^{1/2} \tag{9}$$

Based on this equation and assuming that the vertical component of the screen acceleration approaches 1.0 g, they produced a nomograph relating crank radius, crankshaft speed and hanger angle. Kepner (1978) cited a German study that the crank speed should be determined from the relation, $w^2r = 2g$. Under these conditions the magnitude of the centrifugal force is twice the force of gravity, which makes the net upward force at the top of travel equal to $-g$. Joshi (1981) explained that contact between sieve and material could be lost intermittently only if acceleration of the sieve is kept greater than *g*. Using this relation and noting that $w = 2\pi n$, where n = speed in rpm, the relation between speed, *n*, and crank radius *r*, can be derived as

$$n = (30/\pi)(2g/r)^{1/2} \tag{10}$$

Experimental validation of equation (10) was provided by Hu Hexing (1989). He found that at a crank radius of 13 mm, the best level of crankshaft speed was 350 rpm, a little less than the calculated 370 rpm. By comparison equation (9) yields only 282 rpm. It was observed that straw accumulates on the screen when speed was at 250 rpm because of inadequate acceleration. A further validation is provided by Reed et. al (1974). They reported a straw walker with speed of 210 rpm and a throw of 50.8 mm. Based on these evidences, it could be stated that equation (10) is a better approximate of *n* for a given *r*, or vice versa, than equation (9) which tends to underestimate it.

Oscillating Frequency or Crankshaft Speed

At no-drop entrance condition, feed rate of 125 lb/min (57 kg/min; near maximum capacity), and frequency of 340 cpm, there was greater breakup of the material on the screen and a greater quantity of chaff becoming airborne as compared to 260 cpm (Lee and Winfield, 1969). When frequencies of 260, 300, 340, 380 cpm were used at a constant input rate of 125 lb/min, the amount of grain collected increased with increasing frequency of oscillation up to 340 cpm (because of higher transport rate). From 340 to 380 cpm, there was no significant variation in the amount of grain collected, but grain loss decreased from 8 to 4%.

Using the test set-up of Lee and Winfield, German and Lee (1969), observed that increasing the frequency of oscillation from 260 to 460 cpm at the high feed rate of 200 lb/min reduced the grain loss linearly. Small increases in capacity (with grain loss reduction) however, would not warrant the increase in frequency because of increased vibration on structural components, and possible increase grain loss at low load rates. A combination of increased air volume and increased oscillating frequency increased fluidation and improved the transport characteristics of the screen.

MacAulay (1969) reported that the effect of frequency on grain loss was slight, with higher frequencies of 380 cpm appeared to cause a slight decrease in the slope of the grain loss-feed rate curve at the higher feed rates. ANOVA results of Hu Hexing (1989), showed that grain loss was affected firstly by crankshaft speed, followed by hanger angle, crank radius, and other parameters. Clarke (1985) designed a continuous fluidizing cleaner as an alternative to aspiration. Even this required a moderate amount of vibration to break down cohesion of the materials in the bed.

Centripetal Acceleration and Crankshaft Radius

Centripetal acceleration of the crankshaft as reported by Hu Hexing (1989), is one of the important parameters which significantly affects grain cleaning losses. He defined this as

$$a_{cp} = (2\pi n / 60)^2 r \tag{11}$$

Since it is dependent on crankshaft speed *n*, and crank radius *r*, it indicates motion characteristics of the oscillating screen. From experimental results he derived regression equations relating a_{cp} with grain losses and grain purity. The optimum value for an oscillating sieve-blower rice cleaner he designed was 17.5 m/s^2. Douthwaite (1993) used this optimum value to arrive at the appropriate crankshaft speed and crank radius of a thresher he designed, with excellent results. However, the centripetal acceleration for IRRI threshers TH7, TH8 and grain cleaner GC7 are 28, 12, and 18.7 m/s^2, respectively. This indicates that the optimum value of a_{cp} may be specific to a design, e.g. screen dimensions, or there may be other contributing factors.

Hanger Angle and Screen Support Type

Lee and Winfield (1969) in their studies, used the shoe assembly and adjustable upper sieve from a conventional combine. This had 89 mm long links and midstroke angle of 12.5° to the vertical, or a total angular movement of 25°. The effect of this hanger angle was not quantified. All IRRI designed power-threshers and cleaners, however, used 25° hanger angle, with good results. The results of Diestro et al. (1981) suggested the optimum parameters of 17.5 to 22.5° hanger angles, 14 to 18 mm crank radius, and vertical acceleration of 0.88 to 0.94g. Among the three factors they studied, hanger angle had the greatest effect on grain loss.

Hu Hexing (1989) tested the effect of hanger angles of 5, 15, 25, 35 and 45° to cleaning performance. He found optimum hanger angle of 15° for minimum grain loss and high grain purity. Grain losses increased with increase in angle from 25 to 45°. He explained that screen hanger angle determines the screen oscillation orientation and oscillation amplitude in both x and y direction. As hanger angle increases beyond 25°, screen has a larger vertical oscillation angle that it may lift and move materials along the screen by a larger trajectory per cycle. Some grains may be discharged with the impurities before they are separated from the mixture. This causes higher grain loss. Inversely at 5°, the smaller oscillation angle does not produce enough vertical amplitude such that it cannot loosen the mixture mat during its movement over the screen. This causes very low purity. His tests also showed that there is no significant difference in grain cleaning performance when screen support type changed from upper support to lower support at the same hanger angle of 15°.

Size, Shape of Perforations, and Screen Length

Hu Hexing (1989) reported that 12.5 x 12.5 mm screen (square wire mesh) gave the lowest rice grain loss but lowest purity, while 10.5 dia perforated screen yielded the highest grain purity. He recommended screen holes of 10.5 to 12.5 to strike a balance between grain loss and grain purity. Tables for appropriate screen sizes for each kind of crop can be referred to in standard references such as Hall (1963), Gregg (1970), and Vaughan et.al (1968).

Reed et.al (1974) observed that separation of grain from straw takes place in a decaying exponential fashion along the length of the walker. The equation they derived relates the grain remaining on the walker G_r, with the distance along the walker L, such as

$$G_r = G_0 e^{bL} \tag{12}$$

where G_o is the grain onto the walker and b is attenuation coefficient (slope of the straight line on a semi-log plot; dependent on feed rate, MOG:G, moisture content, crop variety and walker design). The equation is applicable when straw velocity is nearly constant along the walkers. The straw walker may be lengthened but practical considerations prevent this.

Effect of Number of Screens

Available cleaners are either of single screen (as in IRRI axial flow threshers) or double screen (as in grain combines). Double layer oscillating screens are generally more effective in separating impurities. MacAulay and Lee (1969) used an upper screen, with an auxiliary airstream introduced over the front, and a lower screen with airstream above and below it (Figure

3). The lower screen provided a secondary cleaning area to separate the grain from debris that penetrated the upper screen. Grain separation tended to occur towards the front of the upper screen. Their results showed that the addition of a lower screen resulted in a decrease in the grain losses at the highest feed rate when the no-drop entrance condition was used. The lower screen had a marked effect of displacing the transition zone of the grain loss-feed rate curve towards the higher feed rates and decreasing the slope of the curve at high feed rates (Figure 4). However, the optimum duct entrance condition without the lower screen gave the best results over the range of feed rates tested. The debris penetrating the upper screen is carried onto the rear third of the lower screen, hence the leading two-thirds of the lower screen could be eliminated. They also cited the possibility of changes in the air-distribution profile over the upper screen because of the grain load on the lower screen.

Air Stream Parameters

Air Stream Theoretical Considerations

An air stream separates a mixture by density difference. The grains either directly enter the airstream with an initial velocity, or move along the sieve with an inclined or horizontal stream of air blown over them. Klenin et al (1985) stated that separation of grains by an air stream occurs because the vertical component of air velocity, V_{ay} is less compared to the terminal velocity of the particle, V_t; that is $V_{ay} < V_t$. Their statement refers to the grain terminal velocity. For straw and chaff, the basis of separation is $V_{ay} > V_t$, such that one group (grains) have terminal velocities greater than V_{ay}, thus will not be significantly displaced by airstream, and another group with terminal velocities lesser than V_{ay}, thus causing them to be displaced distinctly further by the airstream.

Using the assumptions of laminar flow of air stream, the magnitude of velocity constant, and the particles move in the air stream along a trajectory, Klenin et al (1985) and Bilanski et al (1989) derived the equation of divergence of a cluster of trajectories as

$$\tan\left(a_{t\max} - a_{t\min}\right) = V_a \cos b\left(V_{t\max} - V_{t\min}\right) / \left[V_{t\max} V_{t\min} - V_a \sin b\left(V_{t\max} + V_{t\min}\right)\right] + V_a^2 \qquad (13)$$

where, V_a is air velocity, V_t is particle terminal velocity, a is the inclination of the particle flow from the vertical, and b is the inclination of the air stream velocity from the horizontal (Figure 5).

The following could be noted from the equation: the divergence of the particle trajectories depends upon the difference between the terminal velocities and the angle a; the divergence increases with increase of the difference V_{tmax}-V_{tmin}; reduction of the angle a reduces the divergence; and for horizontal flow ($\cos b = 1$) divergence is smaller than when it is inclined ($\cos b < 1$; Figure 6). From the graph, divergence of the cluster of trajectories increases to some maximum value, with increase of velocity V_a, and thereafter decreases. The maximum divergence of the particle trajectories occurs at the air velocity,

$$V_{a\max} = \left(V_{t\max} V_{t\min}\right)^{1/2} \qquad (14)$$

which means the velocity of the inclined stream which causes maximum dispersal of grain equals the geometric mean of the two extreme terminal velocities. Klenin (1985) stated that based on experimental data, the angle *b* is assumed to vary from 18 to 30° and the velocity of the air stream in the working region to be 6 to 8 m/s for wheat and rye.

A proper combination of velocity and direction of airstream for good separation were reported by several authors. Misener and Lee (1973) reported that grain losses were minimum when the velocity and direction of the airstream were 9.2 m/s and 40-45°, respectively (Figure 7). Jiang et al (1984) found the most efficient separation at jet angle of 40° and velocity of 7.2 m/s. Other combinations which yielded less than 0.5% losses were 20° and 8.7 m/s, and 30° and 7.6 m/s. They observed that grain loss is more closely correlated with the linear combination of the two components of air velocity than with the resultant air velocity alone. They concluded that if air velocity increases, the horizontal component need to be reduced to meet the same grain loss requirement. Zhang Laixing (cited by Hu Hexing, 1989) recommended the angle between air flow orientation and screen surface to be about 25-30°. Hu Hexing's (1989) results with blower orientation angle (which is similar to air velocity angle) was lower at 15°. Klenin (1985) found maximum divergence between grains and MOG at 25° airstream, at terminal velocity range of 8.5-11.5 m/s (Figure 6).

Effect of Air Velocity

Air velocity has a significant effect on separation because the drag force caused by the airstream is proportional to the second power of the air velocity. Klenin, (1985) stated that the blower must be able to generate an air velocity V_a at the exit that must be exceed the terminal velocity V_t of the components of the grain mass which have to be removed, that is

$$V_a = cV_t \tag{15}$$

where *c* is an excess velocity coefficient. The excess velocity coefficient for straw (up to 200 mm in length), chaff, husk, and broken ears are 1.1-1.7, 1.9-3.7, 2.5-5, and 1.5-3.0, respectively.

Goryal (1991) in his separation studies using horizontal air stream, observed that it is possible to separate 95% of the wheat grains from the MOG at an air velocity of 11 m/s, at a duct length of 160 cm. He concluded that high air velocity of 11 m/s and low feed rates are essential for good pneumatic separation of grains from MOG in a horizontal air stream. German and Lee (1969) observed that increased air velocity through the sieve reduced the amount of impurity of low terminal velocity from passing through the sieve, and improved the sieve's transport characteristic.

Effect of Number and Location of Air Blasts

MacAulay and Lee (1969), introduced a volume of air over an upper sieve through an auxiliary fan, and observed that at low feed rates, straw and chaff are blown right away, leaving only grains to fall on the sieve. Theirs was a pioneering study in the use of triple air blast to effect better cleaning. Their findings were confirmed by further studies (Rumble and Lee, 1970; Misener and Lee, 1973). A Japanese stoner employed two fans for separation: the first fan blows a large amount of air from underneath the sieve to lift the grains and carry them down to the discharge spout, while the second blower lifts stones which are transported to the top of the sieves (Araullo & de Padua, 1976).

The study of MacAulay and Lee (1969) provided experimental evidence that the location at which the air blast is directed is critical. When air velocity was increased over the rear of the upper screen, aerodynamic separation was enhanced: transition zone was moved towards the higher feed rates and the slope of the aeromechanical curve was reduced. Zhang Laixing, cited by Hu Hexing (1989) recommended air velocities of 7-8 m/s over the front of the screen, 5-6 m/s at middle of the screen, and 3-4 m/s at the rear of the screen. A diminishing velocity profile from front to rear is generally desirable.

EFFECTS OF MATERIAL PARAMETERS AND FEED CONDITIONS

MOG/Grain Ratio and Initial Impurity

MacAulay & Lee (1969) studied the effect of MOG to grain ratio (MOG:G) of 0.5 and 0.25 to grain loss at varying feed rates (25-200 lb/min) and entrance conditions (0,2,4, in. duct). They observed that MOG:G of 0.25 caused the shifting of the transition zone of the feed rate-grain loss curve towards the higher feed rate, from about 100 lb/min at 0.5, to about 150 lb/min at 0.25 (Compare Figures 8 and 9). This means higher values of feed rates are included under aerodynamic separation for mixtures having lower MOG:G. There is a positive correlation between MOG:G and percent grain loss (Reed et al, 1974). Their results showed that at the 95% efficiency level the walker could handle 100 lb/min of grains with MOG:G of 0.96, but only 47 lb/min with MOG:G of 1.43. They also observed that the manner in which the MOG:G was obtained (e.g. reducing straw length or adding free chaff) had little or no effect on walker efficiency. Hu Hexing (1989) used the parameter material initial impurity (MII) which is equal to 100%*MOG. He reported that when MII was lower than 17.2%, there was no significant effect of change in MII on grain cleaning performance. But when MII was in the range of 18.8 to 22.2%, grain cleaning losses increased and grain purity decreased significantly with an increase in MII.

Feed or Input Rate

At nonzero drop heights and low feed rates, separation of straw and chaff occurs purely by aerodynamic action in the airstream above the upper sieve such that straw and chaff were airbone over the front of the sieve, heavy straw contacted the rear of the sieve, and the grains contacted and penetrated the upper sieve with some evidence of grain bouncing over the sieve. MacAulay and Lee (1969) observed low feed rates lies in the range of about 25-100 lb/min (11-45 kg/hr) per foot width. At low feed rates, the grain loss-feed rate curve is nearly flat. Beyond the transition zone, 100 lb/min, the curve is steeply sloped and approximately linear (Figure 9). As feed rate increases, the straw contacts the sieve closer to the front, the material introduced to the screen is compacted like a mat (even with the introduction of air over the upper screen), which is transported rearward in contact with the screen. This can be solved by mechanical agitation to breakup the mixture, and dropping from a certain height for good dispersion (Lee and Winfield 1969, MacAulay 1969).

MacAulay (1969) suggested the use of a device to disperse the material mat completely before it reaches the screen, hence reducing the material to be sifted by the screen. They found that when separation and transport over the screen was done by aerodynamic action, grain losses were minimum and nearly constant regardless of feed rate. Jiang (1984) confirmed this observation. He designed a precleaner that disperses the material mat completely before it reaches the screen. It was placed ahead of the regular cleaning system and would replace the oscillating grain pan. The multiple-air-jet sieve would preclean the material passing from the concave and transport them pneumatically to the cleaning system by an air stream, thus reducing MOG before contacting the upper sieve. The MOG to grain ratio was reduced by as much as 80% by this precleaner. Rumble and Lee (1970) reported that feed rates could be doubled if aerodynamic-mechanical separation would be employed, although they observed that grain loss was minimum when separation was occurring by pure aerodynamic action. Hu Hexing (1989) observed in his oscillating screen of rice axial flow threshers that when feed rate is higher than 1350 kg/h, the effect of material discharge height was significant.

Discharge Height and Injection Velocity

In a comparison between 8-in (203 mm) and no drop condition, Lee and Winfield (1969) observed that more chaff was carried by the airstream at 8-in drop condition. Grain loss was reduced at high feed rates when mixtures of grain were dropped from the pan to the upper screen. They also noted that higher oscillation frequency will have to compensate for no-drop conditions, especially at high feed rates. MacAulay and Lee (1969) compared grain loss over four entrance conditions: no-drop, 2 in-(51 mm), 4 in-(102 mm) and 6 in-(152 mm) duct. Four in- (102 mm) duct gave the least grain loss over the whole range of feed rates, whereas, no drop resulted in highest grain loss (Figure 8 and 9). Hu Hexing (1989) found among other factors, the discharge height of 70 mm as optimum for minimum grain loss and high grain purity, especially at feed rates greater than 1350 kg/hr.

Dropping the material onto the front of the chaffer sieve through and over parallel-rod fingers that tend to break the bunches is typical of most combines. A portion of the airstream is directed to the falling material providing initial separation of the chaff. Rumble and Lee (1970) reported that entrance parameters are not critical if the air velocity is sufficient to disperse the material. Misener and Lee (1971) used a beater assembly to impart a high initial velocity to the material entering the separation region. The beater rotates 400 rpm and imparts an injection velocity of 2.4 m/s to the grain mixture. With an appropriate air velocity, this injection velocity was found sufficient for good separation of the components in an air stream.

Interactions and Optimum Combinations

The literature points to clear interactions between several factors affecting grain cleaner performance. Previous studies at most, were able to quantify the relationship of only two variables. So far only Gregory and Fedler (1987) has successfully related straw walker performance with variables such as grain amount, amount of MOG, length and width of straw walker, speed of material flow, and type of crop. Based on Fick's Law of diffusion and the fraction of open space in the mass other than grain, the mathematical relationship which predicts grain separation in combines is

$$G_f / G_i = e - \left[\left(\left(C_v / d^2 \right) V_a W B_{mog} / M \right)^{e - kC_3M/(WV)} \right]^L \tag{16}$$

where G_f is the final mass of grain, G_i is the initial mass of grain, C_v is a constant which varies with the vibration of energy level of the machine, d is the grain diameter, V_a is the average velocity, W is the width of separation area, B_{mog} is the bulk density of MOG, M is the rate of flow of MOG over the straw walker, k is a residue coefficient which varies with vegetation, C_3 is a constant to reduce the total mass of cover to an effective mass of cover, V is flow velocity and L is the length of separation area. The model was verified for variations of length and feed rate of conventional straw walker using published data from three previous studies. The correlation was in excess of 0.99 which proved it was a valid model for separation. There is a need to confirm this model for cleaning unit of axial flow threshers and grain cleaners for rice, or to derive an equivalent model should this be proven inadequate.

CONCLUSION

1. Grain cleaning by pneumatic means requires distinct differences between the terminal velocities of the grain and MOG to achieve complete separation. When terminal velocities of the two groups overlap, good separation could be achieved by reducing the length of the straw (materials with intermediate terminal velocity)

2. Mechanical agitation of the screens becomes necessary only at zero discharge height, or at nonzero discharge height but high feed rates. There is a feed rate range (specific to each grain cleaner design) where aerodynamic action is sufficient for separation; beyond this range mechanical action becomes necessary. In practice, nearly all cleaners operate at high feed rates that if screens are needed they must be oscillating.

3. The effect of oscillating frequency on cleaning performance is significant only when the material is dense, (e.g. at high feed rates, or no drop height, or when is no mechanism to impart initial velocity to the grain mass), such that mechanical agitation is needed to disperse the mixture. High oscillating frequency is desirable at high feed rates, but the constraints are increased vibration loads on the frame, and high grain loss at lower feed rates due to grain bounce.

4. The optimum oscillating frequency depends upon several factors, such as height of drop of the mixture, feed rate, MOG to grain ratio, and air velocity. For a given crank radius, the choice of the appropriate oscillating frequency (or crank speed) is determined by the relationship, $n = (30/\pi)(2g/r)^{1/2}$.

5. Dispersing the material mat before reaching the sieve, either by imparting initial velocity through a beater, or by a strong airblast over the upper screen, appears to be a promising alternative to, or an adjunct of oscillating sieves. The advantages of limits of this concept should be further studied.

6. The direction and velocity of the airstream are both critical in cleaning. Minimum grain (wheat) losses has been obtained at a velocity range of 7.2 to 9.2 m/s, and direction of 40 to 45°. Theory and experimental data showed inclined airstreams (20-45°) are more effective in cleaning grains than a horizontal airstream.

7. At high feed rates, where air velocity is insufficient to disperse the materials before contacting the screen, the drop height of materials is critical. Studies showed good cleaning results at 70 to 102 mm drop height.

8. For low grain loss and high grain purity, hanger angles of 15-25° should be used, depending on crank radius and speed.

9. Despite the widespread use of oscillating screen-blower cleaners, the available literature are limited; most of them are concerned with wheat and other temperate grains. These results need to be validated for rice threshers and cleaners. Attempts at relating cleaning parameters with two or more design and operating factors are rare. Further studies are needed to derive a universal cleaning equation applicable to horizontal and inclined oscillating screen-blower cleaners. This equation must relate cleaning performance with screen, blower, and material parameters. The analysis of particle motion as influenced by several factors has not yet been done. The best air velocity distribution above and below the screens still needs to be studied.

REFERENCES

Araullo, E.V., D.B. de Padua and M. Graham (1976). Rice Post Harvest Technology, IDRC, Ottawa, Canada.

Bilanski, W.K., Collins, S.H. and Chu, P. (1962). Aerodynamic Properties of Seed Grains. Agricultural Engineering, vol. 43, no.3, pp.216-219.

Bilanski, W.K. and Lal, R. (1965). Behaviour of Threshed Materials in a Vertical Wind Tunnel. Transactions of the ASAE, vol. 8, no.3, pp. 411.

Bilanski, W.K., W.D. Graham, D.N. Mowat, S.S. Mkomwa. (1989). Separation of Alfalfa Silage into Stem and Leaf Fractions in a Horizontal Airstream. Transactions of the ASAE, pp. 1684-1690.

Clarke, B. (1985). Cleaning Seeds by Fluidization. Journal of Agricultural Engineering Research, vol.31, no.3, pp. 231-243.

Cooper, G.F. (1966). Combine Shaker Shoe Performance. ASAE Paper No. 66-607. ASAE, St. Joseph, Michigan.

Diestro, M.S., Caballes, A.L. and Nafziger M.L. (1981). Design Parameters for Horizontal Oscillating Screen. Paper presented at the 31st Annual Convention of the Philippine Society of Agricultural Engineers, University of the Philippines at Los Baños. April 29-30, 1981. Agricultural Engineering Division Paper, IRRI.

Douthwaite, B. (1993). Personal Correspondence. Agricultural Engineering Division, IRRI.

German, R.F. and J.H.A. Lee. (1969). Grain Separation on an Oscillating Sieve as Affected by Air Volume and Frequency. Transactions ASAE, vol.12, no.6, pp.883-885.

Gorial, B. Y. and J.R. O'Callaghan. (1990). Aerodynamic Properties of Grain/Straw Materials. Journal of Agricultural Engineering Research, vol. 46, pp. 275-290.

Glorial, B.Y. and J.R. O'Callaghan. (1991). Separation of Particles in a Horizontal Air Stream. Journal of Agricultural Engineering Research, vol. 49, no.4, pp.273-284.

Goryachkin, V.P. (1973). Collected Works in Three Volumes, vol.1. Transiated from the Russian, Moskva 1965.

Gregg, B.R., A.G. Law, S.S. Verdi and J.S. Bali, 1970. Seed Processing. Avion Printers, India.

Gregory, J.M. and C.B. Fedler. (1987). Mathematical Relationship Predicting Grain Separation in Combines. Transactions ASAE, pp.1600-1604.

Hu Hexing. (1989). Effect of Design Parameters on Cleaning Performance in an Oscillating Screen-Blower Cleaning Unit. Unpublished Masteral Thesis: University of the Philippines at Los Baños.

Jiang, S., W.K. Bilansky and J.H.A. Lee. (1984). Analysis of the Separation of Straw and Chaff from Wheat by an Air Blast. Canadian Agricultural Engineering, vol.26, no.2, pp. 181-187.

Joshi Hem Chandra. (1981). Design and Selection of Thresher Parameters and Components. Agricultural Mechanization in Asia, Africa and Latin America (AMA), vol.12, no.2, Spring, pp. 61-68.

Klenin, N.I., I.F. Popov and V.A. Sakun. (1985). Agricultural Machines. Translated from Russian. Published for USDA and National Science Foundation, Washington, D.C. by Amerind Publishing Co., New Delhi.

Lee, J.H.A. and R.G. Winfield. (1969). Influence of Oscillating Frequency on Separation of Wheat on a Sieve in an Airstream. Transactions of ASAE, vol.12, no.6, pp. 886-888.

MacAulay and J.H.A. Lee. (1969). Grain Separation on Oscillating Combine Sieve as Affected by Material Entrance Conditions. Transaction Of ASAE, vol.12, no.5, pp. 648-654.

Misener, G.C. and J.H.A. Lee. (1971). Aerodynamic Separation of Grain from Straw and Chaff in a Dispersed Air Stream. Canadian Agricultural Engineering, vol. 15, no.2, pp. 62-65.

Mohsenin, N.N. (1970). The Properties of Plant and Animal Materials New York: Gordon and Breach.

Reed, W.B., G.C. Zoerb and F.W. Bigsby. (1974). Laboratory Study of Grain-Straw Separation. Transaction of ASAE, vol.17, no.3, pp. 453-460.

Rumble, D.W. and J.H.A. Lee. (1970): Aerodynamic Separation in a Combine Shoe. Transactions of ASAE, vol.13, no.1, pp. 6-8.

Sadhna Arora. (1991). Physical and Aerodynamic Properties of Rough Rice. Indian Journal of Agricultural Engineering, vol.1, no.1, pp. 17-22.

Uhl, J.B. and B.J. Lamp. (1966). Pneumatic Separation of Grain from Straw Mixtures. Transactions of ASAE, vol.9, no.2, pp. 244-246.

Vaughan, C.E., B. Gregg and J.C. Delouche. (1968). Seed Processing and Handling. Seed Technology Lab. Mississippi State University. Handbook No. 1.

Table 1. Terminal velocity, drag coefficient, Reynolds number sphericity and coefficient of friction of selected grains.

Material	Terminal Velocity (m/s)	Drag Coefficient (Cd)	N_{Re}	Sphericity	Coefficient of Friction
Rice[1]	7.2 11.5[4]	0.84	1269	0.45	0.32
Rice (IR-8)[6]	7.89	0.89	2008.2 (14.7% MC)		
		0.90	2009.4 (19.00% MC)		
		0.92	2008.2 (23.2% MC)		
		0.94	2059.6 (28.0% MC)		
Maize[1]	11.6 (10.4--12.8) 7.8-12.6[2] 10.5[3] 12.5-14.0[5]	0.81	5721	0.70	
Wheat[1]	7.8 (6.5-10.10) 5.7-9.0[2] 8.9[3] (8.8-9.2) 8.3[4] 5.1-9.7[5] Straw with node < 6 cm (4.9 m/s)	0.85	1692	0.61	0.32-0.38
Barley & Wheat straw with end node	7.75[1]	0.97	2002	-	-
Straw (<100 mm)	5-6.0[4]				
Straw (100-150 mm)	6-8.0[4]				
≤180 mm	2.0-6.1[5]				
Threshed head (no seed)	3.5-5.0[4]				
Wheat head (threshed)	2.6[1]	-	-	-	-
unthreshed	6.8	-	-	-	-
part-thresh	4.5-5.4	-	-	-	-
Chaff	1.5-2.5[5]				

[1] Goryal & O'Callaghan, 1990
[2] Uhl & Lamp, 1966
[3] Bilanski & Lal, 1965
[4] Zhang Lai Xing 1980 (cited by Hu Hexing 1989)
[5] Cooper, 1966
[6] Arora, 1991

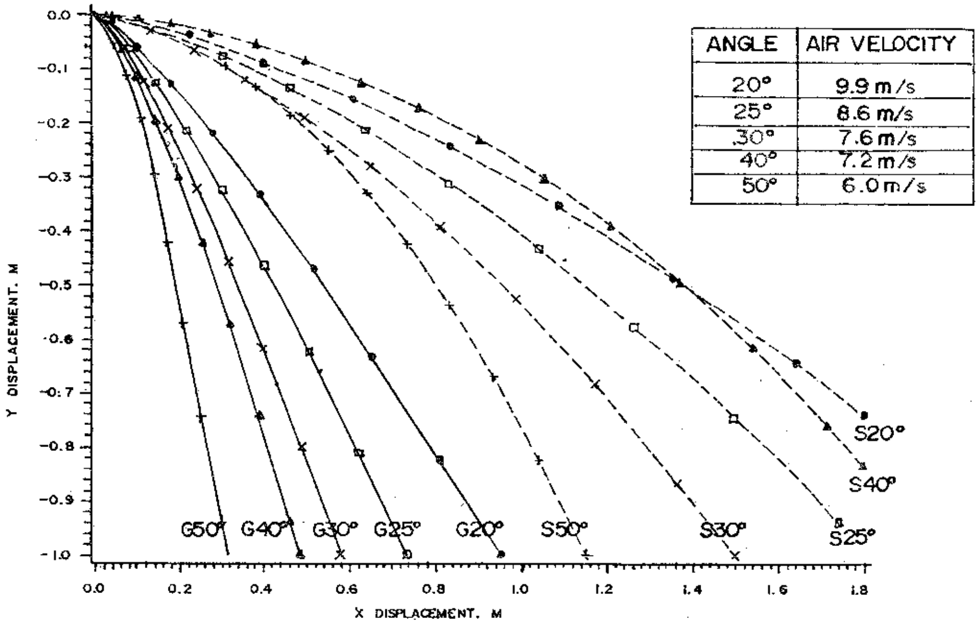

Figure 1. Theoretical motion paths of grain and straw in air stream with different combinations of air velocity and air direction angles. (Jiang et al, 1984), G=grain, S=straw

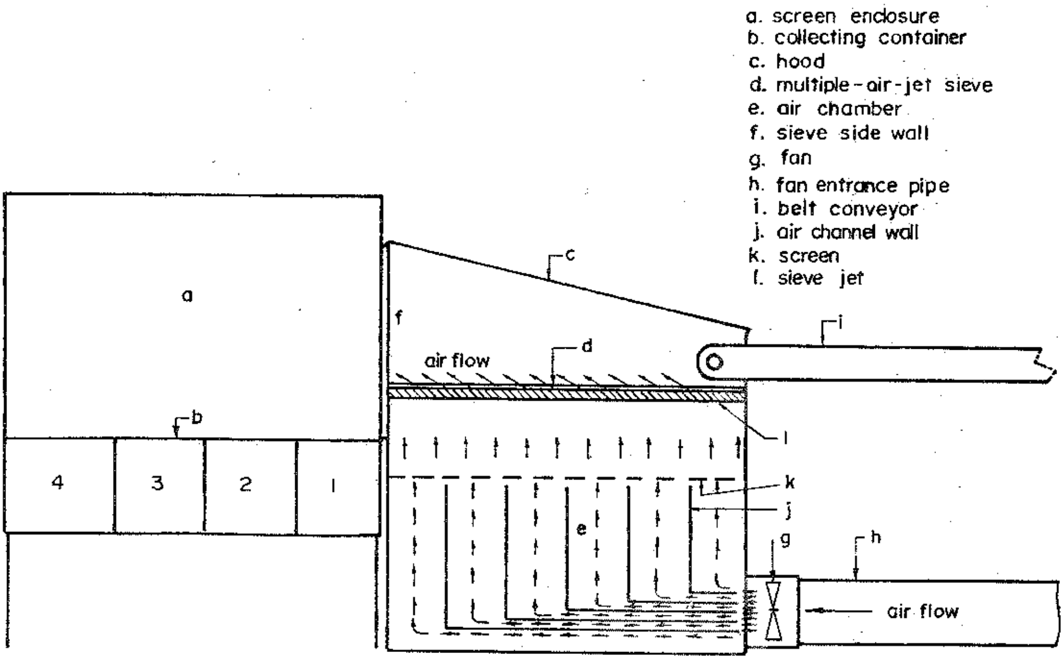

Figure 2. Schematic diagram of experimental apparatus. (Jiang et al, 1984)

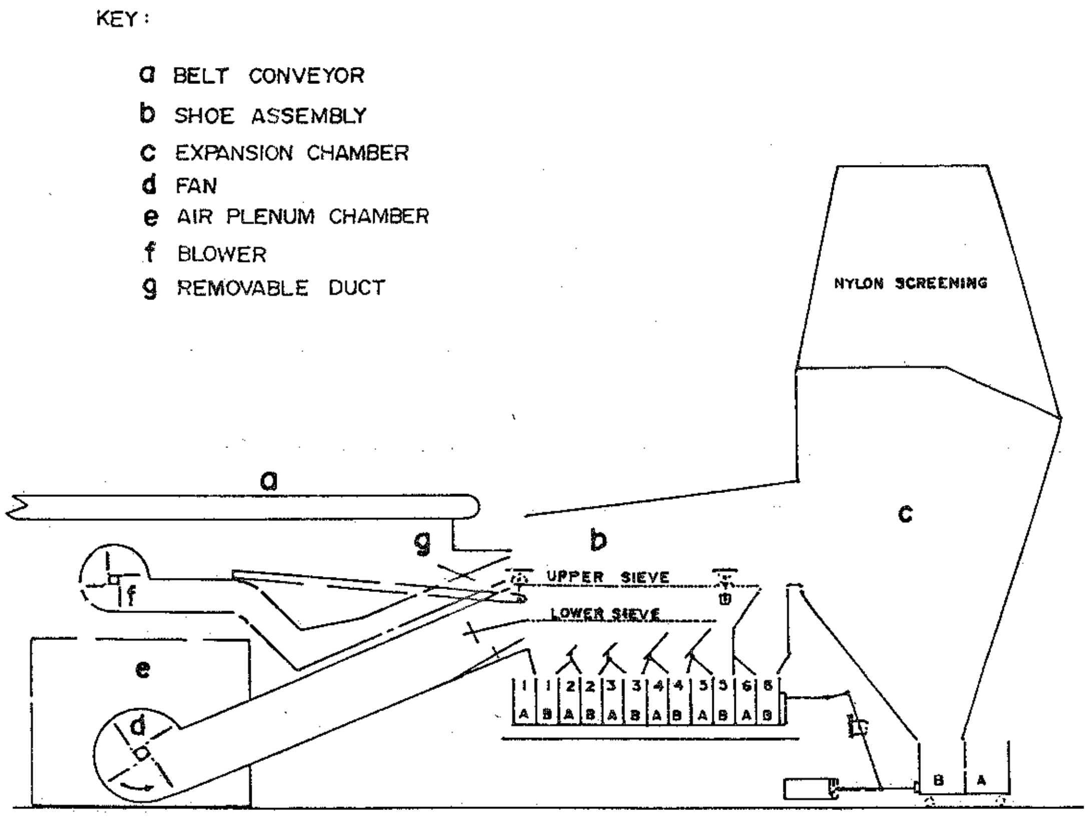

Figure 3. Schematic diagram of the separation apparatus. (Source: MacAulay and Lee, 1969)

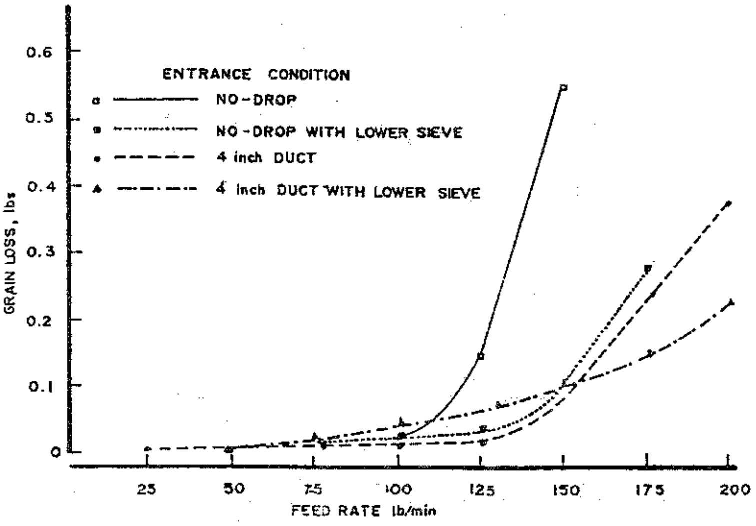

Fig.4. Effect of lower sieve on grain loss for two entrance conditions of a frequency 330 cpm and a traw-chaff-to-grain ratio of 0.5(MacAulay and Lee, 1969)

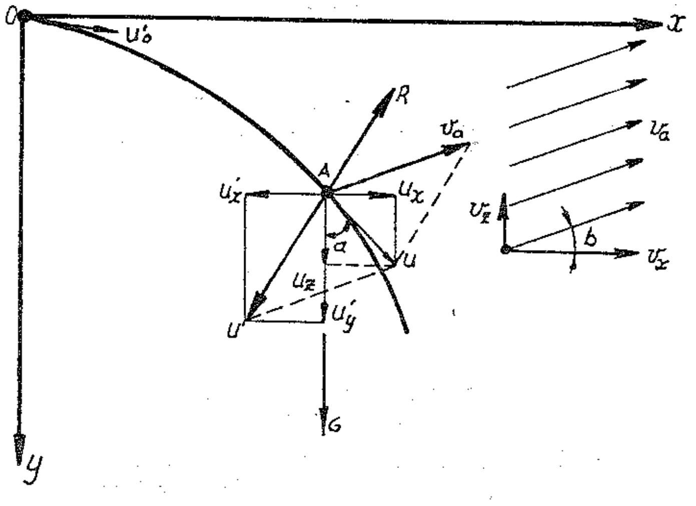

Fig.5. Action of an inclined air stream on particles. (Klenin et al, 1985).

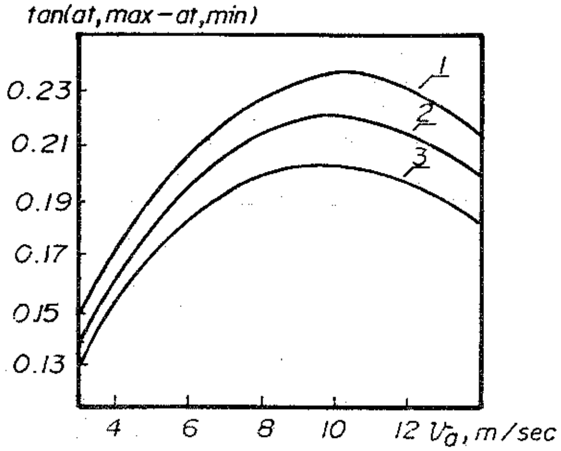

Fig.6. Variation of the function tan (at, max-at, min) as a function of the air stream, velocity at different angles: b= 25° (curve 1), b=20° (curve 2), b=15° (curve 3) (Klenin et al, 1985).

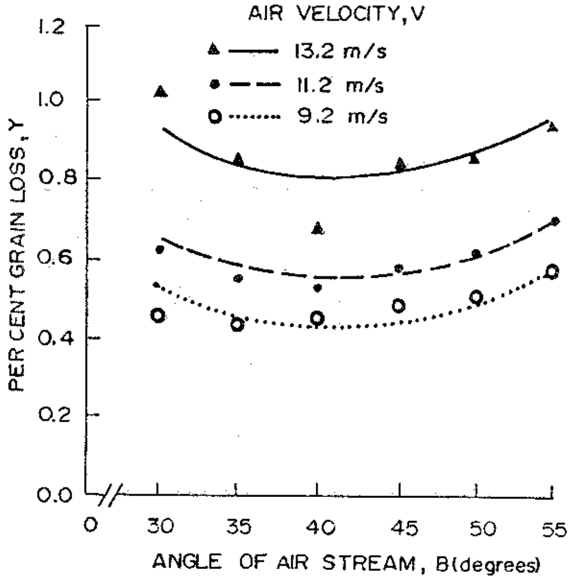

Fig.7. Effect of the direction of the air stream introduced over the sieve on grain loss for three air velocities. Grain, straw, and chaff were mixed by the standard method (shoe input rate 68.0 kg/min). (Misener and Lee, 1973).

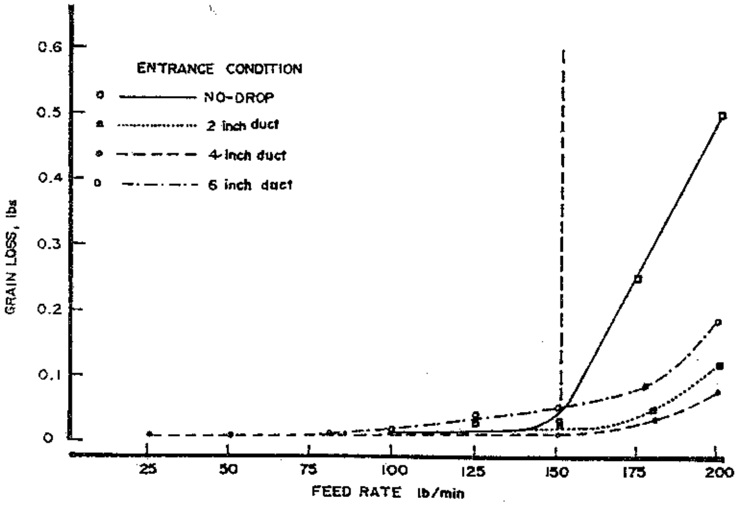

Fig.8. Effect of entrance conditions on grain loss at a frequency of 330 cpm and a straw-chaff-to-grain ratio of 0.25 (MacAulay and Lee, 1969)

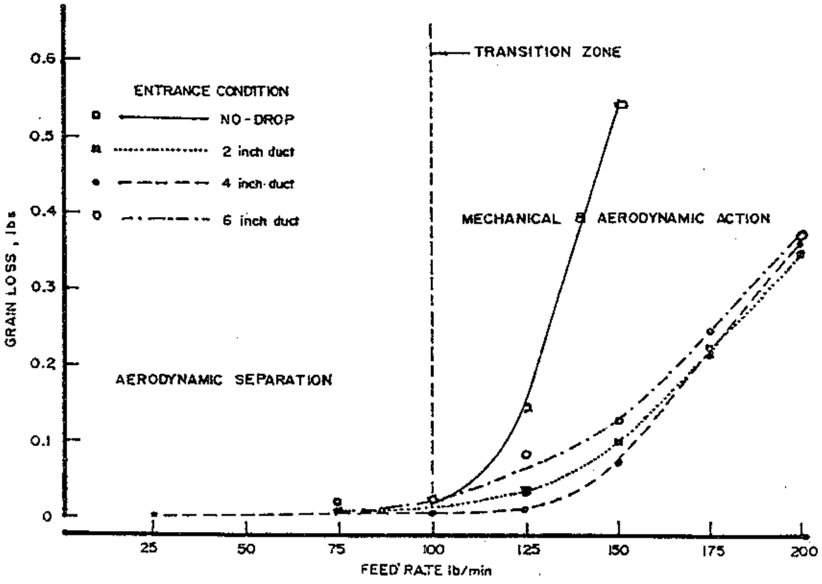

Fig.9. Effect of entrance conditions on grain loss at a frequency of 330 cpm and a straw-chaff-to-grain ratio of 0.5.