Proceedings of the International Conference for Agricultural Machinery & Process Engineering
October 19-22, 1993, Seoul, Korea

A Mathematical Model Simulating A Grain-Straw Separation Process in an Axial-Flow Separator

Seung-Kyu Lee	Sung-Tae Kim	Kyu-Hong Choi
Professor	Professor	Professor
Gyeongsang Nat. Univ.	Gyeongsang Nat. Univ.	Konkuk Univ.
Chinju, Korea	Chinju, Korea	Seoul, Korea

ABSTRACT

A mathematical model was developed to quantify the separation process of threshed grain-straw mixtures. It was made to predict the separation loss from a separation unit consisted of stationary crimped sieve with rotating inner rotor. Experiments were performed to prove the mathematical model by changing various levels of pertinent variables for rice.

Good agreements between the simulated results and observed data under the various test conditions, such as inclination angle of the separator, vane pitch, rotor speed, MOG/G ratio, feed rate, and crop variety and moisture content, were confirmed.

Key Words : Mathematical model, Separator, Combine, Axial-flow, Rice.

INTRODUCTION

Since the numerous factors affect the performance of the machine, it has been shown to be very difficult to develop or to design a grain-straw separator by means of the practical approaches. Until now, the separator has been developed only by the empirical approach. For developing a separator, it is desirable to execute theoretical approaches at first and performance prediction of the predetermined separator should be made by the simulation work. Many attempts have been made by several investigators to develop mathematical representations for separation processes as well as grain loss characteristics. Although a number of significant changes have been made in separator design, many of the variables have not been formulated into one function to predict separator performance. And thus, an analytical description of separation process is still far from satisfaction.

"Harrison(1992)" investigated the passing patterns of grain through the concave and separating grates of an axial-flow combine for barley. The pattern for the separating grate parallel to the rotor axis showed a decaying function that was affected only the crop entry, but not by the feed rate, moisture content, helix angles of the transport vanes, rotor speeds and concave clearances.

Developing a system of motion equations for simulating separation process is not feasible because of the complexity of separator mechanics and numerous degrees of freedom involved. In fact, particle movements inside a separating unit, to a great extent, are random. "Kaye and Robb (1979)" concluded that the sieve kinetics do not result in a simple probability relationship between the size distribution function of the particle and the sieve aperture distribution function.

"Song et al.(1990)" developed a stochastic compartmental model simulating a grain cleaning process of rotating sieve/indent cylinder to predict the separation efficiency as a function of time. "Huynh et al.(1978, 1982)" developed a mathematical model using an exponential probability density function to qunatify the separation process in a cleaning shoe and concave. In analyzing the motion of a loose kernel moving through straw mat, they adopted a resistive force model from "Long et al.(1969)", and axial motion of a kernel was neglected. "Wang et al.(1987)" represented the separation characteristics by a decaying exponential equation applicable for both conventional and rotary combines. "Bjork(1991)" developed a three-dimensional arithmetic model to calculate grain separation through the concave and separation grate of a rotary combine.

The objectives of this study were :

1. To develop a mathematical model of the grain-straw separation process which can be applied for the prediction of the grain distribution pattern and the amount of grain loss.

2. To examine if the developed model is feasible by testing rice samples in a predetermined grain-straw separator.

THEORETICAL ANALYSIS

"Lee et al.(1983,1986)" designed and tested a cylindrical grain-straw separator that was analyzed in this study to get the predicting information.

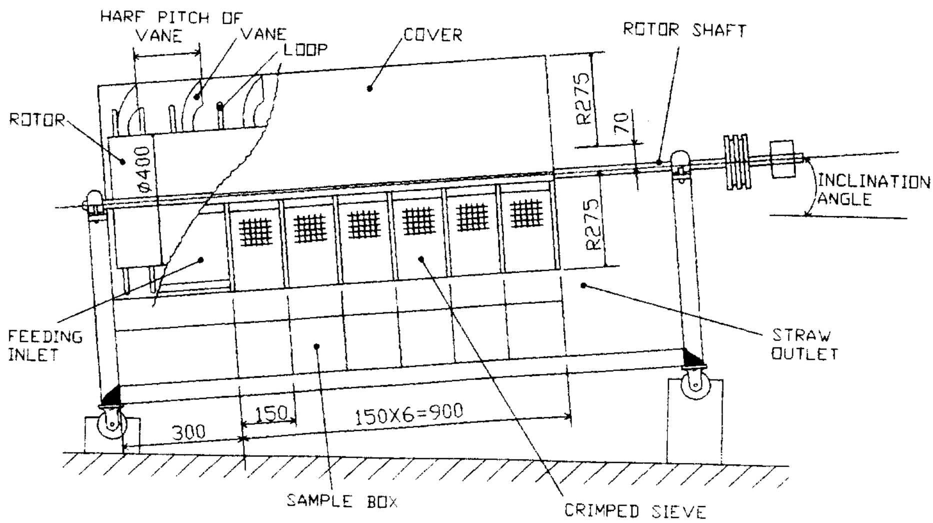

Fig. 1. Schematic of the axial-flow grain-straw separator analyzed.

Its configuration is shown in Fig. 1. A rotor of 1.1 m long and 0.4 m indiameter, equipped helically with 39 wire loops, is rotating inside the concentric cylindrical sieve. A 1.2 m long fixed sieve with 0.55 m diameter made out of a sheet metal in upper half. The crescent vane was attached helically at the inside of the upper half to control the crop movement. The lower half of the sieve was made with 9.7 mm squared openings crimped wire mesh at a rate of 70.4 percent open area. The clearance between rotor loop to sieve surface was 14 mm.

The idealized separation process will be subjected to the following assumptions. The material to be separated is homogeneous mixture of grain and straw and is fed uniformly and continuously at the entrance. The effect of material entrance and exit conditions is ignored. Separation of the kernels uniformly distributed in the straw from the crop mixture is accomplished through the motion of kernels relative to straw during passing the separator.

For the purpose of this analysis, we can assume the separation process to be random process indescribable by way of constant mechanical process. Therefore, the model assumed that any kernel is equally likely to be separated at any time or at any displacement. These assumptions fit the general probabilistic law described in a random process, which is defined by a exponential density function in case of grain-straw separation process.

It was considered that the penetration of kernels through the crop mixture is determined by the motion of the kernels relative to straw layer and resistance of crop mixture to the motion of kernels. However, the crop layer acted as highly damped, low elasticity and compressible viscoelastic layer, the deviation might be occurred to predict the dynamic behavior if the thickness of layer increased. And the resistance of crop layer to the motion of kernels was not constant as the crop layer disturbed by the rotor which exerted alternating compressive and tensile stresses on the crop layer.

The kernels are considered to move around the sieve at the different tangential and axial velocity from the straw layer, and the kernel acceleration relative to straw layer shifted at the lower half and upper half of the sieve due to rotation. Thus the localized velocity differential due to the relative motion between grain and straw can not be ignored("Lee et al.(1985)", "Lee(1986)"). And the resistance of mixture layer was susceptible to influences from crop moisture and friction. Therefore, the possibility of great deviation come into existence always in the end results if the layer resistance to the motion of kernels assumed to be constant.

Also the kernel trajectory in separation chamber is subject to highly random fluctuations, moreover, the direction of kernel movement in crop layer cannot to be limited towards sieve surface. Especially, the penetration of kernels through the crop layer is difficult to express quantitatively and to validate experimentally.

In the event of reaching sieve surface, the loose kernels execute a random approaches onto the sieve surface while migrate with materials to be separated. Grain separation occurs if the kernel trajectory ends at an opening in the sieve or the rebound trajectory immediately after impact with sieve wire proceed beneath the aperture. If not, the kernel bounces off the sieve and it is then carried toward the next opening to repeat the process.

The geometric probability reported by many investigators is usually based on the assumption such as a kernel shape simplified as a sphere or a kernel cannot pass the aperture if a part of it contact with the wire. However, both shape and size of a kernel affect the separation process. And neither the approaching angle of grain is normal to the sieve surface nor the rebound trajectory after impact with wire return to the approaching direction. The passage of grains through the openings of the sieve, therefore, can not be regulated in a simple probability relationship between the size of the kernel and sieve aperture.

To make a compromise between reality and expedience, the separation process was assumed as a simple random process lumped together with the penetration of kernels through the crop layer and the event of passage of kernels through the sieve aperture.

It has a limit to describe the separation process as a single functional relationship since the movement of the material to be separated and the separation process is compounded with physical relationship and randomness. In order to overcome these limits and to simplify the model, the separation process is made up to be coincident with the functional configuration of the physical model explained above. The results of the separation event is described as a exponential probability density function. The distance to occurrence of the random event of separation is selected as the random variable. Therefore, the grain collected on the compartment beneath the sieve is considered to the outcomes forming the probability space. The separation process is modeled that the random variable is exponential distribution of expected value estimated by mean distance between significant events.

$$f(z) = \begin{cases} (1/\beta)\exp(-z/\beta) = \lambda \exp(-\lambda z) & \text{if } 0 \le z < \infty \\ 0 & \text{otherwise} \end{cases} \quad \text{----- (1)}$$

where $f(z)$: probability density function.

z : control parameter, the axial distance from entrance to occurrence of the random event of separation.

β : scale parameter, the mean distance to occurrence of the event.

λ : mean rate of occurrence of the event, reciprocal of β

Parameter λ is assumed to be a constant at any interval since it is the mean separation rate per unit length, and derived from the various factors affecting the separation event.

The accumulated probability distribution function for the axial distance from entrance to occurrence of the event is then given by:

$$F(z) = \int_0^z f(z)\, dz = \begin{cases} 1 - \exp(-\lambda z) & \text{if } 0 \le z < \infty \\ 0 & \text{otherwise} \end{cases} \qquad \text{-----} \ (2)$$

where F(z) is the fraction of grains separated through the sieve.

Hence, the corresponding fraction of grains unseparated through the sieve, namely the point grain loss L is given by an exponential equation of the form:

$$L = 1 - F(z) = \exp(-\lambda z) \qquad \text{-----} \ (3)$$

SIMULATION PROCEDURES

The appropriate parameters which influenced the performance of the separator have been identified in proposed models. Especially, the parameter λ should be predetermined before starting the numerical analysis. In order to provide a simplified and workable model for the analysis, the parameter λ was determined from the data obtained by "Lee et al.(1983, 1986)" as follows.

At first, the separation loss of the cylindrical grain-straw separator for all factors adopted in their experiments were analyzed by multiple regression. The logarithmic loss model provided the best fit. For simplicity, the variables of which contribution to R^2 was below 5 percent were excluded, and the closely interrelated variables, such as moisture content of grain and that of straw, were made it one having higher value of contribution to R^2. Then, the lumped coefficient is assumed to be:

$$\lambda = A\ [\exp(\xi)/(\omega\ P\ S\ D\ M\ G\ V\ H)] + B \qquad \text{-----} \ (4)$$

where ξ is the inclination angle of separator(rad), ω is the rotor speed(rad/s), P is the pitch of vane(m), S is the rate of open area in the wire mesh(decimal), D is the harmonic three axial mean diameter of grain(m), M is the moisture content of straw, wet basis(decimal), G is the material other than grain to grain ratio(real), V is the feeding velocity of crop(m/s), H is the depth of straw layer(kg/m), and A and B are the coefficients. The influence of other variables not included in Eq. (4) could be adjusted by A and B.

For a broad application of the model under various conditions, Eq.(3) is transformed into the general equation as follows:

$$L = C \exp(-\lambda z) \qquad \text{-----} \ (5)$$

where L is the point grain loss(%), and C is the coefficient to be adjusted experimentally.

The values of coefficients simulated were 0.0123, 2.97, and 48.05 for A, B and C, respectively.

MATERIALS AND METHODS

For the purpose of mathematical model validation, a cylindrical grain-straw separator was tested and compared the measured value with the calculated value. The specifications for the separator was same as the physical model explained above(Fig. 1). The crops tested were two rice varieties under dry and wet conditions; see Table 1.

Table 1. Crop conditions

Parameter	Value	
Variety	Samgang 55(Hybrid)	Dongjin(Japonica)
Moisture content(%, w.b.) Grain	15.7(dry), 18.1(wet)	14.1(dry), 21.1(wet)
Straw	39.9(dry), 65.4(wet)	47.3(dry), 63.5(wet)
Plant length after cut(cm)	70.0 ± 4.6	103.6 ± 6.1
Thousand kernel mass(g)	26.3 ± 1.3	29.2 ± 1.1
Grain size(mm)	L8.07 W2.08 T2.79	L7.47 W2.29 T3.20
Harmonic mean dia. of grain(mm)	3.115	3.397
Mass of single ear stalk(g)	5.59 ± 0.82	8.02 ± 0.67
MOG/G ratio after cut	1.66 ± 0.14	2.21 ± 0.15

The material was cut by binder and threshed at first by axial-flow threshing unit, then the grain and straw were collected and their weights were measured. The predetermined amount of straw was placed on the conveyor velt as evenly as possible and grain was mixed on the straw layer as uniformly as possible to supply the material fit to the test conditions. The sieve was devided into eight compartments laterally, and for each test, separated grains beneath the sieve and grains discharged with straw from straw outlet were collected in each sampling box, and cleaned and weighed. Point grain loss, the fraction of grains remaining on the sieve, at the axial distances from entrance were determined and compared with the calculated value by Eq.(5).

The two levels of vane pitch(0.15 m, 0.45 m), inclination angle of separator(0 deg, 10 deg), rotor speed(500 rpm, 800 rpm), MOG/G ratio(1, 4), and depth of straw layer(0.25 kg/m, 0.625 kg/m) were tested. Five feeding velocities of 0.4, 0.6, 0.8, 1.0 and 1.2 m/s were used. In each block, constant levels of fixed factors were as follows: the crop was wet Dongjin, the inclination angle was 5 degree, the vane pitch was 0.45 m, the rotor speed was 700 rpm, the MOG/G ratio was 2, the depth of straw layer was 0.5 kg/m, and the feeding velocity was 0.6 m/s. The corresponding crop feed rate and MOG feed rate were 1.62 t/h and 1.08 t/h, respectively.

RESULTS AND DISCUSSION

In order to figure out the characteristics of the model and to validate the accuracy of this model, the distribution of grain separated through the sieve was investigated. The results are shown in Fig. 2. A logarithmic plot of point grain loss versus the axial distance from feeding inlet shows the expected linear trend throughout the tests. Generally, the predicted value coincided with the measured value. The partial discrepancy between the predicted value and the actual value was accounted for the fact that the actual value is measured with no replication and the lumped coefficient of the model simulated from different crop varieties and constant vane pitch and inclination of the separator. The developed model could be applicable to the prediction of the separator performance and the separator length required to the range of a certain permissible loss could be obtained from these diagrams.

As the vane pitch increases, the axial velocity of the mixture in the separation chamber increases. Thus, the grain loss is increased. The steeper inclination of the separator was effective in preventing the axial movement of the crop to be separated and resulted in a less grain loss. However, the inclination showed less effect on the loss than the vane pitch did in the range of this test. As the rotor speed increases, the axial velocity of crop in the separating zone increases. Thus, the crop dwell time in the separator is dropped and the grain loss is increased, but a too long dwell time will eventually cause rotor plugging.

With low MOG/G ratio, grain loss is lower than that of high MOG/G ratio. These results are perhaps attributed to the fact that there is less amount of grain in the mixture as the MOG/G ratio increases under the constant MOG feed rate condition. To analyze the effect of MOG/G ratio more precisely, therefore, it is required to carry out the test under various amount of MOG or various length of straw with the amount of grain in the mixture maintained constant.

Rice variety had small effect on grain loss since the MOG/G ratio kept constant in this case. It was also noticed that grain loss of wet crop was higher than that of dry crop. Further trials is necessary to determine the effect of physical properties of crop including moisture content and to calibrate the parameter of the model.

The effect of feed rate on grain loss was calculated and measured for two different factors. The MOG/G ratio in these cases were kept constant. The

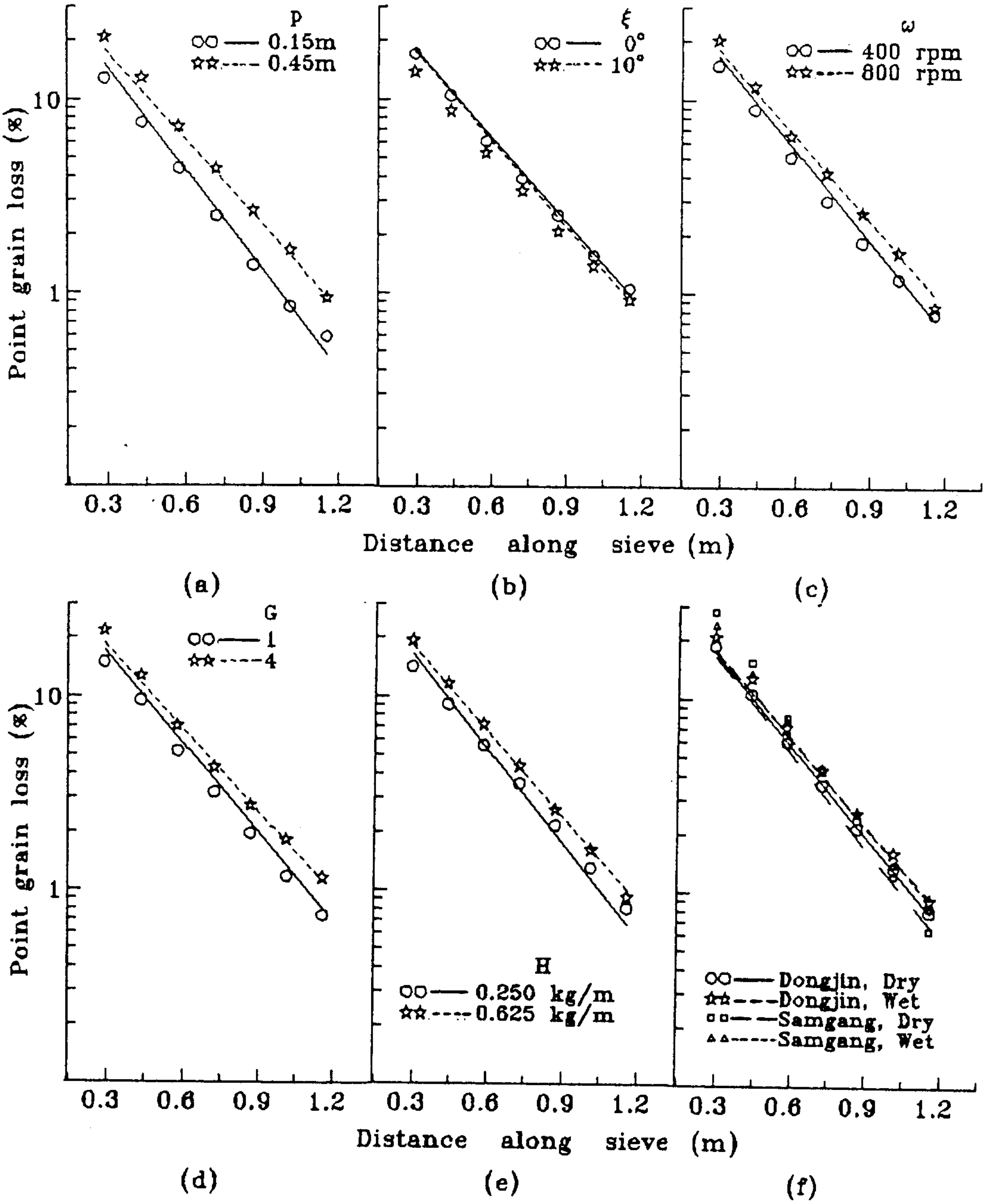

Fig. 2. Point grain loss versus distance along sieve :
(a) for the 0.15 and 0.45 m vane pitch, (b) for the 0° and 10° inclination angle of the separator, (c) for the 400 and 800 rpm rotor speed, (d) for the 1 and 4 MOG/G ratio, (e) for the 0.25 and 0.625 kg/m depth of straw layer, (f) for the Dongjin and Samgang rice variety at dry and wet condition.

Symbols represent the measured value and lines represent the predicted value.

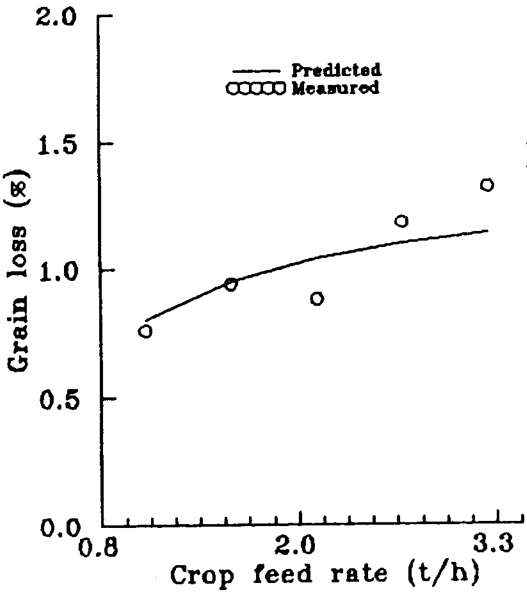

Fig. 3. Effect of feed rate on separation performance.

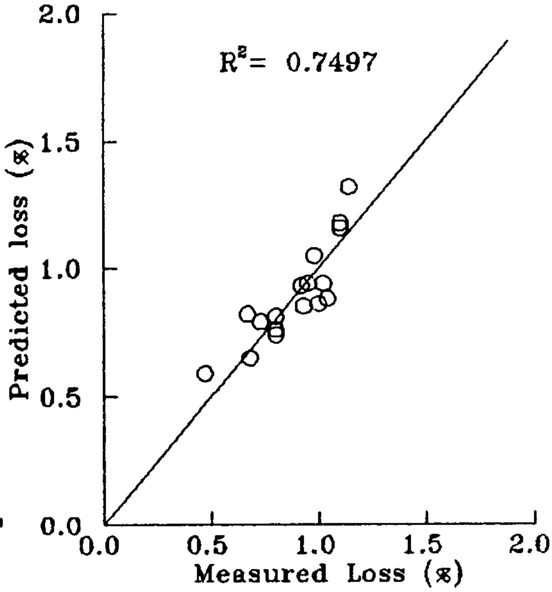

Fig. 4. Comparison of measured and predicted value of grain loss.

point grain loss versus distance along sieve from different straw layer depth with constant feeding velocity is shown in Fig. 2(e). And grain loss at the distance of 1.2 m along sieve versus feeding velocity with constant depth of straw layer is shown in Fig. 3. It should be noted that feeding velocity and depth of straw layer increases, the grain loss increases insignificantly in the range of this test condition.

A comparison of all measured and predicted values of grain loss at the distance of 1.2 m along sieve is shown in Fig. 4. An R^2 of 0.748 was obtained which was significant at the 99.9 percent probability level. It is believed that this model contributes to a better understanding of the separation process and provides a valuable tool for use in grain-straw separator design.

No attempt is made here to compare the effect of wire mesh size with the model. Some relationships still rely on inexactly defined parameters that are felt to correspond to particular factors within the limited ranges. As these relationships are further defined by greater theoretical understanding and observed data, the quality of the model will be refined.

CONCLUSIONS

A mathematical model was developed to describe the separation process of cereal crops in a grain-straw separator which was consisted of cylindrical sieve and rotor. The parameters for the process were determined by simulation. Experiments were performed to validate the mathematical model by changing various levels of pertinent variables for rice. The trends predicted by the model was found to be similar to the measured phenomena for various test conditions, such as inclination of separator, vane pitch, rotor speed, MOG/G ratio, depth of straw layer, feeding velocity, and crop variety and moisture content. In practical design, this mathematical model can be used as a useful tool to reduce time and effort in carrying out elaborious experiments. More research in this area would be benificial to improve the model.

REFERENCES

1. Bjork, A. 1991. A three-dimensional arithmetic model to calculate grain separation and losses for a rotary combine. Canadian Agricultural Engineering 33(2):245-253.
2. Harrison, H. P. 1992. Grain separation and damage of an axial-flow combine. Canadian Agricultural Engineering 34(1):49-53.
3. Huynh, V. M. and T. E. Powell. 1978. Cleaning shoe performance prediction. ASAE Paper No. 78-1565, ASAE, Michigan.
4. Huynh, V. M., et al. 1982. Threshing and separating process - A mathematical model. Transactions of the ASAE 25(1):65-73.
5. Kaye, B. H. and N. I. Robb. 1979. An algorithm for deducing an effective sieve residual from the rate of powder passage through a sieve. Powder Technology 24(2):125-128.
6. Lee, C. H., C. S. Kim and S. K. Lee. 1985. Theoretical analysis and performance prediction of axial-flow rotary separator. Bul. Agr. Col. Chonbuk Natl. Univ. 16:163-174.
7. Lee, S. K. 1986. Studies on axial-flow thresher. Ph.D. Thesis, Kyoto Univ.
8. Lee, S. K., S. T. Kim and K. H. Choi. 1986. Fundamental studies on the development of axial-flow combine(I) - Evaluation of the design parameters of grain-straw separator. J. Korean Soc. Agr. Mach. 11(2):31-40.
9. Lee, S. K., Y. B. Min and H. L. Choi. 1983. Centrifugal grain-straw separation. J. Inst. Agr. Res. Util. Gyeongsang Natl. Univ. 17(2):67-74.
10. Long, J. D., et al. 1969. Centrifugal force and wheat separation. Agricultural Engineering 50(10):578-580.
11. Song, A., D. S. Chung and R. Nassar. 1990. A stochastic compartmental model simulating a grain cleaning process. Transactions of the ASAE 33(3):877-884.
12. Wang, G., G. C. Zoerb and F. W. Bigsby. 1987. A new concept in combine separation analysis. Transactions of the ASAE 30(4):899-903.