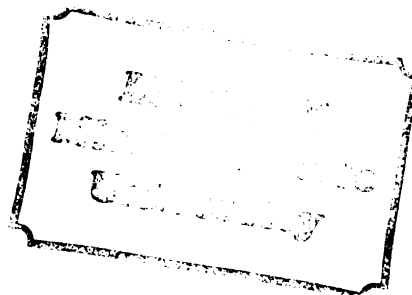


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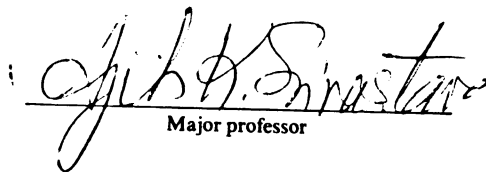
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FOR AXIAL FLOW-COMBINES

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A STUDY OF THE ROTARY CLEANING SYSTEM
FOR AXIAL-FLOW COMBINES

by

Abolfazl Famili

A DISSERTATION

Submitted to
Michigan State University
partial fulfillment of the requirements
for the degree of

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ABSTRACT

A STUDY OF THE ROTARY CLEANING SYSTEM FOR AXIAL-FLOW COMBINES

By

Abolfazl Famili

In an attempt to develop a new cleaning system, to replace the cleaning shoe, a horizontal rotating cylinder perforated at the circumferential end which was fitted over a $\frac{1}{2}$ scale model of an axial-flow combine was fabricated and tested. Two series of experiments were performed to separate grain from a mixture of grain and chaff. Experimental results showed that it was possible in principle to separate grain from chaff in a mechanism which does not depend upon gravity. Theoretical analysis of the rotating cylinder with helical blades mounted on the inside showed that crop angular and axial displacements were a function of cylinder speed.

Approved: 

Major Professor


Department Chairman

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1.0 INTRODUCTION

The combine is the most widely used means of grain harvesting in developed countries and its use is rapidly increasing in developing countries as well. Therefore, any improvement in performance of combines will have worldwide impact.

There are five processes performed in a combine. These are cutting, conveying, threshing, separating and cleaning. The cutting and conveying are performed by the header which includes the reel, the cutter bar, a platform and a conveyor that receives the cut material and conveys it to the cylinder. Threshing, in the conventional combine, which detaches the grain from the stalks, is accomplished by a mechanism consisting of a rotating cylinder and a fixed concave grate. Kepner et al. (1978) found that 60-90% of the seed is also separated during the threshing. The remaining seed and unthreshed pods, as well as considerable amounts of chaff and other small debris, are usually separated by means of multiple-section straw walkers. Cleaning operation begins with the unclean grain consisting of dirt, chaff, bits of straw and some unthreshed heads. The objective of the cleaning process

is to obtain clean grain from the mixture of grain and other material.

In recent years, axial-flow or rotary combines have been introduced commercially. The crop material in these combines is rubbed against the cylindrical separating grates as it is rotated and moved rearward. Centrifugal forces cause the dense seeds to move outward through the straw and finally through the grate openings. The most significant changes in the axial-flow combines are:

1. The threshing area has been increased considerably.
2. The straw walkers are eliminated.
3. The spiral motion of the crop in the threshing cylinder allows the crop to pass over the grates several times instead of once.
4. Threshing and separation are integrated and depend upon gravity to a lesser degree.

A general arrangement of the basic functional components of an axial-flow self-propelled combine is shown schematically in Fig. 1.

Since the emphasis of this study is on the cleaning process, only problems associated with and possible improvements thereof will be discussed here.

Under favorable conditions, the cleaning mechanism works satisfactorily from the view point of grain recovery. Favorable harvesting conditions means that the crop moisture content is optimum, the crop is weed free, and

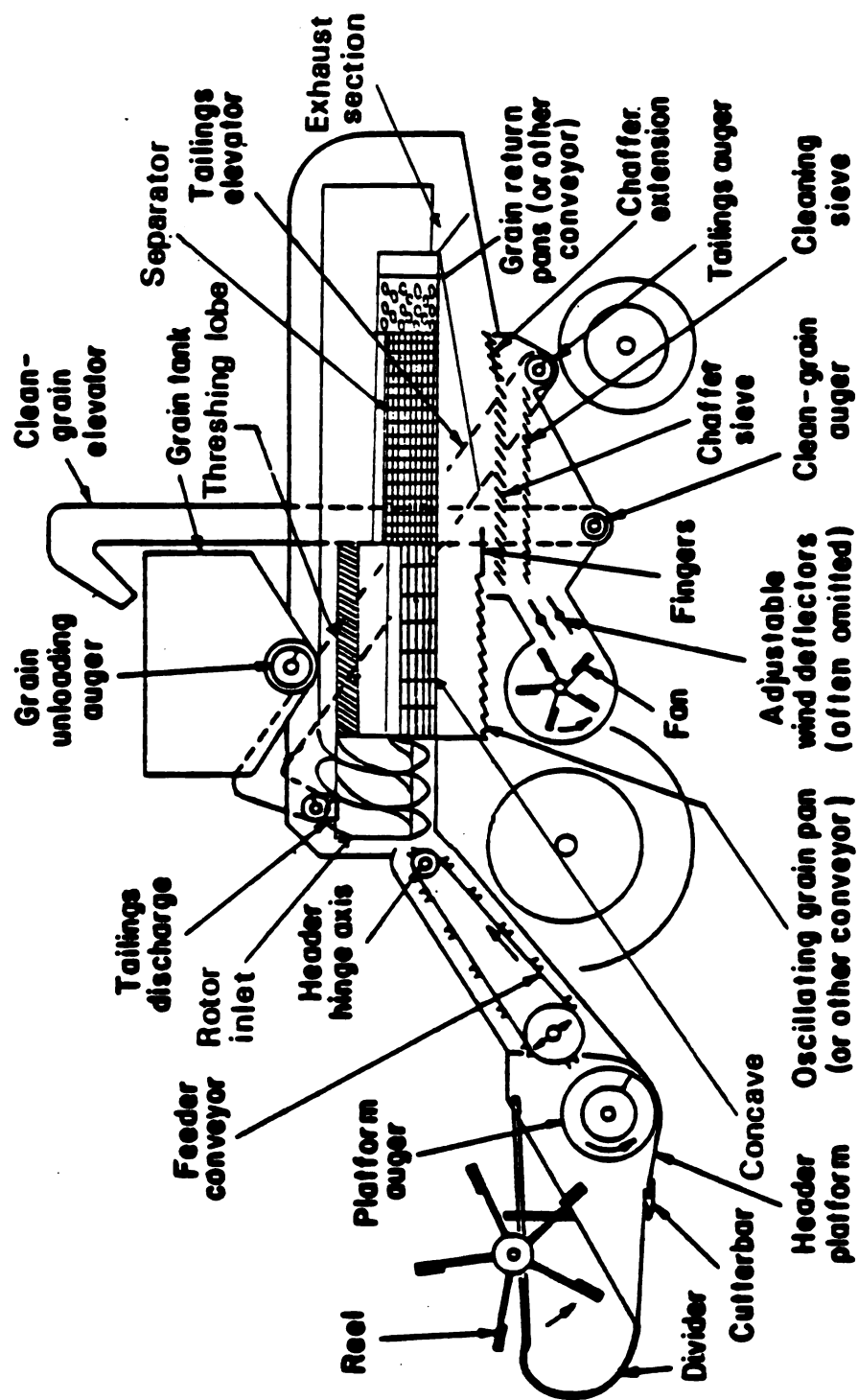


Fig.1 Schematic arrangement of the basic functional components of a self-propelled axial-flow combine.

the machine has been properly adjusted. In conventional and axial-flow combines, cleaning depends upon aerodynamic action and gravity force. Aerodynamic cleaning depends upon the existence of a differential between the terminal velocities of the components to be separated. Although this method has generally been accepted, problems have been encountered. If the air velocity is too high, losses are increased because some seeds are lifted and blown or bounced out of the rear of the machine and the downward movement of other seeds through the mat of material is inhibited. High air velocities also interfere with the passage of seeds through the openings in the cleaning sieve, thereby increasing the amount of free seeds in the tailings (Goss and Kepner, 1958).

In addition, the bulky cleaning mechanism which exists in axial-flow combines depends upon gravity. This makes the mechanism susceptible to variation in field topography. Simpson (1966) investigated the effects of fore-and-aft shoe slope. Average shoe losses in field tests with wheat were about 4% at a longitudinal slope of +15°, 1.5% at 0° slope, and 0.5% at -15° slope as long as the shoe was not overloaded. Greatly increased losses were also observed in a few downhill tests where high feed rates caused the shoe to become overloaded when its discharge end was high (Simpson 1966).

Two major improvements that would be very desirable on the cleaning mechanism are to make the operation independent of ground topography and to make the mechanism less bulky.

2.0 OBJECTIVES

The objective of this research was to investigate new cleaning concepts which could be employed in most of the existing axial-flow combines. The specific objective was:

To investigate the design requirements for a cleaning system for axial-flow combines which would be gravity independent while utilizing the centrifugal and aerodynamic force fields to separate grain from other material.

3.0 REVIEW OF LITERATURE

Crop aerodynamic properties have been investigated by many researchers. Bilanski and Lal (1964) studied the behavior of threshed materials in a vertical wind tunnel. They used a six foot wind tunnel to subject wheat, straw, and chaff samples to different air velocities. The results showed that the orientation of straw in the supporting air stream was a function of straw length and node position on the straw. The straw samples of about 1.27 cm had the highest terminal velocity. The terminal velocity of wheat was 9.10 m/s and for chaff was 1.20 m/s.

In a similar research that was done by Farren and MacMillan (1979) grain-chaff separation in a vertical air stream was investigated. Grain mixed with either polystyrene balls (simulating chaff) or actual sieve materials were injected at rates comparable to those occurring in combine harvesters. They concluded that not only air velocity and feed rate were important in determining the effectiveness of separation and the level of grain loss, but also the speed and direction of the injected material.

Uhl and Lamp (1966) experimentally studied the pneumatic separation of grain, straw and chaff mixtures. During free fall under gravitational force, chaff-like

materials were easily removed from grain pneumatically. For wheat, rye and soybeans, the chaff-like materials were completely removed at 3.04 m/s air velocity. This velocity was less than the grain air-born velocity.

The curves introduced by Uhl and Lamp (1966) showed that air velocities required for separation of α 100 percent of chaff and grain from a mixture of both were 3 and 9 m/s, respectively. These air velocities were used as terminal velocities of chaff and wheat in this study. In other words, it was assumed that 100 percent of chaff can be separated from a mixture of chaff and grain if it was introduced in an air stream with a velocity of 3 m/s.

To increase the cleaning shoe capacity, Rumble (1968) studied the effect of introducing a high velocity stream of material into an air stream above the sieve. He used a system of belts to introduce the material in a form such that the air stream over the sieve could easily separate the components. He found that it was possible to double the normal input material rate to the shoe.

Misener (1969) studied the aerodynamic separation of grain from straw and chaff. He developed a mathematical model to simulate the aerodynamic separation and experimentally investigated the separation of wheat and barley in a dispersed stream of chaff and straw. During his investigation, he varied the following conditions:

1. Velocity of air stream over the sieve.
2. Angle of stream over the sieve.
3. Input velocity of the material stream.
4. Entrance angle of the material stream.
5. Material terminal velocity.

The most significant conclusions that he obtained were:

1. The optimum grain loss occurred when the input velocity was sufficient to allow the material stream to be in a dispersed stream.
2. The best angle of air stream through the chaffer sieve was found to be 40 degrees above the horizontal.
3. Velocity of the air stream passing through the sieve was found to be very critical.

Edward and Collier (1973) studied the aerodynamic resistance coefficients of agricultural particulates. Three hundred gram samples of granular fertilizers and oat, wheat and rye seeds were used in an apparatus based upon the principle of elutriation (which is particle sizing by subjecting them to a vertical air stream). They experimentally determined the mass distributions of values for both particle terminal velocity and aerodynamic resistance coefficients. Experimental value of wheat terminal velocity was found to be 30.50 ft/s, and its aerodynamic resistance coefficient was 99 slug/ft.

Following the investigations that were performed on the aerodynamic properties of particles, some researchers studied the possibility of using slope insensitive cleaning and rotary screens.

Park and Harmond (1966) developed a vertical rotating and vibrating screen-separator to compare its performance efficiency with flat screens. Higher capacity per unit area of screen, simpler feeding, uniform seed layer on the screen and insensitivity to slope were the most important advantages found on vertical rotating screens. Parameters which were investigated included, screen rpm, frequency of screen vibration, feed rate and size and shape of screen openings. The results showed a 99% separating efficiency at screen speeds ranging from 250 to 350 rpm. Optimum frequency of vibration of the screen was found to be critical for each specific screen rpm. The optimum rotational speed was approximately 300 rpm and the optimum frequency at that speed was 19.17 Hz.

In another investigation in 1972, Park tested two vertical rotating-screen separators. The results showed those units could handle trashy materials on combine harvesters as well as in processing plants. Higher capacity and insensitivity of the screens to slopes were also concluded.

Claar (1971) studied the performance of a rotary straw and grain separator. He tested a rotary separator

containing six rotors and a concave screen. The factors which were examined in this study were two rotor speed combinations of 170 and 210 rpm, two concave screen areas of 3.20 m² and 3.30 m² and two screen materials with approximately 60 and 80 percent openings. He concluded that:

1. The rotary separator successfully accelerated and stretched the mat of threshed material to allow the grain to be separated from the material other than grain.

2. Rotor speed and concave screen area were the most significant design factors.

3. Six separator rotors were able to separate 98% of the total grain from the mat of straw.

Saijpaul (1973) tried to integrate separation and cleaning processes in a compact single-stage operation by the simultaneous use of centrifugal and aerodynamic force fields. His objective was to obtain clean grain from a mixture of grain, straw and chaff in a single step. He tested a mechanism consisting of a cylindrical-lipped screen and an inner auger. Both screen and auger were rotating, with the screen rotating slower than the auger. He concluded that it was possible, in principle, to integrate separation and cleaning. The following comment can be made about Saijpaul's work: since most of the chaff in the mixture of grain, straw and chaff that was utilized, escaped from the perforations of the lipped screen, it was

therefore appropriate for him to attempt to integrate separation and cleaning in a two-step operation instead of one.

In a study that was done by Jan et al. (1974), separation of a grain-straw mixture was investigated with a rotating, perforated drum. Three variables, feed rate, drum speed and air velocity, were considered in two drums of 1.20 m and 1.65 m diameter and 2.40 m in length. They concluded that the separating efficiency was affected primarily by the axial velocity of the straw-grain mixture. Also, the feed rate and drum speed were the variables which determined the air flow requirements for conveying the straw-grain mixture along the drum. Drum efficiencies of over 99% were found to be possible through a feed rate of 138-228 kg/min of crop material having a grain to m.o.g. (material other than grain) ratio of 1.0.

Habicht et al. (1974) designed and tested a roto-thresh combine. The cleaner on the model consisted of a rotating screen which was placed parallel to the separating drum. They found that the drum separating efficiency could be increased to the point where the performance was at least equal to that of straw walkers. In another part of this research one of the prototype combines was modified so that an aspirator cleaner could be mounted beside the drum separator. Field tests showed that the aspirator section worked well but that the

rotating screen did not separate chaff and unthreshed heads well enough to give a clean sample. Finally, they found that the components would work satisfactorily if they could be arranged to overcome conveying problems and to improve the separation of threshed heads. The results of laboratory and field experiments indicated that the capacity of the machine was about 500 bushels per hour at 2% loss when the m.o.g. to grain ratio was one.

The studies conducted by Jan and Habicht suggest the following points:

1. A rotating screen could provide more cleaning area and have a thinner mat of material (grain and chaff) than a flat screen used in conventional cleaning systems.
2. Partial or complete cleaning might be feasible by using a rotating screen.
3. A blower located at the front end of the rotating cylinder could initiate the movement of chaff from the feeding to the exit end. This could also produce partial separation of chaff from grain.

Huynh and Powell (1978) developed the physical and mathematical models of cleaning shoe performance. To develop the mathematical model, certain assumptions were made to simplify the process of cleaning. They defined the process of cleaning as two random events: penetration of the kernel through the mat, and subsequent passage of the kernel through the chaffer openings. The mathematical

model was then used to determine the performance of a grain combine. Numerical results obtained from the model analysis were compared to the experimental data from field tests. The following conclusions of their study were significant for this research:

1. The air flow through the mat played a role in keeping the mat matrix open to reduce the tendency of kernel lodging between the mat layers.

2. The air distribution over the cleaning area was also understood to be a key factor. This will obviously keep the chaff airborne.

3. It was realized that crop transport velocity was affected by the frictional property of crop material. The coefficient of friction increased as crop moisture rose.

A.R. Wilshusen (1971) developed a rotary grain separator to replace the beater, straw walkers and chaffer sieve as employed in conventional combines. His invented machine consisted of a perforated auger with rake teeth on the periphery located horizontally on top of a flat sieve together with fans and collecting pan and auger assembly for the clean grain. He suggested installation of the separator next to the threshing cylinder, so that the threshed material could be directly fed into the separator.

C.J. Huether (1968) invented a separating device for installation in agricultural combines designed to specifically replace the flat sieves. His design, which was suggested to be installed under the straw walkers, consisted of a plurality of individual open-topped auger housing compartments. Each compartment was expected to receive equal amounts of chaff and grain for cleaning so that the crop would not tend to collect on one side of the machine.

W.R. Reed and F.W. Bigsby (1976) developed a pneumatic concave grain separator to remove as much chaff and straw as possible from the grain as the mixture is forced through the concave and grate below the threshing cylinder of a combine. Two fans were used to draw air through the concave. Air velocity arrangement was provided to permit removal of the majority of chaff and straw with a negligible amount of grain kernels.

J.L. Shaver (1977) introduced a grain accelerator precleaner which was designed to be installed under the threshing cylinder of conventional combines. The threshed material leaving the threshing cylinder of a combine was accelerated into a transverse air stream by a pair of rollers. The rollers accelerated the threshed material to a velocity greater than the speed at which such material would fall by gravity. A wide stream of relatively high speed air was directed transversely through the

accelerated material to provide a precleaning of straw and chaff from the material normally passed to the grain separation or cleaning shoe section of the combine. The grain in the accelerated material continued in a relatively straight line trajectory and the straw and chaff were separated from the grain by the transverse air stream.

The following points were concluded from this literature review:

1. Wheat and chaff terminal velocities which were obtained by Bilanski and Lal (1964) and Uhl and Lamp (1966) can be used in this research.

2. Although vertical rotating and vibrating screens have many advantages such as high capacity and insensitivity to slope, they cannot be used in an axial-flow combine because:

- a) The crop has to be directed through channels to the entrance of the screen.

- b) Installation of vertical rotating screen will add to the size of the combine.

3. A horizontal rotating screen equipped with helical blades on the inside, which could fit over the threshing-separation mechanism of axial-flow combines, will provide a slope-insensitive condition to separate grain from chaff.

4. An air stream can be used to separate some of the chaff from the mixture of chaff and grain.

4.0 EXPERIMENTAL ANALYSIS

The last process performed in an axial-flow combine is to clean the chaff and other material from the seed. During the cleaning process, the material passes through the openings of a threshing-separation cylinder and is delivered to the grain pan. This material which consists of threshed seed, unthreshed material, chaff and other material is transferred from the grain pan onto the front of the oscillating chaffer sieve (Fig. 1). As the material moves rearward over the chaffer sieve, an air blast directed upward through the sieve aids in separating out the free (threshed) and unthreshed heads and blows the light chaff out at the rear of the machine. Obviously, the air blast should not be strong enough to blow the grain out of the rear of the combine.

The cleaning mechanism which exists in conventional and axial-flow combines has the following disadvantages:

1. The performance of the mechanism is effected by ground topography.
2. It makes the combine bulky.
3. It often limits the machine capacity.

Any improvements that make the cleaning operation independent of ground topography, less bulky and with

higher capacity would be very desirable. It was also realized that development of a new cleaning mechanism which satisfies the above mentioned functional requirements, would be valuable if it is adaptable to the axial-flow combines. In addition, such a mechanism should satisfy the following functional requirements:

1. It's operation should be continuous.
2. It's operation should not depend on gravity force.
3. It should not add to the size of the combine.
4. It should have a positive means of supplying energy to the crop.

It was, therefore, conceived that a rotating cylinder perforated at the circumferential end of the wall and equipped with helical blades at the inside could take care of the above functional requirements. In other words, by using the rotating cylinder, the operation would not depend upon gravity; helical blades inside the cylinder would be a positive means of supplying energy to the crop and making the operation continuous. Finally, the perforated section at the outlet of the rotating cylinder could be used for the cleaning process.

To incorporate the above idea, the threshing-separation mechanisms of axial-flow combines existing in the market were studied. Among those, the White-9700 Axial was realized to have the simplest threshing-

separation unit. The threshing-separation mechanism in a White-9700 consists of a rotor with auger flights at the beginning and rasp bars mounted next to the augers. A fixed cylinder with the lower part being the concave grate and the upper part having guiding vanes on the inside, fits over the rotor. The cleaning mechanism is the same as conventional combines. Figure 2 shows threshing-separation and cleaning mechanism of a White 9700 Axial.

4.1 One Stage Cleaning Concept

4.1.1 Experimental Apparatus and Material. A half scale model of the threshing-separation unit of a White 9700 axial-flow combine was designed and fabricated. The schematic diagram of the threshing-separation mechanism with the rotating cylinder to be fitted over the separating cylinder is given in Figure 3.

It was conceived that the incoming material which is fed through the hopper will pass through the perforations of the fixed cylinder. This material will then be moved axially by the helical blades of the rotating cylinder and the air stream provided by a fan located at the entrance of the rotating cylinder. The material will then be located at the perforated section of the rotating cylinder where the cleaning process should be performed. As shown in Figure 3, it was conceived that an inward

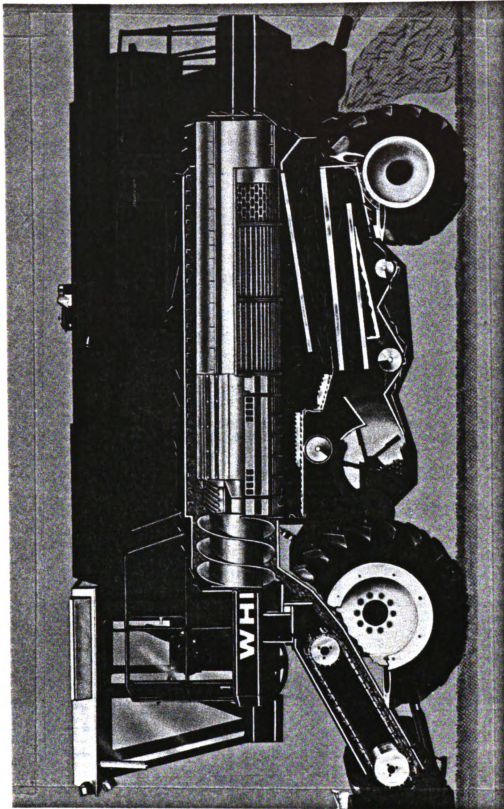


Fig. 2 Threshing-separation and cleaning unit of White-9700 Axial
(courtesy of the White Farm Equipment Canada Limited).

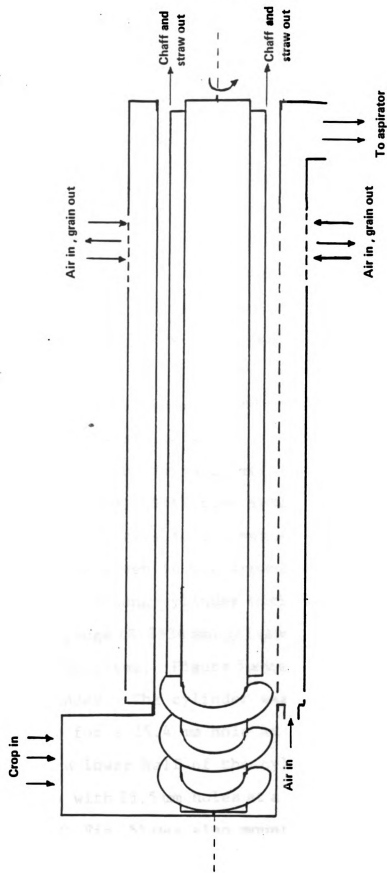


Fig. 3 Schematic diagram of one stage cleaning concept :
A. Rotor , B. Fixed cylinder, C. Rotating cylinder.

air flow, created at the perforated section of the rotating cylinder, will hold chaff back and allow the grain to escape. This grain will then be collected as clean grain.

Dimensions of the half scale model which were determined, based on the available information for the prototype and applying the theory of models discussed by Murphy (1950), are as follows:

A rotor of 2.43 m in length and 0.25 m in diameter which had a 2.54 m length shaft at the centerline (Fig. 4). the rotor was equipped with auger flightings (A, Fig. 4) at the first 0.50 m. The rest of the rotor had two 35 mm paddles (B, Fig.4) located 180° apart. The rotor was rotated by a hydraulic motor (A, Fig. 10). The shaft of the rotor and the hydraulic motor were connected by sprockets and a chain. Different rotor speeds were obtained by varying flow rate to the motor. The horsepower calculations are given in the Appendix A.

A 2.43 m long cylinder with 0.40 m diameter, made out of 22-gauge (0.8534 mm) galvanized sheet metal, was fitted over the rotor. Figure 5 shows a photograph of the fixed cylinder. The cylinder was closed from the entrance end except for a 25.4 mm hole at the center for the rotor shaft. The lower half of the cylinder was perforated (D, Fig. 5) with 15.5 mm holes at a rate of 45 percent open area. A hopper (C, Fig. 5) was also mounted at the closed end of the



Fig. 4 Photograph of the rotor: A. Auger flighting; B. Straight paddles.

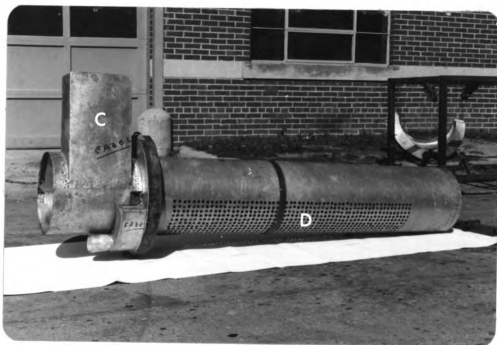


Fig. 5 Photograph of the fixed cylinder : C. Feeding trough; D. Perforations on the lower half.

cylinder to serve as a feeding end. The opening area of the hopper was $0.20\text{ m} \times 0.30\text{ m}$. The schematic representation of the rotor and the fixed cylinder are given in the Appendix E.

A frame made out of 50 mm square tubing was fabricated as shown in Fig. 6. Dimensions of the frame are given in the Appendix E. The rotor was supported by two bearings on the frame. The fixed cylinder was also secured to the frame by two pairs of semi-circular clamps.



Fig. 6 Photograph of the frame.

The rotating cylinder (C, Fig. 11) 1.71 m long and 0.60 m in diameter, was fabricated of 20-gauge (1.0058 mm) galvanized sheet metal with three circular belts, two at the ends and one where the two pieces of the cylinder were connected. The 0.33 m of the cylinder circumferential end was perforated with 1.27 mm holes. The percent open area in the perforated section of the cylinder was 42.

Figures 7 and 8 are the side and front photographs of the rotating cylinder. A helical flight with 75 degree helix angle (the angle between the blade and the axis of rotation) was mounted inside the cylinder and was extended from one end to the other. The axial pitch of the helix was calculated as follows:

$$\begin{aligned} P &= \cot \beta \cdot \pi \cdot r & [1] \\ &= (0.2679) \cdot (3.14) \cdot (0.3) \approx 0.25 \text{ m} \end{aligned}$$

where

- P = axial pitch, meters.
- β = helix angle, degrees.
- r = cylinder radius, meters.

The cylinder was supported by eight rubber wheels, four on each end. The rubber wheels were mounted by a separate mechanism to the frame (Fig. 6). This mechanism provided two degrees of freedom for the adjustment and rotation of the cylinder. The entrance end of the cylinder was closed with a circular wall. Rubber seals



Fig. 7 Front photograph of the rotating cylinder.



Fig. 8 Side photograph of the rotating cylinder.

were used to prevent any material from coming out at the joints. The circular wall had two plastic spool-rollers fixed on the top and the bottom to separate the wall from the rotating cylinder.

The cylinder was rotated by a Lamina A-25 hydraulic motor. The motor was powered by a tractor and transmitted power by means of a V-belt to the cylinder. Different cylinder speeds were obtained by changing the rpm of the tractor engine. Power calculations for the rotating cylinder are given in Appendix A. Figures 9, 10, and 11 show the schematic diagram and photographs of drive systems

A centrifugal fan equipped with a 0.75 kw electric motor provided $0.24 \text{ m}^3/\text{s}$ air flow rate between the rotating and fixed cylinder spacing

A doughnut shape air duct with an outlet in one side was mounted at the end of the rotating cylinder. This outlet was connected to the inlet of a paddle type fan in order to work as an aspirator.

A box ($0.90 \text{ m} \times 0.90 \text{ m} \times 0.33 \text{ m}$) with top and bottom closed and four sides open was built from 20-gauge (1.006 mm) galvanized sheet metal (Fig. 12). The narrow sides were connected to the side ducts (Fig. 13) equipped with guiding vanes. The wide side of the box had circular holes of 0.65 m in diameter (50 mm larger than the diameter of the cylinder), so that the box was fitted

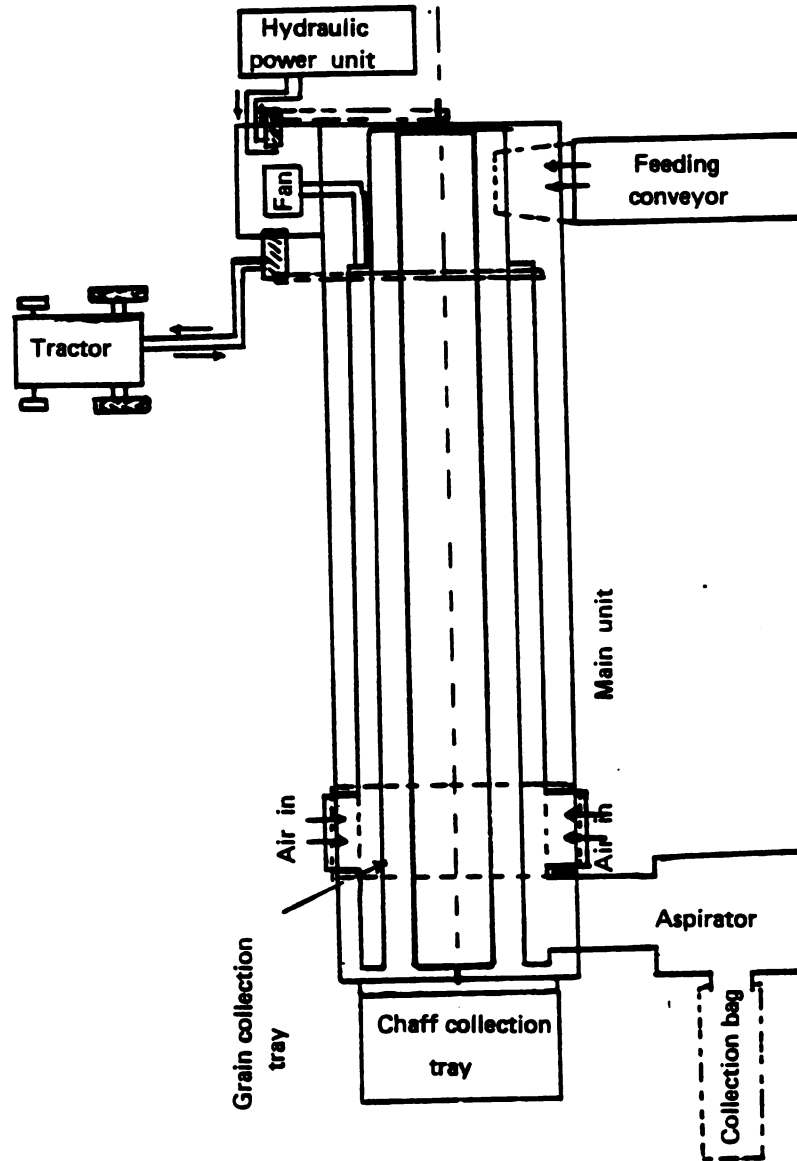


Fig. 9 Schematic diagram of the experimental set up, one stage cleaning concept.

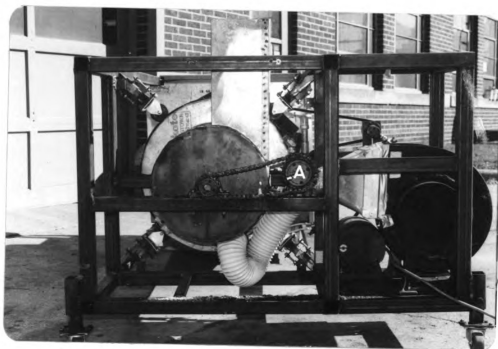


Fig. 10 Drive system for the rotor : A. Hydraulic motor.

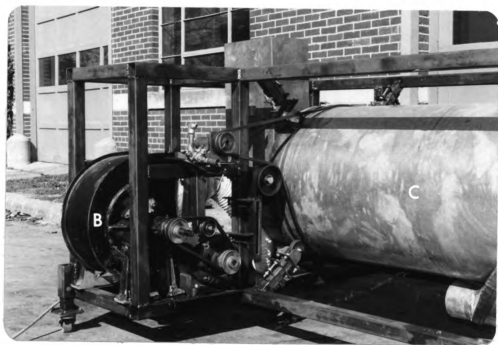


Fig. 11 Drive system for the inlet fan(B) and the rotating cylinder(C).

over the rotating cylinder. Rubber seals were used in order to prevent the escape of air and material from the clearance between the edge of the box and the rotating cylinder. All material coming out at the perforated section of the rotating cylinder was therefore trapped inside the box and was collected in the lower section of the box.

A cross-flow fan (B, Fig. 11) equipped with a 7.5 kw electric motor capable of producing a $1 \text{ m}^3/\text{s}$ air flow rate, and mounted on top of the frame and its outlets were connected to the side ducts of the cleaning box.

The feeding device consisted of a belt conveyor independently driven by a 0.25 kw electric motor. The conveyor belt had a rough surface with a width of 0.4 m. The belt speed was 0.21 m/s. A chute made from 24-gauge (0.7010 mm) sheet metal connected the feeding end of the conveyor to the feeding hopper of the fixed cylinder.

The wheat crop used for the investigation was grown at Williamston, Michigan and planted during Oct. 1-4, 1980. Wheat and chaff needed for the experiment were collected during the harvesting operation on July 31, 1981. Wheat was obtained from the grain tank and chaff from the rear of a John Deere 6620 modified combine in which a $1.20 \text{ m} \times 1.20 \text{ m} \times 1.20 \text{ m}$ bag could be mounted to collect the samples. Wheat and chaff were stored indoors and their moisture contents were measured before each series of tests.

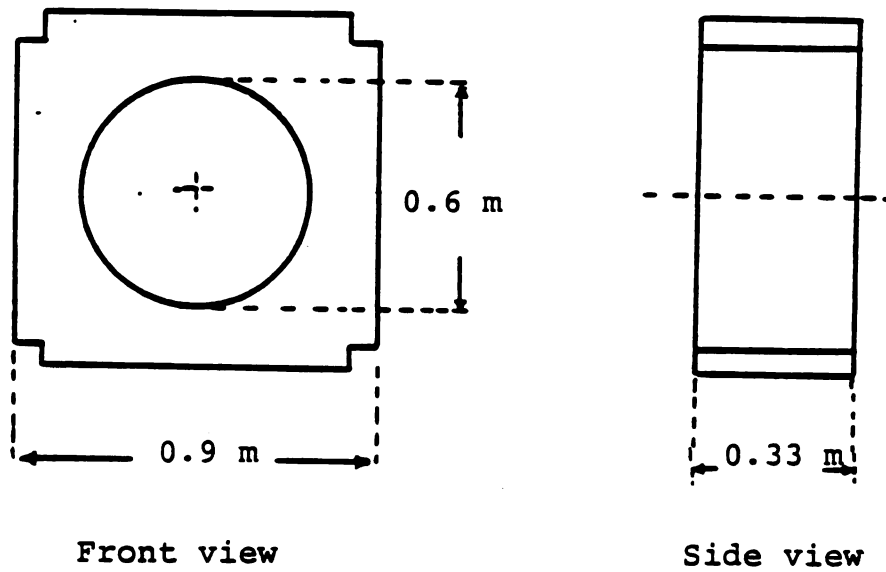


Fig. 12 Front and side views of cleaning box

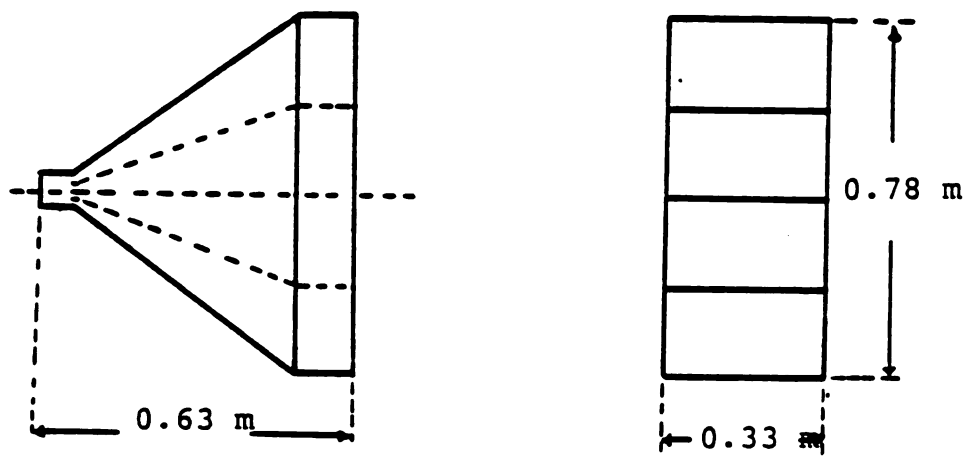


Fig. 13 Front and side views of side air duct

4.1.2 Experimental Design. The purpose of this experiment was basically to evaluate the performance of the desing developed in this research. The specific objectives were:

1. To evaluate the cleaning efficiency of the unit.
2. To investigate the influence of each independent variable on the performance of the unit.

Independent variables were, rotor speed (rpm), material flow rate (kg/min), air flow rate (m /s), and cylinder speed (rpm). Three levels of each independent variable were used (i.e. three treatments were considered within any independent variable). The dependent variables were related to the performance of the design. These were the percent chaff at the cleaning zone (bottom of the cleaning box) and percent grain loss.

A second-order rotatable experimental design, as introduced by Box and Behnken (1960), was used for this experiment. This design has an assumption that there would be no time trends to change the level of independent variables between different experiments. In addition, this design is usually applied whenever quantitative variables having three or more levels are involved in the experiment. It was also reasonable to assume the design to be rotatable since there was no advance knowledge as to how the response surfaces would orient themselves.

To run the experiment, the cylinder speed was used as the blocking variable. In other words, the experiment was repeated at three cylinder speeds which represented the blocking variable. This was done because changing the cylinder speed was dependent on the tractor rpm and that had a potential of producing some errors. The reason was due to the mechanical problems which existed in the adjustment of the tractor engine rpm.

Preliminary tests were run to determine the levels of other independent variables.

The function of rotor in this model was to convey the material fed through the feeding hopper along the cylinder so that all the material could pass through the perforation area of the fixed cylinder. The lower limit of the rotor was obviously the one below which the material was stuck and the highest limit was when there was a chance of getting some grain losses from the exit end. Preliminary test runs showed that 300-500 rpm was the best range of rotor speed.

Three values of material flow rates used in the experimental analysis based on the total material flow rate (m.o.g. + grain) determined by Jan and Reed (1974) and Wrubleski (1980) were in the range of 150-240 kg/min. For the model used in this experiment, the material flow rate was calculated from an equation which was derived

by applying the theory of models (Murphy 1950). Derivation of the equation is given in Appendix B. The equation is:

$$Q_m = \frac{Q_p}{5.6} \quad [2]$$

Note: $5.6 = n^{5/2}$

where:

n = scale factor, 2.

Q_m = material flow rate in the model.

Q_p = material flow rate in the prototype.

Applying Eq. 2, three total material flow rates of 26.5 kg/min, 35.4 kg/min and 42.4 kg/min were obtained. In order to find the grain to chaff ratio, an m.o.g./grain ratio equal to 1.0 (ASAE-1980, Jan et al. 1974) and grain to chaff ratio of 1:0.425 (Saijpaul 1973) were assumed and the amount of chaff and grain were calculated. The complete calculation is given in Appendix C.

Three levels of air flow rates were also applied which will be discussed in detail in the next section.

The appropriate cylinder speed was determined by considering previous work done by Jan et al. (1974) and preliminary experiments. The experiments which were performed by Jan et al. (1974), revealed that high separation efficiencies were possible using optimum centrifugal acceleration of about 0.87 g.

Graphical representation of experimental design is given in Fig. 14. Tables 1, 2 and 3 are the statistical arrangements of three blocks. Treatment combinations of statistical design are related to the levels of independent variables. For example, +1, 0, -1 refers to the high level of rotor speed (X1), medium level of air flow rate (X2) and low level of material flow rate (X3).

For this design, the total number of treatment combination in each block were 12. The central point was replicated three times so that a total of 15 observations were made. The number of replicated central points were as suggested by Box and Behnken (1960).

4.1.3 Method of Procedure. The model test apparatus discussed earlier was used for the experimental runs. An attempt was made to create an inward air flow at the perforated section of the rotating cylinder in order to hold back chaff while grain escape (See Fig. 3).

The outlet of the air duct which was mounted at the end of the rotating cylinder, was connected to the inlet of a paddle-type fan. The fan air flow rate, as measured at the outlet was 0.62 m³/s. This created an inward air velocity through the perforated section of the rotating cylinder (Fig. 9).

With the aspirator (paddle fan) and the entrance fan working, air velocities were measured along the perforated section of the rotating cylinder on top, bottom and two

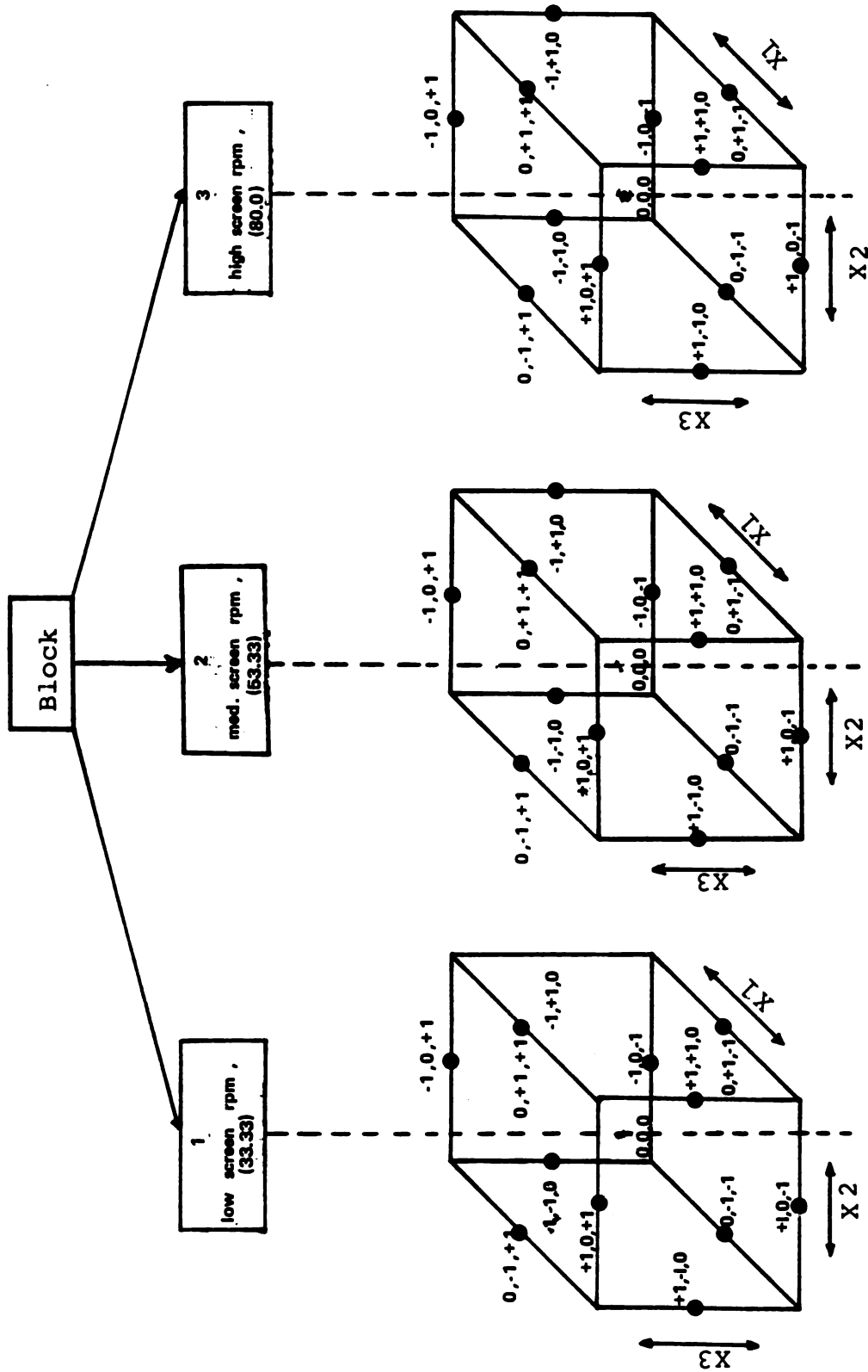


Fig. 14 Graphical representation of Experimental Design

(X_1 = rotor speed, X_2 = air flow rate, X_3 = mat. flow rate).

Tables 1,2, 3 Statistical combinations of three blocks of experiment

Block No. 1 (low screen R.P.M.)

Run No.	Statistical combination		
	X1	X2	X3
1	0	0	0
2	0	0	0
3	0	0	0
4	+1	+1	0
5	+1	-1	0
6	-1	+1	0
7	-1	-1	0
8	+1	0	+1
9	+1	0	-1
10	-1	0	+1
11	-1	0	-1
12	0	+1	+1
13	0	+1	-1
14	0	-1	+1
15	0	-1	-1

Block No. 2 (Med. screen R.P.M.)

Run No.	Statistical combination		
	X1	X2	X3
16	0	0	0
17	0	0	0
18	0	0	0
19	+1	+1	0
20	+1	-1	0
21	-1	+1	0
22	-1	-1	0
23	+1	0	+1
24	+1	0	-1
25	-1	0	+1
26	-1	0	-1
27	+0	+1	+1
28	0	+1	-1
29	0	-1	+1
30	0	-1	-1

Block No.3 (high screen R.P.M.)

Run No.	Statistical combination		
	X1	X2	X3
31	0	0	0
32	0	0	0
33	0	0	0
34	+1	+1	0
35	+1	-1	0
36	-1	+1	0
37	-1	-1	0
38	+1	0	+1
39	+1	0	-1
40	-1	0	+1
41	-1	0	-1
42	0	+1	+1
43	0	+1	-1
44	0	-1	+1
45	0	-1	-1

X1 = Rotor speed X2 = Air flow rate X3 = Material flow rate
 (Note: -1: low level; 0: med. level; +1: high level)

sides in order to obtain the average inward air velocity. The velocities were 1.10, 1.55, 1.40 and 2.31 m/s along the top, sides and the bottom, respectively. The average inward air velocity was 1.59 m/s.

It was realized that 1.59 m/s inward air velocity would not be enough to prevent chaff from escaping and more air was required. The total open area at the perforated section of the rotating cylinder was 0.21 m^2 . The required air flow, was therefore, calculated as:

$$\begin{aligned} Q_r &= A \cdot (V_r - V_i) \cdot K_e \\ &= 0.21 \cdot (V_r - 1.59) \cdot 1.2 \end{aligned} \quad [3]$$

Where

Q_r = required air velocity at the perforated section of the rotating cylinder, m^3/s .

A = total open area at the perforated section of rotating cylinder, m^2 .

V_r = required inward air velocity at the perforated section, m^3/s .

K_e = air escape coefficient.

Note: In the above calculations, a 20% air escape was assumed and was added to the required air flow rate.

Three different air velocities of 3.00, 3.50 and 4.00 m/s were considered for the experiment. The required air flow rate was, therefore, $0.355 \text{ m}^3/\text{s}$, $0.485 \text{ m}^3/\text{s}$, $0.610 \text{ m}^3/\text{s}$ for 3.00, 3.50 and 4.00 m/s of air velocities, respectively. These air flow rates were provided by an extra

fan which was mounted on top of the frame. The required air flow rates were obtained by regulating the outlet opening of the fan.

A total of 45 treatment combinations in three blocks of 15 were run during the experiments. Quantitative levels of different independent variables are given in Table 4. The cylinder speed which was the blocking variable was 33.33, 53.33, and 80.0 rpm for blocks one, two and three, respectively.

Two samples of chaff and grain which had been weighed and labelled earlier were used to run each treatment combination. The sample was prepared by first spreading the chaff over an area of 0.50 m^2 on the conveyor belt and then, sprinkling the grain over the chaff uniformly. The other half of the chaff was spread over this mixture to complete the sample preparation. Grain and chaff moisture contents were 14.55% (D.B.) and 12.74% (D.B.), respectively.

For each test, the material coming through the perforated section of the rotating cylinder was collected and tagged. Material from the exit end, from the aspirator outlet and material spread around the apparatus, were also collected and tagged.

The material in each bag was first weighed, then run through a Clipper M-2 Seed Cleaning Mill manufactured

Table 4 Quantitative levels of independent variables

Run No.	Block No.	Statistical combination X1 X2 X3			Rotor speed, rpm.	Air flow rate, m ³ /s.	Mat. flow rate, kg/min.	Grain, kg.	Chaff, kg.
1	1	0	0	0	400	0.485	35.4	1.768	0.751
2	1	0	0	0	400	0.485	35.4	1.768	0.751
3	1	0	0	0	400	0.485	35.4	1.768	0.751
4	1	+1	+1	0	500	0.610	35.4	1.768	0.751
5	1	+1	-1	0	500	0.355	35.4	1.768	0.751
6	1	-1	+1	0	300	0.610	35.4	1.768	0.751
7	1	-1	-1	0	300	0.355	35.4	1.768	0.751
8	1	+1	0	+1	500	0.485	42.4	2.123	0.902
9	1	+1	0	-1	500	0.485	26.5	1.326	0.563
10	1	-1	0	+1	300	0.485	42.4	2.123	0.902
11	1	-1	0	-1	300	0.485	26.5	1.326	0.563
12	1	0	+1	+1	400	0.610	42.4	2.123	0.902
13	1	0	+1	-1	400	0.610	26.5	1.326	0.563
14	1	0	-1	+1	400	0.355	42.4	2.123	0.902
15	1	0	-1	-1	400	0.355	26.5	1.326	0.902
16	2	0	0	0	400	0.485	35.4	1.768	0.751
17	2	0	0	0	400	0.485	35.4	1.768	0.751
18	2	0	0	0	400	0.485	35.4	1.768	0.751
19	2	+1	+1	0	500	0.610	35.4	1.768	0.751
20	2	+1	-1	0	500	0.355	35.4	1.768	0.751
21	2	-1	+1	0	300	0.610	35.4	1.768	0.751
22	2	-1	-1	0	300	0.355	35.4	1.768	0.751
23	2	+1	0	+1	500	0.485	42.4	2.123	0.902
24	2	+1	0	-1	500	0.485	26.5	1.326	0.563
25	2	-1	0	+1	300	0.485	42.4	2.123	0.902
26	2	-1	0	-1	300	0.485	26.5	1.326	0.563
27	2	0	+1	+1	400	0.610	42.4	2.123	0.902
28	2	0	+1	-1	400	0.610	26.5	1.326	0.563
29	2	0	-1	+1	400	0.355	42.4	2.123	0.902
30	2	0	-1	-1	400	0.355	26.5	1.326	0.563
31	3	0	0	0	400	0.485	35.4	1.768	0.751
32	3	0	0	0	400	0.485	35.4	1.768	0.751
33	3	0	0	0	400	0.485	35.4	1.768	0.751
34	3	+1	+1	0	500	0.610	35.4	1.768	0.751
35	3	+1	-1	0	500	0.355	35.4	1.768	0.751
36	3	-1	+1	0	300	0.610	35.4	1.768	0.751
37	3	-1	-1	0	300	0.355	35.4	1.768	0.751
38	3	+1	0	+1	500	0.485	42.4	2.123	0.902
39	3	+1	0	-1	500	0.485	26.5	1.326	0.902
40	3	-1	0	+1	300	0.485	42.4	2.123	0.902
41	3	-1	0	-1	300	0.485	26.5	1.326	0.563
42	3	0	+1	+1	400	0.610	42.4	2.123	0.902
43	3	0	+1	-1	400	0.610	26.5	1.326	0.563
44	3	0	-1	+1	400	0.355	42.4	2.123	0.902
45	3	0	-1	-1	400	0.355	26.5	1.326	0.563

by A.T. Farrel and Company of Saginaw, Mi.* The grain from the clipper mill was weighed. The differences between the two weights gave the amount of chaff in the sample. A total of 180 bags, four from each experiment were cleaned.

4.1.4 Results and Discussion. Samples obtained from the experimental runs were cleaned and weighed. Tabular results are given in Tables A-1 through A-3 in Appendix D. Fig. 15, 16, 17, 18, 19, and 20 represent the effect of different independent variables on the percent of chaff at the cleaning zone and percent grain loss.

A comparison of Fig. 15, 16 and 17 shows that the medium cylinder speed (53.33 rpm) caused the least amount of chaff (8.2 %-18.8%) to pass through the perforations of the rotating cylinder.

The effect of each independent variable on dependent variables (percent of chaff at cleaning zone, determined from the ratio of total chaff fed to the ratio of chaff at the cleaning zone, and percent grain loss) has been illustrated through the projections of plots on the

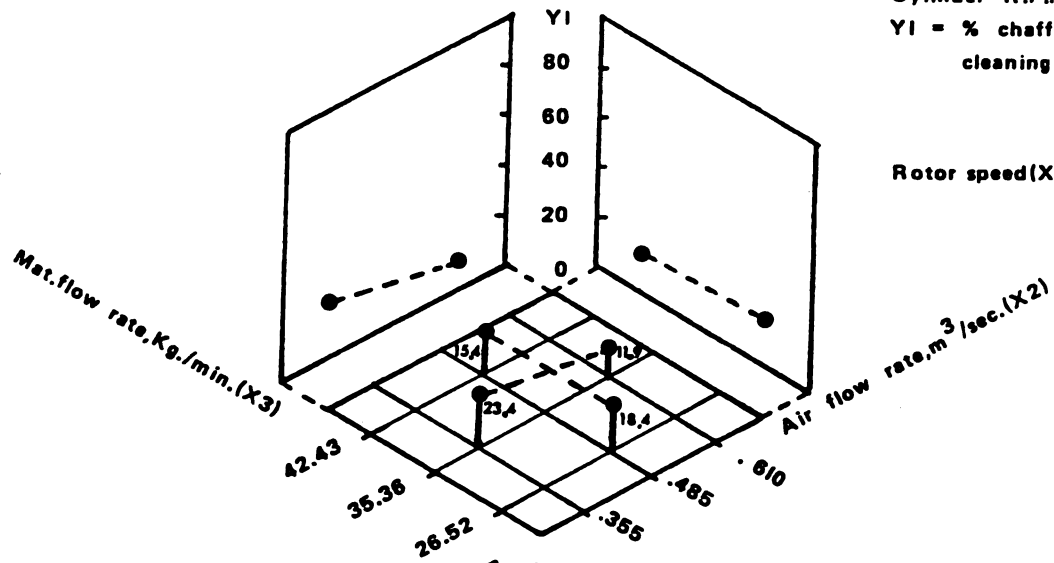
*Note: Trade names are given for identification purposes only and do not constitute an endorsement by the author or Michigan State University.

Block No. : 1

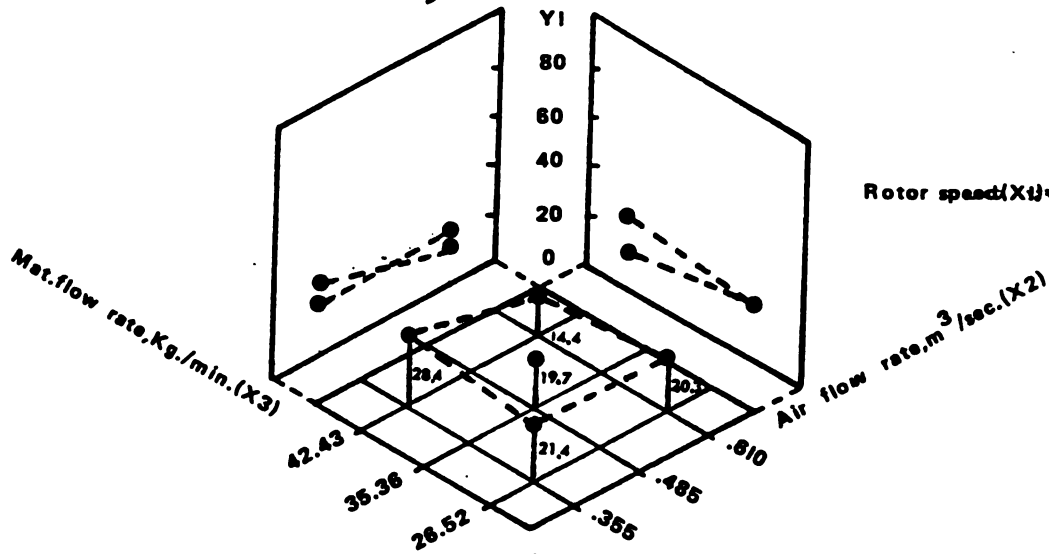
Cylinder R.P.M.: 33.33

YI = % chaff at
cleaning zone

Rotor speed(X1)=300 R.P.M.



Rotor speed(X1)=400 R.P.M.



Rotor speed(X1)=500 R.P.M.

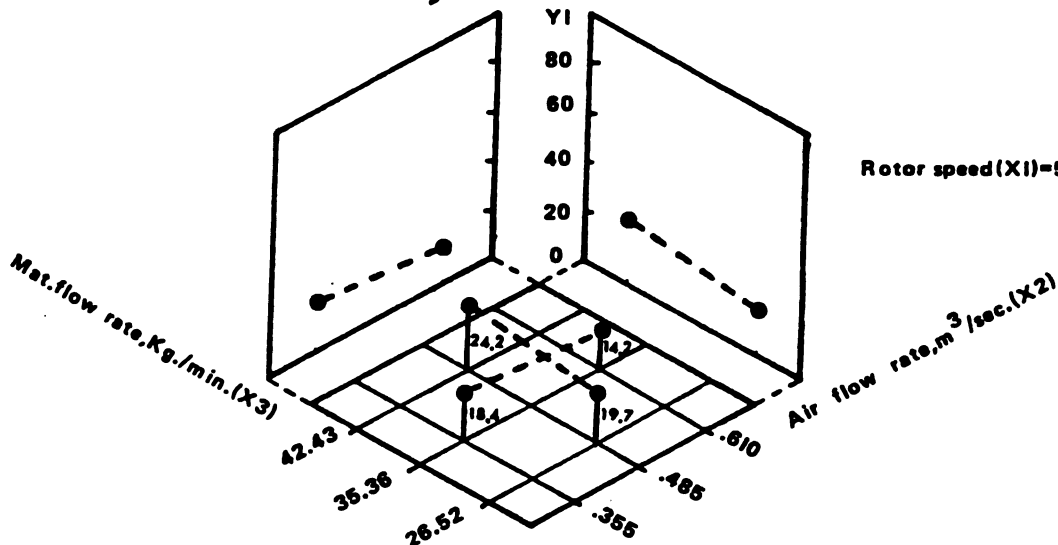


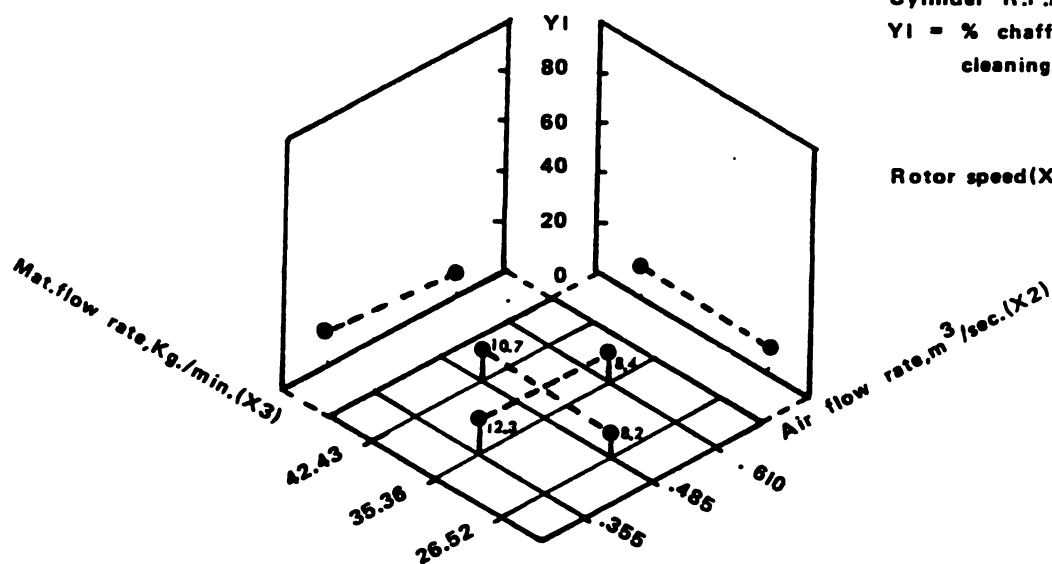
Fig. 15 The effect of air and material flow rates on the percent of chaff at the cleaning zone, cylinder speed: 33.33 R.P.M. , test series 1 .

Block No. : 2

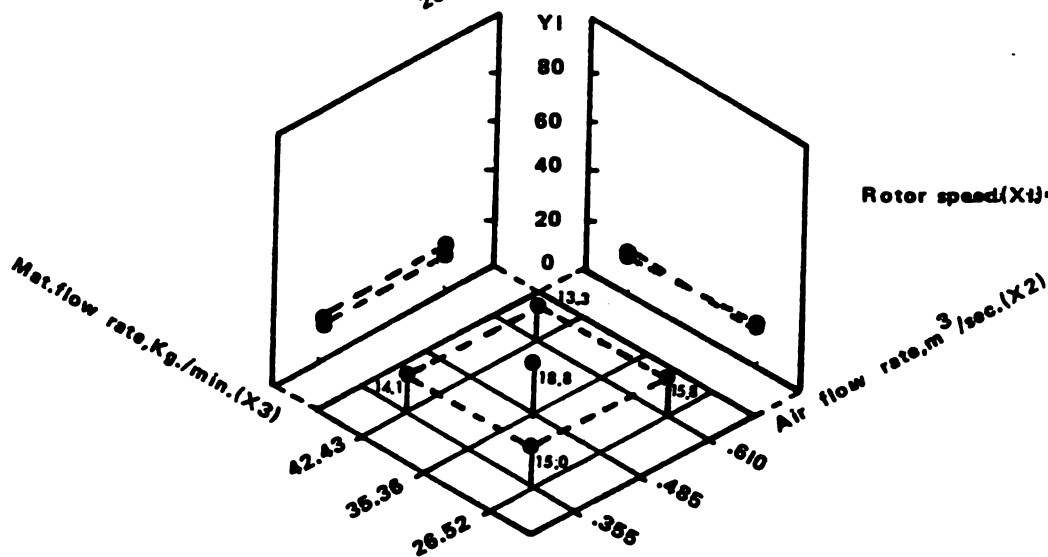
Cylinder R.P.M.: 53.33

YI = % chaff at
cleaning zone

Rotor speed(X1)=300 R.P.M.



Rotor speed(X1)=400 R.P.M.



Rotor speed(X1)=500 R.P.M.

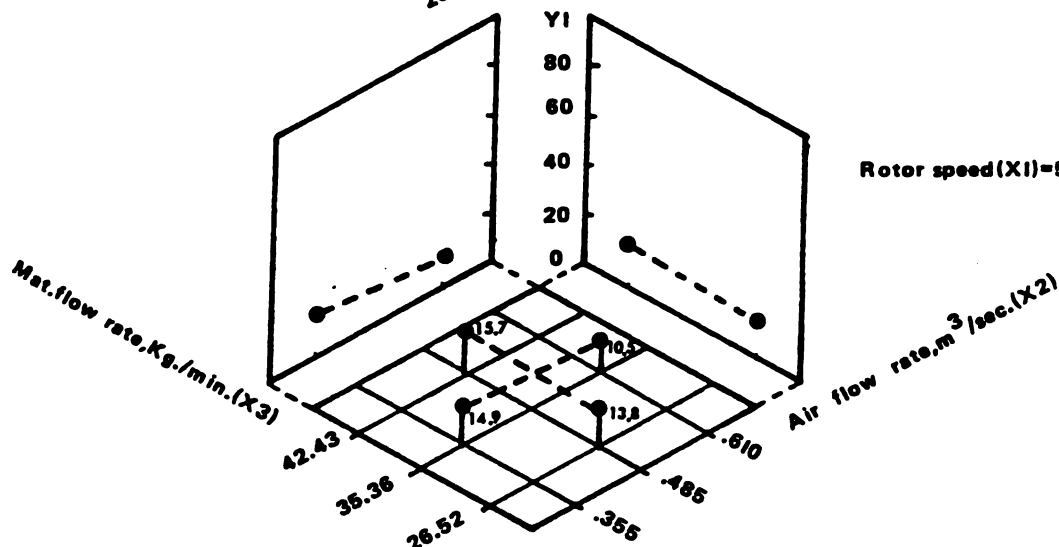


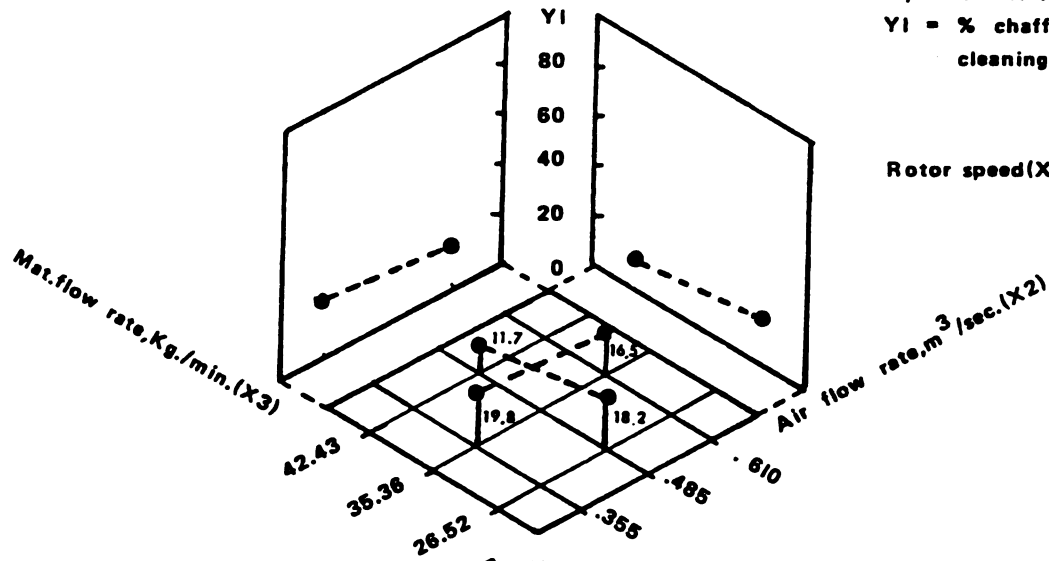
Fig.16 The effect of air and material flow rates on the percent of chaff at the cleaning zone, cylinder speed : 53.33 R.P.M., test series 1 .

Block No. : 3

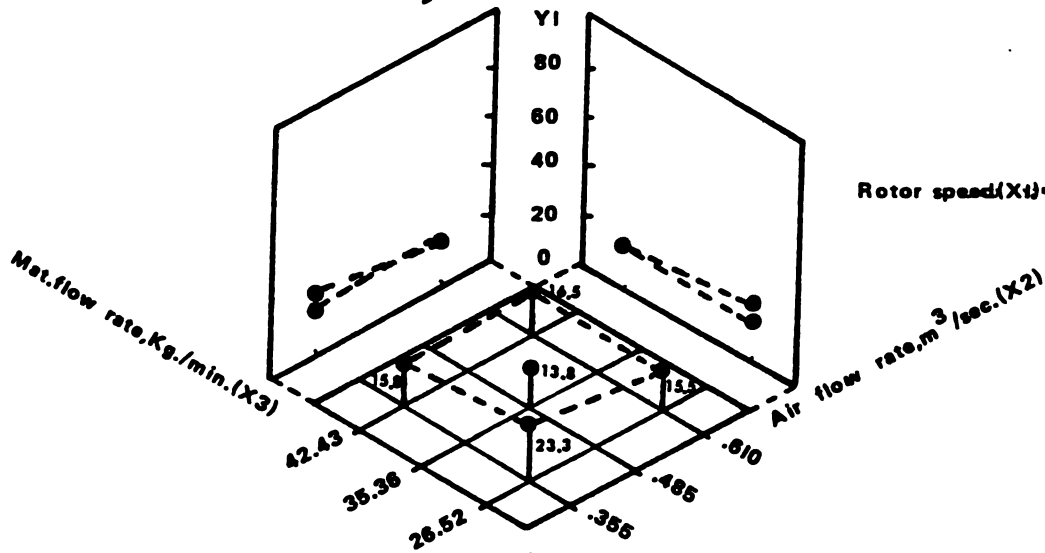
Cylinder R.P.M.: 80.00

YI = % chaff at
cleaning zone

Rotor speed(X1)=300 R.P.M.



Rotor speed(X1)=400 R.P.M.



Rotor speed(X1)=500 R.P.M.

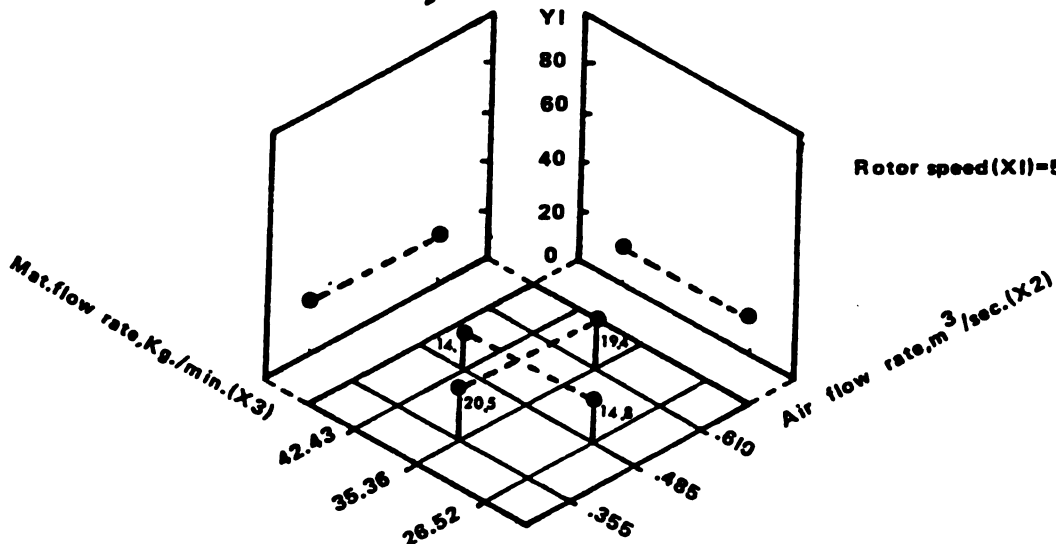


Fig.17 The effect of air and material flow rates on the percent of chaff at the cleaning zone, cylinder speed : 80.0 R.P.M. , test series 1 .

Block No. : 1

Cylinder R.P.M.: 33.33

Y2 = % Grain loss

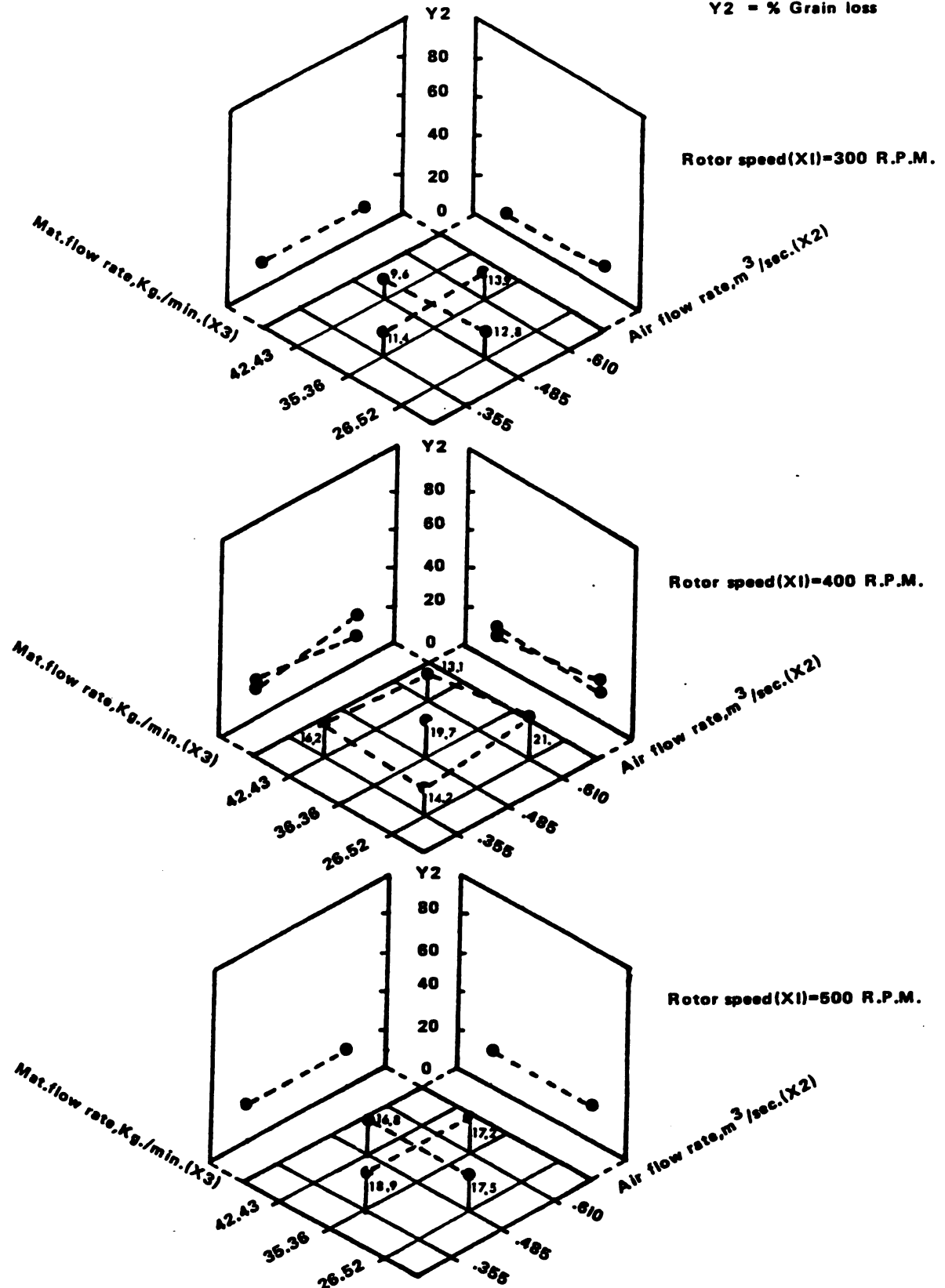


Fig. 18 The effect of air and material flow rates on the percent of grain loss ,
cylinder speed : 33.33 R.P.M. , test series 1 .

Block No. : 2

Cylinder R.P.M.: 53.33

Y2 = % Grain loss

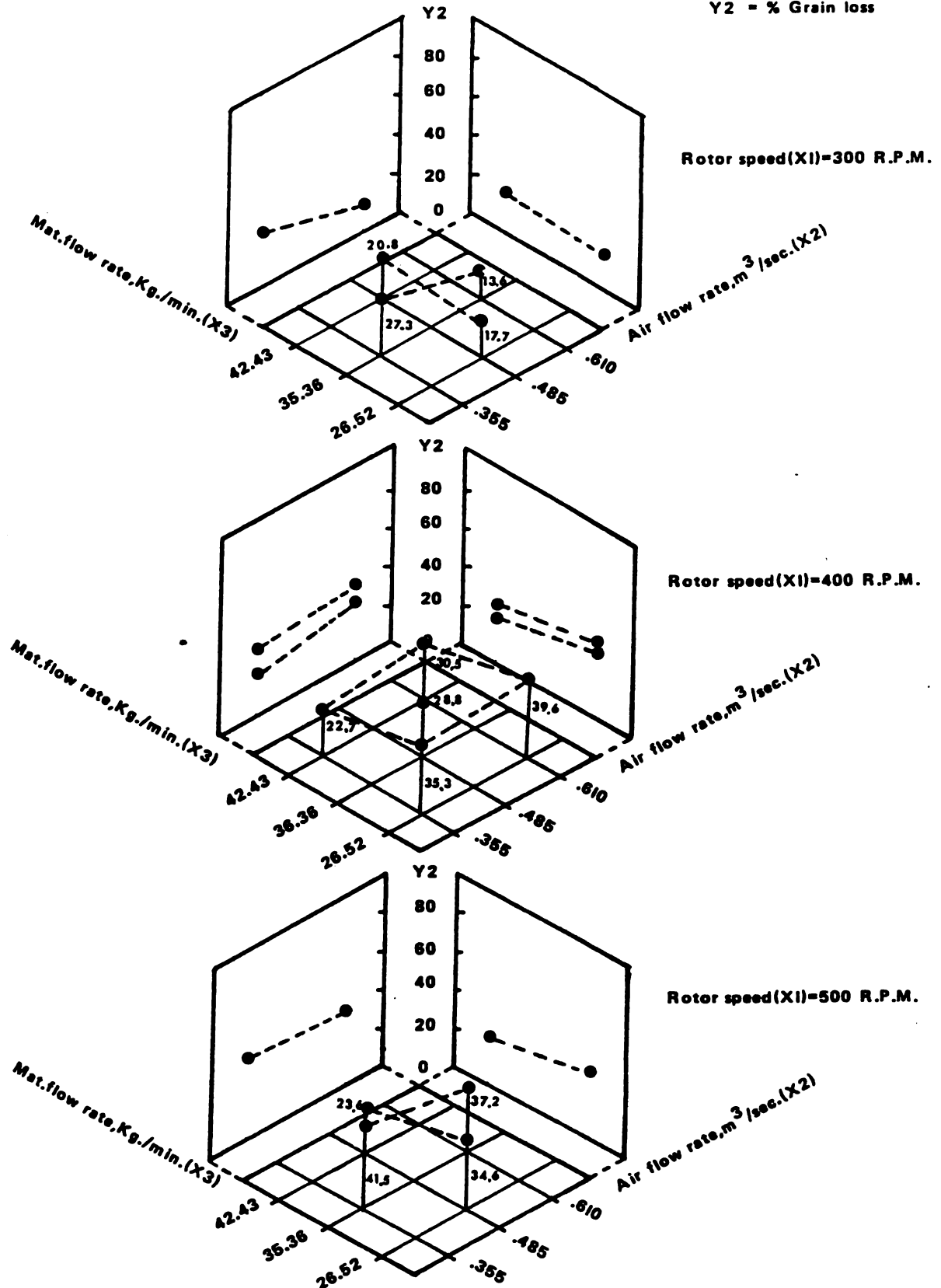


Fig. 19 The effect of air and material flow rates on the percent of grain loss ,
cylinder speed : 53.33 R.P.M. , test series 1.

Block No. : 3
Cylinder R.P.M.: 80.00
Y2 = % Grain loss

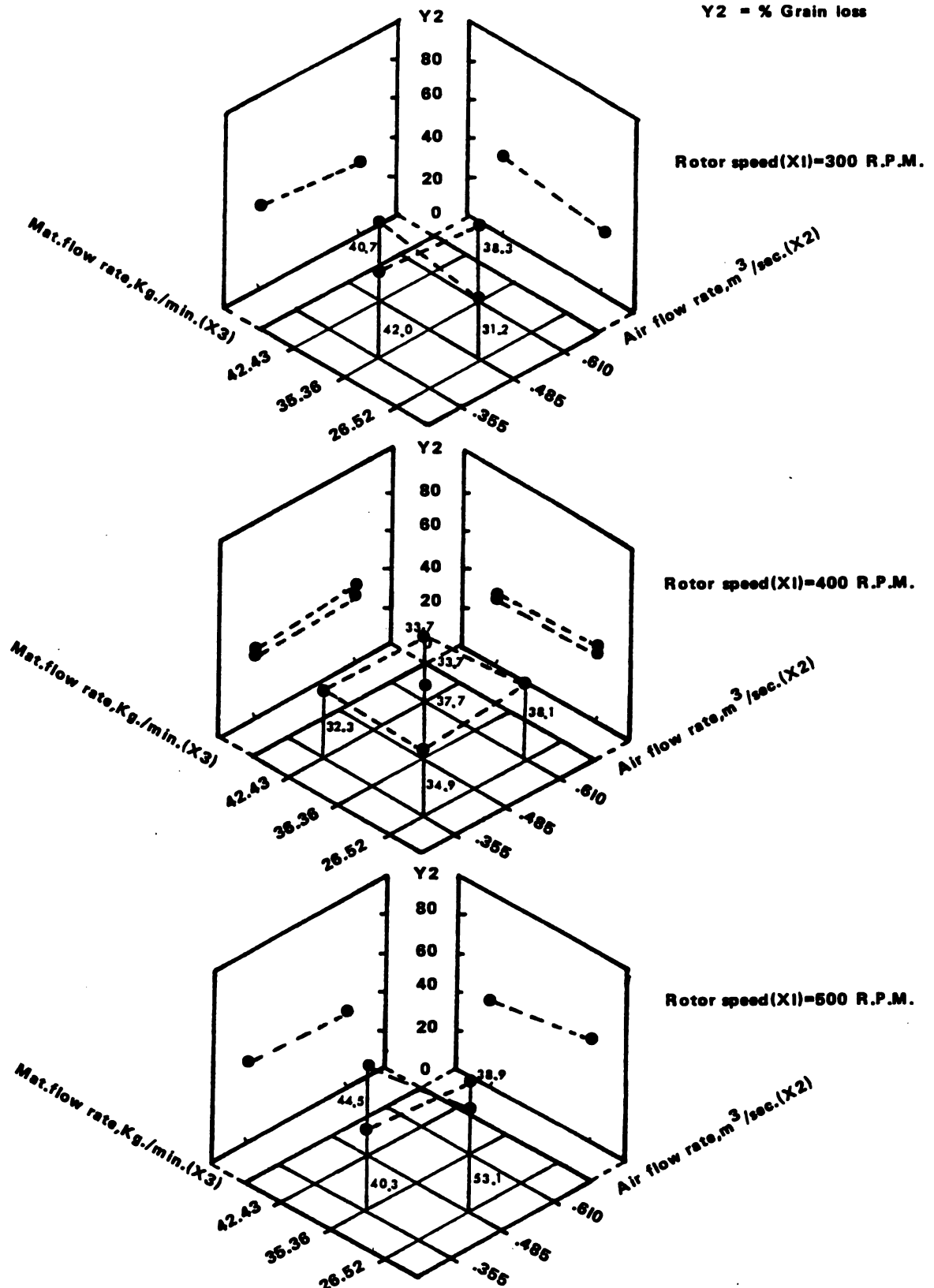


Fig. 20 The effect of air and material flow rates on the percent of grain loss ,
cylinder speed : 80.0 R.P.M. , test series 1 .

vertical walls. Simple and main effects* of each independent variable may be obtained from these projections. Tables 5 and 6 give simple and main effects of Y1 (percent chaff at the cleaning zone) for three blocks of cylinder speed at constant air and material flow rates.

Simple effects of Y1 at constant air and material flow rates are larger than to be attributed to chance or experimental error. The interaction between air and material flow rates with rotor speed, therefore, indicates that these variables are correlated.

In addition, at constant material flow rate, when air flow rate increased, percent of chaff at cleaning zone (Y1) decreased.

Percent grain loss (Y2) was the second dependent variable to be investigated. Figures 18, 19 and 20 show that as the screen speed increased from block 1 to 3, Y2 became larger. Tables 7 and 8 represent simple and main effects of Y2 for three blocks of cylinder rpm.

Tables 7 and 8 show that simple effects of Y2 at constant air and material flow rates are substantial which is an indication of interaction between the air and material flow rates.

*Note: Simple effect is the difference between the response values at high and low levels of independent variables. Main effect is the average of simple effects.

Table 5 Simple and main effects of rotor speed on the percent of chaff in cleaning zone at constant air flow rate.

	Block 1		Block 2		Block 3	
Rotor speed,rpm	Simple effect	Main effect	Simple effect	Main effect	Simple effect	Main effect
300	-3.0	0.75	2.5	2.2	-6.5	-2.85
500	4.5		1.9		0.8	

Table 6 Simple and main effects of rotor speed on the percent of chaff in cleaning zone at constant mat. flow rate.

	Block 1		Block 2		Block 3	
Rotor speed, rpm	Simple effect	Main effect	Simple effect	Main effect	Simple effect	Main effect
300	-11.5	-7.85	3.9	4.15	3.3	2.2
500	-4.2		4.4		1.1	

Table 7 Simple and main effects of rotor speed on the percent grain loss at constant air flow rate.

	Block 1		Block 2		Block 3	
Rotor speed, rpm	Simple effect	Main effect	Simple effect	Main effect	Simple effect	Main effect
300	-3.2	-1.95	3.1	-3.95	9.5	0.45
500	-0.7		-11.0		-8.6	

Table 8 Simple and main effects of rotor speed on the percent grain loss at constant mat. flow rate.

	Block 1		Block 2		Block 3	
Rotor speed, rpm	Simple effect	Main effect	Simple effect	Main effect	Simple effect	Main effect
300	2.5	0.4	-13.7	-9.0	-3.7	-2.55
500	-1.7		-4.3		-1.4	

It was also noticed that percent grain loss was, in most cases, increased with an increase of air flow rate.

Data given in Tables A-1 to A-3 (Appendix D) were subjected to least square analysis. Two different types of models were tested. The general form of the first model, which was fitted for each experiment block (each

cylinder rpm) and included three independent variables, is as follows:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_1^2 + b_5X_2^2 + b_6X_3^2 + b_7X_1X_2 + b_8X_1X_3 + b_9X_2X_3 \quad [4]$$

Where

Y = predicted value of dependent variables,
(Y1 or Y2)

X_1 = rotor speed, rpm.

X_2 = air flow rate, m^3/s .

X_3 = material flow rate, kg/min.

$b_0, b_1, \dots, b_9$ = constants of the regression model.

The statistical estimates of constants and the correlation coefficients (R^2 , which is the ratio of the regression sum of square to the total sum of square) for two different dependent variables and three blocks of the experiment are given in Table 9. High R^2 values of these tables indicate that predicated values would be very close to the observed values. The Analysis of Variance (AOV) Tables for testing the significance of each of the constants are given in Tables A-7 to A-13 in Appendix D. These tables show the significance of each coefficient and the F-tests (which are the ratios of the regression to error mean squares) for the models.

The second model was the lumped model which included all four independent variables. The general form of the second model, which was fitted for each dependent

variable is:

$$\begin{aligned}
 Y = & b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_1^2 + b_6X_2^2 \\
 & + b_7X_3 + b_8X_4^2 + b_9X_1X_2 + b_{10}X_1X_3 + b_{11}X_1X_4 \\
 & + b_{12}X_2X_3 + b_{13}X_2X_4 + b_{14}X_3X_4
 \end{aligned} \tag{5}$$

Where

Y = predicted value of dependent variables
(Y_1 or Y_2)

X_1 = cylinder speed, rpm.

X_2 = rotor speed, rpm.

X_3 = air flow rate, m^3/s .

X_4 = material flow rate, kg/min.

$b_0, b_1, \dots, b_{14}$ = constants of the regression
model.

The statistical estimates of constants and the correlation coefficients (R^2) for lumped models of Y_1 and Y_2 are given in Table 10. The AOV tables for testing the significance of each of the constants are given in Tables A-14 and A-15 in Appendix D.

In order to examine the fitted second-order polynomials, response surfaces were obtained using equations of Table 9. Figures 21 to 26 show the contours of the fitted second-order equation relating response of Y_1 and Y_2 to air and material flow rates at different rotor and cylinder speeds. Examination of response surfaces of

Table 9 Estimates of constants for the regression equations for Y1(% chaff at cleaning zone) and Y2 (% grain loss) for test series 1 .

Block No.	Dep. Variable	b ₀	b ₁	b ₂	b ₃	b ₄	b ₅	b ₆	b ₇	b ₈	b ₉	R ²
1	$\hat{Y}_1$	85.35	-.0541	-17.35	-2.85	-.0001	36.98	.051	.154	.002	-3.139	.9152
	$\hat{Y}_2$	-149.33	.318	172.28	3.447	-.0003	-61.64	-.039	-.058	.0006	-2.444	.9676
2	$\hat{Y}_1$	-149.92	.518	128.24	1.82	-.0006	-66.423	-.008	0.000	-.0001	-2.262	.9215
	$\hat{Y}_2$	-101.65	.7831	-308.61	2.548	-.0008	538.055	.0461	.192	-.004	-9.05	.8886
3	$\hat{Y}_1$	60.802	.180	-210.68	-1.736	-.0003	528.19	.0718	.038	.002	-9.050	.7565
	$\hat{Y}_2$	7.859	-.266	118.204	2.963	.0006	-234.36	-.038	.038	-.006	2.262	.7648

Table 10 Estimates of constants for the regression equations of lumped models for Y1 and Y2 , test series 1 .

Dep. variable	b ₀	b ₁	b ₂	b ₃	b ₄	b ₅	b ₆	b ₇	b ₈	b ₉
$\hat{Y}_1$	-37.882	-1.473	.202	126.527	.864	.0118	-.0002	-166.001	-.017	.0003
$\hat{Y}_2$	-87.853	7.891	-.256	-33.423	1.267	-.063	.0001	-24.152	-.039	.0008

Table 10 Continued :

b ₁₀	b ₁₁	b ₁₂	b ₁₃	b ₁₄	R ²
.168	.004	.026	-.0006	.622	.6101
-3.276	-.011	.173	.002	2.881	.8790

Block No : 1

Cylinder R.P.M. : 33.33

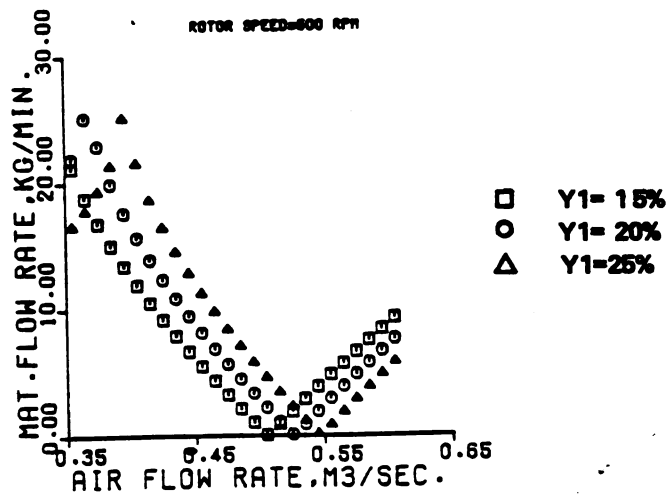
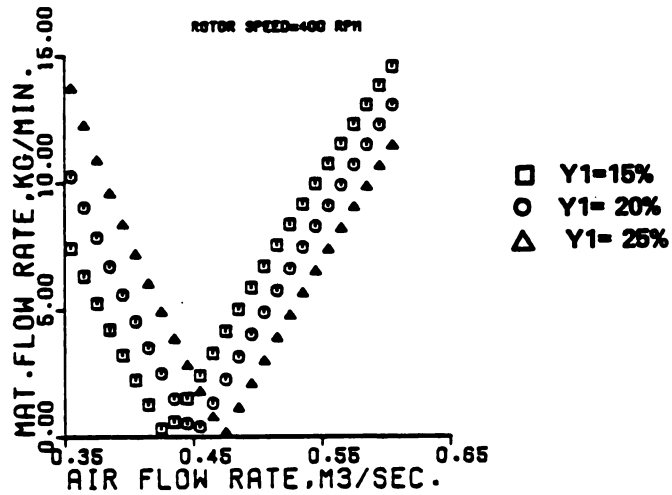
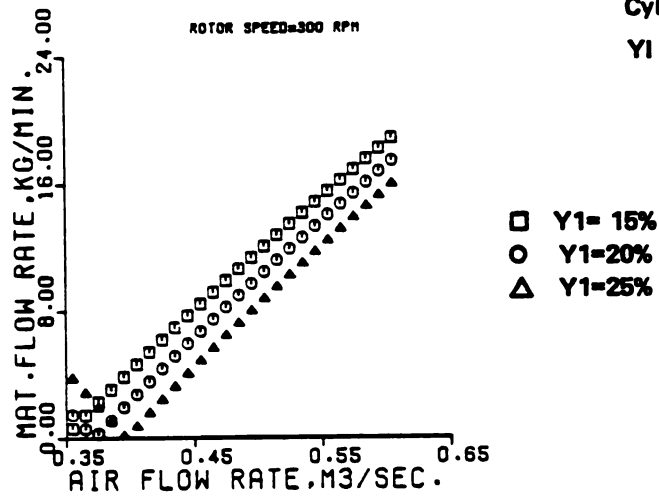
Y1 = % chaff at
cleaning zone

Fig. 21 Contours of the fitted second order equation ($R^2 = 0.91$) relating response of Y1 to the air and material flow rates at : cylinder speed : 33.33 R.P.M. , test series 1 .

Block No : 2

Cylinder R.P.M. : 53.33

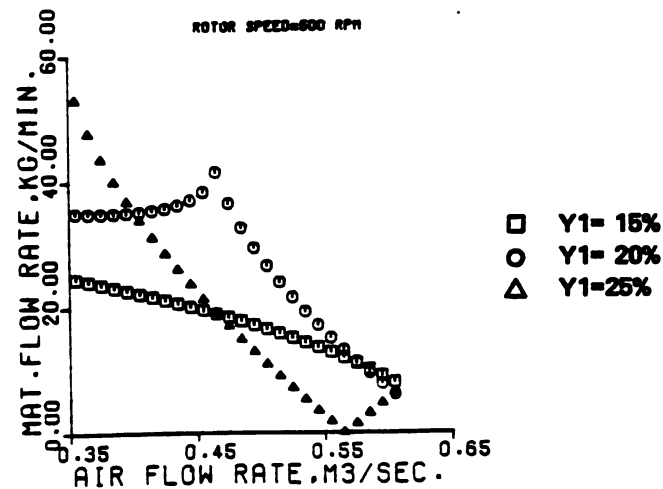
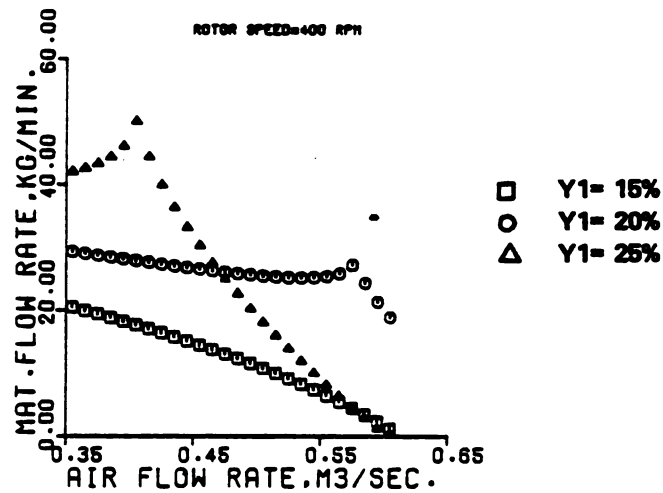
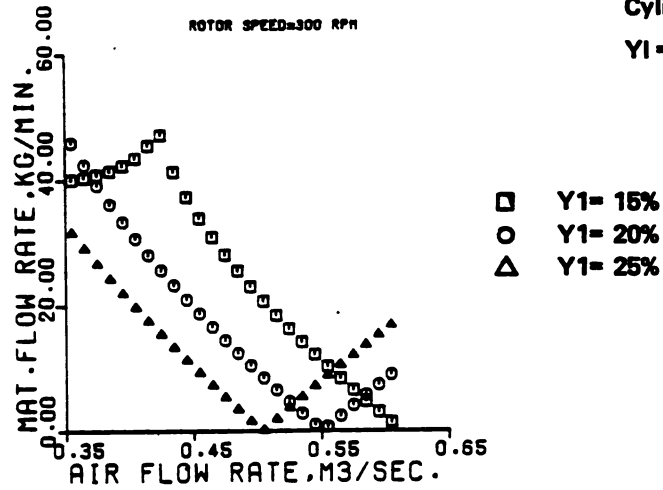
Y1 = % chaff at
cleaning zone

Fig. 22 Contours of the fitted second order equation ($R^2 = 0.92$) relating response of Y1 to the air and material flow rates at : cylinder speed : 53.33 R.P.M. , test series 1.

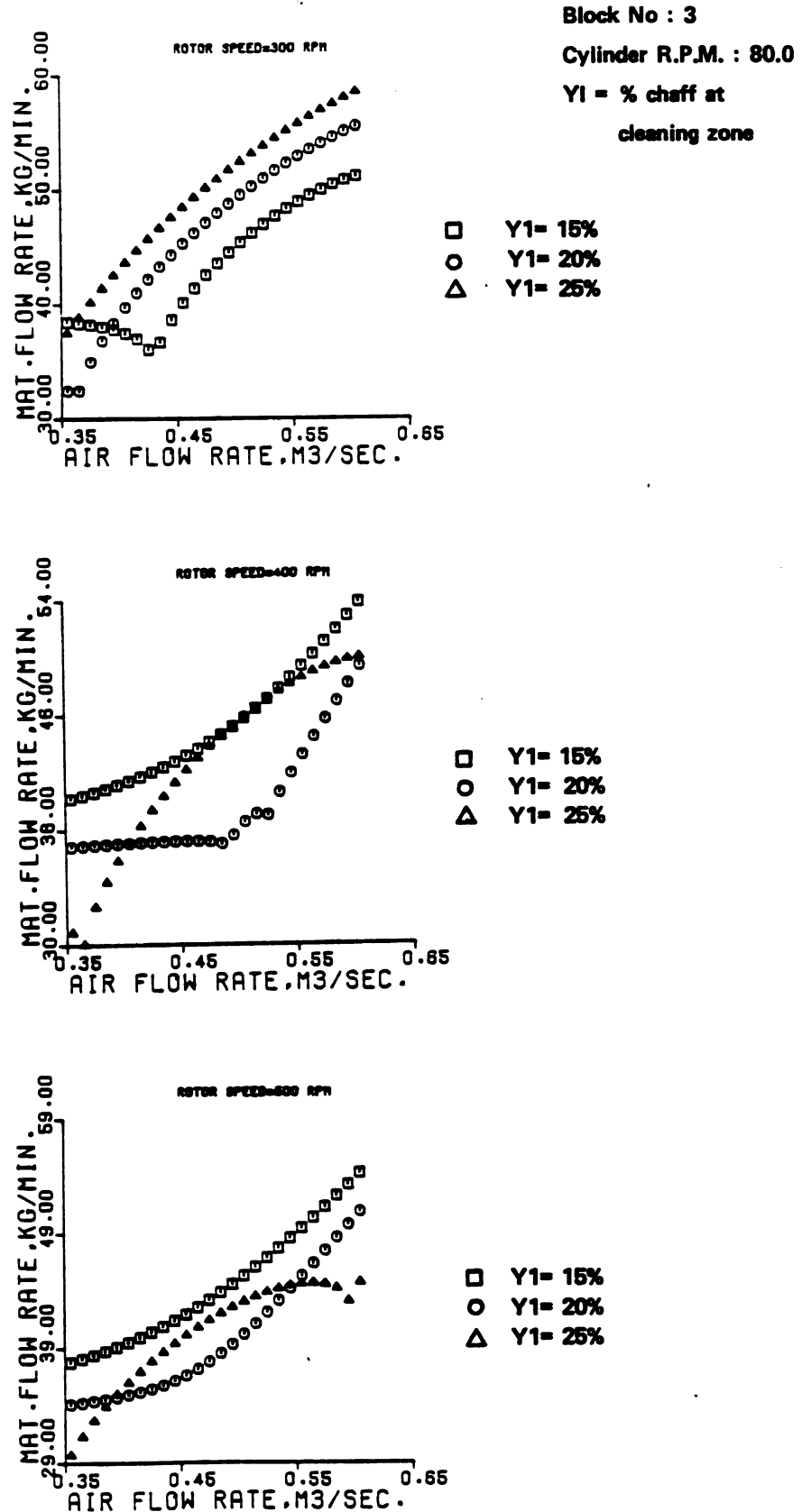


Fig. 23 Contours of the fitted second order equation ($R^2 = 0.76$) relating response of Y1 to the air and material flow rates at : cylinder speed : 80.0 R.P.M., test series 1 .

Block No : 1

Cylinder R.P.M. : 33.33

Y2 = % Grain loss

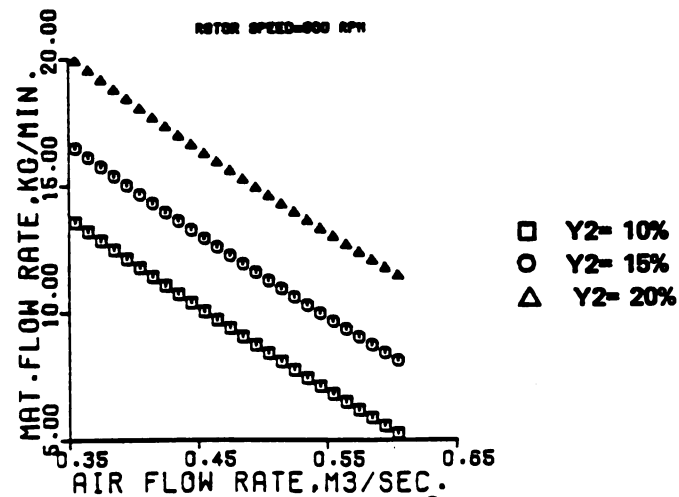
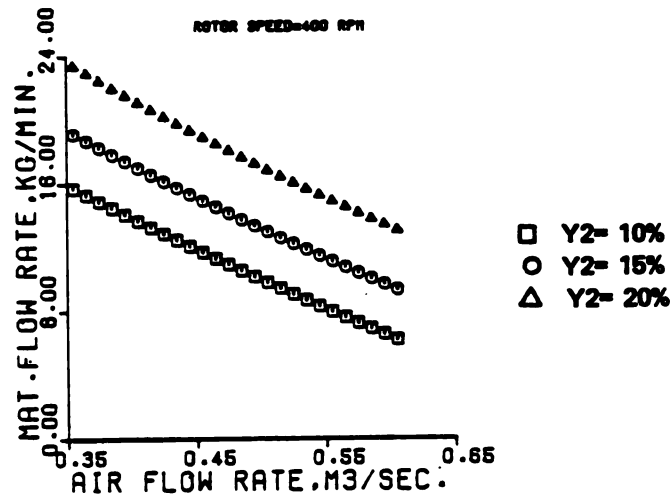
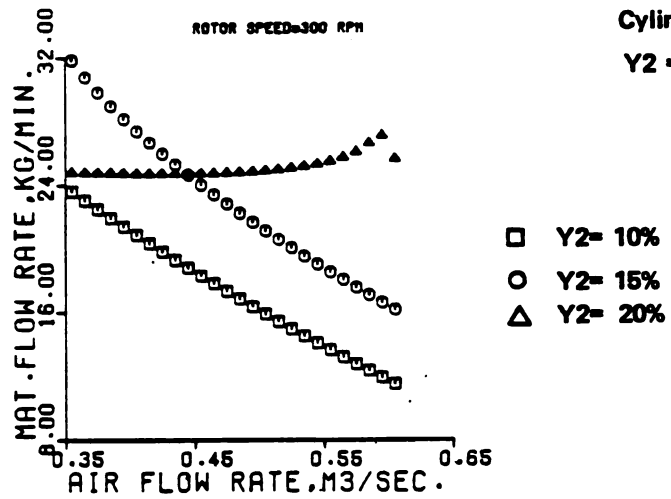


Fig. 24 Contours of the fitted second order equation ($R^2 = 0.97$) relating response of Y2 to the air and material flow rates at : cylinder speed: 33.33 , test series 1 .

Block No : 2

Cylinder R.P.M. : 53.33

Y2 = % Grain loss

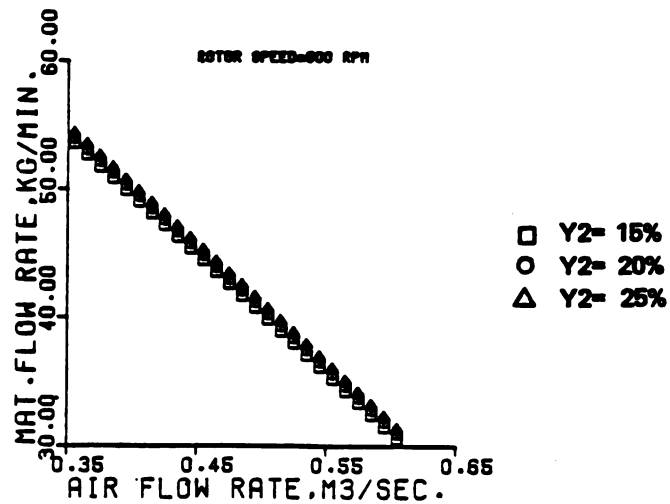
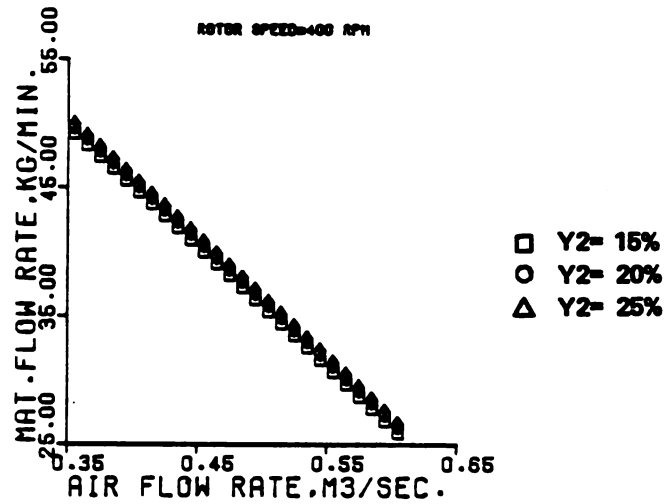
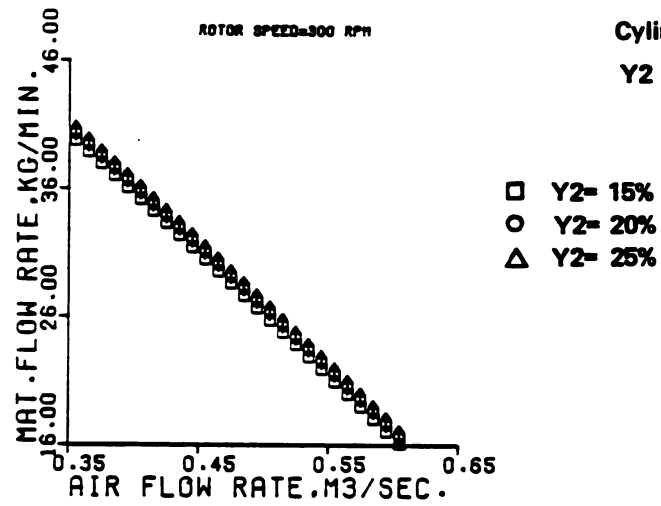


Fig. 25 Contours of the fitted second order equation ($R^2 = 0.89$) relating response of Y2 to the air and material flow rates at ; cylinder speed : 53.33 R.P.M. , test series 1 .

Block No : 3

Cylinder R.P.M. : 80.0

Y2 = % Grain loss

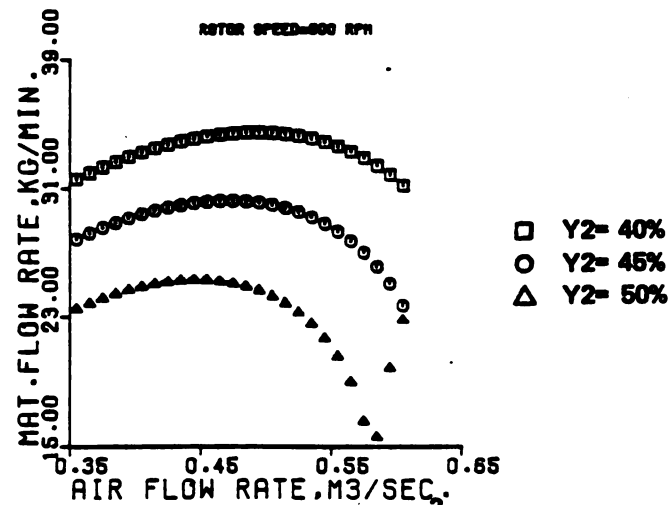
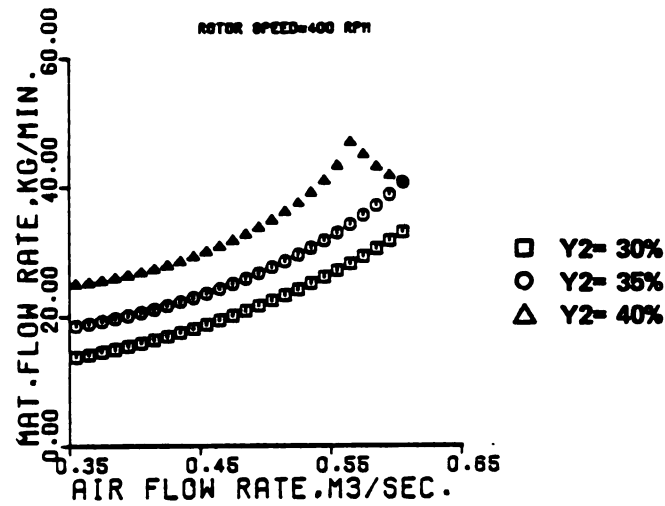
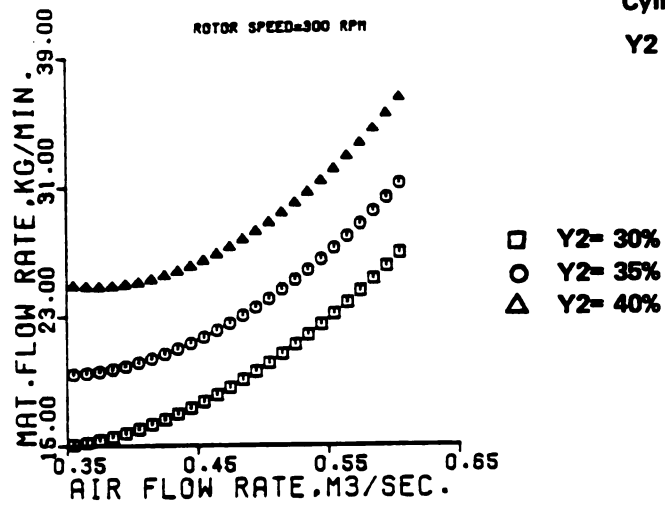


Fig. 26 Contours of the fitted second order equation ($R^2 = 0.76$) relating response of Y2 to the air and material flow rates at ; cylinder speed : 80.0 R.P.M. , test series 1 .

Y1 and Y2 indicates the following points:

1. In order to keep Y1 constant, an increase of material flow rate basically needs higher air flow rate.
2. To keep Y2 constant, when material flow rate increases, air flow rate has to decrease in low cylinder speed and increase in high cylinder speed. This is obvious from Fig. 24 and 25 in which the slope is negative and Fig. 26 with positive slope.

4.2 Two Stage Cleaning Concept

4.2.1 Experimental Apparatus and Material. The 1/2 scale model of threshing-separation unit described earlier, was modified for the second series of tests. The schematic diagram of the two-stage cleaning concept is given in Fig. 27.

It was conceived that the material which is moved axially by the helical blades of the rotating cylinder, should be allowed to pass through the perforated section. The material could then be subjected to an air blast in order to blow chaff forward and to let the grain fall into the collection area (Fig. 27).

Figures 28 and 29 show the photographs of the experimental apparatus for a two stage cleaning concept. Unlike the first series of tests (which were performed in one-stage cleaning concept), the circular duct and the aspirator connected to the rotating cylinder were removed.

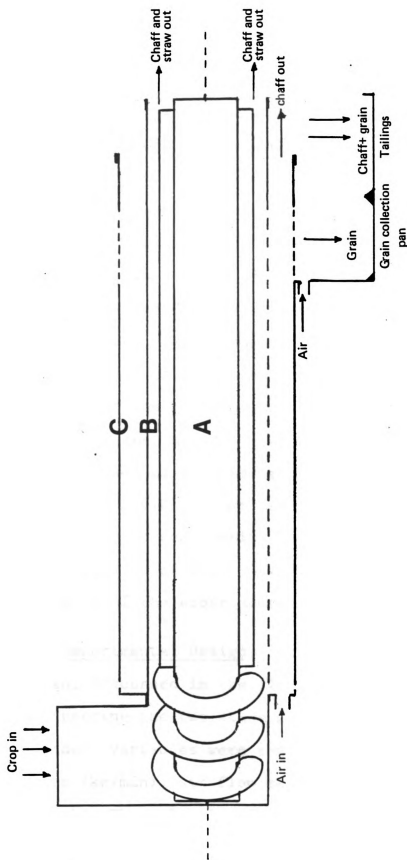


Fig. 27 Schematic diagram of two stage cleaning concept :
 A. Rotor , B. Fixed cylinder , C. Rotating cylinder.

Instead, the exit end was left open. An air duct (B, Fig. 28) with a semi-circular outlet was mounted under the rotating cylinder (Figures 28 and 30). The air duct was equipped with four guiding vanes and its inlet was connected to the cross flow fan used in the first series of tests. The outlet area of the semi-circular duct was 0.1178 m^2 which was divided into five sections.

The cleaning box (A, Fig. 28) used in the first series of tests was modified by closing the top and bottom sides. The outlet of the air duct was mounted on the lower half of the rear side of the cleaning box (Fig 29). The front lower half of the cleaning box was left open to let the air and chaff pass through. The bottom part of the cleaning box was used as a collecting tray. A second tray of $0.85 \text{ m} \times 0.34 \text{ m} \times 0.075 \text{ m}$ was used to collect the blown chaff and the grain or chaff which did not pass through the perforated section of the cylinder. Fig. 31 shows the schematic diagram of the experimental set up.

4.2.2 Experimental Design. The second-order experimental design, discussed in the first series of tests, was used for testing the two-stage cleaning design.

Independent variables were rotor speed (rpm), material flow rate (kg/min), air flow rate (m^3/s) and cylinder speed (rpm). Three levels of each independent variable were used. Dependent variables were related to the

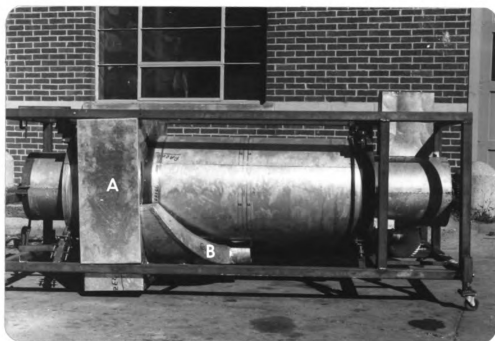


Fig. 28 Front view of experimental apparatus:
A. Cleaning box; B. Semi-circular duct.

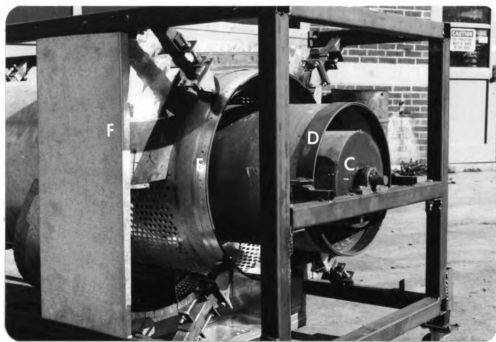


Fig. 29 Side view of experimental apparatus:
C. Rotor; D. Fixed cylinder ; E. rot-
ating cylinder ; F. Cleaning box.

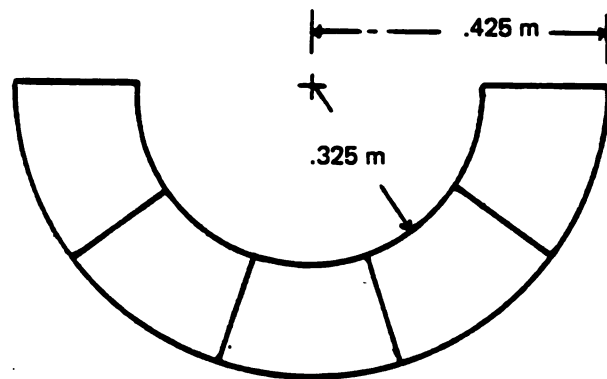
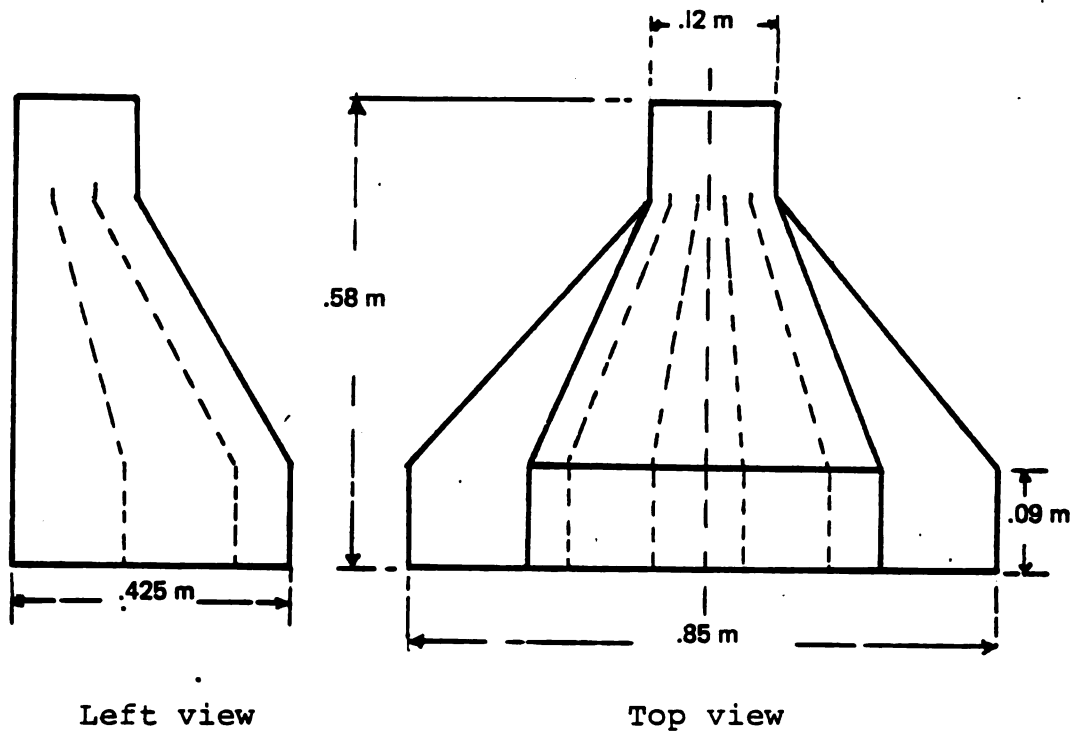


Fig. 30 Semi-circular duct

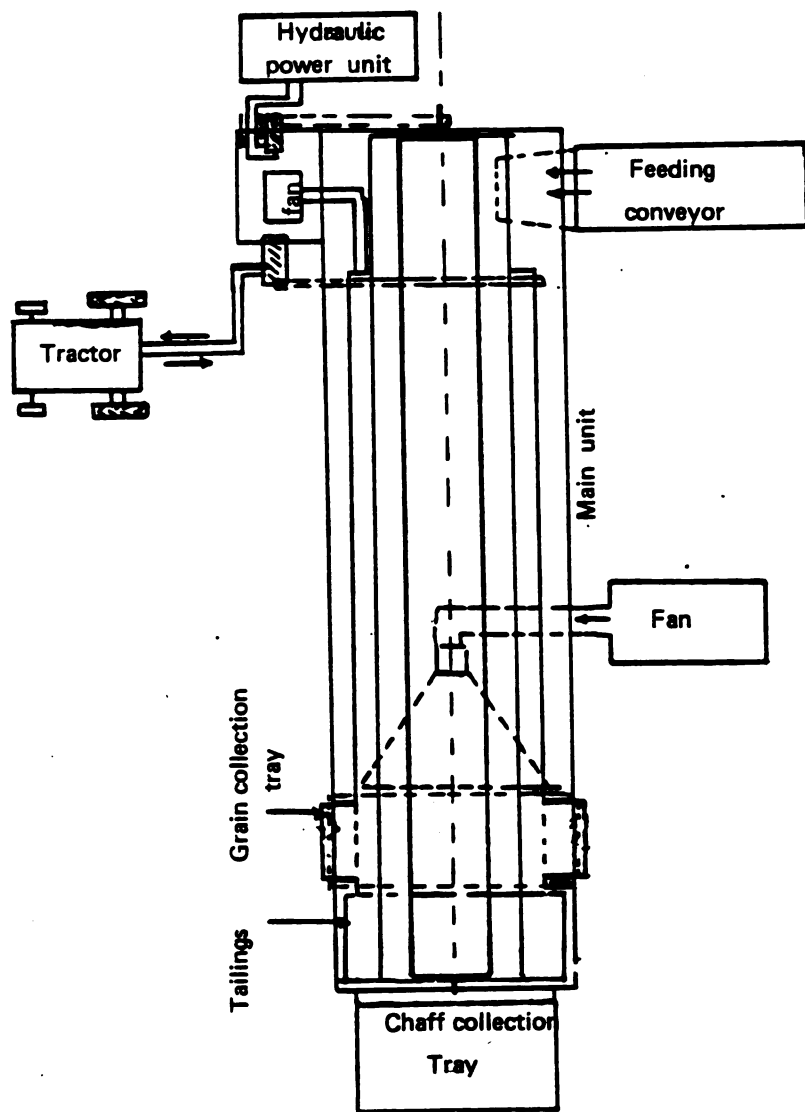


Fig. 31 Schematic diagram of the experimental set up, two stage cleaning concept

performance of the design. These were percent chaff at the cleaning zone and percent grain in the second tray (tailings).

Levels of material flow rate and rotor speed were 26.52 kg/min, 35.36 kg/min and 42.43 kg/min and 300, 400 500 rpm respectively. Air flow rate and cylinder speed had different levels that will be discussed in the next section.

Graphical representation of the experimental design shown in Fig. 14 and Tables 1, 2 and 3 were the statistical arrangements of the three blocks.

The total number of treatment combinations in each block and replications of the central points were the same as before (1, 2 and 3).

4.2.3 Method of Procedure. It was anticipated that an air velocity of more than 3 m/s and less than 9 m/s along the outlet of the semi-circular duct would blow the chaff forward and let the grain fall into the first collection pan. Knowing that the duct outlet area was 0.1178 m^2 for air velocities of 3.00, 3.50 and 4.00 m/s, then 0.3534, 0.4123 and $0.4712 \text{ m}^3/\text{s}$ air flow rates were needed. The theoretical air flow rates were examined during the preliminary tests. The results showed a minimum of 0.80 m/s with the maximum of 5.50 m/s air velocity across the outlet. This was not acceptable because 0.80 m/s is much

below the terminal velocity of chaff. It was therefore decided to increase the air flow rate and to maintain the maximum air velocity at the outlet below 9 m/s (which was the terminal velocity of grain).

Three air flow rates of 0.50, 0.65 and 0.80 m³/s were used and 60 air flow measurements were made for each air flow rate. Air velocity distributions with their mean and standard deviations are given in Fig. 32, 33 and 34.

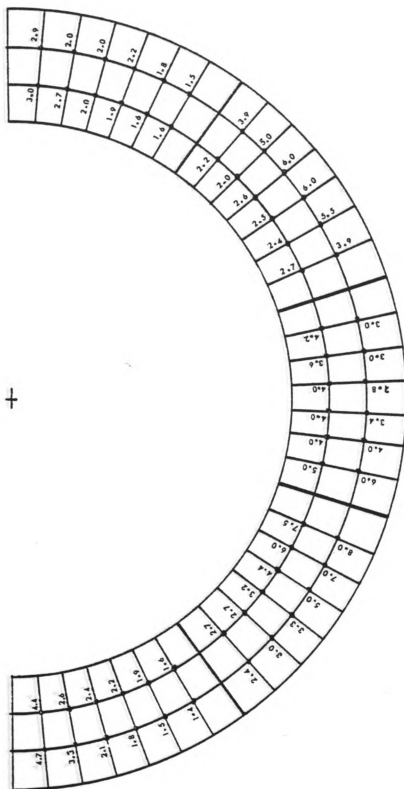
A total of 45 treatment combinations in three blocks of 15 were run during the second series of tests. Quantitative levels of different independent variables are given in Table 11. Cylinder speed which was the blocking variable was 28.66, 35.66 and 43.0 rpm for blocks one, two and three, respectively.

Feeding procedure was the same as for the first series of tests. Grain and chaff moisture contents were 13.5 % and 12.1% (D.B.), respectively.

For each test, the material coming through the perforated section and the exit end of the rotating cylinder were collected in two separate trays. Material from the exit end of the fixed cylinder was also collected and tagged. A total of 135 bags, three from each experiment, were obtained. The material in each bag was first weighed, then run through the clipper mill and then the grain was weighed alone. The difference between the two weights gave the amount of chaff in the sample.

Table 11 Quantitative levels of independent variables

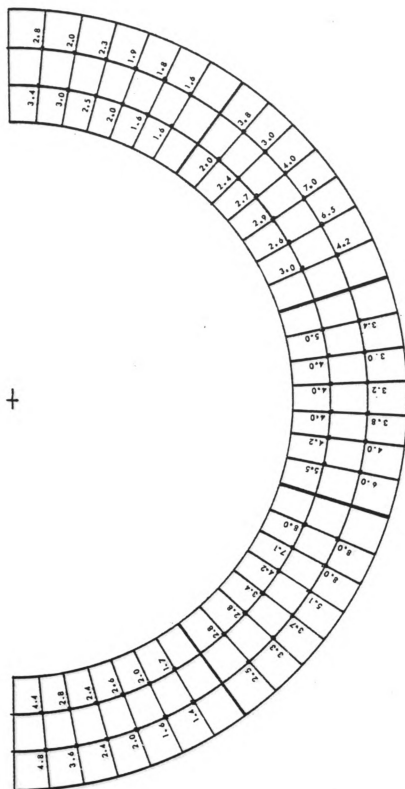
Run No.	Block No.	Statistical combination X1 X2 X3			Rotor speed, rpm.	Air flow rate, m ³ /s	Mat. flow rate, kg/min	Grain, kg.	Chaff, kg.
1	1	0	0	0	400	0.650	35.4	1.768	0.751
2	1	0	0	0	400	0.650	35.4	1.768	0.751
3	1	0	0	0	400	0.650	35.4	1.768	0.751
4	1	+1	+1	0	500	0.800	35.4	1.768	0.751
5	1	+1	-1	0	500	0.500	35.4	1.768	0.751
6	1	-1	+1	0	300	0.800	35.4	1.768	0.751
7	1	-1	-1	0	300	0.500	35.4	1.768	0.751
8	1	+1	0	+1	500	0.650	42.4	2.123	0.902
9	1	+1	0	-1	500	0.650	26.5	1.326	0.563
10	1	-1	0	+1	300	0.650	42.4	2.123	0.902
11	1	-1	0	-1	300	0.650	26.5	1.326	0.563
12	1	0	+1	+1	400	0.800	42.4	2.123	0.902
13	1	0	+1	-1	400	0.800	26.5	1.326	0.563
14	1	0	-1	+1	400	0.500	42.4	2.123	0.902
15	1	0	-1	-1	400	0.500	26.5	1.326	0.563
16	2	0	0	0	400	0.650	35.4	1.768	0.751
17	2	0	0	0	400	0.650	35.4	1.768	0.751
18	2	0	0	0	400	0.650	35.4	1.768	0.751
19	2	+1	+1	0	500	0.800	35.4	1.768	0.751
20	2	+1	-1	0	500	0.500	35.4	1.768	0.751
21	2	-1	+1	0	300	0.800	35.4	1.768	0.751
22	2	-1	-1	0	300	0.500	35.4	1.768	0.751
23	2	+1	0	+1	500	0.650	42.4	2.123	0.902
24	2	+1	0	-1	500	0.650	26.5	1.326	0.563
25	2	-1	0	+1	300	0.650	42.4	2.123	0.902
26	2	-1	0	-1	300	0.650	26.5	1.326	0.563
27	2	0	+1	+1	400	0.800	42.4	2.123	0.902
28	2	0	+1	-1	400	0.800	26.5	1.326	0.563
29	2	0	-1	+1	400	0.500	42.4	2.123	0.902
30	2	0	-1	-1	400	0.500	26.5	1.326	0.563
31	3	0	0	0	400	0.650	35.4	1.768	0.751
32	3	0	0	0	400	0.650	35.4	1.768	0.751
33	3	0	0	0	400	0.650	35.4	1.768	0.751
34	3	+1	+1	0	500	0.800	35.4	1.768	0.751
35	3	+1	-1	0	500	0.500	35.4	1.768	0.751
36	3	-1	+1	0	300	0.800	35.4	1.768	0.751
37	3	-1	-1	0	300	0.500	35.4	1.768	0.751
38	3	+1	0	+1	500	0.650	42.4	2.123	0.902
39	3	+1	0	-1	500	0.650	26.5	1.326	0.563
40	3	-1	0	+1	300	0.650	42.4	2.123	0.902
41	3	-1	0	-1	300	0.650	26.5	1.326	0.563
42	3	0	+1	+1	400	0.800	42.4	2.123	0.902
43	3	0	+1	-1	400	0.800	26.5	1.326	0.563
44	3	0	-1	+1	400	0.500	42.4	2.123	0.902
45	3	0	-1	-1	400	0.500	26.5	1.326	0.563



Mean = 3.37 m/sec.

Standard deviation = 1.59 m/sec.

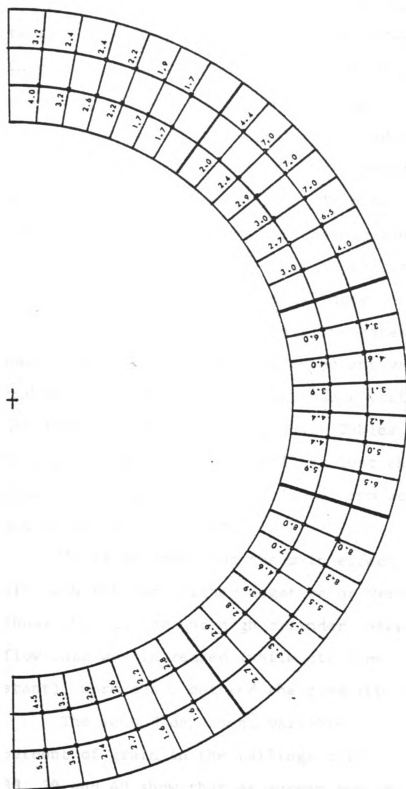
Fig. 32 Air velocity distribution at the outlet of the semi-circular air duct (B, Fig. 28) at 0.50 m³/s air flow rate.



Mean = 3.52 m/sec.

Standard deviation = 1.68 m/sec.

Fig. 33 Air velocity distribution at the outlet of the semi-circular air duct (B, Fig. 28) at 0.65 m³/s air flow rate.



Mean = 3.81 m/sec.

Standard deviation = 1.76 m/sec.

Fig. 34 Air velocity distribution at the outlet of the semi-circular air duct (B, Fig. 28) at $0.80 \text{ m}^3/\text{s}$ air flow rate.

4.2.4 Results and Discussion. Tables A-4, A-5 and A-6 give the experimental data of the second series of tests. Fig. 35 to 40 represent the effect of different independent variables on the percent of chaff at cleaning zone and percent of grain in tailings.

A comparison of Fig. 35 to 37 indicates that the higher the cylinder speed, the less would be the amount of chaff at the cleaning zone. In other words, decreasing the residence time of the material in the rotating cylinder will lower the amount of chaff that passes through the perforations of the rotating cylinder.

The projection of plots illustrates the effect of each independent variable on dependent variables. Simple and main effects of each independent variable may be obtained from these projections. Tables 12 and 13 give simple and main effects of Y1 (percent chaff at cleaning zone) for three blocks of cylinder rpm at constant air and material flow rates.

It is noticed that the main effect of Y1 at constant air flow rate was either negative or very small. This shows that at low and high cylinder speeds, when material flow rate was increased (while air flow rate was kept constant), more chaff entered the cleaning area.

The second dependent variable, Y2, in this case was percent of grain in the tailings collection tray. Fig. 38, 39 and 40 show that as screen rpm increased from block

Block No. : 1
 Cylinder R.P.M.: 28.66
 Y1 = % chaff at
 cleaning zone

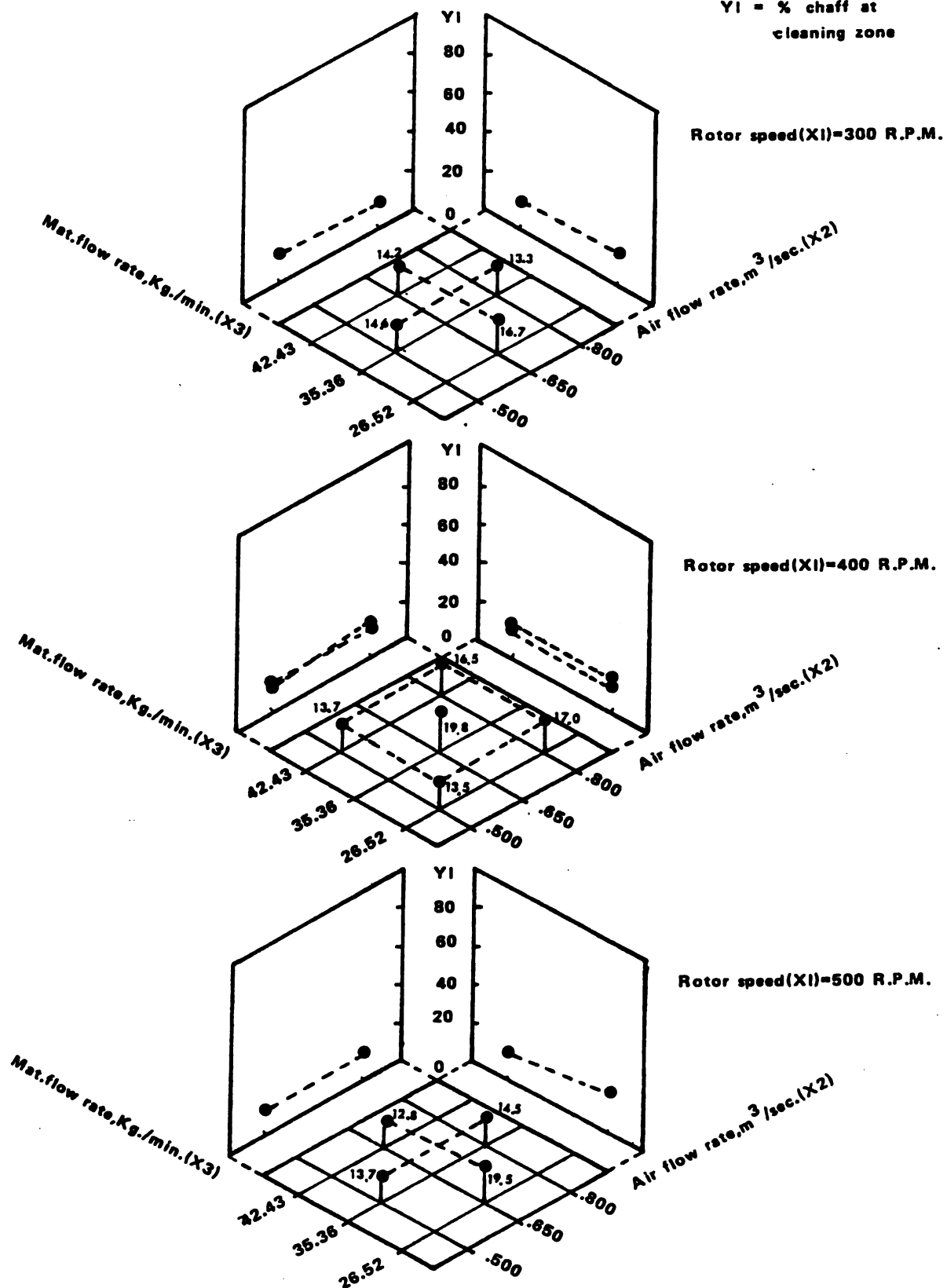


Fig. 35 The effect of air and material flow rates on the percent of chaff at the cleaning zone, cylinder speed : 28.66 R.P.M. , test series 2 .

Block No. : 2
 Cylinder R.P.M.: 35.83
 YI = % chaff at
 cleaning zone

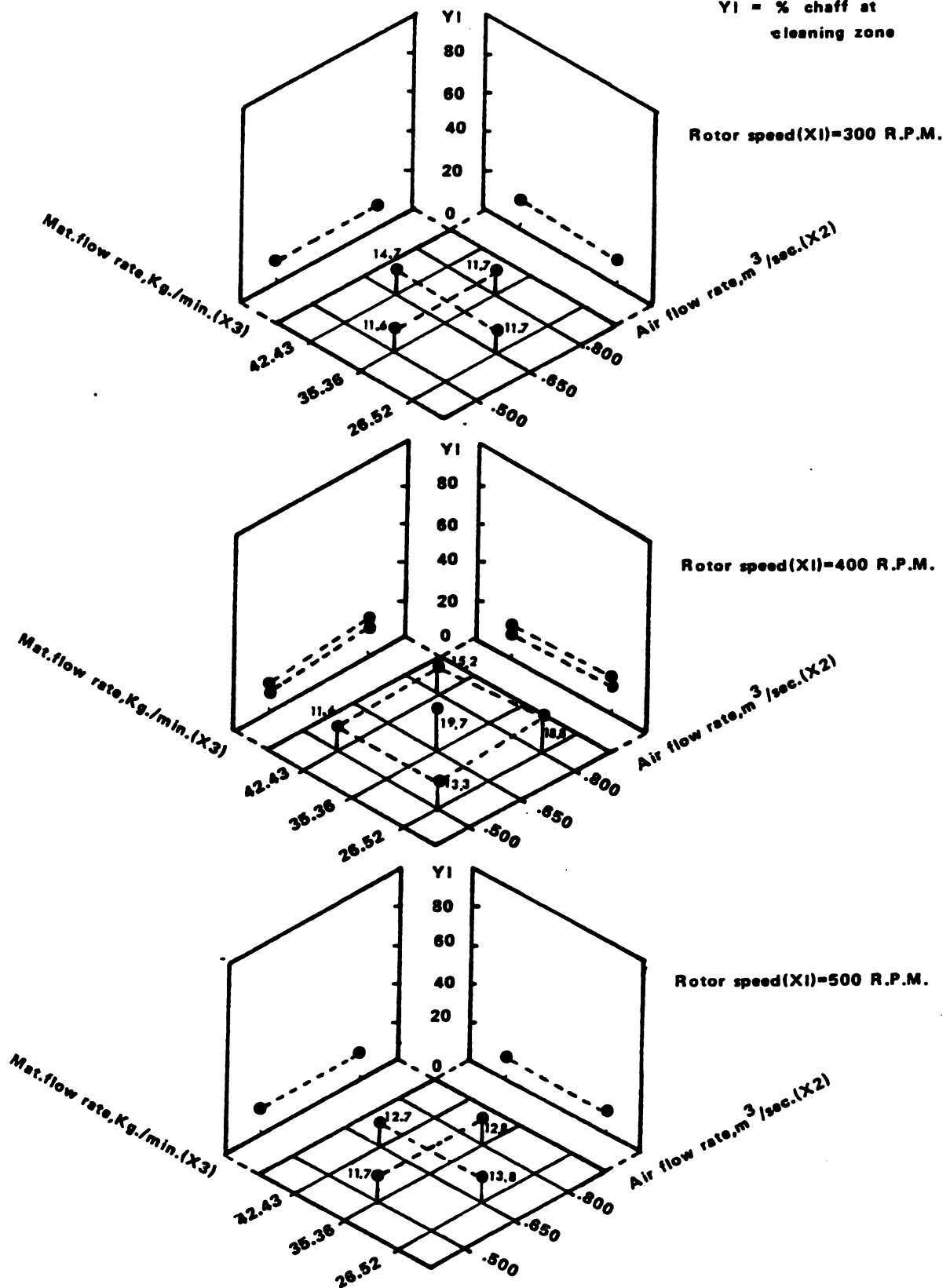


Fig. 36 The effect of air and material flow rates on the percent of chaff at the cleaning zone, cylinder speed : 35.83 R.P.M. , test series 2.

Block No. : 3

Cylinder R.P.M.: 43.00

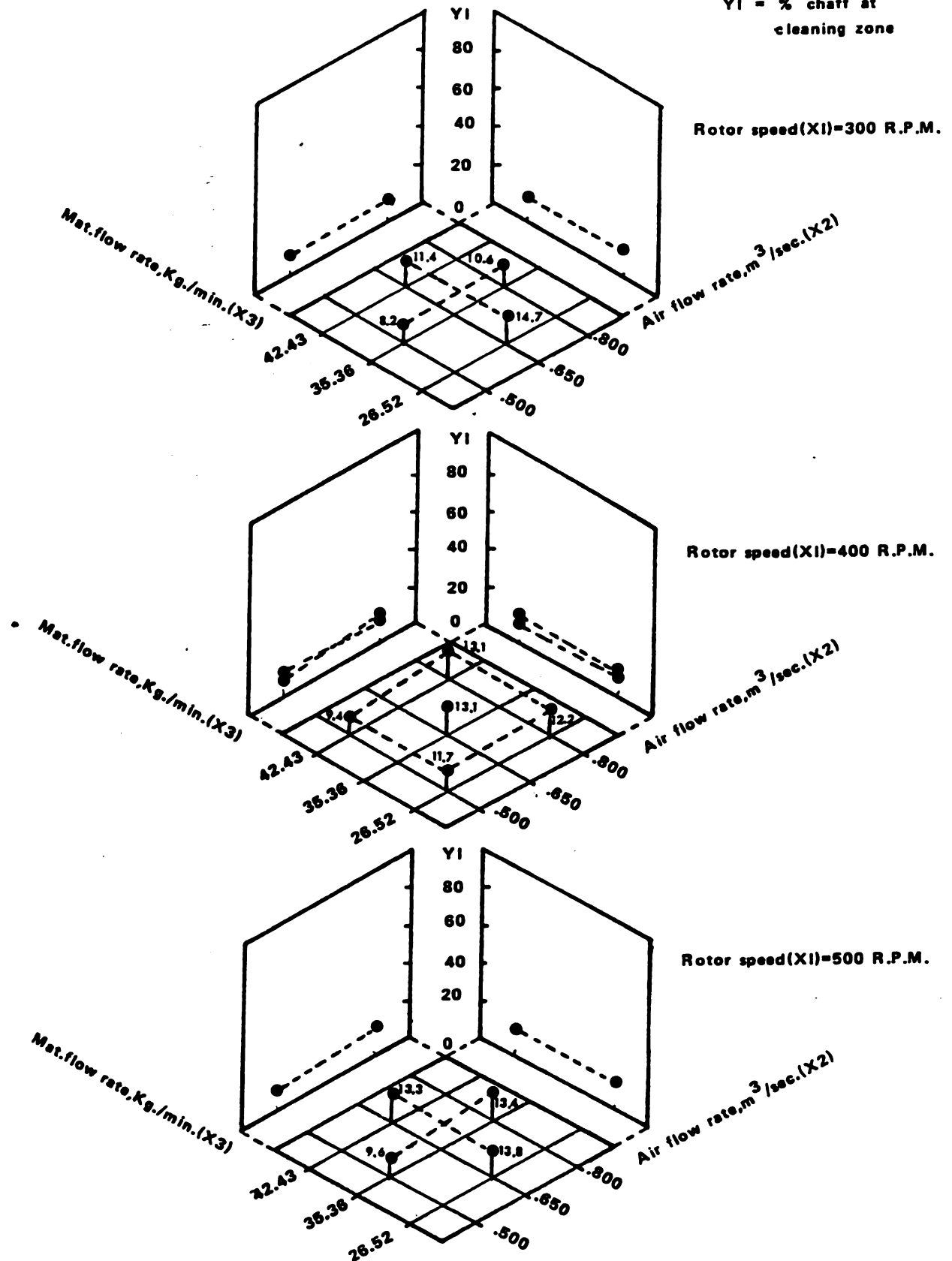
YI = % chaff at
cleaning zone

Fig. 37 The effect of air and material flow rates on the percent of chaff at the cleaning zone, cylinder speed : 43.0 R.P.M. , test series 2.

Block No. : 1

Cylinder R.P.M.: 28.66

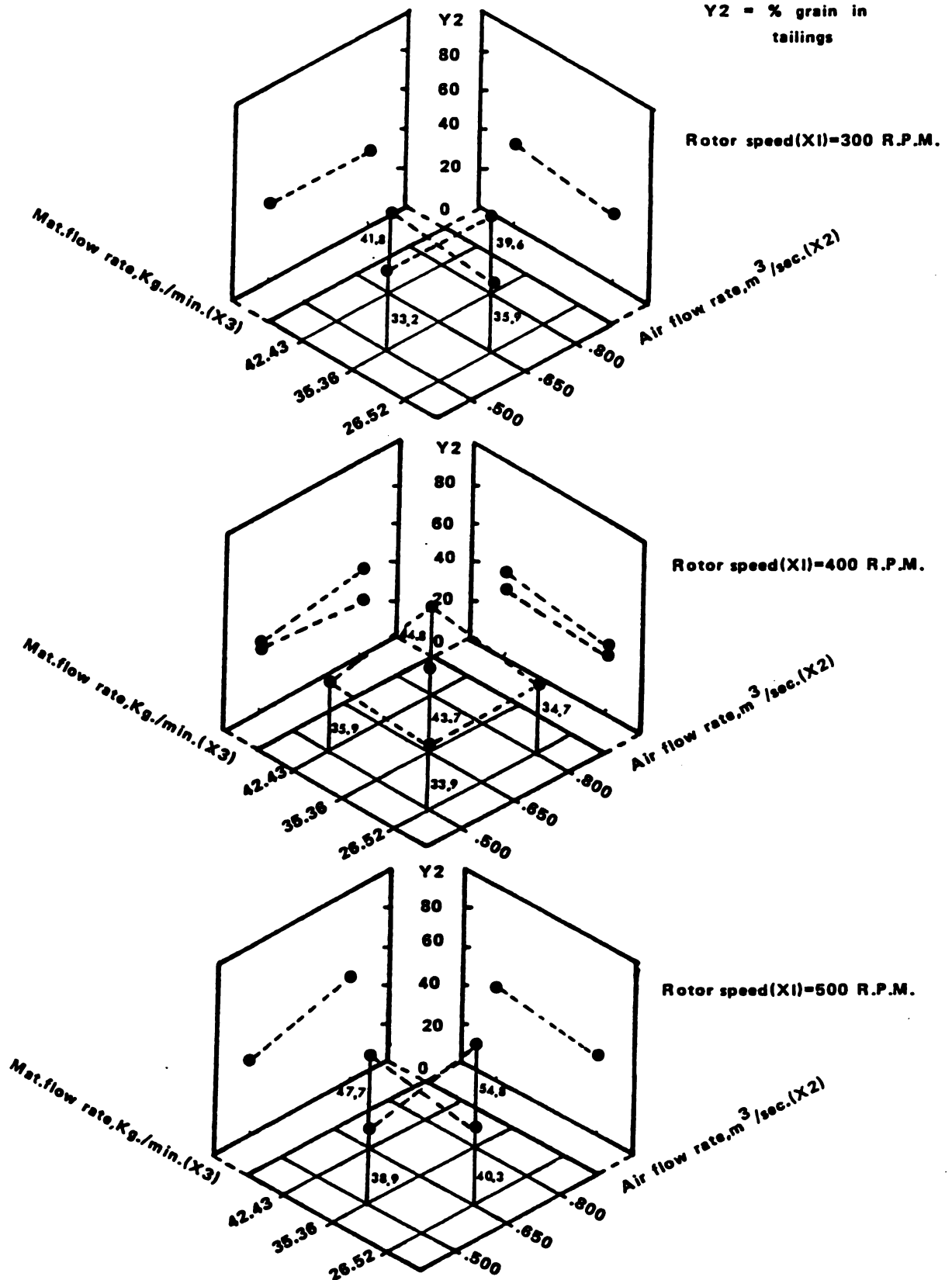
Y2 = % grain in
tailings

Fig. 38 The effect of air and material flow rates on the percent of grain in tailings,
Cylinder speed : 28.66 R.P.M. , test series 2 .

Block No. : 2
Cylinder R.P.M.:35.83
Y2 = % grain in
tailings

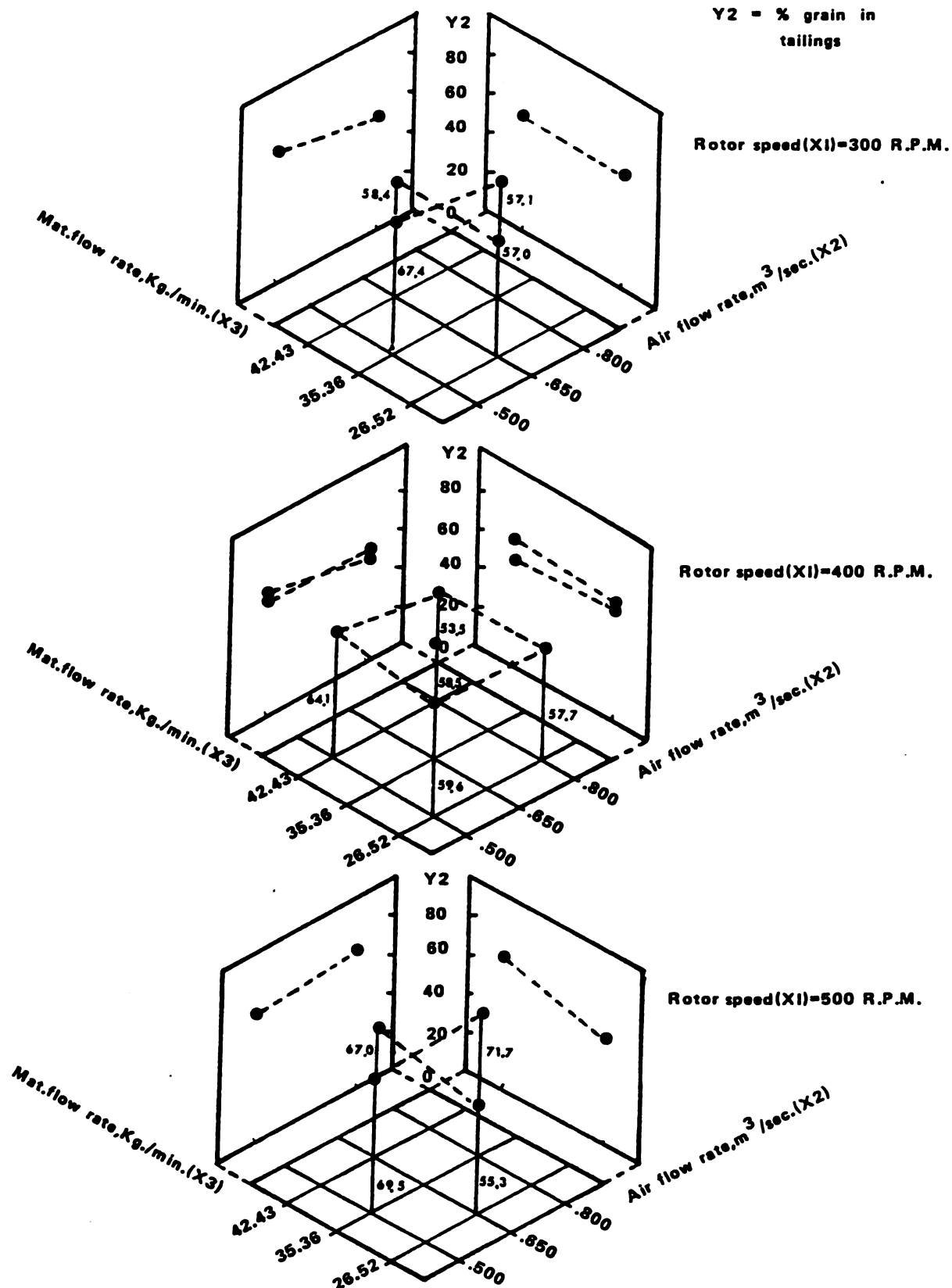


Fig. 39 The effect of air and material flow rates on the percent of grain in tailings,
cylinder speed : 35.83 R.P.M. , test series 2 .

Block No. : 3
 Cylinder R.P.M.: 43.00
 Y2 = % grain in
 tailings

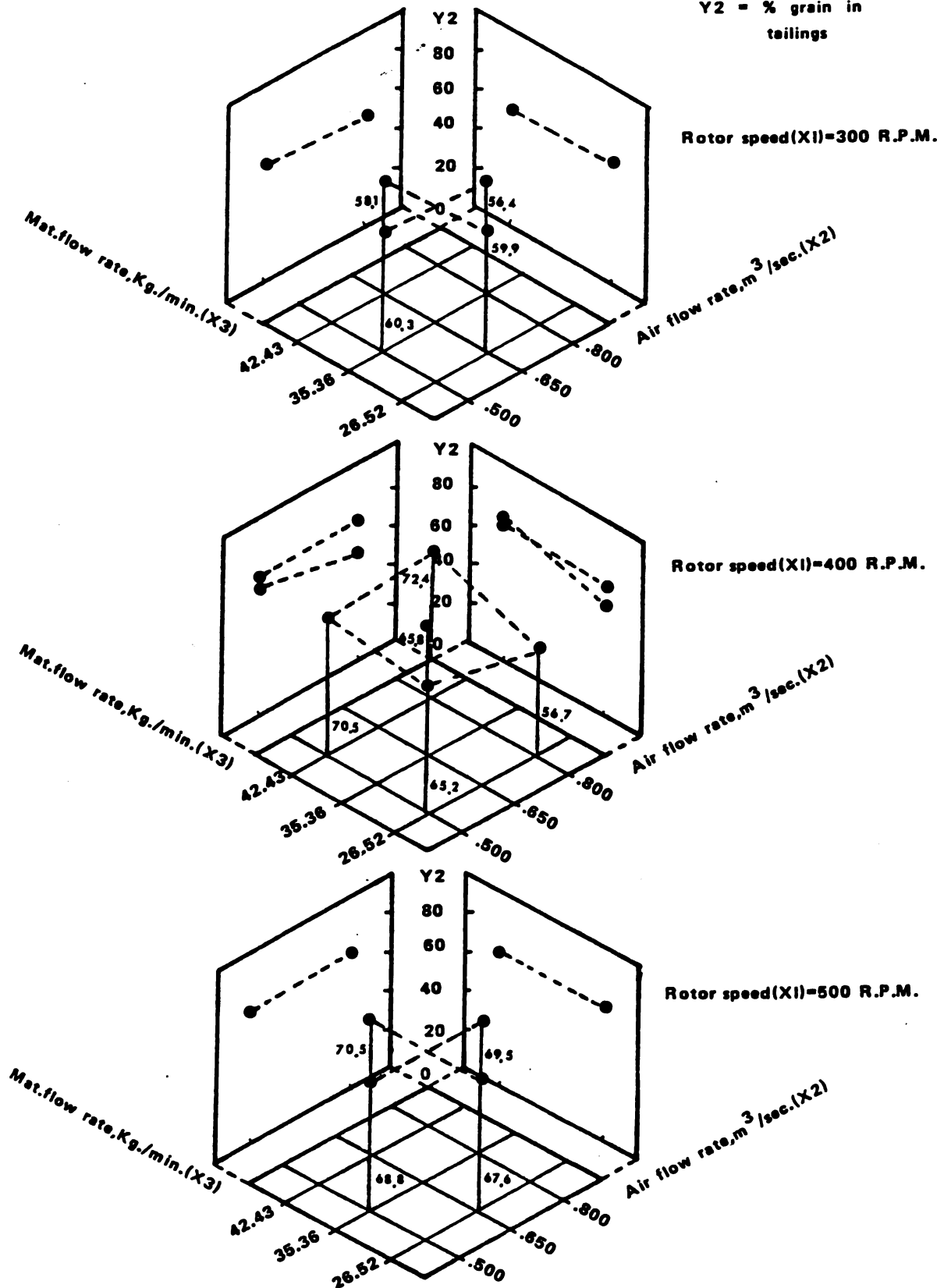


Fig. 40 The effect of air and material flow rates on the percent of grain in tailings ,
 cylinder speed : 43.0 R.P.M. , test series 2 .

Table 12 Simple and main effects of rotor speed on the percent chaff in cleaning zone at constant air flow rate.

	Block 1		Block 2		Block 3	
Rotor speed, rpm	Simple effect	Main effect	Simple effect	Main effect	Simple effect	Main effect
300	-2.5	-4.6	3.0	0.95	-3.3	-1.9
500	-6.7		-1.1		-0.5	

Table 13 Simple and main effects of rotor speed on the percent chaff in cleaning zone at constant mat. flow rate.

	Block 1		Block 2		Block 3	
Rotor speed rpm	Simple effect	Main effect	Simple effect	Main effect	Simple effect	Main effect
300	-1.3	-.25	0.1	0.6	2.4	3.1
500	0.8		1.1		3.8	

1 to 3, Y2 was mainly increased. Table 14 and 15 represent the simple and main effects of Y2 for three blocks of cylinder rpm.

Simple and main effects of Y2 show that at a constant air flow rate when material flow rate increased, it resulted in more grain entering the tailings. Main effects

Table 14 Simple and main effects of rotor speed on the percent grain in tailings at constant air flow rate.

	Block 1		Block 2		Block 3	
Rotor speed, rpm	Simple effect	Main effect	Simple effect	Main effect	Simple effect	Main effect
300	5.9	6.65	1.4	6.55	-1.8	0.55
500	7.4		11.7		2.9	

Table 15 Simple and main effects of rotor speed on the percent grain in tailings at constant mat. flow rate.

	Block 1		Block 2		Block 3	
Rotor speed, rpm	Simple effect	Main effect	Simple effect	Main effect	Simple effect	Main effect
300	6.4	11.15	-10.3	-4.05	-3.9	-1.60
500	15.9		2.2		0.7	

of Y2 at constant material flow rates indicated that at medium and high cylinder speeds, when air flow rate increased, percent of grain in tailings decreased.

Data given in Tables A-4 to A-6 (Appendix D) were subjected to least square analysis. Two different models were tested. The general form of the first model which

was fitted for each experiment block (each cylinder rpm), and included three independent variables, is given in Eq. [4]. The statistical estimates of constants and the R^2 for two different dependent variables and three blocks of the experiment are given in Table 16. The AOV Tables for testing the significance of each of the constants are given in Tables A-15 to A-20 in Appendix D. These tables show the significance of each coefficient and the F-tests for the models.

The lumped models including all four independent variables for Y1 and Y2 were also tested. The general form of the lumped models was the same as Eq. [5]

The statistical estimates of constants and the correlation coefficients (R^2) for lumped models are given in Table 17. The AOV Tables for testing the significance of each of the constants are given in Tables A-21 and A-22 in Appendix D.

Using equations of Table 16, the response surfaces of the regression models were obtained. Fig. 41 to 46 show the contours of the fitted second order equations relating response of Y1 and Y2 to air and material flow rates at different rotor and cylinder speeds. Response surfaces of Y1 and Y2 indicates the following points:

1. To keep Y1 constant, when material flow rate increases, air flow rate has to increase. This is true in all cases.

Table 16 Estimates of constants for the regression equations for Y1(% chaff at cleaning zone) and Y2(% grain in tailings) for test series 2

Block No.	Dep. variable	b ₀	b ₁	b ₂	b ₃	b ₄	b ₅	b ₆	b ₇	b ₈	b ₉	R ²
1	$\hat{Y}_1$	-114.30	.251	182.755	2.343	-.0003	-187.377	-.025	.038	-.002	-.330	.7322
	$\hat{Y}_2$	-5.297	-.1597	58.874	2.563	.0001	-184.911	-.0487	.192	.0004	2.078	.9429
2	$\hat{Y}_1$	-16.68	-.239	69.144	3.981	.0003	-654.36	-.160	.00000	-.0012	15.837	.5032
	$\hat{Y}_2$	652.254	-2.812	-629.37	7.052	.003	-1453.18	-.495	.231	.0036	54.298	.9144
3	$\hat{Y}_1$	14.679	0.0000	87.922	-1.487	-.0001	-123.27	.0098	.038	.0009	.734	.8815
	$\hat{Y}_2$	81.069	.161	-127.94	-1.779	-.0002	-14.793	.005	.096	.0013	2.697	.8077

Table 17 Estimates of constants for the regression equations of lumped models for Y1 and Y2 , test series 2 .

Dep. variable	b ₀	b ₁	b ₂	b ₃	b ₄	b ₅	b ₆	b ₇	b ₈	b ₉
$\hat{Y}_1$	32.2603	-.8191	.1281	-58.976	-.2711	.0060	-.0002	95.9220	.0195	-.0001
$\hat{Y}_2$	-109.25	1.2633	.2618	-24.043	2.4057	-.0054	-.00016	65.8076	-.0101	-.0001

Table 17 continued :

b ₁₀	b ₁₁	b ₁₂	b ₁₃	b ₁₄	R ²
.5836	-.0036	.0641	.0015	-3.0269	.6362
-.4133	.0022	.0577	-.0032	-1.553	.8636

Block No : 1

Cylinder R.P.M. : 28.66

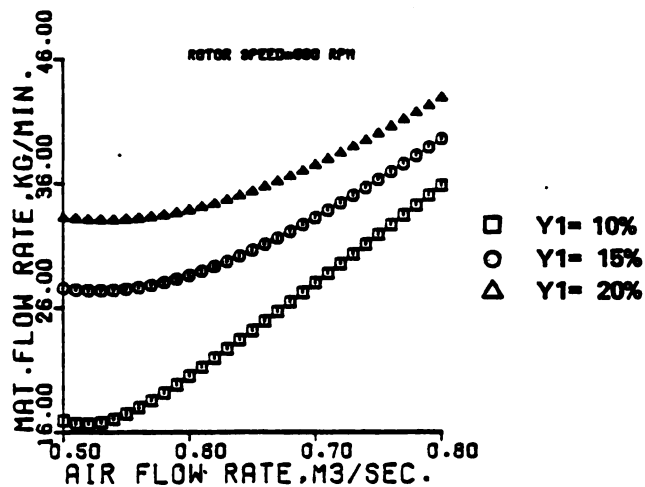
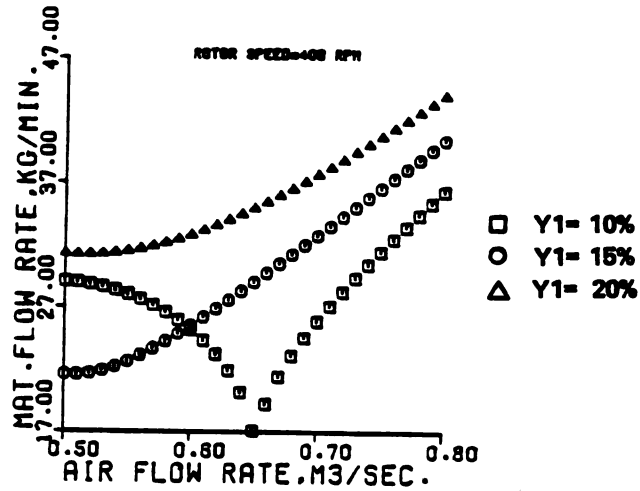
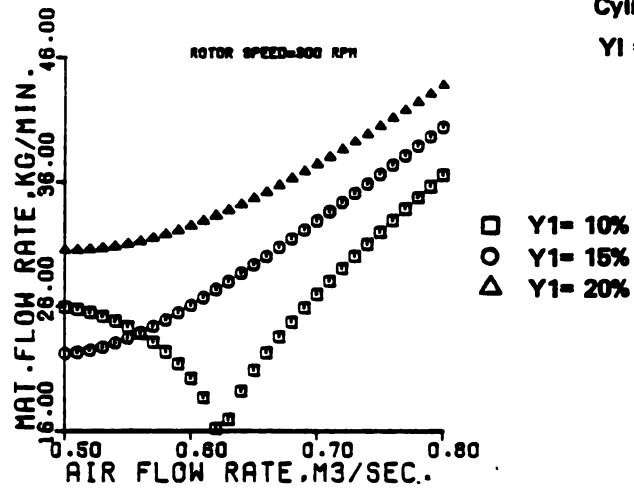
Y1 = % chaff at
cleaning zone

Fig. 4.1 Contours of the fitted second order equation ($R^2 = 0.73$) relating response of Y1 to the air and material flow rates at ; cylinder speed : 28.66 R.P.M. , test series 2 .

Block No : 2

Cylinder R.P.M. : 35.83

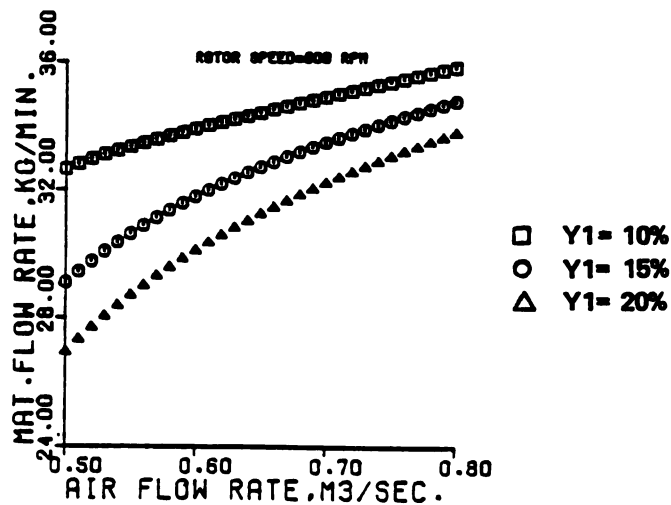
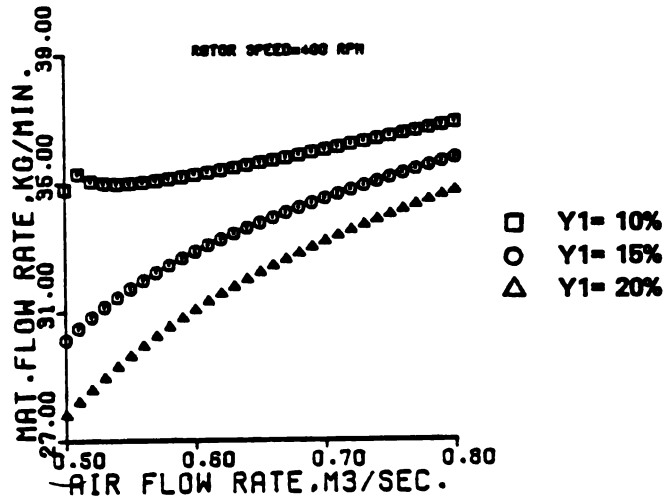
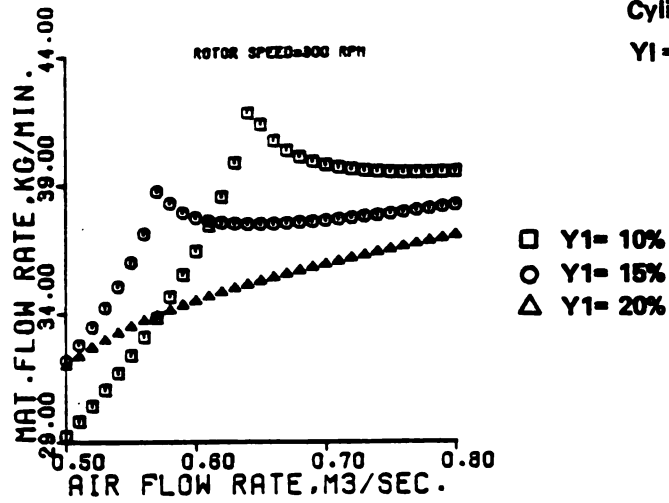
Y1 = % chaff at
cleaning zone

Fig. 42 Contours of the fitted second order equation ($R^2 = 0.5$) relating response of Y1 to the air and material flow rates at ; cylinder speed : 35.83 , test series 2 .

Block No : 3

Cylinder R.P.M. : 43.0

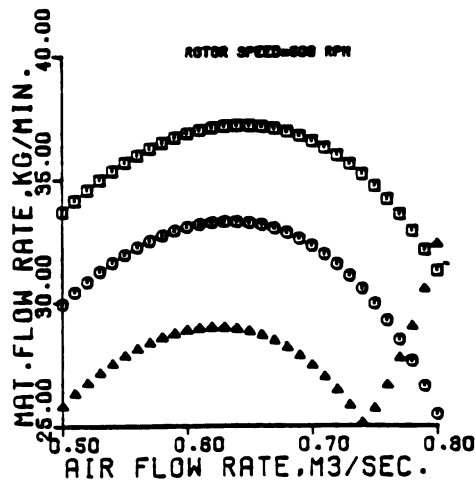
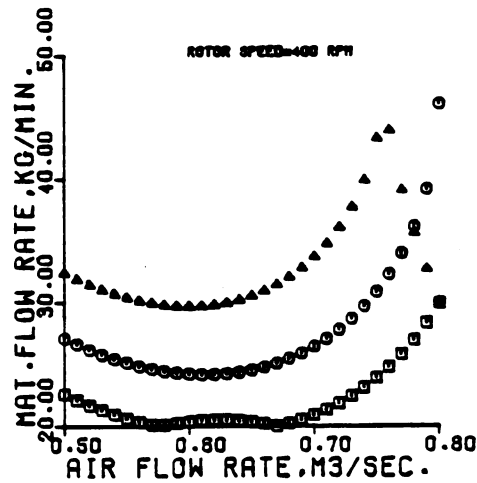
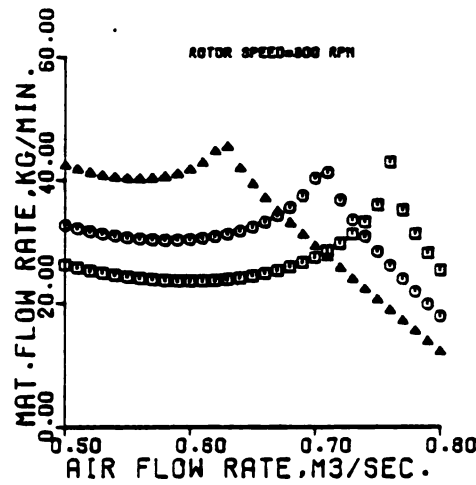
YI = % chaff at cleaning
zone .

Fig. 43 Contours of the fitted second order equation ($R^2 = 0.88$) relating response of YI to the air and material flow rates at ; cylinder speed : 43.0 R.P.M. , test series 2 .

Block No : 1

Cylinder R.P.M. : 28.66

Y2 = % grain in tailings

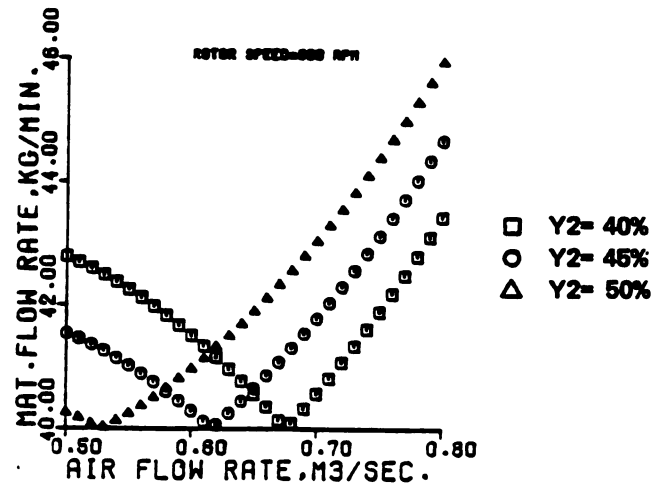
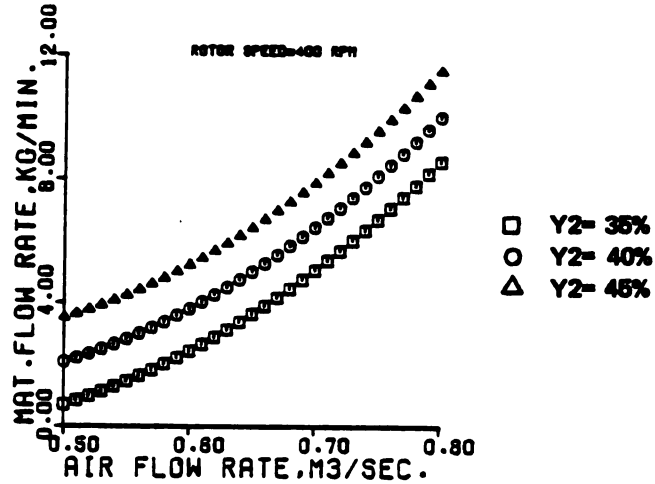
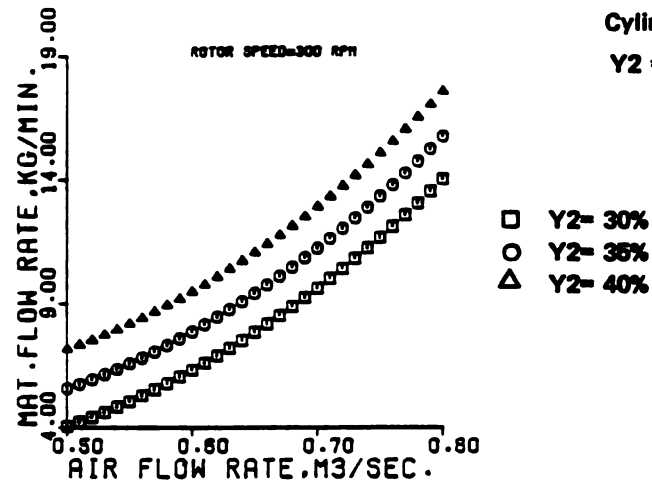


Fig. 4.4 Contours of the fitted second order equation ($R^2 = 0.94$) relating response of Y2 to the air and material flow rates at ; cylinder speed : 28.66 R.P.M. , test series 2 .

Block No : 2

Cylinder R.P.M. : 35.83

Y2 = % grain in tailings

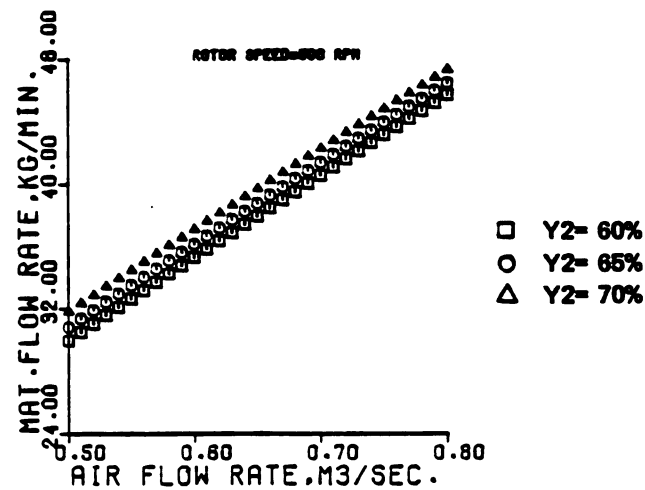
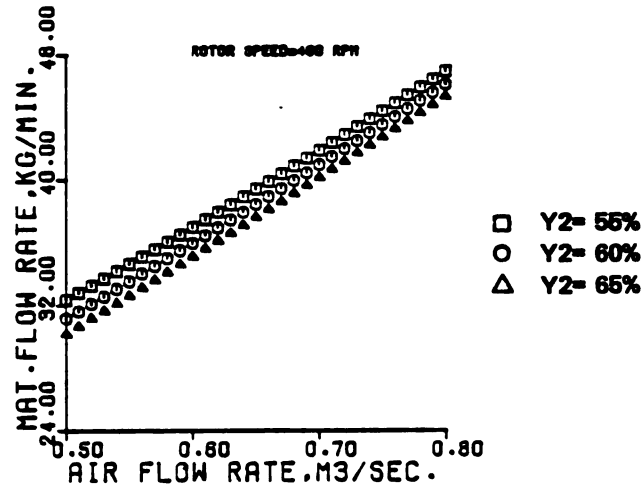
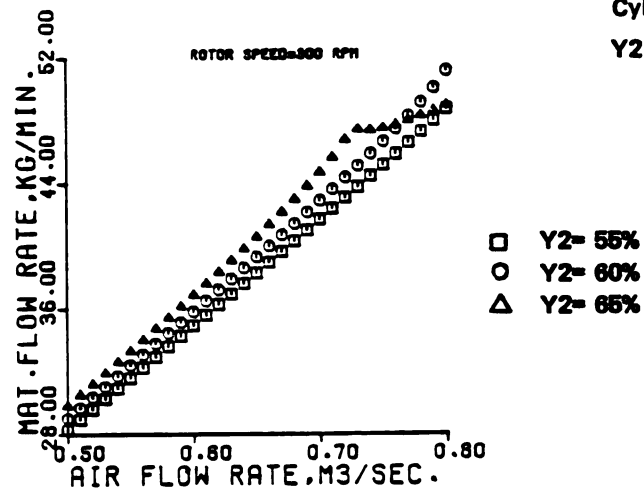


Fig. 45 Contours of the fitted second order equation ($R^2 = 0.91$) relating response of Y2 to the air and material flow rates at ; cylinder speed : 35.83 R.P.M. ; test series 2 .

Block No : 3

Cylinder R.P.M. : 43.0

Y2 = % grain in tailings

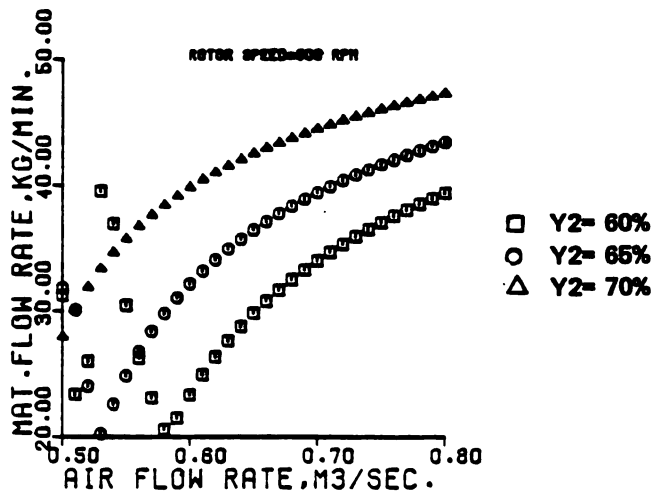
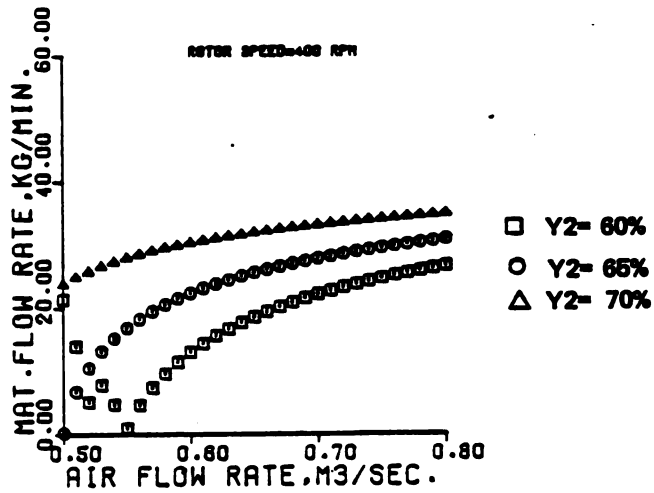
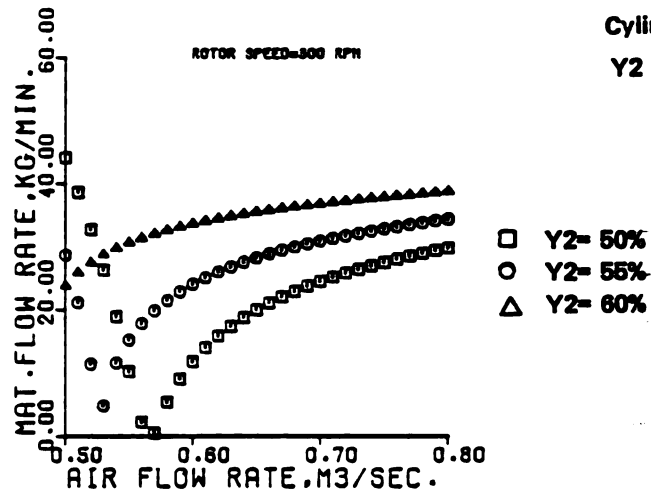


Fig. 46 Contours of the fitted second order equation ($R^2 = 0.81$) relating response of Y2 to the air and material flow rates at ; cylinder speed : 43.0 R.P.M. , test series 2 .

2. The response of Y2 to variations of air and material flow rates indicated that to keep Y2 constant, when material flow rate increases, air flow rate has to increase.

5.0 THEORETICAL ANALYSIS

Modeling of crop motion inside rotary combines has been attempted by many researchers. Lamp (1960) developed the equations of motion of a particle in a vertical rotor in the form of an inverted frustum of a right cone. Neglecting the air movement through the rotor, he analytically investigated the motion of the crop inside the rotor. He treated the crop as an aggregate of disconnected particles sliding inside the rotor. He neglected the horizontal component of the friction force assuming that it was considerably less than the one along the slope. He also assumed that the particle would attain the angular velocity of the cone and maintain it as it moved along the slope.

Buchanan and Johnson (1964) developed the equations of a particle motion inside a horizontal rotating cone. They neglected the force of gravity but considered the force of air movement through the cone. By solving the equations of motion, they concluded that, a) dwell time of the crop in the cone was critical to allow acceleration of the material b) air flow, cone angle and cone speed critically influenced dwell time.

Hamdy et al. (1967) theoretically analyzed a horizontal conical rotor and a vertical generalized rotor by developing the equations of motion and forces imparted to a particle within these threshers. He solved the equations on an analog computer to study the thresher performance as a function of system parameters. He determined that some vertical generalized rotors were theoretically capable of subjecting the particles sliding inside them to centrifugal acceleration of the same order as that necessary to thresh wheat under typical harvesting conditions. He neglected the effect of air drag on the particle and the interaction between the particles.

Long (1969) developed a model for resistive force experienced by kernels moving through a straw mat. He found that the resistive force was proportional to the centrifugal acceleration and relative velocity of the kernel to straw. He determined that the separation time increased by decreasing the straw length from 177.8 mm to 101.1 mm.

Srivastava (1972) tested two mechanisms as a centrifugal separator. The first design was in the form of a perforated, truncated conical rotor with helical blades fixed on the inside. The second design was a rotating auger inside a rotating, perforated cylindrical screen. Assuming the crop as a collection of disconnected particles, he developed the equations of motion of particles

inside the conical rotor and the cylindrical screen. Using an analog computer, he solved the equations and concluded that: crop motion inside the horizontal, conical rotating screen was very sensitive to the crop frictional characteristics. However, this was not so in the case of horizontal cylindrical screens.

In summary, previous theoretical analysis show that:

1. All researchers have treated the crop as an aggregate of disconnected particles. Therefore, no interaction effects have been considered.
2. The effect of air drag was in most studies neglected.
3. Most studies showed that dwell time of the crop inside the rotor was critical.

The rotating cylinder which was used during the experimental analysis consisted of two sections (Figures 3 and 47).

- 1) A solid section at the entrance of the rotating cylinder with the function of accelerating the particles in axial and tangential directions so that when the particles leave the threshing cylinder they can be directed toward the exit end of the system.

2. The perforated section at the circumferential end of the rotating cylinder, which was designed for the separation of the kernels from chaff. This section was designed either to allow the kernels to be separated from

the chaff (as described in Section 4.1) or the kernels and chaff can leave the perforated section under the gravity force and be subjected to an air blast parallel to the long axis of the cylinder to separate grain from chaff (as described in Section 4.2).

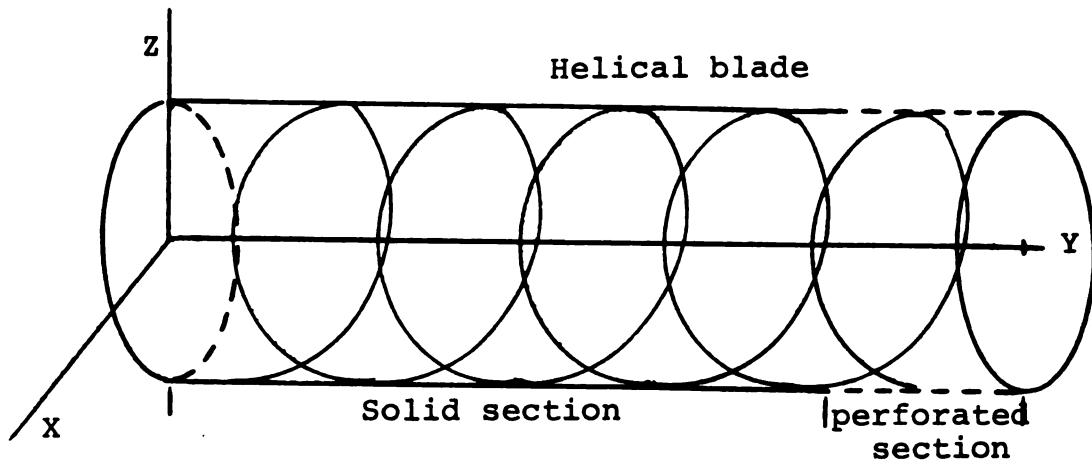


Fig. 47 The horizontal rotating cylinder.

The objective of the theoretical analysis was to investigate the effect of the rotating cylinder rpm on the axial motion of the particles inside the cylinder. This would allow determination of the effect of the particle dwell time on the performance of the system.

The following assumptions were made to derive the equations of motion:

1. The crop was assumed to be a collection of disconnected particles. This allowed the interaction between

the particles to be neglected, and therefore crop motion was represented by the motion of a single particle.

2. The friction force between blade and particles was related to the normal force between them by the coefficient of dynamic friction.

3. The particles were at all times in contact with the rotating cylinder and were moved by helical blades.

Two sets of coordinates were used in this analysis. The XYZ-system, shown in Fig. 48, is the fixed inertial reference frame. The $r\theta y$ system in which the r and θ axes were rotating with the particle in a manner such that the particle was kept on the r -axis at all times.

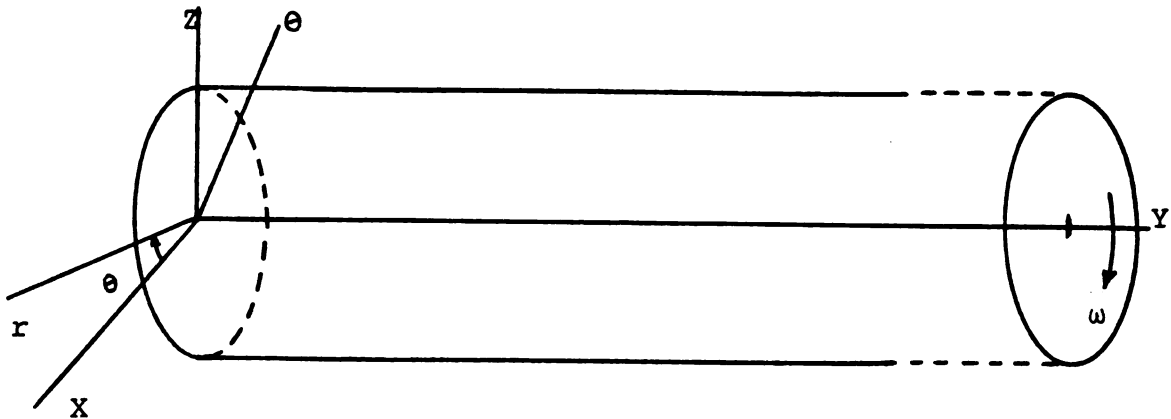


Fig. 48 Two sets of coordinates

The origins of both coordinate systems were located at the entrance end of the cylinder axis. Fig. 49 shows the left end-view of the cylinder and two sets of axes.

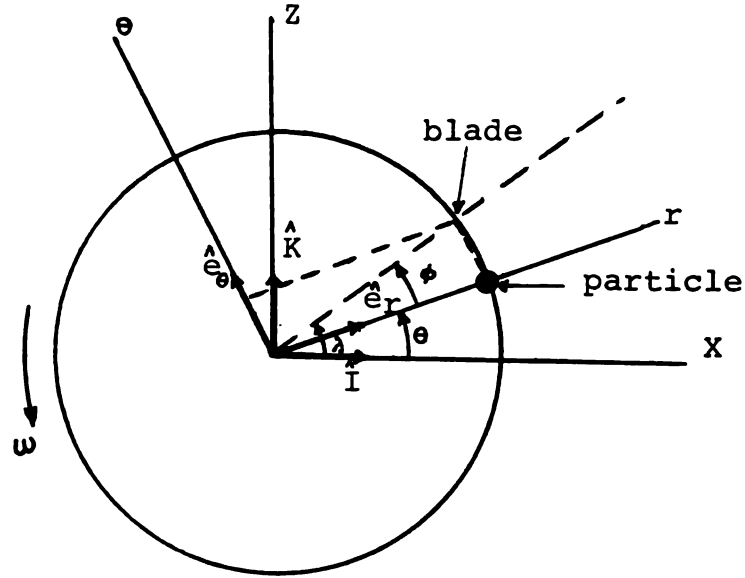


Fig. 49 Left end-view of the cylinder and two sets of coordinates.

From Fig. 49, $\lambda - \theta = \phi$ and $\dot{\lambda} = \omega$ (constant).

Therefore, $\dot{\lambda} - \dot{\theta} = \dot{\phi}$ or $\omega - \dot{\theta} = \dot{\phi}$ and $\ddot{\phi} = -\ddot{\theta}$

where

ω = cylinder angular velocity, rad/sec.

λ = the angle between the blade and the inertial reference frame, radians.

θ = the angular position of the particle in the XYZ-reference frame, radians.

ϕ = the angle between the particle and blade, radians.

Note: At $t=0$, $\theta=0$, i.e. $\lambda=\theta$

$\hat{I}$ = unit vector in the X-direction.

$\hat{J}$ = unit vector in the Y-direction.

$\hat{K}$ = unit vector in the Z-direction.

$\hat{e}_r$ = unit vector in the r-direction.

$\hat{e}_\theta$ = unit vector in the θ -direction.

The position vector of the particle at any instance is

$$\bar{r}_p = r_o \hat{e}_r + y\hat{J} \quad [6]$$

Where

$\bar{r}_p$ = position vector of the particle

r_o = radius of the rotating cylinder, meters.

Differentiating Eq. [6] with respect to time, the velocity was obtained as

$$\bar{v}_p = \frac{d\bar{r}_p}{dt} = \dot{r}_o \hat{e}_r + r_o \frac{d\hat{e}_r}{dt} + \dot{y}\hat{J} + y\frac{d\hat{J}}{dt} \quad [7]$$

Since r_o = constant, $\dot{r}_o = 0$ and also $\frac{d\hat{J}}{dt} = 0$. So

$$\bar{v}_p = r_o \frac{d\hat{e}_r}{dt} + \dot{y}\hat{J} \quad [8]$$

The following transformations can be written from Fig. 49:

$$\hat{e}_r = \cos \theta \hat{I} + \sin \theta \hat{K} \quad [9]$$

$$\hat{e}_\theta = -\sin \theta \hat{I} + \cos \theta \hat{K} \quad [10]$$

Therefore

$$\begin{aligned} \frac{d\hat{e}_r}{dt} &= \frac{d}{dt}(\cos \theta \hat{I} + \sin \theta \hat{K}) = -\dot{\theta} \sin \theta \hat{I} + \dot{\theta} \cos \theta \hat{K} \\ &= \dot{\theta}(-\sin \theta \hat{I} + \cos \theta \hat{K}) = \dot{\theta} \hat{e}_\theta \end{aligned}$$

So

$$\bar{V}_p = r_o \dot{\theta} \hat{e}_\theta + \dot{y} \hat{J} \quad [12]$$

The acceleration of the particle may be obtained by differentiating the velocity term (Eq. 12). Thus,

$$\bar{a}_p = r_o \ddot{\theta} \hat{e}_\theta + r_o \dot{\theta} \frac{d\hat{e}_\theta}{dt} + \ddot{y} \hat{J} \quad [13]$$

Here

$$\begin{aligned} \frac{d\hat{e}_\theta}{dt} &= \frac{d}{dt}(-\sin\theta \hat{I} + \cos\theta \hat{K}) = -\dot{\theta} \cos\theta \hat{I} - \dot{\theta} \sin\theta \hat{K} \\ &= -\dot{\theta}(\cos\theta \hat{I} + \sin\theta \hat{K}) = -\dot{\theta} \hat{e}_r \end{aligned} \quad [14]$$

So the acceleration of the particle is given by

$$\bar{a}_p = r_o \ddot{\theta} \hat{e}_\theta - r_o \dot{\theta}^2 \hat{e}_r + \ddot{y} \hat{J} \quad [15]$$

The position vector of the blade at any point may be introduced as (Fig. 49)

$$\bar{r}_b = r_o \cos \phi \hat{e}_r + r_o \sin \phi \hat{e}_\theta + y_o \hat{J} \quad [16]$$

here

y_o = the axial position where a point on the blade is located.

The velocity of the blade at a particular point may be obtained by differentiating Eq. [16]. It is

$$\begin{aligned}\bar{V}_b = & -r_o \dot{\phi} \sin \phi \hat{e}_r + r_o \cos \phi \frac{d\hat{e}_r}{dt} + r_o \dot{\phi} \cos \phi \hat{e}_\theta \\ & + r_o \sin \phi \frac{d\hat{e}_\theta}{dt} + \dot{y}_o \hat{j}\end{aligned}\quad [17]$$

Substituting $\frac{d\hat{e}_r}{dt}$ and $\frac{d\hat{e}_\theta}{dt}$ from Eq. [11] and [14],

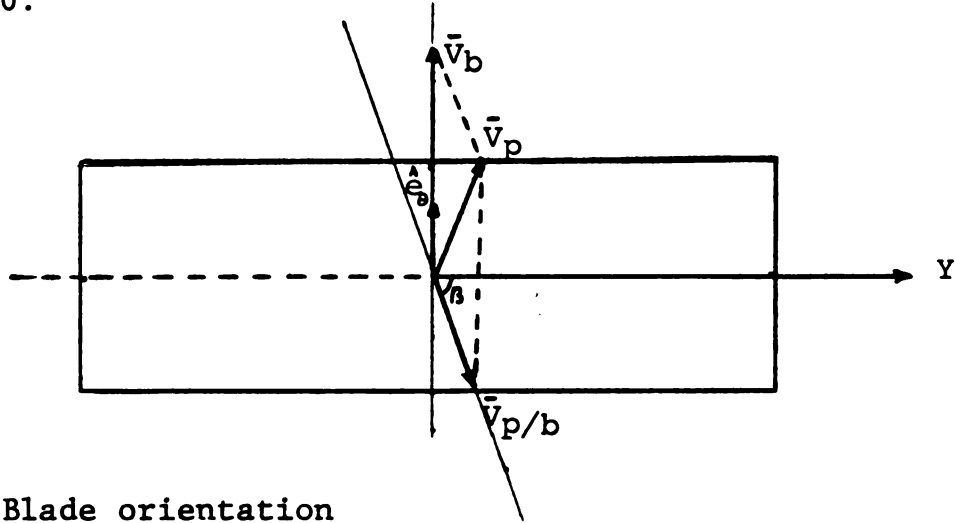
we get

$$\bar{V}_b = -r_o \dot{\phi} \sin \phi \hat{e}_r + r_o \dot{\theta} \cos \phi \hat{e}_\theta + r_o \dot{\phi} \cos \phi \hat{e}_\theta - r_o \dot{\theta} \sin \phi \hat{e}_r \quad [18]$$

where

$\bar{V}_b$ = velocity vector of blade.

The velocity diagram of the particle is shown in Fig. 50.



Blade orientation

Fig. 50 Velocity diagram of the particle in a plane tangent to cylinder at point where the particle contacts the cylinder surface.

From the velocity diagram, we can write

$$\bar{V}_p = \bar{V}_b + \bar{V}_{p/b} \quad [19]$$

Fig. 51 shows the helical blades of the rotating cylinder and the forces acting on the particle.

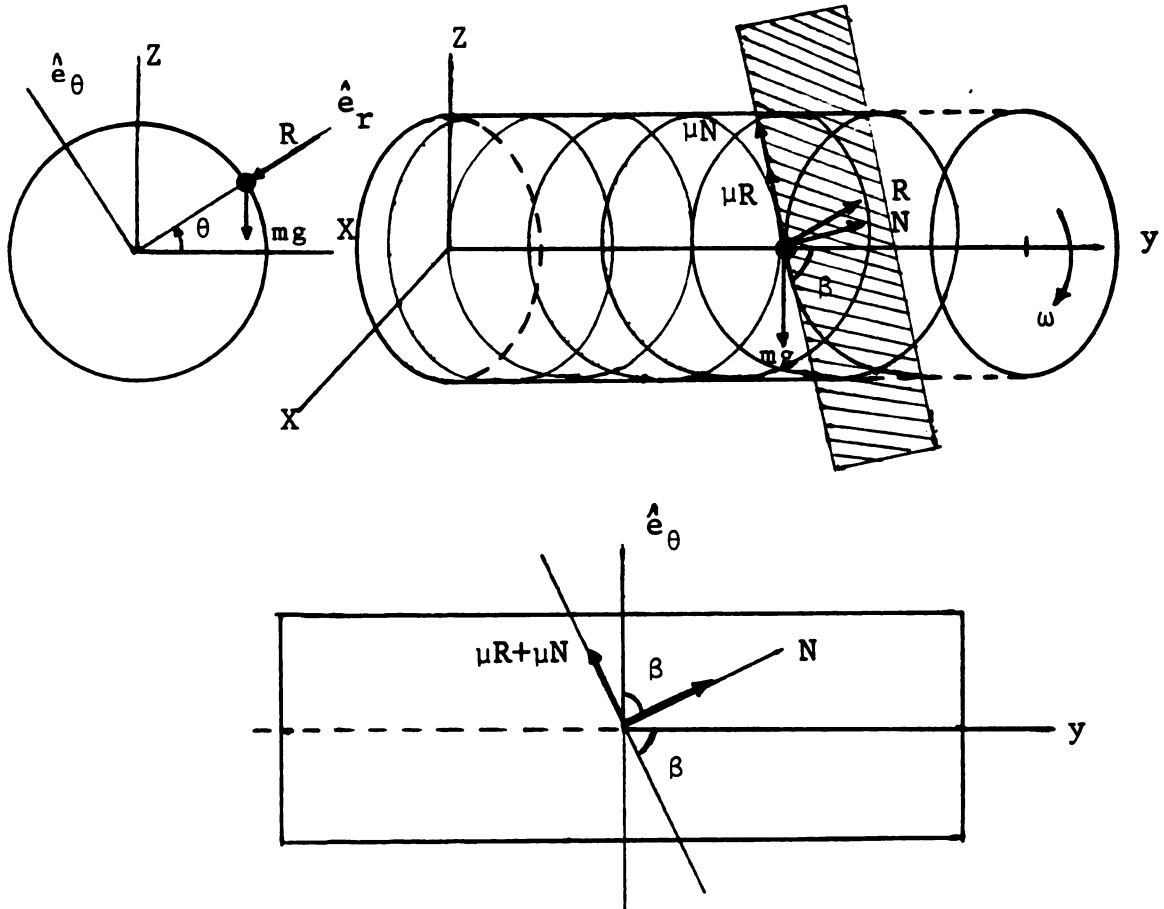


Fig. 51 Coordinate diagram and forces for the rotating cylinder.

The equations of motion were derived by using Newton's laws of motion. The summation of external forces acting on the particle in the r -, θ - and y - directions are given by

Substituting Eq. [12] and [18] in Eq. [19] we get

$$r_o \dot{\theta} \hat{e}_\theta + \dot{y} \hat{J} = -r_o \dot{\phi} \sin \phi \hat{e}_r + r_o \dot{\theta} \cos \phi \hat{e}_\theta + r_o \dot{\phi} \cos \phi \hat{e}_\theta \quad [20]$$

$$-r_o \dot{\theta} \sin \phi \hat{e}_r + V_{p/b} \cos \beta \hat{J} - V_{p/b} \sin \beta \hat{e}_\theta$$

Collecting the terms:

$$r_o \dot{\theta} = r_o \dot{\theta} \cos \phi + r_o \dot{\phi} \cos \phi - V_{p/b} \sin \beta \quad : \hat{e}_\theta \quad [21]$$

$$\dot{y} = V_{p/b} \cos \beta \quad : \hat{J} \quad [22]$$

$$+r_o \dot{\phi} + r_o \dot{\theta} = 0 \quad : \hat{e}_r \quad [23]$$

Rearranging and dividing Eq. [21] by [22], we get:

$$\tan \beta = \frac{-r_o \dot{\theta} + r_o \dot{\theta} \cos \phi + r_o \dot{\phi} \cos \phi}{\dot{y}} \quad [24]$$

The following is the list of symbols which were used in the derivation of equations of motion:

g = Acceleration due to gravity, m/s^2 .

m = Mass of the particle, kg.

N = Normal force exerted by the blade to the particle, Newtons.

R = Normal reaction of cylinder wall, Newtons.

y = Axial displacement, meters.

β = Blade angle, the angle between the blade surface and the cylinder long axis, rad.

$V_{p/b}$ = Velocity of particle with respect to blade, m/s

ω = Cylinder angular speed, rad/s.

μ = Coefficient of friction between the blade and the particle.

$$\Sigma F_r = -R - mg \sin\theta \quad [25]$$

$$\Sigma F_\theta = -mg \cos\theta + N \cos\beta + \mu N \sin\beta + \mu R \sin\beta \quad [26]$$

$$\Sigma F_y = -\mu R \cos\beta + N \sin\beta - \mu N \cos\beta \quad [27]$$

where ΣF_r , ΣF_θ and ΣF_y are the summation of forces in r-, θ - and y- directions, respectively.

Substituting the acceleration terms from Eq. [15], we get

$$mr_o \dot{\theta}^2 = R + mg \sin\theta \quad [28]$$

$$mr_o \ddot{\theta} = \mu N \sin\beta - mg \cos\beta + N \cos\beta + \mu R \sin\beta \quad [29]$$

$$m\ddot{y} = -\mu R \cos\beta + N \sin\beta - \mu N \cos\beta \quad [30]$$

R and N can be determined from Eq. [28] and [29], respectively. We obtain

$$R = mr_o \dot{\theta}^2 - mg \sin\theta \quad [31]$$

$$N = \frac{mr_o \ddot{\theta} + mg \cos\theta + \mu m \sin\beta (g \sin\theta - r_o \dot{\theta}^2)}{\mu \sin\beta + \cos\beta} \quad [32]$$

Substituting $\phi = \lambda - \theta$ and applying the trigonometric identity of $\cos(\lambda - \theta) = \cos\lambda \cos\theta + \sin\lambda \sin\theta$ in Eq. [24] we get

$$\begin{aligned} \dot{y} = \frac{1}{\tan\beta} \left[-r_o \dot{\theta} + r_o \dot{\theta} (\cos\lambda \cos\theta + \sin\lambda \sin\theta) \right. \\ \left. + r_o \dot{\phi} (\cos\lambda \cos\theta + \sin\lambda \sin\theta) \right] \end{aligned} \quad [33]$$

Substituting $\lambda = \omega t$ and $\phi = \omega - \theta$ in Eq. [33], results

$$\dot{y} = \frac{1}{\tan\beta} [-r_o \dot{\theta} + r_o \omega \cos(\omega t - \theta)] \quad [34]$$

Differentiating Eq. [34] with respect to time, the acceleration is obtained to be

$$\ddot{y} = \frac{1}{\tan\beta} [-r_o \ddot{\theta} - r_o \omega^2 \sin(\omega t - \theta) + r_o \omega \dot{\theta} \sin(\omega t - \theta)] \quad [35]$$

Also, substituting Eq. [31] and [32] in [30], we get

$$\ddot{y} = -\mu \cos\beta (r_o \dot{\theta}^2 - g \sin\theta) \quad [36]$$

$$+ K \left[r_o \ddot{\theta} + g \cos\theta + \mu \sin\beta (g \sin\theta - r_o \dot{\theta}^2) \right]$$

$$K = \frac{\sin\beta - \mu \cos\beta}{\mu \sin\beta + \cos\beta} \quad [37]$$

Equating Eq. [35] and [36] and rearranging,

$$\begin{aligned} \left[K r_o + \frac{r_o}{\tan\beta} \right] \ddot{\theta} = & \left[\frac{1}{\tan\beta} \left[r_o \dot{\theta} \omega \sin(\omega t - \theta) - r_o \omega^2 \sin(\omega t - \theta) \right] \right. \\ & \left. + \mu \cos\beta (r_o \dot{\theta}^2 - g \sin\theta) - K \left[g \cos\theta + \mu \sin\beta (g \sin\theta - r_o \dot{\theta}^2) \right] \right] \end{aligned} \quad [38]$$

Eq. [34], [36] and [38] define the motion of a particle inside the rotating cylinder.

5.1 Solutions of the equations of motion

Due to nonlinearity of the equations of motion, it was not possible to solve the equations analytically.

Numerical solution was therefore applied and Subroutine DVERK which is available in the MSU Computer Laboratory was used to solve the equations of motion. The following table lists the initial conditions.

Three different cylinder speeds of 2.5 rad/s, 3.0 rad/s and 3.5 rad/s were used for ω .

Table 18 Initial conditions for the solution of equations of motion.

Time	y_0	θ_0
0.0	0.0	270.0
Constants		
$\beta = 75.$		$\mu = 0.50$
$r = 0.30$		$g = 9.81$

5.2 Simulation Results and Discussion

Fig. 52 and 53 show the axial and angular displacements of a particle at three cylinder angular speeds of 2.5 rad/s, 3.0 rad/s and 3.5 rad/s.

Fig. 52 shows that as cylinder speed increased, the particle travelled faster and therefore its dwell time inside the rotating cylinder decreased.

Fig. 53 shows that crop angular displacement was usually in the range of 260 to 340 degrees. In other words, the axial motion of the particles, which was a combination of rotation and transformation, occurred in the lower right quadrant of the rotating cylinder.

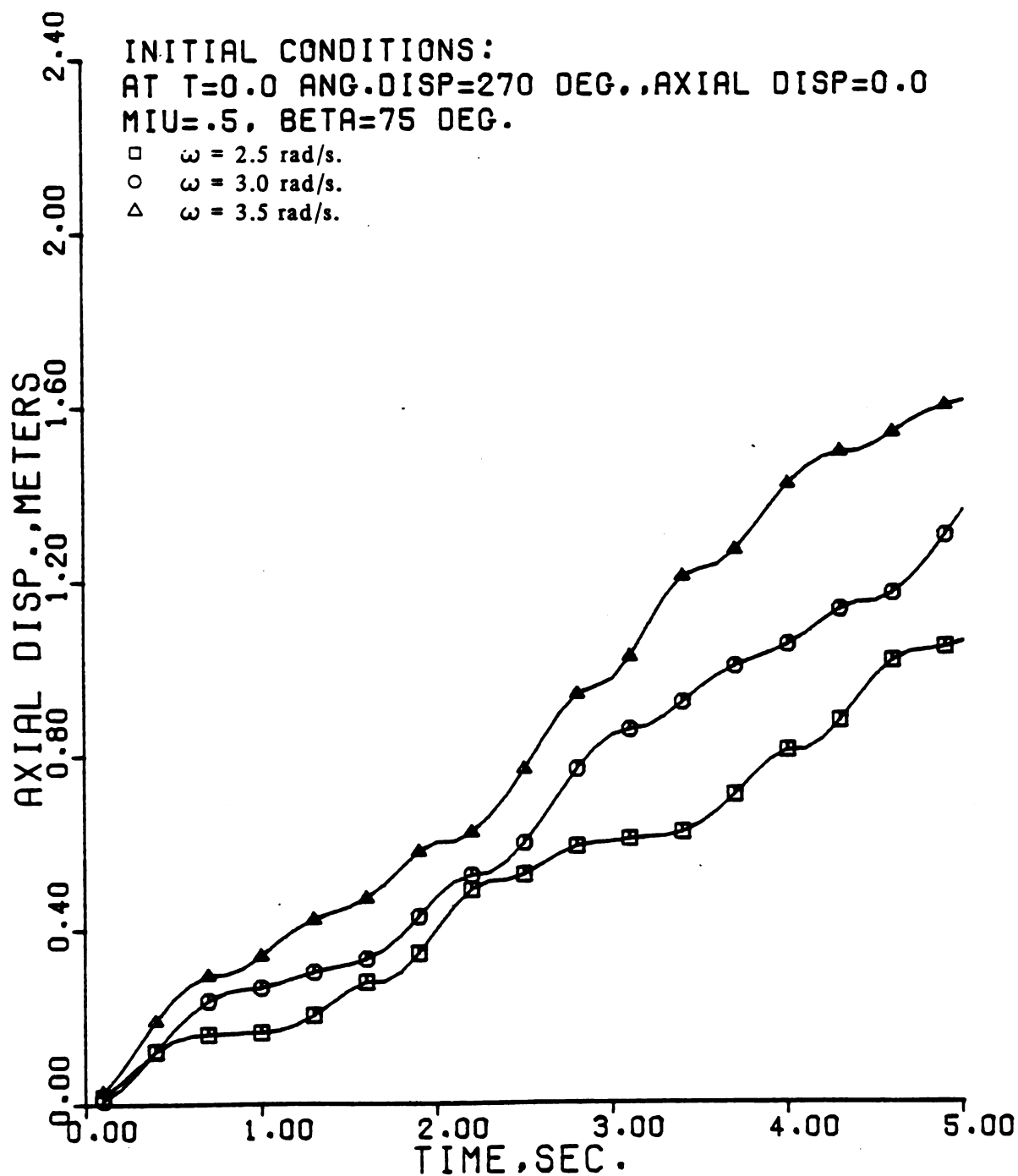


Fig. 52 Axial displacement of a particle at three cylinder speeds.

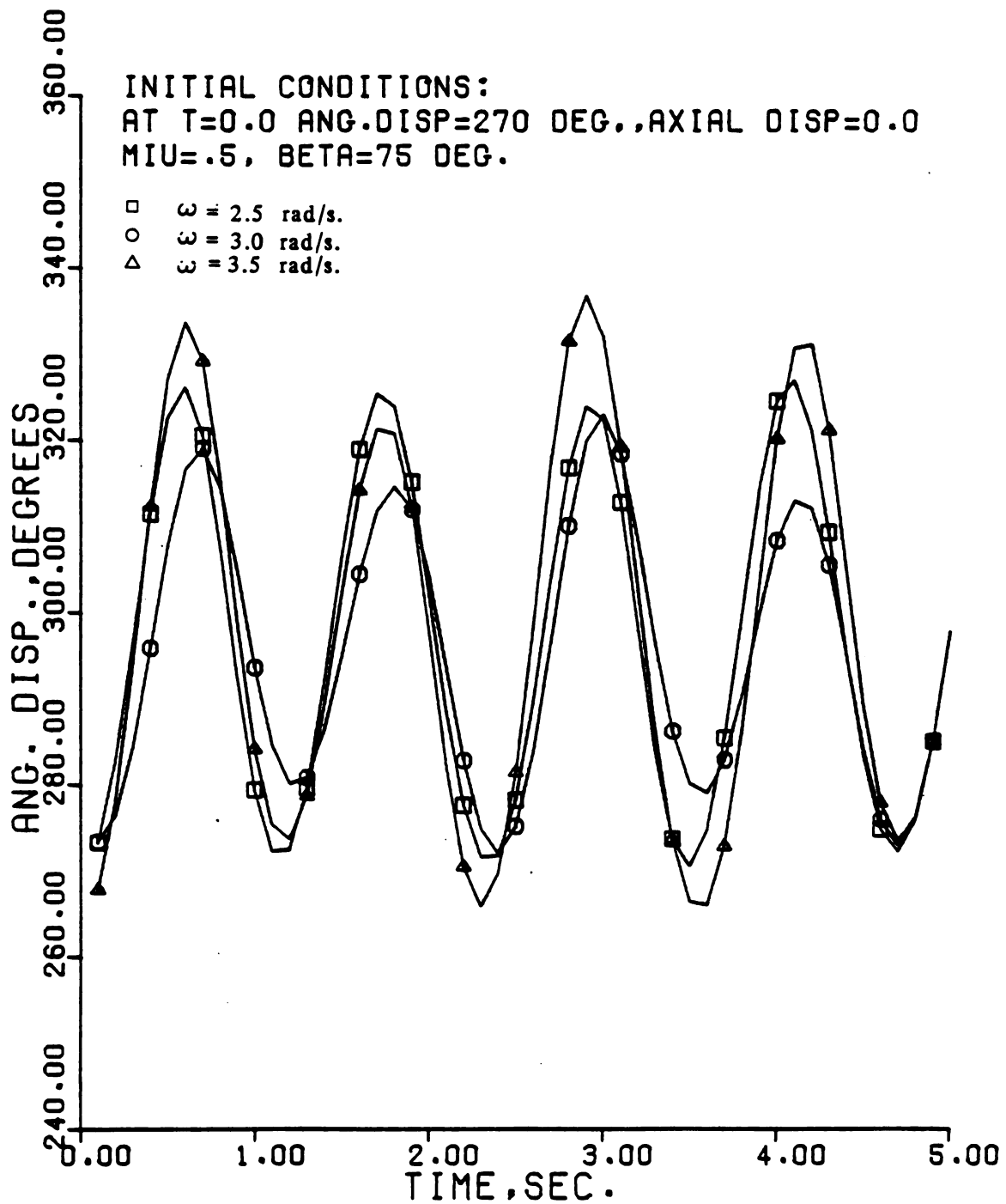


Fig. 53 Angular displacement of a particle at three cylinder speeds.

6.0 CONCLUSIONS

1. Experimental analysis of the horizontal rotating cylinder, perforated at the circumferential end which was designed to separate grain from chaff under one- and two-stage cleaning concepts, indicated that cylinder speed, air and material flow rates were the key factors for the performance of the cleaning system.

2. The mechanisms tested under the one- and two-stage cleaning concepts can be compared as follows:

i. Air flow requirement in the second design was 30% - 40% less than the first.

ii. The cleaning efficiency in the second design was considerably higher than the first.

iii. The power requirement in the second design was 22% less than the first.

3. The cleaning efficiency indicated that the concepts had potential for practical application.

4. The mechanisms developed in this research would have 20-30% less bulk than the conventional cleaning system.

5. Theoretical analysis of the rotating cylinder showed that crop residence time was a function of cylinder speed. This was understood from the experimental

results as well. In other words, experimental results pointed out that as cylinder speed increased, percent grain losses (in the first series of tests) and percent grain in tailings (in the second series of tests) increased while percent chaff in the cleaning zone decreased.

7.0 SUMMARY

The cleaning mechanism used in axial-flow combines is bulky and gravity dependent. In an attempt to investigate the design requirements for a cleaning system for axial-flow combines, which could be gravity independent while utilizing the centrifugal and aerodynamic force fields, a $\frac{1}{2}$ scale model of a White 9700 axial-flow combine was designed and fabricated. The model consisted of a rotor and a fixed cylinder perforated on the lower half which was equipped with a feeding hopper at the entrance end. Both were mounted on one frame. A rotating cylinder equipped with helical blades on the inner surface and perforated at the circumferential end was designed to be fitted over the fixed cylinder.

Two series of experiments were performed. First, an inward air flow rate was created at the perforated section of the rotating cylinder in order to hold back chaff and to allow the grain to escape. Experimental results of more than 90 percent cleaning efficiency were obtained.

In the second, which was a two stage cleaning mechanism, the material in the rotating cylinder was allowed to pass through the perforated section. This material was then subjected to an air blast in order to blow chaff

forward and let the grain fall into a grain collection area. A semi-circular air duct was mounted under the rotating cylinder. The outlet of the duct was located at the rear of the perforated section of the rotating cylinder. Cleaning efficiency of more than 90 percent was obtained from this design. Grain loss in the tailings was as low as 33 percent.

Treating the crop as an aggregate of disconnected particles, the equations of motion of crop in the rotating cylinder were derived. The computer simulation results indicated that crop residence time and angular displacement were a function of cylinder speed. In other words, the faster the cylinder rotates, the quicker the crop leaves the cylinder outlet. This had an important effect on the separation of grain from chaff and percent of grain in the tailings.

In addition, theoretical results showed that displacement of particles will usually take place in the range of 260° - 340° . This was exactly what happened during the experimental tests.

8.0 SUGGESTIONS FOR FUTURE RESEARCH

There are some concepts that were not fully developed in this research and thus further study should be undertaken in order to obtain a complete understanding of them:

1. The crop properties were considered to be fixed during this experiment. It is suggested that the experiment be repeated under different crop conditions to investigate the sensitivity of these mechanisms to variation of crop properties.

2. Wheat was the only crop which was used during this experiment. It is suggested that the experiments be repeated with other crops such as soybeans and corn.

3. It is thought that a more uniform air velocity distribution across the outlet of the semi-circular duct in the second series of tests would give a better result. This will, in fact, prevent the large differences that existed between the air velocity measurements which were done at the outlet.

4. The semi-circular duct used in the two-stage cleaning concept had an outlet of 180 degrees. Theoretical results and experimental observations showed that crop angular displacement is usually in the lower right

quadrant (260° - 340°) of the cylinder and as cylinder speed increased, the particles tend to pass this range. It is therefore suggested to replace a new duct with 200 degrees or more outlet with a larger open area on the right side.

5. The experimental design which was used in this research did not require replications. It is proposed to replicate the treatments to get better averages. This might improve the confidence levels of the regression coefficients.

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APPENDICES

Calculations

A. Calculations of horsepower :

For the hydraulic motors (Fig. 10 and 11), used to run the rotor and the rotating cylinder, the supply and return pressures were recorded while working under high and low material flow rates. The range of the required horsepower was calculated as follows :

$$\text{Liquid H.P.} = \frac{\text{psi} * \text{GPM}}{1714}$$

1. Rotor, hydraulic motor, orbit power made by
Char Lynn :

R.P.M.	P ₁ , supply pressure, psi.	P ₂ , return pressure, psi.	P ₁ - P ₂ , psi.	G.P.M.	H.P. = $\frac{\text{psi} \times \text{G.P.M.}}{1714 \times 0.7}$
low, 150	300	2.0	298	3	0.745
high, 250	550	2.0	548	6	2.740

2. Rotating cylinder, hydraulic motor, Lamina

A-25 :

R.P.M.	P ₁ , supply pressure, psi.	P ₂ , return pressure, psi.	P ₁ - P ₂ , psi.	G.P.M.	H.P. = $\frac{\text{psi} \times \text{G.P.M.}}{1714 \times 0.7}$
low. 400	700	80	620	1.5	0.775
high, 600	800	60	740	2.5	1.542

B. Calculation of material flow rate for the model

(apparatus tested) :

Let $g_m = g_p$

where

g_m = acceleration due to gravity for the model, m/s^2 .

g_p = acceleration due to gravity for the prototype (commercial combine), m/s^2 .

They can dimensionally be written as

$$\frac{L_m}{T_m^2} = \frac{L_p}{T_p^2}$$

Or,

$$\left(\frac{L_m}{L_p}\right)^{\frac{1}{2}} = \left(\frac{T_m}{T_p}\right)$$

Since $\frac{L_m}{L_p} = \frac{1}{2}$, therefore,

$$T_m = \frac{1}{\sqrt{2}} T_p$$

also ;

$$V_m = \frac{L_m}{T_m} = \frac{L_p}{2} \left(\frac{\sqrt{2}}{T_p} \right) = \frac{1}{\sqrt{2}} V_p$$

Where :

T_m = Time in the model, seconds.

L_m = Length in the model, meters.

V_m = Velocity in the model, meters per sec.

T_p = Time in the prototype, seconds.

L_p = Length in the prototype, meters.

V_p = Velocity in the prototype, meters per second.

In addition :

$$Q_p = (\text{Area})_p * (\text{Velocity})_p$$

and ,

$$Q_m = (\text{Area})_m * (\text{Velocity})_m$$

where :

Q_p = Material flow rate in prototype.

Q_m = Material flow rate in the model.

Substituting in Q_m , we get :

$$\begin{aligned} Q_m &= (\text{Area})_m * (\text{Velocity})_m = \frac{1}{4} (\text{Area})_p * \frac{1}{\sqrt{2}} (\text{Vel.})_p = \\ &= \frac{1}{5.656} Q_p \end{aligned}$$

C. Calculation of material flow rate :

Three material flow rates of 26.5 kg/min, 35.4 kg/min and 42.4 kg/min were calculated using the equation derived earlier.

The conveyor used in this experiment had a belt speed of 0.21 m/s . A $1.2 \times 0.4 = 0.5 \text{ m}^2$ area on the conveyor was used to spread the chaff and grain. The feeding time was therefore

$$\text{Feeding time} = \frac{1.25 \text{ m}}{0.21 \text{ m/s}} \approx 6 \text{ seconds}$$

So for three material flow rates of 26.5, 35.4 and 42.4 kg/min, the following values were obtained

$$\frac{26.5 \times 6}{60} = 2.6 \text{ kg}$$

$$\frac{35.4 \times 6}{60} = 3.5 \text{ kg}$$

$$\frac{42.4 \times 6}{60} = 4.2 \text{ kg}$$

With the m.o.g./grain ratio of 1.0 and grain-chaff ratio of 1:0.425, the following grain and chaff values were obtained for three material flow rates :

Mat. flow rate, Kg/min.	Mat. for the conveyor, Kg.	Grain, Kg.	Chaff, Kg.	Test duration, seconds.
26.5	2.652	1.326	0.563	6.0
35.4	3.536	1.768	0.751	6.0
42.4	4.243	2.123	0.902	6.0

.

D) Tabular results of test series 1 & 2,
Statistical analysis of test series 1 & 2 .

Table A-1 Quantitative levels of independent variables and experimental results, test series 1.

Run No.	Block No.	Code No.	Screen R.P.M.	Statistical combinations, X1 X2 X3	Rotor speed, X1 R.P.M.	Air flow rate, X2 m ³ /sec.	Material flow rate, X3 Kg./min.	Grain, Kg.	Chaff, Kg.	% chaff at the cleaning zone, Y1	% grain loss, Y2	Avg. of central points(Y1)	Avg. of central points(Y2)
1	1	A-II-1	33.33	0 0 0	400	0.485	35.4	1.768	0.751	17.9	18.2		
2	"	A-II-2	"	0 0 0	400	0.485	35.4	1.768	0.751	18.1	21.0		17.5
3	"	A-II-3	"	0 0 0	400	0.485	35.4	1.768	0.751	16.5	19.9		
4	"	A-II-4	"	+1 +1 0	500	0.610	35.4	1.768	0.751	14.2	17.2	Std.	Std.
5	"	A-II-5	"	+1 -1 0	500	0.355	35.4	1.768	0.751	18.4	18.9	deviation	deviation
6	"	A-II-6	"	-1 +1 0	300	0.610	35.4	1.768	0.751	11.9	13.9		
7	"	A-II-7	"	-1 -1 0	300	0.355	35.4	1.768	0.751	23.4	11.4	0.87	1.41
8	"	A-II-8	"	+1 0 +1	500	0.485	42.4	2.123	0.902	24.2	16.8		
9	"	A-II-9	"	+1 0 -1	500	0.485	26.5	1.326	0.563	19.7	17.5		
10	"	A-II-10	"	-1 0 +1	300	0.485	42.4	2.123	0.902	15.5	9.6		
11	"	A-II-11	"	-1 0 -1	300	0.485	26.5	1.326	0.563	18.4	12.8		
12	"	A-II-12	"	0 +1 +1	400	0.610	42.4	2.123	0.902	14.4	13.1		
13	"	A-II-13	"	0 +1 -1	400	0.610	26.5	1.326	0.563	20.3	21.0		
14	"	A-II-14	"	0 -1 +1	400	0.355	42.4	2.123	0.902	28.4	16.2		
15	"	A-II-15	"	0 -1 -1	400	0.355	26.5	1.326	0.563	21.4	14.2		

Table A-2 (cont'd) Quantitative levels of independent variables and experimental results, test series 1.

Run No.	Block No.	Code No.	Screen R.P.M.	Statistical combinations, X1 X2 X3	Rotor speed, X1 R.P.M.	Air flow rate, X2 m ³ /sec.	Material flow rate, X3 Kg./min.	Grain, Kg.	Chaff, Kg.	% chaff at the cleaning zone, Y1	% grain loss, Y2	Avg. of central points(Y1)	Avg. of central points(Y2)
16	2	A- I- 1	53.33	0 0 0	400	0.485	35.4	1.768	0.751	20.7	28.3		
17	"	A- I- 2	"	0 0 0	400	0.485	35.4	1.768	0.751	16.7	32.1	18.8	28.8
18	"	A- I- 3	"	0 0 0	400	0.485	35.4	1.768	0.751	19.0	26.0		
19	"	A- I- 4	"	+1 +1 0	500	0.610	35.4	1.768	0.751	10.5	37.2		
20	"	A- I- 5	"	+1 -1 0	500	0.355	35.4	1.768	0.751	14.9	41.5	Std. deviation	Std. deviation
21	"	A- I- 6	"	-1 +1 0	300	0.610	35.4	1.768	0.751	8.4	13.6		
22	"	A- I- 7	"	-1 -1 0	300	0.355	35.4	1.768	0.751	12.3	27.3	2.0	3.1
23	"	A- I- 8	"	+1 0 +1	500	0.485	42.4	2.123	0.902	15.7	23.6		
24	"	A- I- 9	"	+1 0 -1	500	0.485	26.5	1.326	0.563	13.8	34.6		
25	"	A- I-10	"	-1 0 +1	300	0.485	42.4	2.123	0.902	10.7	20.8		
26	"	A- I-11	"	-1 0 -1	300	0.485	26.5	1.326	0.563	8.2	17.0		
27	"	A- I-12	"	0 +1 +1	400	0.610	42.4	2.123	0.902	13.3	30.5		
28	"	A- I-13	"	0 +1 -1	400	0.355	26.5	1.326	0.563	15.8	39.6		
29	"	A- I-14	"	0 -1 +1	400	0.610	42.4	2.123	0.902	14.1	22.7		
30	"	A- I-15	"	0 -1 -1	400	0.355	26.5	1.326	0.563	15.0	35.3		

Table A-3 (cont'd) Quantitative levels of independent variables and experimental results, test series 1.

Run No.	Block No.	Code No.	Screen R.P.M.	Statistical combinations,			Rotor speed, X1 R.P.M.	Air flow rate, X2 m ³ /sec.	Material flow rate, X3 Kg./min.	Grain, Kg.	Chaff, Kg.	% chaff at the cleaning zone, Y1	% grain loss, Y2	Avg. of central points(Y1)	Avg. of central points(Y2)
31	3	A-III-1	80.0	0	0	0	400	0.485	35.4	1.768	0.751	13.7	39.2		
32	"	A-III-2	"	0	0	0	400	0.485	35.4	1.768	0.751	12.9	36.0	13.8	37.7
33	"	A-III-3	"	0	0	0	400	0.485	35.4	1.768	0.751	14.8	37.9		
34	"	A-III-4	"	+1	+1	0	500	0.610	35.4	1.768	0.751	19.4	38.9		
35	"	A-III-5	"	+1	-1	0	500	0.355	35.4	1.768	0.751	20.5	40.3	Std. deviation	Std. deviation
36	"	A-III-6	"	-1	+1	0	300	0.610	35.4	1.768	0.751	16.5	38.3		
37	"	A-III-7	"	-1	-1	0	300	0.355	35.4	1.768	0.751	19.8	42.0	0.95	1.6
38	"	A-III-8	"	+1	0	+1	500	0.485	42.4	2.123	0.902	14.0	44.5		
39	"	A-III-9	"	+1	0	-1	500	0.485	26.5	1.326	0.563	14.8	53.1		
40	"	A-III-10	"	-1	0	+1	300	0.485	42.4	2.123	0.902	11.7	40.7		
41	"	A-III-11	"	-1	0	-1	300	0.485	26.5	1.326	0.563	18.2	31.2		
42	"	A-III-12	"	0	+1	+1	400	0.610	42.4	2.123	0.902	16.5	33.7		
43	"	A-III-13	"	0	+1	-1	400	0.610	26.5	1.326	0.563	15.5	38.1		
44	"	A-III-14	"	0	-1	+1	400	0.355	42.4	2.123	0.902	15.8	32.3		
45	"	A-III-15	"	0	-1	-1	400	0.355	26.5	1.326	0.563	23.3	34.9		

Table A-4 Quantitative levels of independent variables and experimental results, test series 2 .

Run No.	Block No.	Code No.	Screen R.P.M.	Statistical combinations			Rotor speed, X1 R.P.M.	Air flow rate, X2 m ³ /sec.	Material flow rate, X3 Kg./min	Grain, Kg.	Chaff, Kg.	% chaff at the cleaning zone, Y1	% grain loss, Y2	Avg. of central points (Y1)	Avg. of central points (Y2)
1	1	B- I- 1	28.66	0	0	0	400	0.650	35.4	1.768	0.751	22.4	44.8		
2	"	B- I- 2	"	0	0	0	400	0.650	35.4	1.768	0.751	20.8	43.5	19.8	43.7
3	"	B- I- 3	"	0	0	0	400	0.650	35.4	1.768	0.751	16.4	42.9		
4	"	B- I- 4	"	+1	+1	0	500	0.800	35.4	1.768	0.751	14.5	54.8		
5	"	B- I- 5	"	+1	-1	0	500	0.500	35.4	1.768	0.751	13.7	38.9		
6	"	B- I- 6	"	-1	+1	0	300	0.800	35.4	1.768	0.751	13.3	39.6		
7	"	B- I- 7	"	-1	-1	0	300	0.500	35.4	1.768	0.751	14.6	33.2	3.1	0.9
8	"	B- I- 8	"	+1	0	+1	500	0.650	42.4	2.123	0.902	12.8	47.7		
9	"	B- I- 9	"	+1	0	-1	500	0.650	26.5	1.326	0.563	19.5	40.3		
10	"	B- I-10	"	-1	0	+1	300	0.650	42.4	2.123	0.902	14.2	41.8		
11	"	B- I-11	"	-1	0	-1	300	0.650	26.5	1.326	0.563	16.7	35.9		
12	"	B- I-12	"	0	+1	+1	400	0.800	42.4	2.123	0.902	16.5	44.8		
13	"	B- I-13	"	0	+1	-1	400	0.800	26.5	1.326	0.563	17.0	34.7		
14	"	B- I-14	"	0	-1	+1	400	0.500	42.4	2.123	0.902	13.7	35.9		
15	"	B- I-15	"	0	-1	-1	400	0.500	26.5	1.326	0.563	13.5	33.9		

Table A-5 (cont'd) Quantitative levels of independent variables and experimental results, test series 2 .

Run No.	Block No.	Code No.	Screen R.P.M.	Statistical combinations , X1 X2 X3	Rotor speed,X1 R.P.M.	Air flow rate, X2 m ³ /sec.	Material flow rate, X3 Kg./min	Grain, Kg.	Chaff, Kg.	% chaff at the cleaning zone,Y1	% grain loss, Y2	Avg. of central points(Y1)	Avg. of central points(Y2)
16	2	B-II- 1	35.83	0 0 0	400	0.650	35.4	1.768	0.751	24.9	59.7	19.7	58.5
17	"	B-II- 2	"	0 0 0	400	0.650	35.4	1.768	0.751	11.8	58.4		
18	"	B-II- 3	"	0 0 0	400	0.650	35.4	1.768	0.751	22.4	57.4		
19	"	B-II- 4	"	+1 +1 0	500	0.800	35.4	1.768	0.751	12.5	71.7		
20	"	B-II- 5	"	+1 -1 0	500	0.500	35.4	1.768	0.751	12.8	69.5		
21	"	B-II- 6	"	-1 +1 0	300	0.800	35.4	1.768	0.751	11.7	57.1		
22	"	B-II- 7	"	-1 -1 0	300	0.500	35.4	1.768	0.751	11.6	67.4	6.9	1.1
23	"	B-II- 8	"	+1 0 +1	500	0.650	42.4	2.123	0.902	12.7	67.0		
24	"	B-II- 9	"	+1 0 -1	500	0.650	26.5	1.326	0.563	13.8	55.3		
25	"	B-II-10	"	-1 0 +1	300	0.650	42.4	2.123	0.902	14.7	58.4		
26	"	B-II-11	"	-1 0 -1	300	0.650	26.5	1.326	0.563	11.7	57.0		
27	"	B-II-12	"	0 +1 +1	400	0.800	42.4	2.123	0.902	15.2	53.5		
28	"	B-II-13	"	0 +1 -1	400	0.800	26.5	1.326	0.563	18.8	57.5		
29	"	B-II-14	"	0 -1 +1	400	0.500	42.4	2.123	0.902	11.6	64.1		
30	"	B-II-15	"	0 -1 -1	400	0.500	26.5	1.326	0.563	13.3	59.6		

Table A-6 (cont'd) Quantitative levels of independent variables and experimental results, test series 2 .

Run No.	Block No..	Code No.	Screen R.P.M.	Statistical combinations, X1 X2 X3	Rotor speed, X1 R.P.M.	Air flow rate, X2 m ³ /sec.	Material flow rate, X3 Kg./min	Grain, Kg.	Chaff, Kg.	% chaff at the cleaning zone, Y1	% grain loss, Y2	Avg. of central points(Y1)	Avg. of central points(Y2)
31	3	B-III-1	43.0	0 0 0	400	0.650	35.4	1.768	0.751	14.5	68.2	13.1	66.6
32	"	B-III-2	"	0 0 0	400	0.650	35.4	1.768	0.751	11.6	69.7		
33	"	B-III-3	"	0 0 0	400	0.650	35.4	1.768	0.751	13.1	61.6	Std. deviation	Std. deviation
34	"	B-III-4	"	+1 +1 0	500	0.800	35.4	1.768	0.751	13.4	69.5		
35	"	B-III-5	"	+1 -1 0	500	0.500	35.4	1.768	0.751	9.6	68.8	Std. deviation	Std. deviation
36	"	B-III-6	"	-1 +1 0	300	0.800	35.4	1.768	0.751	10.6	56.4		
37	"	B-III-7	"	-1 -1 0	300	0.500	35.4	1.768	0.751	8.2	60.3	Std. deviation	Std. deviation
38	"	B-III-8	"	+1 0 +1	500	0.650	42.4	2.123	0.902	13.3	70.5		
39	"	B-III-9	"	+1 0 -1	500	0.650	26.5	1.326	0.563	13.8	67.6	Std. deviation	Std. deviation
40	"	B-III-10	"	-1 0 +1	300	0.650	42.4	2.123	0.902	11.4	58.1		
41	"	B-III-11	"	-1 0 -1	300	0.650	26.5	1.326	0.563	14.7	59.9	Std. deviation	Std. deviation
42	"	B-III-12	"	0 +1 +1	400	0.800	42.4	2.123	0.902	13.1	72.4		
43	"	B-III-13	"	0 +1 -1	400	0.800	26.5	1.326	0.563	12.2	56.7	Std. deviation	Std. deviation
44	"	B-III-14	"	0 -1 +1	400	0.500	42.4	2.123	0.902	9.4	70.5		
45	"	B-III-15	"	0 -1 -1	400	0.500	26.5	1.326	0.563	11.7	65.2	Std. deviation	Std. deviation

The following are the definitions of the statistical terms that are in the analysis of variance:

$$F = \frac{\text{Regression mean square}}{\text{Error mean square}}$$

SIG = Significance of F values. In other words, the smaller the value of SIG, the higher would be the significance of variables or their coefficients.

Regression coefficients = Coefficients of the regression equation.

$$TB = \frac{\text{Regression coefficient}}{\text{Standard error of regression coeff.}}$$

$$FB = TB \text{ squared}$$

Table A-7 Analysis of variance and regression coefficients for dependent variable Y1(% chaff at cleaning zone)
at ; screen R.P.M.= 33.33 , test series 1 .

DEPENDENT VARIABLE--X(4)										Y1
ANOVA FOR OVERALL REGRESSION										
	SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARE	F	SIG					
REGRESSION (ABOUT MEAN)	244.91601394	9	27.21289044	5.9983	.031					
ERROR	22.68398606	3	4.53679721							
TOTAL (ABOUT MEAN)	267.60000000	14								
MULTIPLE CORR COEFS										
CASES	R2	R	R BAR	STANDARD ERROR OF ESTIMATE						
15	.9152	.9567	.8733	2.12997587						
VAR	REGRESSION COEFFICIENTS	STD. ERRORS OF COEFFICIENTS	BETA WEIGHTS	STD. ERRS OF BETAS	TB	FB	SIG	PARTIAL CORR COEFS	R2 DELETES	
CONSTANT	85.32501428	44.40597392	0.00000	0.00000	1.9215	3.6921	.113	.53174	.85264	
X1	-.05408794	.10787495	-.93520	1.86519	-.5014	-.2514	.637	-.21880	.91097	
X2	-17.35415804	79.72650000	-.39008	1.79204	-.2177	-.0474	.836	-.39689	.91443	
X3	-2.85645566	1.42231887	-3.93688	1.96029	-2.0083	4.0333	.101	-.55920	.84683	
X150	-.80011250	.80011085	-1.56179	1.53885	-1.0149	1.0303	.357	-.41330	.89777	
X250	36.90224852	65.59021229	.80142	1.42137	.5638	-.3179	.597	.24450	.90984	
X350	.05063772	.01778801	4.79777	1.68469	2.8479	8.1103	.036	.79652	.77773	
X1X2	.15384515	.08192215	1.89825	1.81081	1.8780	3.5267	.119	.54312	.85544	
X1X3	.00230084	.00133580	1.89318	1.09912	1.7224	2.9668	.146	.61024	.86493	
X2X3	-3.13964025	1.02753490	-3.24495	1.06200	-3.0555	9.3361	.028	-.80699	.75695	

Table A-8 Analysis of variance and regression coefficients for dependent variable Y1 (% chaff at cleaning zone)
at ; screen R.P.M. = 53.33 , test series 1 .

DEPENDENT VARIABLE--X(4)										
Y1										
AOV FOR OVERALL REGRESSION										
		SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARE	F	SIG				
REGRESSION (ABOUT MEAN)		160.09224138	9	17.78082682	6.5200	.026				
ERROR		13.64109195	5	2.72821839						
TOTAL (ABOUT MEAN)		173.73333333	14							
CASES		MULTIPLE CORR COEFS			S			STANDARD ERROR OF ESTIMATE		
15		R ²	R	R BAR	1.65173194					
		.9215	.9599	.8833						
VAR	CONSTANT	REGRESSION COEFFICIENTS	STD. ERRORS OF COEFFICIENTS	BETA WEIGHTS	STD. ERRS OF BETAS	TB	FB	SIG	PARTIAL CORR COEFS	R ² DELETES
0	-149.92104658	109.95267050	.59165233	0.00000	0.00000	-1.3635	1.8591	.231	-.52062	.89223
X1	.51786046	91.81872729	.59165233	11.11261	11.62316	.9561	.9141	.383	.33314	.90713
X2	128.24573616	91.81872729	.59165233	3.57758	2.56140	1.3967	1.9508	.221	.52978	.89085
X3	1.82048955	1.55942056	.00067444	3.11397	2.66741	1.1674	1.3629	.296	.46281	.90009
X150	-.00062108	.00067444	.00067444	-10.70093	11.62026	-.9209	.8480	.399	-.39080	.90917
X250	-66.42301891	399.87819009	.10714226	-1.78643	10.73313	-.1664	.0277	.874	-.07423	.92105
X350	-.00025273	.00025273	.00025273	-.97805	12.59377	-.0770	.0059	.942	-.03443	.92133
X1X2	.00000000	.00000000	.00000000	.97203	.97203	.0000	.0000	1.000	.00000	.92149
X1X3	-.00018029	.00103507	.00103507	-.10242	1.05782	-.0968	.8394	.927	-.04326	.92134
X2X3	-2.26244344	12.94517482	.00103507	-3.51712	20.12416	-.1748	.8305	.868	-.07792	.92100

Table A-9 Analysis of variance and regression coefficients for dependent variable Y1 (% chaff at cleaning zone)
at ; screen R.P.M. = 80.0 , test series 1 .

		DEPENDENT VARIABLE--X(4)		Y1	
ANOVA FOR OVERALL REGRESSION					
		SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARE	F SIG
REGRESSION (ABOUT MEAN)		114.18669118	9	12.68741013	1.7263 .284
ERROR		36.74664215	5	7.34932843	
TOTAL (ABOUT MEAN)		150.93333333	14		
CASES					
		R2	R	R BAR	STANDARD ERROR OF ESTIMATE
15		.7565	.8698	.5642	2.71095448
MULTIPLE CORR COEFS					
		R2	R	R BAR	STANDARD ERROR OF ESTIMATE
		.7565	.8698	.5642	2.71095448
REGRESSION COEFFICIENTS					
VAR	REGRESSION COEFFICIENTS	STD. ERRORS OF COEFFICIENTS	BETA WEIGHTS	STD. ERRS OF BETAS	TB
CONSTANT	60.80237272	180.46377745	0.00000	0.00000	.3369
X1	.18015977	.08900638	4.14770	20.46715	.2027
X2	-210.60569440	150.70079054	-6.30356	4.51036	-1.3980
X3	-1.73582312	2.55945512	-3.18552	4.69702	-.6782
X150	-.00034265	.00110695	-6.33384	20.46204	-.3095
X250	528.19352593	655.00144157	15.24089	18.89990	.8064
X350	.07185281	.17585109	9.06124	22.17630	.4086
X1X2	.03846154	.10426786	.63189	1.71304	.3689
X1X3	.00227233	.00170016	2.48958	1.86271	1.3365
X2X3	-9.04977376	21.24673404	-15.09373	35.43652	-.4259
PARTIAL CORR COEFS					
		FB	SIG	PARTIAL CORR COEFS	DELTEES
		.1135	.750	.14899	.75101
		.0411	.847	.09026	.75454
		1.9543	.221	-.33013	.66137
		.4600	.528	-.29024	.73414
		.0958	.769	-.13712	.75187
		.6503	.437	.33925	.72497
		.1670	.700	.17976	.74941
		.1361	.727	.16276	.74941
		1.7863	.239	.51305	.66355
		.1814	.688	-.18712	.74770

Table A-1 (Analysis of variance and regression coefficients for dependent variable Y2 (% grain loss)
at ; screen R.P.M.= 33.33 , test series 1 .

DEPENDENT VARIABLE--X(S)										
ANOVA FOR OVERALL REGRESSION										
		SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARE	F	SIG				
REGRESSION (ABOUT MEAN)		173.52817987	9	19.28001999	16.5831	.003				
ERROR		5.81315346	5	1.16263069						
TOTAL (ABOUT MEAN)		179.33333333	14							
CASES										
		R2	R	R BAR	STANDARD ERROR OF ESTIMATE					
15		.9676	.9837	.9535	1.07825354					
MULTIPLE CORR COEFS										
		R2	R	R BAR	STANDARD ERROR OF ESTIMATE					
15		.9676	.9837	.9535	1.07825354					
REGRESSION COEFFS										
VAR	REGRESSION COEFFICIENTS	STD. ERRORS OF COEFFICIENTS	BETA WEIGHTS	STD. ERRS OF BETAS	TB	FB	SIG	PARTIAL CORR COEFS	R2 DELETES	
CONSTANT	-149.32794754	22.47954926	0.00000	0.00000	-6.6428	44.1273	.001	-.34775	.68150	
X1	.31854929	.05460932	6.72808	1.15348	5.8332	34.0267	.002	.33375	.74699	
X2	172.28343618	40.35979086	4.73044	1.10817	4.2687	18.2217	.008	.88582	.84945	
X3	3.44683326	.72001771	5.80310	1.21222	4.7872	22.9171	.003	.30603	.81901	
X1S0	-.00033417	.00005611	-6.00606	.95160	-6.3115	39.8356	.001	-.34259	.70933	
X2S0	-61.63708087	33.20360546	-1.63163	.87895	-1.8563	3.4468	.123	-.63875	.94524	
X3S0	-.036881745	.00900479	-4.49890	1.04179	-4.3108	18.5826	.008	-.88768	.84711	
X1X2	-.05769231	.04147129	-.86956	.62507	-1.3911	1.9353	.223	-.52825	.95504	
X1X3	.00060864	.00067622	.61176	.67968	.9001	.8101	.409	-.37341	.96233	
X2X3	-2.44379129	.52016699	-3.00535	.65672	-4.6981	22.8720	.003	-.30294	.82443	

Table A-1 Analysis of variance and regression coefficients for dependent variable Y2 (% grain loss)
at ; screen R.P.M. = 53.33 , test series 1 .

DEPENDENT VARIABLE--X(S)										Y2	
ANOVA FOR OVERALL REGRESSION											
SUM OF SQUARES		DEG OF FREEDOM		MEAN SQUARE		F		SIG			
REGRESSION (ABOUT MEAN)		9		93.89119985		4.4325		.055			
ERROR		5		21.18250837							
TOTAL (ABOUT MEAN)		14									
CASES											
15										STANDARD ERROR OF ESTIMATE 4.60244591	
VAR		R2		MULTIPLE CORR COEFS		R BAR		R BAR 2		PARTIAL CORR COEFS	
		.8886		.9427		.8295		.6881			
REGRESSION		STD. ERRORS		BETA		STD. ERRS		STD. ERRS		R2	
COEFFICIENTS		OF COEFFICIENTS		WEIGHTS		OF BETAS		OF BETAS		DELETES	
CONSTANT		-101.65262347		0.00000		0.00000		0.00000		.88617	
X1		.78314860		7.18314		13.84330		13.84330		.88262	
X2		-308.61468848		-3.67985		3.05066		3.05066		.85521	
X3		2.54780925		4.34522614		3.17691		3.17691		.88096	
X1S0		-.00082598		-6.08295		13.83985		13.83985		.88432	
X2S0		538.85545887		6.18532		12.78327		12.78327		.88341	
X3S0		.04608356		.29854509		14.99931		14.99931		.88909	
X1X2		.19230769		1.25873		1.15865		1.15865		.86233	
X1X3		-.00407662		-1.77790		1.25988		1.25988		.84419	
X2X3		-9.04977376		-6.01332		23.96889		23.96889		.88722	

ant; screen R.P.M. = 80.0, test series 1.

[illegible]

Table A-14 Analysis of variance and regression coefficients for dependent variable Y2 (% grain loss)
lumped model, four variables included , test series 1 .

DEPENDENT VARIABLE--X(6)									
ANOVA FOR OVERALL REGRESSION									
		SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARE	F	SIG			
REGRESSION (ABOUT MEAN)		6136.32448419	14	438.30889173	16.0870	<0.0005			
ERROR		844.63203755	31	27.24619476					
TOTAL (ABOUT MEAN)		6980.95652174	45						
CASES									
VAR	REGRESSION COEFFICIENTS	STD. ERRORS OF COEFFICIENTS	BETA WEIGHTS	STD. ERRS OF BETAS	T0	FB	SIG	PARTIAL CORR COEFS	R2 DELETES
CONSTANT	-87.85264359	88.93097169	0.00000	0.00000	-1.0855	1.1784	.285	-.17136	.87441
X1	7.89147349	1.66565673	5.54334	1.17109	4.7378	22.4463	<0.0005	.64806	.79140
X2	-23589697	.16736548	-1.50942	.98133	-1.5290	2.3378	.135	-.25481	.86949
X3	-33.42270237	119.34620442	-.25930	.92806	-.2800	.0784	.781	-.05023	.87473
X4	1.26663243	2.10822318	.60308	1.00712	.6008	.3610	.552	.10729	.87763
X1S0	-0.6324333	.00721641	-.436213	.49774	-8.7639	76.8051	<0.0005	-.84405	.57924
X2S0	.00014913	.00015912	.70223	.74919	.9373	.8786	.356	.16601	.87559
X3S0	-24.15234013	94.15667719	-.18061	.70410	-.2565	.0659	.793	-.34502	.87575
X4S0	-.03942447	.02553006	-1.29159	.83639	-1.5442	2.3847	.133	-.26726	.85370
X1X2	.00087169	.00182801	.30745	.64194	.4789	.2294	.635	.08570	.87911
X1X3	-3.27652491	1.38944120	-1.24263	.52695	-2.3582	5.5609	.023	-.39000	.85731
X1X4	-.01153449	.02264337	-.29591	.58287	-.5094	.2595	.614	-.09111	.87800
X2X3	.17307692	.11590948	.73199	.49021	1.4932	2.2297	.143	.23963	.87031
X2X4	.00177348	.00180998	.49950	.53263	.9384	.8805	.355	.15619	.87557
X3X4	2.08111542	1.53701543	1.11630	.59552	1.8745	3.5137	.070	.31907	.86530
MULTIPLE CORR COEFS									
	R2	R	R BAR	R BAR 2	STANDARD ERROR OF ESTIMATE				
46	.8790	.9376	.9079	.8244	5.21978877				

at, screen R.P.M. = 28.66 , test series 2 .

DEPENDENT VARIABLE--X(4)										Y1
AOV FOR OVERALL REGRESSION										
	SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARE	F	SIG					
REGRESSION (ABOUT MEAN)	89.13417763	3	9.90379751	1.5190	.336					
ERROR	32.59915370	5	6.51983114							
TOTAL (ABOUT MEAN)	121.73333333	14								
MULTIPLE CORR COEFS										
	A2	R	R BAR 2	R BAR	STANDARD ERROR OF ESTIMATE					
CASES					2.55339600					
15	.7322	.8597	.2502	.5002						
VAR	REGRESSION COEFFICIENTS	STD. ERRORS OF COEFFICIENTS	BETA WEIGHTS	STD. ERMS OF BETAS	TB	FB	SIG	PARTIAL CORR COEFS	A2 DELETES	
CONSTANT	0	-114.30646357	53.23346282	0.00000	-2.1473	4.6109	.093	-.53264	.48525	
X1	1	.25122801	-12931952	3.31516	1.9427	3.7741	.110	.65585	.53008	
X2	2	162.75490355	95.57541429	3.18515	1.9122	3.6563	.114	.53639	.53639	
X3	3	2.34307724	1.70506312	4.78795	1.3742	1.8804	.229	.52359	.63107	
X1X3	6	-.00026567	.00013284	5.48679	-2.0068	4.0272	.101	-.85792	.51652	
X2X3	7	-187.37672504	78.62695917	-6.02034	-2.3830	5.6789	.063	-.72924	.42805	
X3X3	8	-.02481297	.02132411	-3.48426	-1.1636	1.3540	.297	-.6162	.65969	
X1X2	9	.03846154	.09828754	.70351	.5316	.1534	.711	.17252	.73393	
X1X3	10	-.00158011	.00160134	-1.92766	-.9867	.9737	.369	-.40372	.68076	
X2X3	11	-.33052826	1.23179963	-.58649	-.2683	.0720	.799	-.11915	.72933	

Table A - 1 Analysis of variance and regression coefficients for dependent variable Y1 (% chaff in cleaning zone)
at ; screen R.P.M.= 36.83 , test series 2 .

		DEPENDENT VARIABLE--X(4)		Y1				
ANOVA FOR OVERALL REGRESSION								
		SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARE	F	SIG		
REGRESSION (ABOUT MEAN)		120.76748737	9	13.41860971	.5627	.796		
ERROR		119.23251263	5	23.84650253				
TOTAL (ABOUT MEAN)		240.00000000	14					
CASES		MULTIPLE CORR COEFS		STANDARD ERROR OF ESTIMATE				
15		R2	R	R BAR	4.00326809			
		.5032	.7094	0.0000				
VAR	REGRESSION COEFFICIENTS	STD. ERRORS OF COEFFICIENTS	BETA WEIGHTS	STD. ERRS OF BETAS	FB	SIG	PARTIAL CORR COEFS	DELETES
CONSTANT	0	-16.61796735	325.07125036	0.00000	0.0000	.0026	-.02286	.50294
X1	1	-.23975318	1.60137638	-4.37727	29.23700	.0224	-.35681	.50397
X2	2	69.14375218	271.45887726	1.64110	6.44298	.0649	.11316	.49675
X3	3	3.90144030	4.61037271	5.79431	6.70962	.7458	.36027	.42910
X150	6	.00035508	.00199396	5.21691	29.22971	.0319	.37957	.50003
X250	7	-.654.36825518	1179.06080427	-14.97351	26.99822	.3076	-.24074	.47253
X350	8	-.16013707	.31676237	-16.01485	31.67849	.2556	-.22052	.47790
X1X2	9	-.00000000	.18781877	-.00000	2.44706	.0000	-.00000	.50320
X1X3	10	-.00121728	.00306251	-1.05763	2.66085	.1500	-.17501	.48750
X2X3	11	15.83710407	38.27195960	20.94699	50.62051	.1712	.19197	.48618

Table A-17 Analysis of variance and regression coefficients for dependent variable Y1 (% chaff at cleaning zone)
at screen R.P.M. = 43.00 , test series 2 .

DEPENDENT VARIABLE--X(4)									
AOV FOR OVERALL REGRESSION									
	SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARE	F	SIG				
REGRESSION (ABOUT MEAN)	45.48379448	9	5.05375494	4.1314	.066				
ERROR	6.11628552	5	1.22324110						
TOTAL (ABOUT MEAN)	51.60008000	14							
MULTIPLE CORR COEFS									
CASES	R	R BAR	R BAR 2	R BAR	STANDARD ERROR OF ESTIMATE				
15	.9389	.6601	.4398	.8174	1.10600231				
VAR	REGRESSION COEFFICIENTS	STD. ERRORS OF COEFFICIENTS	BETA WEIGHTS	STD. ERRS OF BETAS	TB	FB	SIG	PARTIAL CORR COEFS	R2 DELETES
CONSTANT	14.67889233	23.05885867	0.00000	0.00000	.6366	.4033	.552	.27382	.87186
X1	-.00000769	.05601469	-.00030	2.20358	-.0001	.0000	1.000	-.00006	.88147
X2	87.92249486	41.39844607	4.50033	2.11908	2.1238	4.5106	.097	.59867	.77454
X3	-1.48690507	.73654731	-4.66687	2.31804	-2.0133	4.0533	.103	-.65912	.78518
X1X2	-.00005833	.00005756	-1.84419	1.81968	-1.0135	1.0271	.357	-.41281	.85712
X2X3	-123.27416174	34.05809768	-6.08355	1.68076	-3.6195	13.1010	.013	-.85075	.57083
X3X3	.00981446	.00233633	2.11679	1.99214	1.0626	1.1291	.337	.42920	.85470
X1X2	.03846154	.04253855	1.08072	1.19328	.9042	.8175	.407	.37487	.86209
X1X3	.00098018	.0069362	1.85166	1.29971	1.4247	2.0297	.214	.53734	.83335
X2X3	.73442319	.53555345	1.72859	1.25581	1.3765	1.8947	.227	.52422	.83655

Table A-18 Analysis of variance and regression coefficients for dependent variable Y2 (% grain in tailings)
at screen R.P.M. = 28.66 , test series 2 .

DEPENDENT VARIABLE--X(5)										Y2	
ANO FOR OVERALL REGRESSION											
		SUM OF SQUARES		DEG OF FREEDOM		MEAN SQUARE		F		SIG	
REGRESSION (ABOUT MEAN)		452.34147526		9		50.26016392		9.1743		.013	
ERROR		27.39185808		5		5.47837162					
TOTAL (ABOUT MEAN)		479.73333333		14							
CASES											
15		R2 .9429		R .9710		MULTIPLE CORR COEFS R BAR 2 .8401		R BAR .9166		STANDARD ERROR OF ESTIMATE 2.34059215	
VAR	REGRESSION COEFFICIENTS	STD. ERRORS OF COEFFICIENTS	BETA WEIGHTS	STD. ERRS OF BETAS	TB	FB	SIG	PARTIAL CORR COEFS	R2 DELETES		
CONSTANT	-5.29751341	48.79692455	0.00000	0.00000	-.1086	.0110	.910	-.04849	.94277		
X1	-.15970892	.11854184	-2.06241	1.53079	-1.3473	1.8152	.236	-.51608	.92217		
X2	58.87428511	87.61001597	.98036	1.47076	.6720	.4516	.531	.23781	.93774		
X3	2.56350952	1.56296060	2.63877	1.60885	1.6402	2.6901	.162	.59145	.91218		
X1X0	.00011258	.00012181	1.16645	1.26296	.9236	.8530	.399	.38176	.93316		
X2X0	-184.91124260	72.07590382	-2.99277	1.16654	-2.5655	6.5818	.050	-.75395	.86774		
X3X0	-.04866966	.81954693	-3.44267	1.38266	-2.4699	6.1995	.055	-.74401	.87211		
X1X2	.19230769	.09002278	1.77218	.82959	2.1362	4.5634	.085	.63078	.89073		
X1X3	.00046312	.00146788	.28460	.90207	.3155	.0995	.765	.13971	.94177		
X2X3	2.07047058	1.12913961	1.60441	.07160	1.0408	3.3804	.125	.53556	.90421		

TableA-19 Analysis of variance and regression coefficients for dependent variable Y2 (% grain in tailings)
at screen R.P.M.= 35.83 , test series 2 .

DEPENDENT VARIABLE--X(19)										Y2
ANOVA FOR OVERALL REGRESSION										
		SUM OF SQUARES	DEG OF FREEDOM	MEAN SQUARE	F	SIG				
REGRESSION (ABOUT MEAN)		449.62514470	9	49.9534941	5.9321	.032				
ERROR		42.10810863	3	0.02163773						
TOTAL (ABOUT MEAN)		491.73333333	14							
CASES										
15		R2	R	R BAR	STANDARD ERROR OF ESTIMATE					
		.9144	.9562	.8719	2.90200581					
		MULTIPLE CORR COEFS								
		R BAR 2	R BAR 2	R BAR	STANDARD ERROR OF ESTIMATE					
			.7602		2.90200581					
VAR	REGRESSION COEFFICIENTS	STD. ERRORS OF COEFFICIENTS	BETA WEIGHTS	STD. ERRS OF BETAS	YB	FB	SIG	PARTIAL CORR COEFS	DELETES	
CONSTANT	0	652.25410160	193.18103723	0.00000	3.3764	11.4000	.020	.83374	.71913	
X1	1	-2.81192287	.95165455	12.13835	-2.9548	8.7307	.032	-.79740	.76444	
X2	2	-629.37695788	-10.43601	2.67494	3.9014	15.2209	.011	-.86760	.65369	
X3	3	7.05220271	7.17014	2.78564	2.5740	6.6253	.050	.73492	.80093	
X15Q	6	.00325588	33.34391	12.13532	2.7477	7.5497	.040	.77562	.79507	
X25Q	7	-1453.18482423	-23.23090	11.20887	-2.0725	4.2954	.093	-.87978	.84080	
X35Q	8	-.49554000	-34.62186	13.15198	-2.6324	6.9298	.046	-.75215	.79553	
X1X2	9	.23076323	2.18050	1.01595	2.0675	4.2747	.094	.57890	.84116	
X1X3	10	.00358990	.00181997	1.10471	1.9725	3.8909	.106	.65153	.84773	
X2X3	11	54.23864253	50.17364	21.01615	2.3874	5.6996	.063	.72986	.81675	

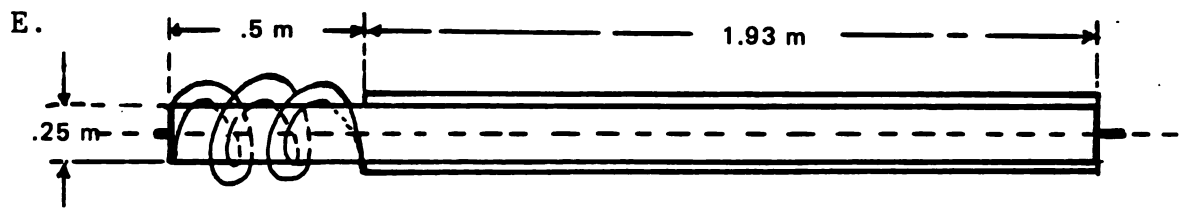
DEPENDENT VARIABLE--X(6)

AOV FOR OVERALL REGRESSION

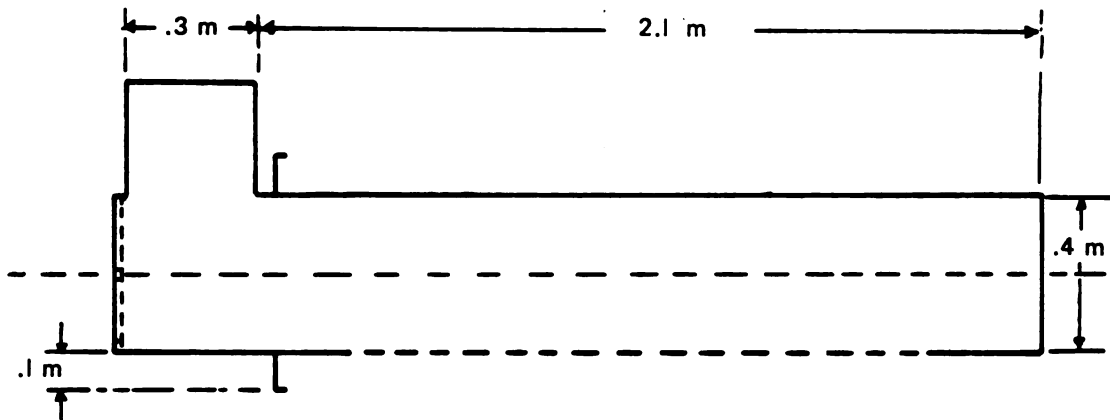
Y2

S
STANDARD ERROR OF ESTIMATE
5.02597569

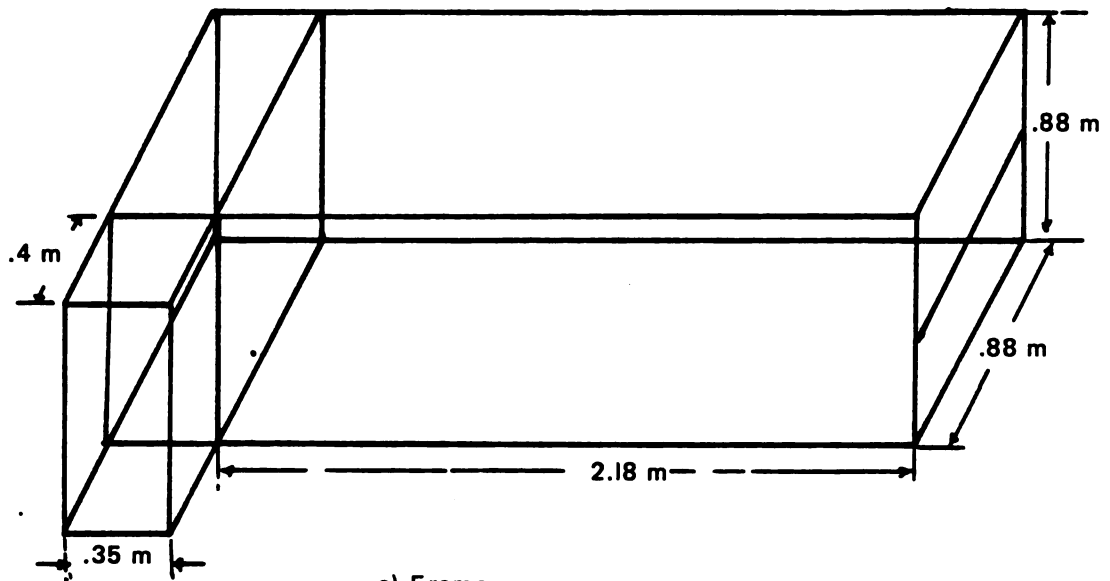
CASES	VAR	REGRESSION COEFFICIENTS	STD. ERRORS OF COEFFICIENTS	BETA WEIGHTS	MULTIPLE CORR R	COEFFS R BAR
44	CONSTANT	-109.25442585	64.78334642	0.0000		0.0000
	X1	1.25327126	.50163498	2.16919		.86
	X2	.25181596	.16013849	1.75019		1.07019
	X3	-24.045334955	109.25348664	1.20444		.89444
	X4	2.40571523	1.08982565	1.25150		.98150
	X1X0	-.00537809	.00307235	-1.06150		.68150
	X2X0	-.00016395	.00016635	-.08012		.89
	X3X0	65.80765943	98.54951255	.54104		.95104
	X4X0	-.01014938	.02666698	-.36368		.93668
	X1X2	-.00006804	.00053664	-.04814		.42
	X1X3	-.41331656	.45151166	-.44621		.44
	X1X4	.00220758	.00738601	.15122		.50
	X2X3	.05769231	1.1160571	-.27308		.52308
	X2X4	-.00318807	.00181981	-1.00350		.57
	X3X4	-1.95320512	2.00174195	-.69221		.89221



a) Rotor



b) Fixed cylinder



c) Frame

Fig. 54 Schematic diagram of the rotor, fixed cylinder and frame