MODELLING THE PERFORMANCE OF SELECTED STATIONARY GRAIN THRESHERS

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DECLARATION

I hereby declare that this thesis has been written by me and that it is a record of my own research work. It has not been presented before in any previous application for a higher degree. All the sources of information which are not my own have been specifically acknowledged by means of references.

Signed:----------

NDIRIKA, VICTOR IFEANYI OBIORA

1997

DEDICATION

I dedicate this work to my beloved wife, Mrs. Maryann Chinwe Ndirika and my daughter, Onyeka Deborah Ndirika with profound affection for their love and encouragement.

CERTIFICATION

This thesis has been read and certified as meeting the requirements for the award of the degree of Doctor of Philosophy, Ph.D (Agricultural Engineering) of the Ahmadu Bello University, Zaria.

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Ndirika, V. I. O

ABSTRACT

Simulation can be achieved by setting up a model, of a real situation (system) and then performing experiments on the model. It is widely used as a research and management tool in Engineering analysis, design and industry because of the complexity of agricultural systems.

In this thesis, simulation models for stationary grain threshers were developed for predicting threshing performance, through careful selection of various threshing parameters and operating conditions in selected stationary grain threshers with a throw-in feedrate system.

The formulated models were verified and validated with established experimental data from stationary mechanical sorghum and millet threshers. All the models were found to correlate and fit well with the experimental data with R-square values greater than 0.91 at 0.001 level of significance. A higher correlation was also achieved with the overall threshing efficiency model with R-square value of 0.99 at 0.001 level of significance when compared with the existing models.

A computer simulation programme was also developed and used at three factor interaction of the process variables to obtain variables for optimum (minimum) grain loss for millet- and sorghum threshers. The utility of this programme is demonstrated in selecting least or minimum grain loss for various combination of process variables. The result obtained from the simulation

revealed that a minimum grain loss of 0.09% was obtained for the millet thresher and 0.35% for the sorghum thresher at 9% grain moisture content, cylinder speed of 5 m/s and feedrate of 0.03 kg/s. These compare favourably with a minimum grain loss of 0.10% and 0.46% respectively, for millet and sorghum obtained from actual measurements at the same values of the parameters.

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LIST OF SYMBOLS

Symbols

a,b,c,d,e,f,g: Power to which dimensional variables are raised

a': Acceleration due to gravitational force and centrifugal acceleration of the cylinder, m/s

a_1: Centreline distance between rods, m

a_2: The rod diameter, m

b_1: Centreline distance between bars, m

b_2: width of the bar, m

C: Concave clearance, m

C_T: Thresher capacity, kgs/sec.

CV: Coefficient of variation, %

d_1: Average size of grain, m

D: Effective diameter of the cylinder, m

D_f: Damage fraction, decimal

D_s: Standard cylinder diameter used for comparism, m

E: Energy required to detach the grain from the panicle, Nm/s

E_n: Energy needed per unit area of impact, Nm/s

E_o: Minimum energy to cause grain damage Nm/s

F: Frictional force to be overcomed before the crop material could move around the concave,

F': Force required to turn the threshing cylinder without load, N

F_r: Feedrate, kg/s

F_c: Force generated on the earhead, N

g': Acceleration due to gravitation, m/s^2

K: Dimenmsionless constant in dimensionless equation

K_a: Friction force coefficient

K_b: slippage factor for beater bar velocity at the exit of the concave

K_d: Damage constant

K_e: Dimensionless constant (energy coefficient)

K_f: Friction Power Constant

K_h: Constant

K_h': Dimension less constant for damage power.

K_m: Yield factor (dimensionless)

K_n: Constant containing all the constant factor in eqn. 3.121

K_s: Dimensionless Constant

K_T: Constant or threshing factor (dimensionless)

L: Dimension for length

L_c: Concave length, m

M: Dimension for mass

m: Mass of earhead/sec, kg/s

M_c: Mass of the threshing cylinder, kg

M_d: Moisture content dry basis, decimal

M_w: Moisture content wet basis, decimal

n: Number of impact

n': Number of bars

N: cylinder speed without load, rpm

P: Total power required for threshing operation, Watt

P_l: Probability of grain passage through the concave opening

P_c: Power transmmitted uniformly onto the concaves surface, watt

P_d: Power required to damage grain in their binding, Watt

$P_{f:}$ Power required to overcome frictional force, Watt

$P_{in:}$ *Input power generated by the beaters or bars*, Watt.

$P_{o:}$ Optimum power oputput generated by the beater bars, Watt

$P_{out:}$ Out put power, Watt

$P_{r:}$ Power required to run the cylinder without load, Watt

$P_{T:}$ Power required to detach the grains from the panicle, Watt

r: Radius of driven pulley of the cylinder, m

R: Coefficient of regression

R^2: Coefficient of determination

$R_{T:}$ Transmisssion ratio

S: Crop stream thickness, m

S_e: Separation efficiency, decimal

t: Time interval through the concave opening, sec

$t_{a:}$ Time interval for the first two event, sec.

$t_{d:}$ Dwell time for crop in the thresher, sec.

t_d': Dwell time for threshed grain in the threshing zone, sec

t_d'': Dwell time for damaged grain after impact, sec.

$t_{f:}$ Time required for the first event (threshing) to occur, sec.

$t_{o:}$ Available time for a grain passing through a given opening at a distance, b1 between bars, sec.

$t_{s:}$ Time required for the second event to occur, sec.

$t_{1:}$ Time of occurance of the random event (threshing of grain), sec.

$t_{2:}$ Mean time for a grain to pass through the crop stream thickness, sec.

T: Dimension for time.

T': Torque required to turn the threshing cylinder without load Nm

T_e: Threshing efficiency parameter, decimal

T_L Threshing loss, decimal

T_1 The average time elapsed between the entry of crop into the thresher and the threshing of a grain, sec.

T_2 Meantime for a grain to pass through the crop stream thickness, sec.

U: Grain velocity from rest, m/s

U_d: Maximum tangential velocity of the damaged grain after impact, m/s

V: Volume occupied by the material, m^3

V_b: Peripheral velocity of the beater, m/s

V_c: Crop velocity, m/s

V_d: Minimum cylinder velocity that will cause vissible grain damage, m/s

V_f: Linear velocity of the feeder, m/s

V_g: Velocity of grain after impact, m/s

W_d: Mass of dried material, kg.

W_m: Mass of wet material, kg.

W_w: Mass of water removed, kg.

X: Mean value

Y_o: Objective function

Z: Grain-straw ratio

&: Sign of proportionality

ß: Moisture content of crop under wet condition, decimals

µ: Dimensional constant, refered to as the coefficient of motion resistance of crop stream on the concave.

σ': Pressure of the crop stream N/m^2

σ: Standard deviation from the mean value

ϱ_d: Bulk density (dry basis) kg/m^3

ϱ_w: Bulk density (wet basis) kg/m^3

η_p: Power efficiency, decimal

λ: Mean rate of random event, sec^{-1}

λ_d: Mean rate of damage grain, sec^{-1}

λ_1: Mean rate of threshing per impact, sec^{-1}

λ_2: Rate of grain migration through the crop stream, sec^{-1}

λ_3: Rate of grain passage through the concave opening, sec^{-1}

ω: Angular velocity of cylinder

π: Pi term, dimensionless

Σ: Sumation.

LIST OF ABBREVIATIONS

CV : Coefficient of Variation

dec.: decimal

dF : Degree of freedom

Eqn.: Equation

Fig.: Figure

K.E : Kinetic Energy

Min.: Minimum

MTGL: Minimum total grain loss

n.s : Not significant

Opt.: Optimum

S.E.: Standard Error

TGL Total grain loss

CHAPTER ONE

INTRODUCTION

1.1 Statement Of Problem

One of the most critical post harvest operations is the threshing of crop. Threshing involves, among others, the detachment of grain kernels from the panicles. It is one of the most important post-harvest operations for cereal. Beating with pestle or stick and bullock treading of the harvested crops have been the traditional methods for threshing crops. The output of these methods is low, leading to delays in handling a large volume of produce and consequent losses while the cost of operation has been quite high (Singh and Joshi, 1979).

Engine-powered threshers such as mechanically operated stationary threshing machine and grain combines have become popular to overcome these difficulties. However, the existing economic structure of agricultural production, coupled with the small size of farms in developing countries make the use of grain combines uneconomical. On the other hand, threshing process that requires 4 days using the traditional method may be accomplished in less than 2 hours using mechanically operated stationary thresher (Ghaly, 1973).

The cereal threshers, if used for pulse threshing results in excessive kernel damage. Such damages can be as high as 40-50% (Tandon et al., 1988). There is also the problem of separation of the seeds from straw. Very little information is available at present about crop, machine and operational parameters pertaining

to the performance of cereal threshers. Moreover, the manufacturers of grain threshers have not been completely unanimous in their views on cylinder concave configurations (Trollope, 1982). Therefore, in developing a stationary cereal thresher, such parameters as cylinder peripheral speed, feed rate, cylinder concave configurations and moisture content, etc., have to be studied.

Recent studies on cereal threshing using mechanical thresher indicate that threshing effectiveness is dependent on crop moisture content (Hoky and Pickett, 1973; Singh, 1975; Singh and Agarwal, 1970). Both threshing effectiveness and damage are influenced by such other factors as temperature, humidity, wind velocity and length of storage of crop after harvesting (Singh and Bachchan, 1981). Machine parameters such as cylinder speed and concave clearance also affect threshing effectiveness and damage of the grain.

Modeling of the threshing and separation process would provide better understanding of the fundamental relationship of different machine and crop variables in order to identify the contribution of each variable. This can be achieved by the use of prediction equations to identify the independent variables (moisture content, feed rate, cylinder speed, etc.) in the order of their contributions to the total variation on the dependent variables (threshing efficiency, grain loss, output capacity, power requirement, etc). However, this information could be useful in assessing the relative importance of various factors influencing

the dependent variable.

In previous studies, most of the models developed for predicting thresher performance were for combine systems which have different crop model from stationary mechanical thresher as found in the models developed by Trollope (1982), Gregory (1988) and Glosberg and Mcgechan (1983). Only few of the models have been applied to rate the performances of grain threshers and most of them could not give a clear explanation on how some of the physical parameters were derived. For instance, Trollope (1982) could not provide exact solutions to the derived equations and his work did not relate the process variable equation to performance characteristic of the threshing process.

In order to select the best interraction among the process variables, there is need to apply Minimization technique on the physical Models to minimize grain losses.

To this end, it is therefore necessary to develop a mathematical model for predicting the threshing and separation processes for stationary grain threshers.

1.2 Objectives Of The Study

The overall objective of this work was to provide an understanding of the parameters affecting the performance of stationary grain threshers.

The specific objectives of the study were:

1. To develop mathematical models for describing the threshing and separation processes of stationary grain threshers.
2. To predict thresher performance using the developed models.
3. To verify and validate the developed models on existing prototypes.
4. To simulate and optimize the performance parameters to obtain variables for minimum loss.

CHAPTER TWO

LITERATURE REVIEW

The crop physical properties influencing threshability, the criteria for evaluating threshing performance, the effects of crop and machine parameter on threshing performance and the previous results of mathematical modeling of grain threshing and separation processes are all discussed in this chapter.

2.1 Crop Physical Properties Influencing Threshability

Some physical properties of cereal crops such as moisture content, bulk density, size of grain and straw-grain ratio are necessary in the design of a grain threshing unit. The moisture content of grain or straw which is determined on wet basis gives the safe range of efficient threshing and grain damage. From various studies (Arnold, 1964; King and Riddols, 1960; Nath et al., 1982; Tandon et al., 1988), it was found that moisture content influences threshability and kernel damage. It was also that straw moisture content has greater effect on threshing performance than grain moisture content.

Dash and Das (1990) reported that there was a range of moisture content for which threshing efficiency, grain damage and output capacity could be affected. Beyond this range, any increase in moisture content had no significant effect in the above performance parameters. The bulk density, which is the weight per unit volume of material, commonly expressed as Kilogramme per cubic meter, is dependent upon the degree of

packing.

Information is limited on how bulk density affects threshability and grain damage. The importance of bulk density is seen in the determination of thresher output capacity and cushioning effect of the material in the cylinder - concave unit. The straw-grain ratio is found by weighing the straw and grain separately after separating the grain from the stalk head, or ear head. The straw-grain ratio finds its usefulness in the determination of the thresher output capacity. (Enaburekhon, 1994).

The size of grain helps in deciding the distance between the two rods in the cylinder concave assembly. The size of grain (millet and sorghum) is found by measuring the length, width and thickness of the grain.

2.2 Criteria For Evaluating Threshing Performance

From available literature on the various stationary mechanical threshers, it was identified that the performance criteria or parameters for evaluating different threshing mechanisms are:

i. Threshing efficiency;

ii. Grain loss or damage;

iii. Grain output capacity;

iv. Power requirement.

These criteria are measured against the following design variables:

i. Crop moisture content

ii. Concave length

iii. Crop feedrate

iv. Concave clearance

v. Cylinder threshing speed

vi. Cylinder width

vii Cylinder diameter

The definitions of these variables considered in this study are as follows (Enaburekhon, 1994):

Threshing efficiency: This is the ratio of grain threshed (by weight) during initial threshing to the total expressed as a percent (or quantity of threshed grain in a sample to total grain in the sample expressed as percent).

Total grain loss: The sum of threshing loss and grain damage loss.

Grain Damage Loss: This is the loss due to mechanical damage of grain as determined by visual examination and can be expressed as the ratio of broken, cracked, or chipped kernels, to the total expressed as percent.

Grain Output Capacity: This is the amount of grain threshed in an hour expressed in kg per hour.

Power Requirement: This is the kilowatt power required to thresh a given quantity of crop material.

Grain Moisture Content: The weight of moisture per unit weight of grain/straw expressed in percent.

Crop Feedrate: The total material including grain, straw and

chaff that passes through the threshing unit measured in kg/hr.

Concave Clearance: The distance between the cylinder bar or spike tooth and the front concave bar measured in mm.

Cylinder Threshing Speed: This is the peripheral speed of the cylinder measured in rev. per min or m/s.

Cylinder Diameter: The diameter of the circle generated by the outer-most point of the cylinder threshing element expressed in meters.

Cylinder width: The length of the cylinder bar measured parallel to the cylinder axis expressed in meters.

Concave length: The distance from the front of the first bar to the rear of the last bar measured around the contour formed by the inner surface of the bars.

2.3 Effect of Crop And Machine Parameters on Threshing Performance.

Vas and Harrison (1969) studied the effect of selected mechanical parameters on kernel damage and threshability of wheat. They reported that the cylinder speed was the primary influencing parameter while concave clearance, although of less significance, was an important factor as well. The effect of three parameters on threshability and kernel damage was described on the basis of "impact model". An increase in feed rate resulted in a decrease in mechanical damage which was described as a result of cushioning effect at higher feed rates. This cushioning did not affect the threshability which

should have decreased in reality. Since this was not supported by the results, therefore, a "frictional model" was developed. According to this model, increased feed rate might have increased the crop stream density which in turn increased the frictional forces between particles in the crop stream. Thus, the cushioning effect of the impact model may have tended to decrease the threshability but was restricted by the frictional model in threshability. The rubbing effect of the frictional model would not result in damaged kernel. In other words, the effect of cylinder speed, concave clearance and feed rate on threshability and grain damage may be described on the basis of an "impact friction" model. They also confirmed that the mechanical parameters causing significant variation in percentage mechanical damage were cylinder speed, concave clearance and feedrate.

Klein and Harmond (1966) studied the effect of varying cylinder speed and clearance on three different threshing cylinders. They tried to determine cylinder type and its setting for efficient threshing without increasing the broken and damaged grain. The cylinders tested were: (i) spike-toothed (ii) rubber covered angle bar and (iii) rubber covered flat bar and their optimum peripheral speed and clearance were 25.75 m/s and 0.40 cm; 20.9 m/s and 0.40 cm; and 24.53 m/s and 0.08 to 0.32 cm respectively. The rubber covered flat bar cylinder recovered about 10% more crimson clover seed than the two cylinders and unthreshed seed loss was reduced to about 5%

in the process.

Singh and Kumar (1976) studied the effect of swinging hammer, spike toothed and rasp bar cylinders on threshing effectiveness and damage of wheat. The cylinder speed was found to be an important variable in unthreshed grain and damage model. Increase in cylinder speed and decrease in concave clearance decreased the rate of unthreshed grain and increased grain damage and power requirement. The swinging hammer type cylinder consumed more power than the rasp bar and spike tooth cylinders.

Goss et al. (1958) found that at a given feed rate (straw and chaff only) an increase in straw grain ratio caused increase in shoe free seed loss. Although the effect was usually small, the increased feedrate tends to reduce seed damage (Arnold, 1964). Dodds (1968) reported that with an increase in feed rate the power requirement at main shaft increased. The spike toothed cylinder required less power and had more positive feeding action than the rasp bar cylinder.

An axial flow, cone shaped apparatus was tested on wheat by Lalor and Buchele (1963) and at 300 to 500 rpm speed of the rotor, 99% threshing efficiency was attained. Below 350 rpm there was problem in the feeding mechanism whereas it worked satisfactorily for higher speeds. There was decrease in overall separating efficiency from 77 to 68% as the rotor speed was increased from 300 to 500 rpm. A cone length of 213.4 cm was extrapolated to achieve 98% separation

efficiency.

Harrington (1970) designed a multicrop thresher having spike toothed cylinder and fixed concave on the basis of acceptance of Japanese paddy threshers and American wheat threshers which used spike-tooth cylinders. The clearance was fixed at 2.5 cm. The losses in paddy and wheat were 3%. The thresher was not suitable for straw making as it normally reduced wheat straw to 25-50% original length depending upon cylinder speed and moisture condition. The cylinder tip speed ranged between 20 m/s and 23.3 m/s resulting in less than 0.1% unthreshed grain and between 13.3 and 16.67 m/s resulted in less than 0.1% visible damage. The unthreshed grains were less than 1.0%.

Singh and Joshi (1977) reported that the Japanese type thresher of 40 cm drum diameter and 90 cm width rotating at 400 rpm by a 3 hp electric motor gave an output of 145 kg/h. A rasp bar thresher of 28.5 cm drum diameter and 32 cm width gave output of 139 kg/h of clean paddy. The energy needed per 50.80 kg of threshing and cleaning was 0.36 hp/h of manual and 1.64 hp/h electrical energy. For throw-in feed rate rasp bar thresher it was 0.44 hp/h of manual and 0.72 hp/h of electrical energy.

As reported by Chhabra (1975), the adequate drum length for an axial flow thresher was 203.2 cm at IRRI and any further reduction in the length caused separation losses. The concave area was increased from 0.73m^2 to 2.09m^2 by using two

concaves, an improvement in separation efficiency was observed.

A threshing output of up to 660 kg/h with 1% separating and threshing loss was obtained when a 35.6 cm diameter and 127 cm long wire loop type threshing drum was used. The length of the cylinder can be reduced by increasing the concave area to obtain desired separating efficiency. The studies made on varying cylinder-concave clearance and pitch of wire loops indicated a 1.9 cm and 10.2 cm pitch as optimum.

Chhabra (1975) developed and tested an axial flow thresher on the basis of drawing procured from IRRI. He found that it can thresh paddy and wheat quite efficiently. In paddy threshing at 500 rpm (13.23 m/s peripheral speed) the threshing efficiency was 10% and the feed rate was 710 kg/h, which resulted into an output of 213 kg clean grain per hour. In wheat threshing at 700 rpm (18.51 m/s peripheral speed) and 63.5 mm peg spacing, threshing efficiency, external damage and separation losses were 99.63, 0.47, and 2.4% respectively. A feed rate of 960 kg/h gave 340 kg/h clean grain. However, the quality of wheat straw was poor and only 65% of the straw was worth cattle feed.

Test reports on some existing wheat thresher of India has been published by P.A.U, Ludhiana. Most of these threshers have the peg-tooth type cylinders with round or rectangular cross-section of pegs. The cylinder diameter varies between 304.8 to 430 mm whereas the length of cylinder varies between

279.4 to 330.2 mm for the peg-type cylinders. In beater bar type threshers, the cylinder diameter and length varies from 660 to 890 mm and 230 to 270 mm, respectively. The ranges for cylinder tip speed, clearance and capacity for the peg-toothed type threshers are 12.78 to 19.16 m/s, 25 to 27 mm and 0.0195 to 0.0268 kg/s, respectively wheareas for beater bar type threshers, these values are 17.91 to 24.16 m/s, 20 to 45 mm and 0.0298 to 0.0360 kg/s, respectively. The energy required by these threshers per 50.80 kg of clean grain is 1.25 to 4.89 kWh.

Tandon et al. (1988) used the step-wise multiple regression technique to study the relationship between different independent variables, namely, cylinder types, concave clearance, cylinder peripheral speed and moisture content in relation to the two dependent variables, namely, threshing efficiency and invisible grain damage on pulse grains. An experimental model of pulse thresher without a cleaning and separating unit was developed. It has the provision to change the machine and operational parameters. The moisture content was found to have a significant effect on threshing efficiency and invisible grain damage. The effect of concave clearance and cylinder peripheral speed, though numerically small, was significant at 5% level.

Singh and Bachchan (1981) reported the effect of crop and machine parameters on threshing effectiveness and seed quality of soyabean. The effect of moisture content,

threshing speed and length of storage period after threshing, on threshing performance and quality of two varieties of soyabean were studied. It was found that unthreshed grain increased with increase in pod moisture content. The percentage unthreshed grain decreased with an increase in cylinder speed for all pod moisture contents. The variety Ankur was a little harder to thresh and was more resistant to damage than PK 71-21. Both storage time and threshing speed had only a small effect on the germination percentage of both varieties.

Desta and Mishra (1990) developed and evaluated the performance of a sorghum thresher. The capacity of the thresher is 188 kg/h, it was designed on the basis of physical properties of sorghum grain. The thresher was evaluated for its performance in terms of threshing efficiency, cleaning efficiency, visible damage, germination percentage and sieve loss. From the result, the threshing efficiency increased with increase in cylinder speed. The threshing efficiency was found to be in the range of 98.3 to 99.9%. Visible damage decreased with increase in cylinder speed and with the decrease in feed rate and cylinder concave clearance. It was observed in the range of 1.12 to 4.22%. The results of the test indicate that for optimum performance, the thresher should be operated at a cylinder speed of 400 rpm (10.05 m/s) with cylinder concave clearance of 7 mm and feed rate of 6 kg/min. The power required for operating the thresher at this

combination was 5 kW and the maximum output was 162.57 kg/h.

Ndirika (1993) developed and evaluated the performance of a millet thresher. The through-put capacity of the thresher is 47.5 kg/h, and was designed for two local varieties of millet (Ex-Borno and Maiwa). The physical properties of millet crop and grain, such as bulk density, grain/straw ratio, moisture content, size and angle of repose were studied. The thresher was fabricated and evaluated for its performance in terms of threshing efficiency, mechanical (visible) damage, cleaning efficiency and sieve loss. The test results revealed that for optimum performance, the thresher should be operated at a cylinder speed of between 800 rpm and 900 rpm respectively with Ex-Borno and Maiwa varieties at feed rate of 20 kg/h. The power requirement for operating the thresher at this combination was 2.24 kW and the maximum output was 38.5 kg/h. Threshing parameters of the thresher and their value/range are shown in Table 2.1

Ghaly (1985) designed, fabricated and tested a tractor-operated stationary threshing machine. The effect of the cylinder concave design on the machine performance was investigated. The experimental part of his study was confined to the determination of the performance criteria of the threshing machine. These criteria were the machine capacity, the power requirement, the total seed losses, the quality of the output seeds and length of straw. Six levels of cylinder speeds (600, 700, 800, 900, 1000 and 1100 rpm) and four sizes

of the chopping concave holes (22,31, 38 and 48 mm diameter) were used in his study. The ambient temperature and crop moisture content were measured. However, their effects were not considered since there were no significant differences in increased from 22 to 45 mm. The total seed damage was affected by cylinder speed, increasing cylinder speed increased the seed damage rapidly. The hole diameter did not have appreciable influence on seed damage, although more damage was noticed in seeds collected under chopping section than that collected under the threshing section. The total seed losses (unthreshed seeds and seed in trailings) were affected by both cylinder speed and hole diameter. Increasing cylinder speed or decreasing the hole diameter decreased the total seed losses. The useful power required for threshing the wheat crop was mainly affected by the cylinder speed; the effect of hole diameter was not profound. The optimum operating condition of threshing wheat can be obtained at cylinder speed of 1000 rpm using a chopping concave with 45 mm hole diameter.

Joshi (1981) gave the recommended cylinder peripheral speeds and concave clearance for three crops, maize, rice and wheat as presented in Table 2.2

Delong and Schwantes (1942) studied the effect of cylinder speed and clearance on mechanical injury of barley for three types of cylinders. A small power take-off driven combine harvester which could be equipped with either a rasp

Table 2.1: Threshing Performance Parameters of the Millet Thresher

Parameters	Value/Range
(1) Cylinder diameter	0.10 m
(2) Cylinder width	0.8 m
(3) Concave length	0.236 m
(4) Cylinder velocity	800 rpm(4.19 m/s)
(5) Feed rate	20 kg/h
(6) Concave clearance	0.006 m
(7) Grain moisture	9-10 (%)
(8) Grain output Capacity	38.5 kg/h
(9) Threshing efficiency	94.4-96.8%
(10) Grain damage	1.30-2.10%
(11) Grain ratio	0.65
(12) Concave hole diameter	0.010 m
(13) Power requirement	2.24 kW
(14) Bulk density	815.73 kg/m^3

Source: Ndirika (1993)

bar cylinder or a rubber faced bar cylinder was used. A stationary thresher was used for spike toothed cylinder for the test. The best clearance for rasp bar cylinder was found to be 0.95 to 1.27 cm as measured to the tips of the bar serrations. The rubber faced bar did the best work at a clearance of 1.27 to 1.59 cm, whereas a 0.40 cm lateral clearance was best for spike toothed cylinder.

Table 2.2 Recommended Cylinder Peripheral Speeds and Concave Clearance for Maize, Rice and Wheat Crops.

Crop	Details of cylinder	Peripheral speed (m/s)	Concave clearance (mm)	Moisture content (%)
Maize	-	12.5-20.33	22-30	-
Rice	spike tooth: 48cm diameter and 59cm length. or	15.83	40-70	13.2% grain 11.0% straw (wet base)
	Spike tooth: 68cm diameter, 140cm length	18.33	25	47.0% straw (dry base)
Wheat	Spike tooth: 68cm diameter and 140cm length	19.83	25	10.5-14.3% grain, 3.6-7.5% straw (wet base)
	spike tooth: 30-43cm diameter, 27-33cm length	12.67-14.13	25	-
	Beater type: 66-89cm diameter, and 230-270cm length	17.91-24.16	20-45	-

Source: Joshi (1981)

The cylinder peripheral speed of 25.4 to 30.47 m/s was the best of all three cylinders. Slower speeds left unthreshed head and higher speeds resulted in much cracking and skinning of barley.

Goss et al. (1958) studied the performance characteristic of self-propelled and trailed combine harvesters on barley. The optimum concave clearance and cylinder speed for threshing were 6 mm and 25.4 to 27.93 m/s, respectively.

Arnold (1964) as reported by Barger et al. (1972), compared front-to-rear clearance ratios of 3-to-1 and 1-to-1 and found very little difference in cylinder loss, vissible damage and germination of barley or wheat for any given mean clearance. Front-to-rear clearance convergence is generally desirable because the wider front opening tends to improve the feeding characteristics of a cylinder.

Arnold (1964) and also Csukes (1964) as reported by Barger et al. (1972), found that the orientation of the material as it enters the cylinder has considerable effect upon cylinder and concave performance. Feeding butts first in laboratoy tests with wheat and barley resulted in cylinder loss at least twice as great as when fed heads first with the stalks parallel and heads on the top of the layer.

A comparative performance of wire loop, peg tooth and rasp bar cylinders on paddy was studied at IRRI (1969). The effect of hold-on feeding and thow-in feeding on theshing performance and damage was investigated. The tests indicated

that high cylinder velocities gave less semi-threshed paddy. Except for the wire loop cylinders without concave, the throw-in feeding gave poorer performance than hold-on feeding at low cylinder velocities. It was accepted that the throw-in type threshers are better suited for high output than the hold-on type.

Goss et al. (1958) found a rapid increase in shoe free-seed loss when the velocity of the wind from fan was either too low or too high.

Harrington (1970) while working on multicrop thresher found that the amount of trash in clean grain was less than 1% at air velocities of 2.5 m/s and above. The loss due to cleaning process was below 1% for air velocities of 5.91 m/s and less. Misner and Lee (1973) found out that an air velocity of 9.2 m/s at a direction of 40 to 45 degrees caused minimum losses in aerodynamic separation of wheat material. The power requirement was 0.52 hp/cm of cylinder width or 2.9 hp/100 kg of throughput per min of combine.

Kashyap and Pathak (1976) studied the effect of air stream depth and air velocity requirement for pneumatic removal of chaff, straw, dust and shrivelled grains from threshed crops. The air velocity requirement for winnowing of wheat grain were determined in a low speed, straight through (open type) suction type of horizontal wind tunnel having a test section 4.57 m long and 1.22 m wide. The test section was used for variable depths of 0.30, 0.61, 0.91 and 1.20 m

keeping the constant width as 1.2 m. An optimum air velocity range from 23 to 27 km/h was obtained for winnowing of wheat grains without employing and separating screens. The range was independent of the depth of the duct.

Simpson (1966) determined the effect of front to rear slope on combine shoe performance and influence of front to rear slope on optimum wind and sieve adjustments for wheat. In laboratory, front to rear shoe slope was varied in 5 degree intervals from 15% (machine travelling up hill) to 15% (machine travelling down hill). The fan regulators were set corresponding to 49, 64, 78 and 91% of maximum fan opening for each shoe position. It was found that when not overloaded, the shoe losses increased exponentially with an increase in fan opening for all shoe positions and shoe losses decreased with increase in chaffer sieve opening. The percentage of foreign material in the clean grain increases exponentially with decrease in front to rear slope. Goss et al. (1958) found that increased threshing effect resulted into substantial reduction in walker free loss and total seed loss from rear of combine. The reduction was due to greater percentage of seed separated through the concave grate which resulted into small percentage of total seed input being fed into walkers.

Lamp and Buchele (1960) reported that wheat and other grains can be threshed by application of centrifugal force. In the case of wheat, a force of 0.14 kg was sufficient to

thresh 98% or more of mature grains independent of the method of holding the head. In typical harvesting conditions the force required was only 0.09 kg. The threshing and separating conditions could be integrated by eliminating the need of special straw separating equipment for centrifugally threshed grain. They reported that the available grain harvesting machines were generally functionally satisfactory, yet it was reasonable to believe that improvement can be made in machines to reduce their weight, to thresh high moisture grain, to get better cleaning and to improve their performance in sloping land.

Buchanan and Johnson (1964) developed a conical thresher. The crop was fed between the inner and outer cones having differential speed. Theoretical analysis and experimentation indicated a good potential to develop a cone type centrifugal threshing separating mechanism. Dwell time of the material in the cone was critical in the acceleration of the materials which was greatly influenced by air flow, cone angle, inner cone design and speed. The cone speed power and capacity were quite reasonable for a practical machine and the need of grain recleaner was felt. They emphasized that methods to decelerate the grain should be developed to retain satisfactory grain quality.

IRRI (1963) designed, fabricated and tested a cone-type thresher. The thresher showed that the principle of the cone type thresher was sound and gave a maximum output of 300 kg/h

using a 6-hp engine. A power take-off driven model (IRRI,-1964) with more power and screen area was built. A 36-hp tractor stalled when the thresher was fed with straw and grain at the rate of 1 kg/s. The centrifugal nature of the cone thresher resulted in increased friction on the screen and drag on the drum, creating a high power requirement. Complete threshing was achieved, but even a 4.5 m^2 screen did not fully separate the grain from the straw. Efforts were made to improve the cone thresher (IRRI, 1970, 1973, 1974). It gave high threshing output but the grain cleaning performance was not satisfactory.

Ramos (1975) tested five types of threshers, namely; (i) single drum - no blower - no separator type; (ii) double drum-single blower - no separator type; (iii) double drum - single blower with oscillating separator type; (iv) axial flow thresher; and (v) single drum - single blower with oscillating screen type. He found that the capacity of these threshers were 704, 250, 1,148, 936 and 2,449 kg/h, respectively, for paddy crop. In these tests the drums used differed from one thresher to another. The crop threshed was wet and the grain and straw moisture contents ranged from 20-23% and 80% respectively, on wet weight basis. The length of material used in the test was 30 - 40 cm with the grain : straw ratio ranging from 0.46 to 0.65. The second, third and fifth type threshers has 23 to 38% blower loss. Unthreshed loss was high in thresher types (i), (ii), and (v).

A drum-type power thresher was also designed and developed by IRRI (1967, 1968) for freshly harvested paddy. The machine was powered by a 4-hp air cooled engine and utilized the U-shaped wire loop type threshing drum. It had a 1.83m long hollow threshing drum which was mounted within a sheet metal housing. Rubber flaps were placed in spiral arrangement on the drum to sweep the housing bottom and to deliver the threshed materials to the rear mounted rotary screen separator. An axially mounted fan was used to blow air through the drum and separator. The threshing drum, therefore, served not only for threshing but also as an auger for moving threshed materials and as a duct for moving air to the separating mechanism. The machine was capable of threshing both dry (14% moisture contents) and wet (over 30% moisture contents) padddy.

A throw-in type multi-crop axial flow thresher was developed at IRRI (1972). It had wire loop threshing drum of 35 cm diameter and 127 cm length with a concave screen enclosing the full length of the cylinder. A 6.5 hp air cooled engine was used as prime mover. A peg-tooth cylinder with bolts of 1.1 cm in diameter as pegs in an axial flow thresher gave better threshing performance and longer life in comparison with wire loop threshing cylinder. The capacity of the thresher was increased by replacing the perforated sheet metal concave with a concave of steel rods.

Verma et al. (1978) conducted a survey on human accident

in wheat thresher. The accidents were highest for the drum-type threshers followed by syndicator and beater type threshers. The number of accidents on spike-toothed thresher was minimum. They suggested an improved design of feeding chute for safe feeding of the crop in the thresher.

Datt and Annamalai (1991) designed and developed a straight through peg-tooth type thresher (model IEP-2) at CIAE-IRRI industrial extension project Coimbatore, Tamil Nadu. The salient features of the thresher are its threshing efficiency of 99.98%, output of 640 kg/h, cleaning efficiency of 98.0%, low cost and low power requirement (6 hp). The straw comes out of the thresher with almost full length.

Singhal and Thierstein (1987) developed an axial flow thresher with multicrop potential. They selected, modified and evaluated an IRRI axial flower thresher, a better design capable of threshing freshly harvested paddy and as a multi crop thresher for a wide range of crops; namely sorghum, millet, chickpea, pigeon pea, wheat and paddy at ICRISAT centre in India and in villages. A threshing efficiency of more than 95% and output of 500-800 kg/h were obtained for most of the crops. They selected the following threshers with multi crop potential for evaluation on threshing of paddy, sorghum, millet, chickpea and pigeon pea:

(1) IRRI portable thresher without cleaning attachments using 3 kW petrol engine.

(2) Rasp-bar type Alvan Blanch midget thresher without cleaning attachment with 2.25 kW petrol engine.

(3) IRRI axial flow thresher with cleaning attachments and using 7.5 kW petrol engine.

Trials conducted at ICRISAT on different threshers available from India and abroad, revealed that certain sorghum genotypes and millet are very difficult to thresh at a moisture content higher than 15% which is most common at the time of harvesting rainy season crops. When the crops are threshed at high moisture levels, the result is that considerable amount of seeds retain their glumes (5 to 15%) reducing the market price considerably (20 to 25%) (ICRISAT, 1978). The pulse crops are quite delicate to thresh and results in high percentage of brokens with little harsh threshing arrangement. The original axial flow thesher with cleaning attachment performed satisfactorily on paddy but failed on most other crops like sorghum, pearl millet, pigeon pea, chickpea and wheat. The thresher was modified to a considerable extent and it made possible to thresh most of these crops with minor adjustments in threshing cylinder concave and cleaning mechanism. On the basis of performance at ICRISAT centre in India and farmers' field the modified thresher performed satisfactorily. The results indicate that this thresher could be operated as a multicrop thresher with a wide range of crops with minor modifications. In village evaluations the thresher was prefered over conventional thresher due to some additional

merits which include low labour requirements, ease in feeding ear heads, less vibrations during operation and operational safety.

Shambaugh (1966) carried out an operation test on Garvie midget thresher for threshing millet, Guinea corn and Rice and gave a comparison of the machine with hand method and developed most practical method of operation of the equipment. The Garvie midget thresher consists of merely drum with 3 rasp bars and a heavy wire concave with one threshing bar across the centre. The thresher was powered with 2.25 hp Briggs and Stratton petrol engine and the cylinder speed was 1500 rpm. On the first trial run of the thresher entirely too much threshed grain flow out of the feeding chute as well as from the grain pan under cylinder. All the material are discharged into a collection box, two sides of which have a canvax shielding to direct the material into the box. The standard shielding was sufficient for rice threshing. Millet and guinea corn grains were thrown outside of the box. For machine threshing and hand winnowing combination, the petrol used is 8.04 litres or 0.581itres/h, machine rate of 464.4 kg/h, machine threshing rate of 85.73 kg/man hour, winnowing rate is 41.69 kg/woman hour. For complete hand threshing and winnowing, hand threshing rate is 31.53 kg/man hour (only small amount). Winnowing rate of 31.53 kg/woman hour (only small amount). However, the following general remarks can be established from his studies:

(1) The Garvie midget thresher is too dangerous for hand feeding of millet and guinea corn without feeding table modifications. It would probably not be too dangerous for rice threshing only since the materials to be threshed is longer and the feeder's hands would not be quite as close to the cylinder.

(ii) Too much of the millet and the guinea corn were thrown out of the machine unless some of the openings are closed.

(iii) The engine works perfectly for the entire period. In the hand threshing and cleaning, the women did an excellent job of both threshing and cleaning millet. In their cleaning process they threshed some additional seed from small sections of the head that was missed by the machine, however, this amounted to a very small percentage of the total amount of seed. He further recommended that the Garvie midget thresher appears to be more suitable for rice threshing than for the threshing of millet or guinea corn since the threshing has no cleaning facilities to clean the grain, he recommended that the cleaning be done by hand winnowing in the field at the threshing site.

Choudhury (1978) worked on the performance of two machines, midget Mark II and super midget II. These machines are of rasp bar rotating drum type with a fixed concave and

were tested for millet, paddy, sorghum (guinea corn), wheat and cowpea. Midget mark II thresher uses a 2.25 kW power unit but has no provision for cleaning and separation of grains from chaff. Consequently, the output was mixed with straw and chaff. With additional cleaning it is broadly satisfactory for paddy and sorghum threshing but is unsuitable for millet, wheat and cowpea. Supper midget II thresher uses a 3.35 kW power unit and has a provision for cleaning and separation of grains which was achieved by a blower and a set of two reciprocating sieves. The machine was broadly satisfactory for paddy and sorghum threshing, but is not suitable for millet, wheat and cowpea. For the Alvan Blanch (A.B) midget Mark II thresher, the test indicated that millet heads were broken in pieces instead of being threshed, the machine as such, is not suitable for millet. For A. B. supper midget II thresher, two varieties of millet, EX Borno and Maiwa, were used for testing. The general indication was that the machine has good threshing ability but the final product mixes with chaff and unthreshed grain in the range of 25 to 40 percent. The percentage of unthreshed grain was 6 to 10 percent.

Choudhury (1979) studied the performance of two threshing machines midget MK II and super midget II on millet and Guinea corn respectively. These machines are modified versions of the original ones tested and reported earlier in the test report of 1978. Originally, the manufacturers claimed that the machines were multicrop threshers but the modifications

have now made them single crop threshers, a point of great significance in the selection of appropriate equipment for local crops. The A.B midget MK II has been reportedly modified for millet by reducing the concave area and opening. However, there is still no provision for separation and cleaning of the grain from chaff and straw. The modification resulted in an improvement in that the threshing of millet is now accomplished. Hitherto, the older machine only broke the crop into pieces and there was no threshing at all. The overall modifications resulted in an improvement in the threshing efficiency but no significant improvement in the cleaning efficiency. The significant changes from the earlier design reported in test report of 1978 are as follows:

(a) The feed chute length was reduced to about one third of its original length.

(b) A screen was bolted to the discharge and of the drum presumably to act as concave. The modified A.B midget II thresher showed considerable improvement on threshing millet. However, the machine still suffers the disadvantage of relatively poor cleaning of about 58.7%.

Wagami (1979) designed and fabricated a prototype thresher for millet. In the work, design, fabrication and performance of a single cylinder axial flow millet thresher for EX Borno and "Maiwa" millet varieties. The essential features of the thresher include:

(a) A single cylinder with two sections; the threshing section which has a spiral rasp bar unit and the cleaning/ separation of grains from chaff and straw by the fanning action of the cylinder.

(b) A concave bar support of millet earheads during the process of threshing.

(c) A stationary screen for separation of threshed grain from chaff and straw.

(d) A grain collection chamber, separate from chaff outlet

(e) Feeding is through feed hopper in longitudinal direction.

(f) Power driven.

From the performance test, the thresher has a threshing efficiency of 70 - 92% (depending on the cylinder speed) at a cylinder concave clearance of 8.0 mm and a capacity (output rate) of 15 - 20 kg/h clean grains.

Choudhury (1980) studied the performance of A.B super midget II thresher for millet which is a modified version of the super midget II thresher reported earlier in the test report of 1978. The A.B super midget II for millet has its straw walker, cleaning and feeding hopper sections modified with a view to improving its performance for millet threshing. The modifications improved both the threshing and cleaning efficiencies but the percentage cracked grain was about 14% which is too high. In addition, the grain loss through screen output and spill over screen accounts about 40% and 18% respectively. On feeding the screen output and spill over

Lazaro and Simalenga (1994) designed, developed and tested a hand operated bean thresher. The threshing mechanism is a rubberized wooden cylinder and a concave with rubber rasp bars. A winnowing mechanism was also incorporated in the design. The thresher was tested for its threshing capacity, threshing effectiveness, seed damage and winnowing effectiveness on two local bean varieties, TMO 241 and TMO 216.

Results obtained gave a threshing effectiveness of 82.26% and 85.6% for TMO 241 and TMO 261, respectively. Threshing capacity was 15kg/h and 13.8kg/h for TMO 241 and TMO 261, respectively. Seed damage was 2.7% for both bean varieties. Winowing effectiveness was 94% at 360 rpm fan speed and the winnower throughput capacity was observed to be 240 kg/h giving 104 kg/h of clean seed.

Miah et al. (1994) conducted a comparative study to investigate the performance of four available rice threshing methods, namely, by pedal thresher, bullock treading, drum beating and manual treading on threshing output, grain damage percentage and unthreshed grain of paddy. Sixteen sets of data were analyzed and results thus obtained show significant difference (at 1% level by LSD) among the treatments on threshing output (kg/h), damaged and unthreshed grain percentage.

The study reveals that pedal thresher gave higher threshing output (103.4 kg/h) than other methods irrespective of rice varieties except Nizersail. Among the four threshing

threshing process in a conventional combine thresher. He derived a set of differential equations which relate variables in the threshing process. The equations were represented as:

(1) $g + h + s + z = 1$

(2) $(S\varepsilon V)' = \Theta$

(3) $1 - Z = (1 - Z_o)ek^{1(P_m - P_o)}$

(4) $(\varrho\varepsilon V^2)' = \mu P_m R$

(5) $\{(g + h)\varepsilon V\}' = - CRh(xR - V)$

(6) $(g\varepsilon V)' = - KP_m Rg(xR - V).$

where,

P_m = Pressure on the material at angle Θ

R = Radius of cylinder (constant)

ω = angular velocity of cylinder (constant)

V = Velocity of material at angle Θ

ε = $f(\Theta) - R$

ϱ = Density of grain and its chaff (constant)

ϱ = Density of straw (constant)

μ = Difference in friction coefficients

k_1 = Constant

P_o = Initial value of P_m

Z_o = Initial value of Z

C = Constant determined by the feedrate

Z = Ratio of voids in the unit

g = Ratio of unthreshed grain head in cylinder concave

h = Ratio of threshed grain and free chaff in the unit.

S = Ratio of straw in the unit.

Prime (′) = diffentiation with respect to angle. The equation does not provide exact solutions. The purpose of the work was to determine the optimum concave shape, so the work did not relate these process variable equation to performance characteristics of the threshing process.

Cooper (1972) developed exponential type relationship between the concave separation and feed rate. The expression is represented as:

$$\text{Concave separation (\%)} = 100 - e^{A+B\,(\text{feedrate})} \qquad 2.4$$

where A and B coefficients were estimated from the curve. The derived expression was based on experiment and only treated the feedrate variable.

Gregory (1988) derived a mathematical model to simulate the threshing process in a conventional axial flow combine. The model was based on the probability of repeated impacts striking unthreshed grain and the ratio of the kinetic energy received to that needed to thresh a unit mass of grain. The basic equation is:

$$F_1 = e^{-[r(P/En)(L/N)]n'RPM/R} \qquad 2.5$$

where

F_1 = Fraction of grain lost due to incomplete threshing.

r = Ratio of straw to grain

p = Power required

R = feed rate

L = Length of concave

n′ = Number of bars

E_n = Energy needed per area of impact to detach a unit mass of grain

This basic equation was expanded using dimensional analysis to include the variables of cylinder diameter (D) concave clearance (C) and concave length (L). The final equation is represented as

$$F_1 = e^{-r(F/En)W(B/R)(0.146 + 0.00139\Pi 4)(1 - e\text{-}0.176\Pi 4)} \qquad 2.6$$

where,

$B = n' \times RPM$

$\Pi 4 = LD_s/CD$

D_s = a standard cylinder diameter used for comparism.

He reported that this final equation was verified with data for conventional combines. An R^2 of 0.97 was obtained which was significant at 99.9 percent level ($\alpha = 0.001$).

However, the moisture content of the crop was not taken into account. Also the equation developed were not used to actually test existing thresher in order to rate its success for practical adaptation. It was noted that the work did not identify the sets of adjustment combinations that yield optimum losses and the crop flow model assumed constant velocity of entry for the crops, which is not practicable when it comes to feeding stationary thresher.

Huynh et al. (1982) developed mathematical models that quantify the threshing and separation process of cereal crops in a conventional thresher. In their work the threshing performance of a given thresher was predicted using the model

and the performance characteristic were determined for different cylinder and concave designs and various operating conditions. These characteristics were then compared with published data. The trends predicted by the model were found to be similar to the observed phenomena in threshing. The mathematical description of the threshing process was represented by the following equations:

For threshing loss, $R_1 = e^{-\lambda t_c}$ 2.7

For Separation loss, $R_2 = 1 - \eta$ 2.8

For threshing power requirement, $H_p = NT + P_n$ 2.9

For grain damage, $D_m = K_d(E/E_m)^n$ 2.10

where,

E = Energy absorbed by the kernel

K_d = Proportional constant for grain damage

N = Cylinder rev per min.

n = Number of impact

P_n = No load power for the thresher

R_1 = Threshing loss

R_2 = Separation loss

t_c = Time duration of grain in the threshing unit.

T = Thresher torque

E_m = Minimum energy to cause grain damage.

λ = Mean threshing rate

η = Overall concave separating efficiency

Their work did not include the effect of moisture content.

Enaburekhan (1994) worked on mathematical and optimization modeling of the threshing process in a stationary grain thresher. The basic equation used was:

$$\text{Threshing Efficiency} = 1 - e^{-3K_T \varrho(1-a)VWDL/2QC} \qquad 2.10a$$

where,

K_T = Threshing constant

ϱ = Bulk density at 10% moisture content or dry condition

a = Moisture content of crop

V = Velocity of the threshing cylinder

W = Width of thresher

L = Concave length

C = Cylinder concave clearance

Q = Feedrate of crop

D = Diameter of threshing cylinder

The moisture content parameter in the developed model was based on the proposed assumption that:

$$\varrho_w = \varrho(1 - \alpha) \qquad 2.10b$$

where,

ϱ_w = bulk density at a given moisture content or wet condition

ϱ = bulk density at 10% moisture content or dry condition

α = moisture content of crop in decimal

Gupta et al. (1986) described a mathematical model which selects an optimum wheat threshing system depending upon the crop area and the power source used on the farm. A computer program written in FORTRAN IV Language was used to compute the

optimum size of wheat thresher for given crop area and power source. The optimum size of thresher model was given as:

$$(CAPTH)_{opt} = [AUC \times YC \times (LCTH + PSCPH + YLTH) \times AUC \times YC \times PC \times 0.5/WHDTH)]^{1/2} \times [PUCTH \times [(1-SVF)/ELTH + (1 + SVF) \times (R_I + SC)/2]^{-1/2} \quad 2.11$$

where,

AUC = area under crop; ha

YC = yield of crop, t/ha

LCTH = labour cost of threshing, Rs/h

PSCPH = The power source cost per hour

The PSCPH was determined using equation 2.12.

$$PSCPH = [PPS \times (1-SVF)/ELPS + (1+SVF)/2 \times (R_I+RIN+SC)]/AUPS \text{ (fixed cost/hr)} + (RMFPS \times PPS)/10,000 \text{ (repair \& maintenance cost)} + (EFR \times 12 \times HPPS)/AUPS \text{ (electricity charges)} \quad 2.12$$

YLTH = yield loss due to delay in threshing operation, kg/kg-day

PC = Price of crop, Rs/t

WHDTH = working hours per day for threshing operation, h/day.

PUCTH = price per unit capacity of thresher, Rs/(t/h)

SVF = Salvage value factor

ELTH = estimated useful life of thresher, years.

RI = rate of interest per year, decimal.

SC = Shelter charge per year, decimal

PPS = Price of power source, Rs

ELPS = estimated useful life of power source, years.

RIN = rate of insurance and taxes per year, decimal.

AUPS = annual use of power source h/year.

RMFPS = repair and maintenance factor for power source.

EFR = electricity flat rate Rs/KW-month.

HPPS = size of power source, KW

Chaudhry (1979) studied the grain losses at the threshing and winnowing stages. He applied the following formulae to quantify losses caused by various factors:

potential yield of grains,

$$Y_g = (G_s \times 20 \times N)/n \qquad 2.13$$

potential yield of straw,

$$Y_s = (S_s \times 20 \times N)/n \qquad 2.14$$

where,

Y_g = Potential yield of grain

G_s = Weight of grains in the sub-sampled bundles.

n = Number of sampled bundles

N = Total number of bundles on the threshing floor

Y_s = Potential yield of straw

S_s = Weight of straw in sub-sampled bundles

Loss caused by insects, $L_i = (G_i.S_w.T.P.I)/1000t$ 2.15

where,

L_i = Loss caused by insects

G_i = Number of grains taken away per insect track per unit of time.

T = Average working hours per insect track per day

P = Period of attack (days)

I = No of insect tracks.

t = Unit of time

Losses caused by grains in the threshing floor,

$$L_t = (G_t.r.\pi.S_w)/(2 \times 1000) \qquad 2.16$$

where,

L_t = Losses caused by grains in the threshing floor

G_t = Grains in the threshing floor per square foot.

r = Radius of threshing floor in feet

S_w = Standard weight of 1000 grains

$\pi = 22/7$

Losses caused by grain in the straw,

$$Ls = (G_s.W_s)/S \qquad 2.17$$

where,

L_s = Loss caused by grains in the straw

G_s = Average number of grains per sample of straw.

S = Weight of sample straw

W_s = Total weight of straw.

Loss caused by shredding of grains,

$$L_g = (G_s.A.S_{w)/1000} \qquad 2.18$$

where,

L_g = Loss caused by shredding of grains

G_s = Average number of grains shredded down per square yard.

A = Area of the field in square yard.

S_w = Standard weight of 1000 grains.

Loss caused by fallen ears,

$$L_e = (E_f.A.G_e.S_w)/1000 \qquad 2.19$$

where,

L_e = Loss caused by fallen ears

E_f = Average number of ears fallen per square yard.

A = Area of the field in square yards.

G_e = Average number of grain per ear.

S_w = Standard weight of 1000 grains.

$$\text{Aggregate loss, } L = L_r+L_b+L_i+L_t+L_n+L_s+L_a+L_p+L_f+L_w \qquad 2.20$$

where,

L = Aggregate loss

L_r = Loss caused by rodent

L_b = " " " bird

L_a = " " " animals

L_p = " " " pilferage

L_f = " " " fire

L_w = Loss caused by windstorm

L_n = " " " rainfall

A close scrutiny of grain losses at the threshing floor showed that the major factors accounting for losses comprised of rodents, birds, insects, rainfall, animals, pilferage, fire and windstorm, and the mode of threshing itself. In case of mechanical threshing, another factor was also noticed namely, the mechanical defect, whereas, for the combine-harvester the factors included mechanical defect, grains shredded and the ears fallen in the field. It was established from his work that losses in the case of bullock threshing, mechanical

that losses in the case of bullock threshing, mechanical threshing, tractor threshing and combine harvester amounted to 3.11 percent, 2.68 percent, 2.01 percent and 1.20 percent respectively. It was found that produce losses during threshing and winnowing are positively associated with the duration of threshing. From this stand-point, the mechanical thresher was found to have the least losses due to the shortest possible period required by it during the process of threshing. Since the grain losses are possitively associated with threshing and winnowing, the losses tended to be highest in the case of bullock threshing. The winnowing losses on the average, accounted for more than 50 percent of the total losses by each mode of threshing. Also, rodents claimed the second highest loss in mechanical threshing, whereas, the threshing floor ranked as the second most important factor in grain losses taking place for bullock and tractor threshing. In general, from the result, mechanical threshing had inflated losses due to the non-availability of repair facilities, existing mechanical defects and lack of proper maintenance.

Glasber and Mcgechan (1983) investigated the stochastic variability in experimental results from an acoustic grain loss monitor and a table auger torque sensor on a combine harvester. A model was identified and used to specify optimal control systems for adjusting combine forward speed to maintain constant threshing losses, which provide upper bounds on the benefits of practical forward speed control systems. They developed a model which

relates average threshing loss to the average speed of combine by:

$$L = K\left(1+\frac{1}{2}\left(\frac{b^2S^2\sigma_r^2}{(1+\sigma_p^2)^2}\right)\exp\left(a+\frac{bs}{(1+\sigma_p^2)}\right)\right)$$

where,

σp^2 = Variance of Up

σr^2 = Variance of U_r

U_p = Component of X_t which can be predicted by the control system

U_r = Component of X_t, excluding sampling variability, which cannot be predicted.

K = Calibration constant

a,b = Parameters in monitor/speed relationship

S = Average speed of combine.

L = Average threshing loss

X_t = Departure of "Crop Density" from unity as observed by the monitor at time (t+4)

t = Index for time, measured in Units of 2s.

The two cases of special interest considered are constant speed and constant threshing loss:

(1) When $\sigma_p^2 = 0$, the speed is constant, $\sigma_r^2 = \sigma_1^2 + \sigma_2^2$ and

$$L = K(1+1/2b^2S^2\sigma_r^2)\exp(a+bs) \qquad 2.22$$

(2) when $\sigma_r^2 = 0$, the loss is constant, and $\sigma_p^2 = \sigma_1^2 + \sigma_2^2$

$$L = K\exp(a+bs/(1+\sigma_p^2) \qquad 2.23$$

where,

σ_1^2= Variance of component X_t, which is auto correlated

σ_2^2 = Variance of component X_t, excluding sampling variability, which is uncorrelated.

Equation 2.23 threrefore, is the idealized situation of perfect control in which threshing loss is held constant. This provides a lower limit on threshing losses at a given average speed achievable using monitoring equipment other than the grain loss monitor and auger torque sensor.

From the results it was found that the monitor control system performs poorly at low speeds because sampling variability in the monitor obscures the true grain losses. At higher speeds the results are slightly better because sampling variability is smaller, although none of the uncorrelated component can be predicted. Addition of the auger torque makes a small improvement to the control because the correlation between the correlated components of "crop density" in the auger and monitor is 63%. The optimal control considered takes no account of the rate at which the forward speed of the combine can be varied, and in respect a practical control system might have a lower performance. In their work, the threshing loss has been considered to be a fixed proportion of the monitored loss per unit distance, excluding sampling variability, but this is probably not completely true. Therefore, the effect of the monitor in controlling the grain loss will have been overestimated and the effect of the auger torque could have been underestimated.

Reznicek (1971) established a relation for the minimum

energy required for release of grain from ear. The value of the minimum energy required for the release of 1 kg of grain for wheat and rye were estimated. From his work, the minimum energy W required for releasing a grain mass unit was given as:

$$W = NKLF = (1/M)KLF \qquad 2.24$$

where,

N = Number of grains per kg

M = Average mass of grain expressed in kg,

Then, N = 1/M

K = Coefficient expressing the course of the binding force.

L = Grain length

F = Bond strength.

K, L and F are mean values obtained from measuring n grains. He made the following conclusion from the measurement of the binding force:

(a) The binding force first increases to reach a maximum, i.e the bond strength. At that moment the pedicel is severed from the grain and the binding force drops abruptly practically to zero. The further course of the binding force was determined by the closure of the glume and of the lemma and its maximum is rather low in comparison with the bond strength, even neligible at times.

(b) The course of the binding force of all the 50 grains investigated is similar.

(c) The movement (elongation) at which the pedicel is severed from the grain and at which the binding energy attained the value of bond strength is with ripe wheat and rye always less than 6% of the grain length.

From his report, the procedure described by which the grain was released from the ear for the purpose of determining the binding energy does not correspond to the procedure used during threshing. It may be visualized as ideal threshing. Inspite of this, however, the mean values of minimum energy required for the release of the grain from the ear and the value computed on the basis of the above consideration may well serve for assessing the energy balance of threshing.

From the above review it is obvious that not much has been done on the modeling of performance predicting parameters for stationary grain threshers. Most of the models were for combine systems which have different crop model from stationary mechanical threshers. Also most of the models have not been implemented to rate their success, some could not give clear explanation on how some of the physical parameters are derived. Most of the mathematical models that have been developed did not include moisture content parameter in their formulation, except the threshing process model developed by Enaburekhan (1994) which included moisture content parameter.

His moisture content parameter was proposed from intuitive reasoning.

It is therefore necessary to develop performance simulation models for describing and predicting the performance of the threshing and separation processes for stationary grain threshers which will eliminate the problems observed in the previous developed models.

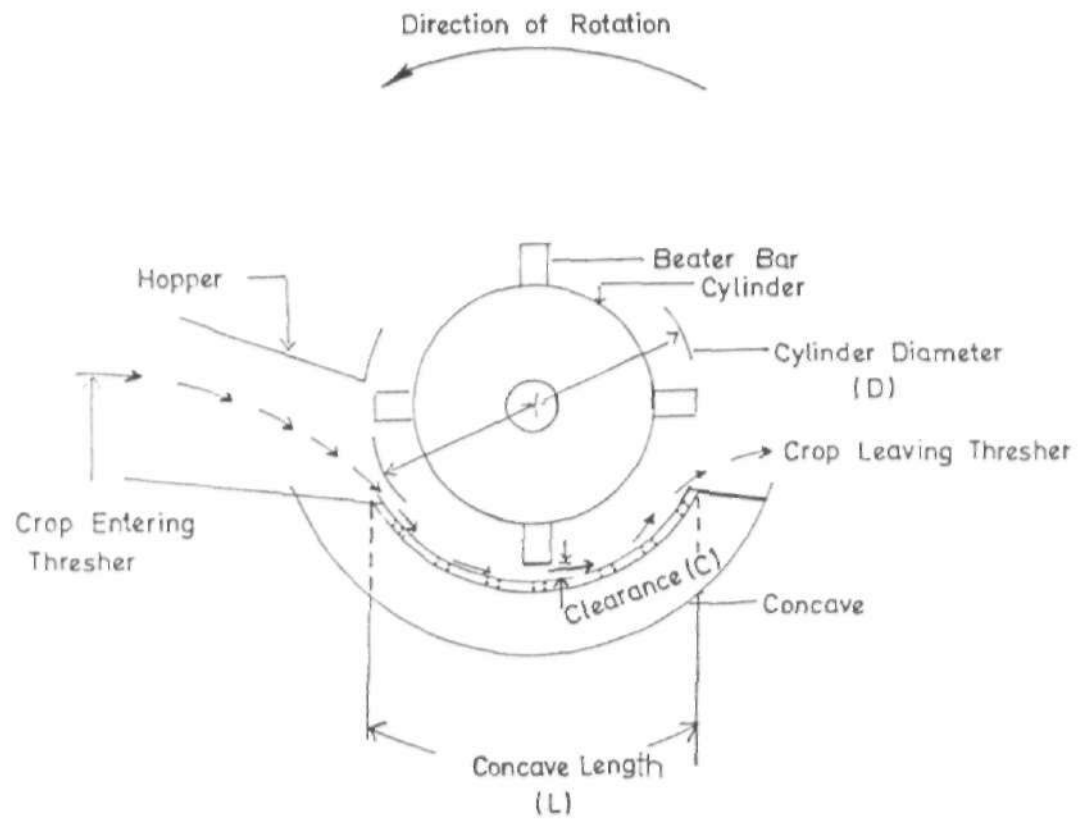


Fig. 3·1. Cylinder–Concave Arrangement of a Spike Tooth Thresher

3.2 Crop Motion analysis

3.2.1 Threshing process

When the crop is fed in at the concave entrance, it forms a crop stream which is accelerated by the spike-tooth during impact. The crop heads were assumed to be uniformly distributed in the crop stream. The grains are detached from the panicles by a combination of stripping, rubbing and impact action. This action involves the application of tensile, compressive, bending and twisting forces and their combination on a head of grain.

Threshing is also achieved by the impact or impulsive acceleration occuring when a cylinder bar strikes the grain. This impact action is based on differences in the coefficients of restitution of the grain and the stalk. In this analysis, the rate of grain removal from the panicle is modelled as a function of the energy transmitted to the crop stream during threshing.

3.2.2 Separation Process

Separation of the threshed grains from the crop mixture is accomplished through the radial (outward) motion of grains relative to the crop stream under the action of gravity and centrifugal force. These forces give rise to the radial motion of the grains. This motion starts after the grains are detached from the panicles. After penetrating the crop stream, the grains bounce along the concave surface.

Separation occurs when a grain bounces through an opening in the concave. If the grain strikes a rod or bar, it bounces off and is carried by the crop stream towards the exit. This process is repeated until the grain penetrates the concave opening, otherwise, it will be lost at the exit. A schematic description of crop motion during threshing and separation processes is presented in Fig 3.2.

Grain separation through the concave opening can fail under the following conditions:

i. If the grain cannot find An opening in the concave opening within the allowed time.

ii. If the grain fails to penetrate the crop stream to reach the concave surface before exiting to the rear of the concave.

iii. If within the time duration in the threshing zone, the grain is not completely detached from the stalk.

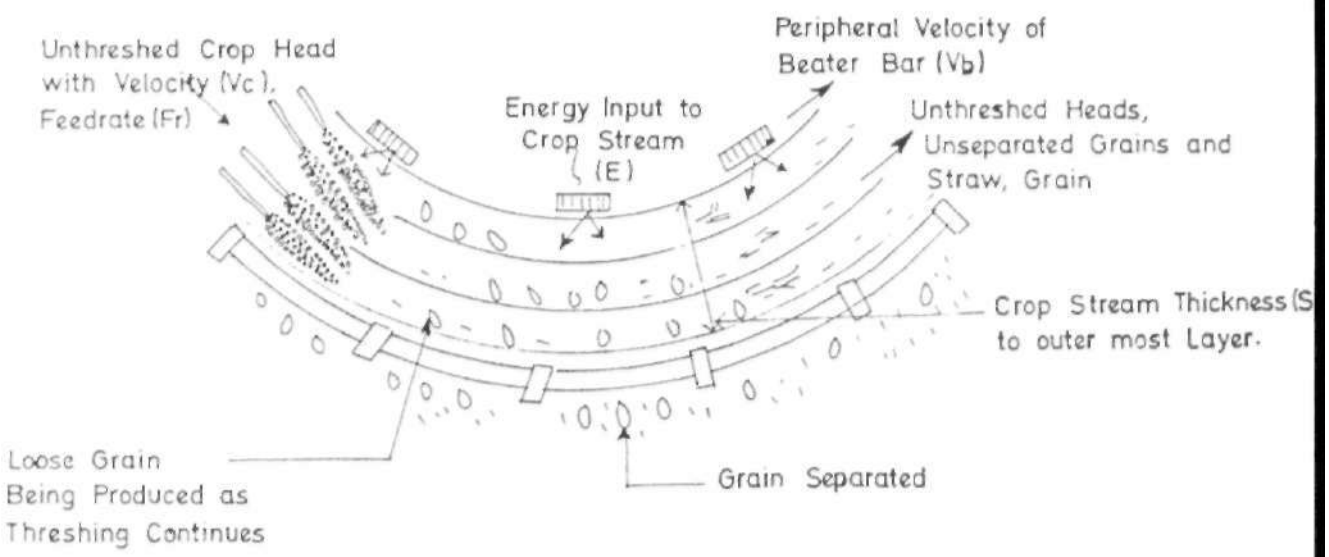


Fig. 3·2. Schematic Description of Crop motion during Threshing and Separation Processes.

3.3 Crop Motion Parameters

The establishment of some crop motion parameters is necessary to define the flow of the threshed material in the concave area. Therefore, such parameters as the velocity of crop in the threshing zone, dwell time, and crop stream thickness were considered in order to describethe motion of the crop during threshing and separation processes.

3.3.1 Velocity of crop in the threshing zone

The average velocity of the crop in the threshing zone can be estimated by representing the peripheral velocity of the cylinder or beater (V_b), linear velocity of the feeder (V_f) and the velocity of the crop in the threshing zone in a velocity diagram and then resolving the velocities to obtain the crop velocity (V_c) as shown in Fig. 3.3

Resolving the velocities by Pythagoras theorem

(Assumed velocity diagram be right angled)

$$V_c = (V_f^2 + V_b^2)^1/2 \qquad (3.1)$$

Since the feeding is manual then, V_f is small compared to Vb and can be assumed negligible.

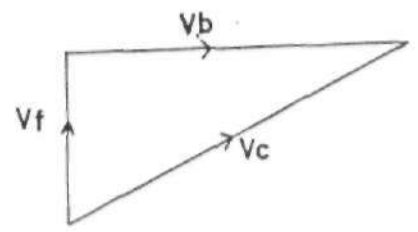


Fig. 3·3. Velocity Diagram for Crop Velocity in the Threshing Zone

Therefore from Equation 3.1

$$V_c = V_b$$

If the slippage factor for beater bars is K_b

Then $V_c = K_b V_b$ (3.2)

Hence the crop mixture is assumed to haul around the concave at the velocity given in Equation 3.2

3.3.2 Dwell time

For a given concave length (L_c) and crop velocity V_c, the dwell time (t_d) of the crop in the thresher can be expressed as (Huynh et al., 1982).

$$t_d = \frac{L_c}{V_c} \quad (3.3)$$

Substituting the value of Vc from equation 3.2 into equation 3.3 gives

$$t_d = \frac{1}{k_b}\left(\frac{L_c}{V_b}\right) \quad (3.4)$$

3.3.3 Crop stream thickness determination using dimensional analysis

The crop stream thickness (S) as shown in Fig 3.2 can be determined using dimensional analysis by relating the crop stream thickness (S) to the factors influencing it. Assume

that the variables of importance are the cylinder velocity V, crop bulk density, ρ_w (wet basis) and feedrate, F_r.

Then,

$$S = f(V_b, \rho_w, F_r) \tag{3.5}$$

Using the [M], [L], [T] system of dimensions, the dimensions of the variables used in this study are presented in table 3.1 and the dimensional matrix is presented in table 3.2. Applying the Buckingham pi theorem to identify the dimensionless group to be formed:

The total number of variables = 4

Number of fundermental dimensions = 3

Number of dimensionless groups to be formed = 4-3 = 1

The required solution would be:

$$\pi_1 = K_s \tag{3.6}$$

where, π_1 = Pi term = dimensionless constant, K_s

Using the Buckingham's Pi theorem, π_1 was obtained to be:

$$\pi_1 = S\, V_b^{1/2} \rho_w^{1/2} F_r^{-1/2} \tag{3.7}$$

or

$$\pi_1 = [S^2 V_b \rho_w / F_r]^{1/2} = K_s \tag{3.8}$$

Rearranging equation 3.8, then,

$$S = K_s\, [F_r / \rho_w V_b]^{1/2} \tag{3.9}$$

where:

K_s = Constant containing all the constant factors in equation 3.8.

Table 3.1: Dimensions of Mechanical Variables Influencing (S)

Variable	Symbol	Dimensions [M],[L],[T]
Maximum Crop Stream thickness	S	L
Cylinder Velocity	V_b	L/T
Bulk density of Crop material (wet basis)	ρ_w	M/L^3
Feed rate of crop material	F_r	M/T

Table 3.2: Dimensional Matrix of Variables

Parameters / Dimensions	S	V_b	ρ_w	F_r
M	0	0	1	1
L	1	1	-3	0
T	0	-1	0	-1

3.4 Force Analysis Of The Crop Stream In The Threshing Zone

Fig. 3.4 could be used for the force analysis of the crop stream in the threshing zone. Assuming that the pressure (q') of the crop stream on the concave surface is uniformly distributed over the entire length and width of the concave, then by dimensional analysis of the force (F) required to move the crop material around the concave is related to the mass feedrate and velocity as

$$F = \mu F_r V_c \tag{3.10}$$

where,

F = Frictional force to be overcome before the crop material move around the concave

μ = dimensional constant which is refered to as the coefficient of motion resistance of crop stream on the concave.

All other symbols are as defined above.

Substituting the value of V_c from Equation 3.2 into equation 3.10

yields,

$$F = \mu K_b F_r V_b \tag{3.11}$$

Let $\mu K_b = K_a$ (3.12)

then,

$$F = K_a F_r V_b \tag{3.13}$$

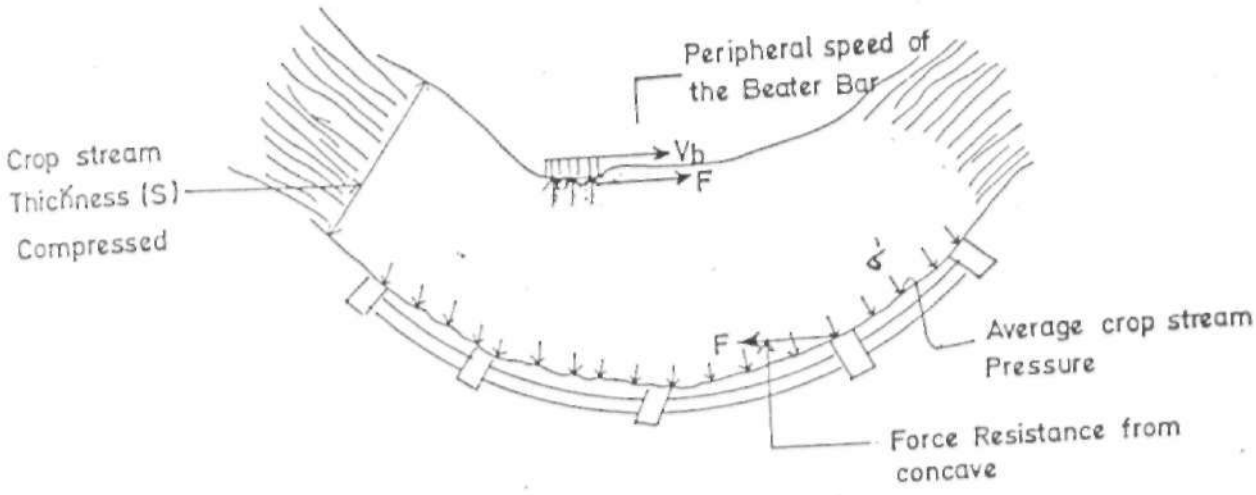


Fig. 3·4. Force Analysis of the crop stream in the Threshing Zone

3.5 Concept of Moisture Content Parameter

Since the moisture content of crop is an important factor influencing threshability, it is therefore necessary to establish a relationship between bulk density and moisture content. From literature, generally at same standard volume

Bulk density (dry basis) $\rho_d = W_d/V$ (3.14)

Bulk density (wet basis) $\rho_w = W_m/V$ (3.15)

where,

V = Volume occupied by the material

W_d = Mass of dried material

W_m = Mass of wet material

Moisture content dry basis, $M_d = W_w/W_d$ (3.16)

Moisture content wet basis,

$$M_w = \frac{W_w}{W_w + W_d} \quad (3.17)$$

where,

Ww = Mass of water removed

But $W_m = W_w + W_d$ (3.18)

From equation 3.18,

$W_w = W_m - W_d$ (3.19)

Substituting, W_w into equation 3.17 then,

$$M_w = \frac{W_m - W_d}{W_m} \quad (3.20)$$

Now, substituting W_d and W_m obtained from equations 3.14 and 3,15 respectively into equation 3.20, gives:

$$M_w = \frac{\rho_w - \rho_d}{\rho_w} \qquad (3.21)$$

Let Mw = β, then equation 3.21 becomes,

$$\beta\rho_w = \rho_w - \rho_d$$

or $\rho_d = \rho_w - \beta\rho_w$

or $\rho_d = \rho_w(1 - \beta)$

Therefore,

$$\rho_w = \frac{\rho_d}{1-\beta} \qquad (3.22)$$

where

β = moisture content of wet crop (decimal).

Equation 3.22 gives the relationship between bulk density and moisture content of crop.

3.6 Power Requirement Model

The power requirement model was developed by a combination of dimensional analysis, using the concept of Buckingham's Pi theorem and Mechanic Theory.

3.6.1 Determination of Energy Required to Detach Grains from Panicle using Dimensional Analysis

The power required to detach the grains from the stalk, P_t can be determined by first determining the energy required to detach the grain from the panicle. Using dimensional analysis energy required to detach the grain from the panicle, E can be related to the factors influencing E. Assume that the variables of importance are the crop velocity V_o, crop bulk density ρ_w (wet basis), feedrate F_r, concave clearance C, concave length L_o and cylinder diameter D. Since the concave clearance C, concave length L_c, and cylinder diameter D are usually fixed during threshing operation for a particular crop type, these 3 variables are assumed constant.

then,

$$E = f(V_b, \rho_w F_r) \tag{3.23}$$

Using the [M], [L], [T] system of dimension, the dimension of the variables are presented in table 3.3 and the dimensional matrix is presented in table 3.4.

Applying the Buckingham's pi Theorem to identify The dimensionless group to be formed:

The total number of variables = 4

Number of fundermental dimensions = 3

" " dimensionless groups to be formed = 4-3 = 1.

The required solution would be:

$$\pi_1 = K_c \tag{3.24}$$

where,

π_1 = P_1 term = dimensionless constant, K_e

K_e = Energy coefficient

Using the Buckingham's Pi theorem, π_1 was obtained to be:

$$\pi_1 = E\, V_b^{\,b}\, \rho_w^{\,b}\, F_r^{\,-3}/_2 \qquad (3.25)$$

or

$$\pi_1 = [\frac{E^{\,b}\,\rho_w^{\,b}}{V_b F_r}]^{\,b} = K_e \qquad (3.26)$$

Rearranging equation 3.26, then,

$$E = K_e[\frac{V_b F_r^{\,b}}{\rho_w}]^{\,b} \qquad (3.27)$$

3.6.2 Power requirement to detach grains from panicle

The power required to detach the grains from the panicle, P_r could be expressed as, $P_r = E/t_d$ (3.28)

Substituting the value of t_d from equation 3.4 into equation 3.28 yields:

$$P_r = K_b[EV_b]/L_c \qquad (3.29)$$

Where,

E = As defined earlier.

Now, substituting the value of E from equation 3.27 into equation 3.29 gives:

Table 3.3: Dimensions of the Variables influencing (E)

Variable	Symbol	Dimensions [M],[L],[T]
Energy	E	ML^2T^{-2}
Velocity	V_b	LT^{-1}
Bulk density (wet basis)	ρ_w	ML^{-3}
Mass Feed rate	F_r	MT^{-1}

Table 3.4: Dimensional Matrix of Variables

Parameters / Dimensions	E	V_b	ρ_w	F_r
M	1	0	1	1
L	2	1	-3	0
T	-2	-1	0	-1

$$P_T = K_b K_a \left[\frac{(V_b F_r)^3}{\rho_w L_c^2} \right]^{1/2} \quad (3.30)$$

Let $K_b . K_c = K_h$ = constant (3.31)

Therefore,

$$P_T = K_h \left[\frac{(V_b F_r)^3}{\rho_w L_c^2} \right]^{1/2} \quad (3.32)$$

Equation 3.32 predicts the power required to detach the grain from the panicle for a given crop bulk density, ρ_w.

3.6.3 Power required to overcome friction

From equation 3.13, the force required to overcome triction is given by $F = K_a F_r V_b$.

Now, the power required to overcome friction force P_f, can be expressed as:

$$P_f = F.V_c \quad (3.33)$$

Substituting the value of V_c from equation 3.2 into equation 3.33:

$$P_f = K_b F V_b \quad (3.34)$$

Substituting the value of F from 3.13 into equation 3.34 then,

$$P_f = K_b K_a F_r V_b^2 \quad (3.35)$$

let $K_b K_a = K_f$ = constant (3.36)

Therefore, $P_f = K_f F_r V_b^2$ (3.37)

Equation 3.37 predicts the power required to overcome trictional force.

3.6.4 Power required to turn unloaded cylinder

The force F' required to turn the threshing cylinder without load can be expressed as

$$F' = M_c a' \quad (3.38)$$

where,

M_c = Mass of the threshing cylinder

a' = The sum of acceleration due to gravitational force (g') and the centrifugal acceleration of the cylinder ($2V_b^2/D$).

or $a' = g' + 2V_b^2/D$ (3.39)

where,

V'_b = Velocity of the cylinder without load (m/s)

D = Effective diameter of the cylinder.

Since the acceleration of the cylinder is influenced by the acceleration due to gravitational force (g') and the centrifugal acceleration of the cylinder $2V'^2_b/D$. Substituting the value of a' from equation 3.39 into equation 3.38 gives,

$$F' = M_c (g' + 2V'^2_b/D) \quad (3.40)$$

The Torque T' required to turn the threshing cylinder without load can be expressed as (Ndirika, 1988):

$$T' = F'r \quad (3.41)$$

where,

r = Radius of the driven pulley of the cylinder.

Substituting the value of F′ from equation 3.40 into equation 3.41 then,

$$T' = M_c \times (g' + 2V'^{2}_{b}/D) \qquad (3.42)$$

The power P_r required to run the cylinder without load is expressed as (Ndirika, 1988):

$$P_r = NT' \qquad (3.43)$$

where,

N = Cylinder rpm without load

Substituting the value of T′ from equation 3.42 into equation 3.43 then,

$$P_r = M_c \times N(g' + 2V'^{2}_{b}/D)$$

and expressing P_r in the unit of Power:

$$P_r = 2\pi M_c \times N(g' + 2V'^{2}_{b}/D)/60 \qquad (3.44)$$

The total power P required for threshing operation can be expressed as

$$P = P_f + P_t + P_r \qquad (3.45)$$

Substituting the values of P_f, P_t and P_r obtained from equation 3.51, 3.46 and 3.58 respectively into equation 3.59 then,

$$P = K_1 F_t V_b^2 + K_t \left[\frac{(V_b F_t)^2}{\tau_w L_c^2}\right]^{1/2} + \frac{2\pi M_c N (g' + 2V_b^2/D)}{60} \qquad (3.46)$$

Again, substituting the value of τ_w from equation 3.22 into equation 3.46 then,

$$P = K_1 F_r V_b^2 + K_2 \left[\frac{(V_b F_r)^2 (1-\beta)}{\rho_g L_c^2} \right]^{1/2} + \frac{2\pi M_c N (g' + 2 V_b^2/D)}{60}$$

(3.47)

Equation 3.47 predicts the total power required for threshing operation.

3.7 Modeling of Threshing Process

In this section the development of the threshing parameter, threshing efficiency and total grain loss models are presented.

The threshing efficiency and total grain loss models were developed by a combination of probabilistic theory and dimensional analysis using the concept of Buckingham;s pi theorem.

3.7.1 Threshing parameter

The Threshing frequency or the meanrate of threshing, λ_1 can be determined by the use of dimensional analysis. Assuming that the variables of importance influencing λ_1 are: cylinder velocity, V_b, crop bulk density, ρ_w, Feedrate, F_r and cylinder diameter, D. Then,

$$\lambda_1 = f(V_b, \rho_w, F_r, D) \qquad (3.48)$$

Using the [M],[L],[T] system of dimension, the dimensions of the variables are presented in table 3.5 and the dimensional matrix is presented in table 3.6. Applying the Buckingham's

pi theorem to identify The dimensikonless group to be formed:

The dependent variable = Δ_1

The repeating variables = V_b, ρ_w, F_r

Total number of variables = 5

Number of fundermental dimensions = 3

Number of dimensionless groups to be formed = 5-3 = 2.

The required solution will be:

$$\pi_1 = K_T f(\pi_2) \tag{3.49}$$

where,

π_1, π_2 = First and second Pi terms respectively

K_T = Threshing constant

Using the Bbuckingham's Pi theorem, π_1 and π_2 were found to be:

$$\Pi_1 = \left[\frac{\Delta_1^2 F_r}{V_b^3 \rho_w}\right]^{\frac{1}{2}} \tag{3.50}$$

$$\Pi_2 = \left[\frac{D^2 V_b \rho_w}{F_r}\right]^{\frac{1}{2}} \tag{3.51}$$

The required relationship is herefore,

$$\left[\frac{\Delta_1^2 F_r}{V_b^3 \rho_w}\right]^{\frac{1}{2}} = K_T \left[\frac{D^2 V_b \rho_w}{F_r}\right]^{\frac{1}{2}} \tag{3.52}$$

Since $\pi_1/\pi_2 = K_T$

Table 3.5: Dimensions of The variables influencing (Λ_1)

Variable	Symbol	Dimensions [M],[L],[T]
Threshing frequency	Λ_1	T^{-1}
Cylinder velocity	V_b	LT^{-1}
Bulk density (wet basis)	ρ_w	ML^{-3}
Feedrate	F_r	MT^{-1}
Cylinder Diameter	D	L

Table 3.6: Dimensional Matrix of the Variables

Parameters / Dimensions	Λ_1	V_b	ρ_w	F_r	D
M	0	0	1	1	0
L	0	1	-3	0	1
T	-1	-1	0	-1	0

Then, equation 3.52 becomes:

$$K_T = \frac{\lambda_1 F_r}{V_b^2 \rho_w D} \qquad (3.53)$$

Rearranging equation 3.53

$$\lambda_1 = K_T[V_b^2 \rho_w D/F_r] \qquad (3.54)$$

Substituting the value of ρ_w, from equation 3.22 into equation 3.54 then,

$$\lambda_1 = K_T \left[\frac{V_b^2 \rho_g D}{(1-\beta)F_r}\right]^{1/n}. \qquad (3.55)$$

Equation 3.55 expresses The threshing frequency or rate of threshing.

From Euler's theorem of momentum, the force, F_c, generated on the earhead can be expressed as

$$F_c = \dot{M}(V_b - V_g) \qquad (3.56)$$

where,

V_g = Velocity of grain after impact,

V_b = Velocity of beaters

$\dot{M}$ = Mass of earhead/sec. since mass changes with time.

Therefore, input power P_{in}, generated by the beaters or bar can be expressed as

$$P_{in} = \dot{M}(V_b - V_g)V_g \qquad (3.57)$$

The output power, P_{out} can be expressed as the rate of change in kinetic energy (K.E) of the ear head. This can be expressed mathematically as,

$$P_{out} = 1/2\ \dot{M}V_g^2 \qquad (3.58)$$

The power efficiency, η_p of this process can be expressed as

$$\eta_p = \frac{Power\ output}{Power\ input} = \frac{P_{out}}{P_{in}} \qquad (3.59)$$

Substituting the values of P_{in} and P_{out} from equations 3.57 and 3.58 into equation 3.59 yields,

$$\eta_p = \tfrac{1}{2}V_g(V_b - V_g)^{-1} \qquad (3.60)$$

To obtain the maximum tangential velocity of the grain after impact equation 3.60 is set equal to unity (1) which is the condition for maximum power efficiency.

$$\tfrac{1}{2}V_g(V_b - V_g)^{-1} = 1 \qquad (3.61)$$

or $V_g = {}^2/_3\ V_b \qquad (3.62)$

Therefore, the value of V_g obtained in equation 3.62 is the maximum velocity of grain after impact and must not exceed two-third of the velocity of the beaters (V_b).

3.7.2. Threshing efficiency and threshing loss models

Threshing process has been defined by an exponential function (Huynh et al., 1982 and Gregory, 1988). Therefore, the exponential probability density function is considered fit for describing and predicting the process performance and

various variables influencing threshability. The process is considered as a probability of equal likely events which assumes that any grain has equal chance of being threshed at any time and has equal chance of reaching the concave surface at a given position.

The exponential probability density function is defined as

$$f(t) = \lambda e^{-\lambda t} \tag{3.63}$$

where,

$t = t_1$ = time to occurence of the random event (threshing of grain)

$\lambda = \lambda_1 = 1/T_1$ (mean rate of threshing)

T_1 = The average time elapsed between the entry of crop into the thresher and threshing of a grain.

Integrating equation 3.63 with respect to time, t at time intervals ($o < t < t'_d$) to obtain fraction of grain threshed within the interval, then,

$$T_o = \int f(t) = \int_o^{t'_d} \lambda e^{-\lambda t}\, dt \tag{3.64}$$

$$= [-e^{-\lambda t}]_o^{t'_d}$$

$$= [-e^{-\lambda t'_d}] - [-1] = 1 - e^{-\lambda t'_d}$$

for grain threshing $\lambda = \lambda_1$

Therefore, $T_o = 1 - e^{-\lambda_1 t'_d}$ (3.65)

Equation 3.65 describes the threshing efficiency parameter (T_o) which depends on the rate of threshing (λ_1) and the dwell time, t'_d of threshed grain in the threshing zone. But dwell time,

$$t'_d = L_c/V_g = L_c/(^2/_3 V_b) = 3L_c/(2V_b) \quad (3.66)$$

Substituting t'_d and λ_1 from equations 3.66 and 3.55 respectively into equation 3.65, then threshing efficiency parameter is:

$$T_e = 1 - e^{\frac{1.5K_T \omega_g D V_b L_c}{(1-\beta)F_r}} \quad (3.67)$$

Equation 3.67 can be used to predict threshing efficiency.

Threshing loss, T_L which is the fraction of unthreshed grains by the process can be expressed as:

$$T_L = 1 - \int_0 \lambda e^{-\lambda t d} \, dt \quad (3.68)$$

or $$T_L = 1 - T_e \quad (3.69)$$

$$T_L = e^{\frac{-1.5K_T \omega_g D V_b L_c}{(1-\beta)F_r}} \quad (3.70)$$

Substituting equation 3.67 into equation 3.69 then threshing loss,

Equation 3.70 can be used to predict threshing loss by the process.

3.8 Damage Model

3.8.1 *Damage parameter, λ_d (mean rate of damage grain).*

The damage frequency or the meanrate of damage of grain, λ_d can be determined by the use of dimensional analysis. Assuming that the variables of importance influencing, λ_d are: Cylinder Velocity, V_b, Crop bulk density, ω_g, Feedrate, F_r, Cylinder dimeter, D and Minimum velocity to cause grain

damage,

V_d. Then,

$$\Delta_d = f(V_b, \rho_w, F_r, D, V_d) \quad (3.71)$$

Using The [M],[L],[T] system of dimension, the dimensions of The variables are presented in table 3.7 and the dimensional Matrix is presented in table 3.8. Applying The Buckingham's P_i theorem to identify the dimensionless groups to be formed:

The dependent variable = Δ_d

The repeating variables = V_b, ρ_w, F_r

Total number of variables = 6

Number of fundermental dimensions = 3

Number of dimensionless groups to be formed = 6-3 = 3.

$$\pi_1 = K_d f(\pi_2, \pi_3) \quad (3.72)$$

where,

π_1, π_2, π_3 = First, second and third Pi terms respectively.

K_d = Damage Constant.

Using the Buckingham's Pi theorem, π_1, π_2 and π_3 were found to be:

$$\pi_1 = [\Delta_d^2 F_r / V_b^3 \rho_w]^{1/2} \quad (3.73)$$

$$\pi_2 = [D^2 V_b \rho_w / F_r]^{1/2} \quad (3.74)$$

$$\pi_3 = V_b / V_d \quad (3.75)$$

$$[\Delta_d^2 F_r / V_b^3 \rho_w]^{1/2} = K_d f[(D^2 V_b \rho_w / F_r)^{1/2}, V_b / V_d] \quad (3.76)$$

(3.77)

Let $\pi_2 \times \pi_3 = \pi_4$, then

Table 3.7: Dimensions Of The Variables Influencing (λ_d)

Variable	Symbol	Dimensions (M),(L),[T]
Damage frequency	λ_d	T^{-1}
Cylinder Velocity	V_b	LT^{-1}
Damage Velocity	V_d	LT^{-1}
Bulk density (wet basis)	ρ_w	ML^{-3}
Feedrate	F_r	MT^{-1}
Cylinder diameter	D	L

Table 3.8: Dimensional Matrix of The Variables

Parameter / Dimension	λ_d	V_b	ρ_w	F_r	D	V_d
M	0	0	1	1	0	0
L	0	1	-3	0	1	1
T	-1	-1	0	-1	0	-1

Substituting ρ_w from equation 3.31 into equation 3.82 gives,

$$\lambda_d = K_d \frac{[\rho_d D V_b^2]}{1.8(1-\beta)F_r} \quad 1/\text{sec} \qquad (3.83)$$

Equation 3.83 is the mean rate of grain damage per sec. (damage parameter).

3.8.2 Damage Fraction Model

The integral of exponential probability density function as in equation 3.63 was used to develop expression for the fraction of grain damage within the time interval $0 < t < t_d$" in the threshing zone. From this interval it implies that, the fraction threshed within the interval

$$= \int_0^{t_d} \lambda_d e^{-\lambda_d t}\, dt \qquad (3.84)$$

The damaged fraction (decimal)

D_f = 1 - (the fraction threshed within the interval)

$$= 1 - \int_0^{t_d} \lambda_d e^{-\lambda_d t}\, dt \qquad (3.85)$$

$$= 1 - [1 - e^{-\lambda_d t_d}]$$

$$= e^{-\lambda_d t_d} \qquad (3.86)$$

To obtain the maximum tangential velocity of the damaged grain after impact, the power efficiency of the process is equated to be unity (1) as applied in equation 3.61 i.e

$$\frac{U_d}{2(V_d - U_d)} = 1 \qquad (3.87)$$

where,

U_d = The maximum tangential velocity of the damaged grain after impact

V_d = Minimum cylinder velocity that will cause grain damage.

Substituting the value of V_d from equation 3.81 into equation 3.87 then,

$$U_d = 1.2V_b \tag{3.88}$$

Equation 3.88 expresses the maximum tangential velocity of the damaged grain after impact. But dwell time for the damage grain after impact, $t_d'' = L_c/U_d = L_c/(1.2V_b) = 0.83L_c/V_b$

or

$$t_d'' = 0.83L_c/V_b \tag{3.89}$$

Substituting equation 3.82 and 3.89 into equation 3.86 yields:

$$D_f = e^{\frac{0.46K_d\,\rho_g\,DV_b\,L_c}{(1-\beta)F_f}} \tag{3.90}$$

Equation 3.90 expresses the fraction of damaged grain after impact in decimal.

3.9 Total Grain Loss (TGL) Model

All damaged or unthreshed grain are considered as loss in the modeling of the total grain loss. These are considered as losses due to the following reasons:

i Damaged grain may result in poor seed germination.

ii Cracked kernels may result in dockage when sold for

milling purpose.

iii Unthreshed heads which are retained for rethreshing often results in damaged kernels

iv Small kernel fragments which result from damaged grain are likely to be lost totally during pneumatic separation.

Thus, the total grain loss in threshing unit is presented as the sum of the threshing loss (T_L) and grain damage loss (D_f). That is:

Total grain loss, $TGL = T_L + D_f$ (3.91)

$$\exp.\ \frac{1.5K_T\rho_g DV_b L_c}{(1-\beta)F_r} \cdot \exp.\ \frac{0.46K_d\rho_g DV_b L_c}{(1-\beta)F_r} \quad (3.92)$$

3.10 Separation Process Model

A separation process model is proposed to describe:

i Grain migration through the crop stream;

ii Grain passage through the crop stream and concave openings.

The rate of grain passage through the crop stream and concave openings are used to quantify the two processes.

3.10.1 Grain migration parameter, Λ_2

(through the crop stream).

This model is based on the application of Newton's second law of motion for a body under uniform acceleration starting from rest. It was assumed that the crop motion resistance

(Force) is constant and proportional to the force acting on the grain. Expressed mathematically from the Newton's law of motion,

$$S = Ut_2 + \tfrac{1}{2}a't_2^2 \qquad (3.93)$$

Applying this to the cylinder-concave situation where,

S = Crop stream thickness

$t_2 = T_2$ = mean time for a grain to pass through the crop stream thickness.

a' = acceleration due to gravitational force (g') and the centrifugal acceleration of the loose grain in a horizontal direction ($2V_b^2/D$).

U = grain velocity from rest.

From rest U = 0, therefore, equation 3.93 becomes

$$S = \tfrac{1}{2}a'T_2^2 \qquad (3.94)$$

$$\text{Hence, } T_2 = [2S/a']^{\frac{1}{2}} \qquad (3.95)$$

Since the acceleration of the grain, a' is influenced by the acceleration due to gravitational force (g') in the vertical direction and the centrifugal acceleration of the loose grain in a horizontal direction $2V_b^2/D$.

Then,

$$a' = g' + 2V_b^2/D \qquad (3.96)$$

where,

D = Effective diameter of the cylinder

V_b = peripheral velocity of the beaters

Also, from equation 3.9,

$$S = K_s \left[\frac{F_r}{\rho_w V_b} \right]^{1/2}$$

Substituting the value of a' from equation 3.96 and S from equation 3.19 into equation 3.95 yields:

$$T_c = \left[\frac{2K_s \left(\frac{F_r}{\rho_w V_b} \right)^{1/2}}{(g' + 2V_b^2/D)} \right]^{1/2} \qquad (3.97)$$

or

$$[2K_s]^{1/2} \left[\frac{\left(\frac{F_r}{\rho_w V_b} \right)^{1/2}}{(g' + 2V_b^2/D)} \right]^{1/2} \qquad (3.98)$$

Let $(2K_s)^{1/2} = K_n$ = constant (3.99)

Therefore,

$$T_c = K_n \left[\frac{\left(\frac{F_r}{\rho_w V_b} \right)^{1/2}}{(g' + 2V_b^2/D)} \right]^{1/2} \qquad \textit{(Huynh et al., 1982)} \qquad (3.100)$$

Thus the mean rate of occurence of separation for a grain through the crop stream thickness is

$$\frac{1}{T_c} = \nu_2 = \frac{1}{K_n} \left[\frac{g' + 2V_b^2/D}{(F_r/\rho_w V_b)^{1/2}} \right]^{1/2} \qquad (3.101)$$

Substituting the value of ρ_w from equation 3.12 into equation 3.101 then

$$\lambda_2 = \frac{1}{K_n}\left[\frac{g' + 2V_b^2/D}{\left(\frac{(1-\beta)F_r}{\rho_d V_b}\right)^{1/2}}\right]^{1/2} \qquad (3.102)$$

Equation 3.102 expresses the grain migration parameter (mean rate of migration or separation for a grain through the crop stream thickness).

3.10.2 Concave separation parameter, (λ_3)

The following assumptions were made in determining the rate of grain passage through concave opening:

i That the grain slides through the crop stream with constant velocity, V_g across the concave surface.

ii That the passage of grain through a given concave opening formed by the rods and bars as shown by the concave geometry in fig 3.5 is only possible if the projection of the grain on the concave surface is within the concave opening and

iii that if the grain fails to pass through the concave opening it will move to the next concave opening at a constant speed (V_g).

The probability of grain passage through the concave opening was determined using the relation (Huynh et al., 1982)

$$P' = (a_1 - a_2 - d_1)(b_1 - b_2 - d_1)/(a_1 b_1) \qquad (3.103)$$

for the concave geometry in Fig 3.5 (Enaburekhan, 1994)

where,

a_1 = Centre line distance between rods

b_1 = Centre line distance between bars

a_2 = The rod diameter

b_2 = Width of the bar

d_1 = average size of the grain which is considered spherical.

P′ = Probability of grain passage through the concave opening. The time available for a grain passing through a given opening, t_o at a distance b_1 between bars is expressed as (Huynh et al., 1982).

$$t_o = b_1/V_g \qquad (3.104)$$

Susbstituting the value of V_g from equation 3.62 into equation 3.104 then,

$$t_o = (3/2)[b_1/V_b] \qquad (3.105)$$

Also the probability of a grain passing through the concave opening is given as (Huynh et al., 1982)

$$P' = \lambda_3 t_o \qquad (3.106)$$

where,

λ_3 = mean rate of occurence of grain separation through the concave opening.

Substituting the value of P′ from equation 3.106 into equation 3.103 then,

$$\lambda_3 = (1/t_o)(a_1 - a_2 - d_1)(b_1 - b_2 - d_1)/a_1b_1 \qquad (3.107)$$

Substituting the value of t_o from equation 3.105 into equation 3.107 yields (Huynh et al., 1982)

$$\lambda_3 = \tfrac{3}{2}V_b(a_1 - a_2 - d_1)(b_1 - b_2 - d_1)/a_1b_1^2 \qquad (3.108)$$

Equation 3.108 describes the number of grains passing through the concave openings in one second per impact (concave parameter).

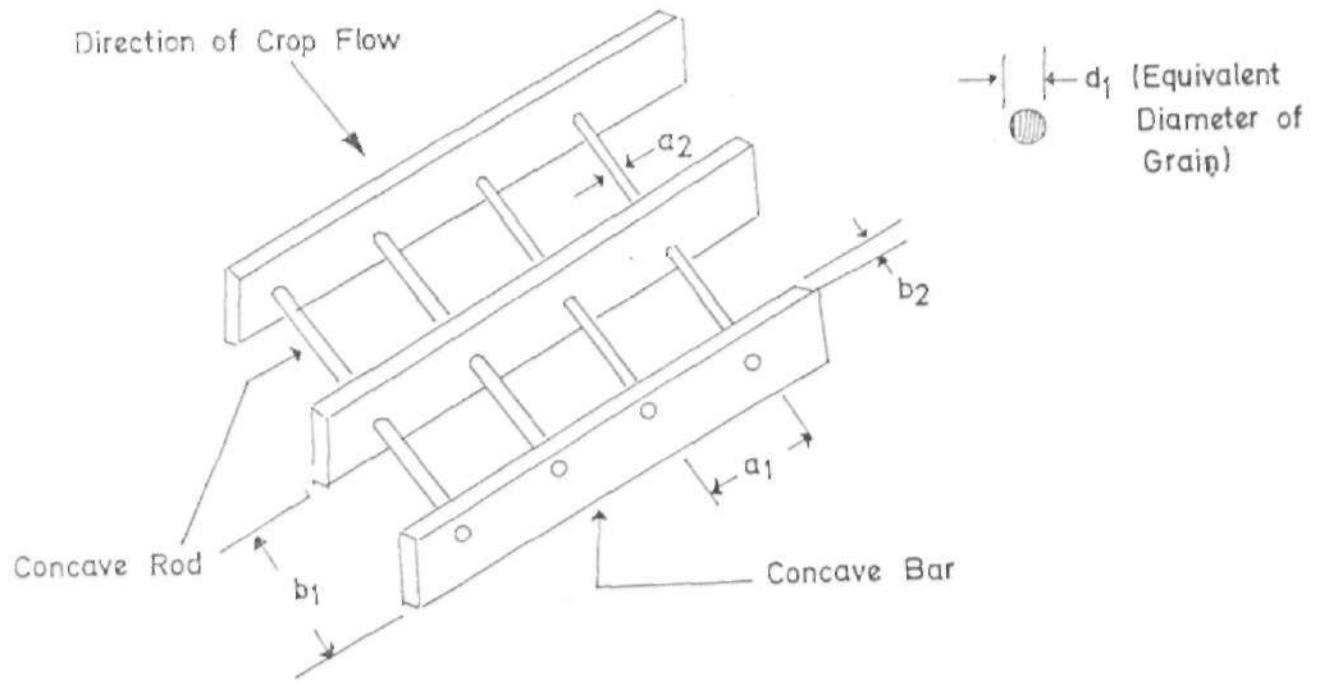


Fig. 3·5. Concave Configuration.

3.10.3 Separation efficiency model

The dependent events considered in the modeling of the separation efficiency are:

i Detachment of the grain from the crop head

ii Migration of the grains through the crop stream.

iii Passage of grain through opening.

Hunyh et al. (1982) predicted separation efficiency as:

$$S_e = 1 - \frac{1}{(\lambda_1-\lambda_2)(\lambda 3-\lambda_2)(\lambda_3\lambda_1)}\left[\lambda_1\lambda_3(\lambda_3-\lambda_1)e^{-\lambda_2 t_d} + \lambda_2\lambda_1(\lambda_1-\lambda_2)\right.$$

$$\left. e^{-\lambda_3 t_d} + \lambda_2\lambda_3(\lambda_2\lambda_3)e^{-\lambda_1 t_d}\right] \qquad (3.109)$$

Equation 3.109 predicts the fraction of threshed grain that was recovered through the concave openings.

3.11 Thresher capacity model.

The thresher output capacity model was developed by dimensional analysis, using the concept of Buckingham's pe theory.

The output capacity of a thresher (C_t) can be determined by the use of dimensional analysis. Assume that the variables of importance are the feedrate, F_r, grain-straw ratio (Z) and the separation efficiency (S_e) which is the fraction of threshed grain that was recovered through the concave opening by the concave configuration). Then,

$$C_t = f(F_r, Z, S_e) \qquad (3.110)$$

Using the [M],[L],[T] system of dimension, the dimensions of the

variables are presented in table 3.9 and the dimensional Matrix is presented in table 3.10. Applying The Buckingham pi theorem to identify the dimensionless group to be formed:

The total number of variables = 4

Number of fundermental dimensions = 3

Number of dimensionless groups to be formed = 4-3 = 1.

The required solution would be:

$$\pi_1 = K_m \qquad (3.111)$$

where,

π_1 = P_1 term = dimensionless constant, K_m

K_m = yield factor

Using the Buckingham's Pi theorem, π_1 was found to be:

$$\Pi_1 = \frac{C_T}{F_t Z S_e} = K_m \qquad (3.112)$$

Rearranging equation 3.112, then,

$$C_T = K_m F_t Z S_e \qquad (3.113)$$

Substituting the value of S_e from equation 3.110 into equation 3.113 then,

$$C_T = K_m F_t Z\left[1 - \frac{\lambda_1\lambda_3(\lambda_3-\lambda_1)e^{-\lambda_2 t_d} + \lambda_2\lambda_1(\lambda_1+\lambda_2)e^{-\lambda_3 t_d} + \lambda_2\lambda_3(\lambda_2-\lambda_3)e^{-\lambda_1 t_d}}{(\lambda_1-\lambda_2)(\lambda_2-\lambda_3)(\lambda_1-\lambda_3)}\right] \qquad (3.114)$$

Equation 3.114 predicts the capacity of grain thresher.

Table 3.9: Dimensions of the variables influencing (C_T)

Variable	Symbol	Dimensions [M],[L],[T]
Output capacity	C_r	MT^{-1}
Feedrate	F_r	MT^{-1}
Grain-straw ratio	Z	-
Separation efficiency	S_e	-

Table 3.10: Dimensional Matrix of Variables

Dimensions \ Parameters	C_T	F_r	Z	S_e
M	1	1	0	0
L	0	0	0	0
T	-1	-1	0	0

CHAPTER FOUR

DETERMINATION OF COEFFICIENTS IN THE MODELS

The unkown coefficients in the formulated models were determined from the available literature and published data.

4.1 Determination Of The Slippage Factor, K_b

The slippage factor K_b for beater bars established in equation 3.2 was determined using the value established by Huynh et al. (1982) obtained by linear regression analysis. The value of K_b generated by Huynh et al (1982) was obtained by plotting the values of straw velocity, V_c, against the peripheral speed of the beater bars graphically, then the slope of the graph gives the value of K_b.

That is,

$K_b = 0.4$

4.2 Determination of K_e and K_h

The energy coefficient (K_e) in equation 3.26 was determined by calculating the mean value of the Pi term using data obtained from Wagami (1979), Gurama (1977) and P.A.U. Test reports (1970-1972) on millet, sorghum and wheat threshers respectively as presented in Table A_1. The K_e values for each of the threshers was first determined and the K_h values for each of the thresher was then calculated using equation 3.31. The estimated values of K_e and the corresponding K_h values for the threshers are presented in

Table 4.1.

In order to determine the effect of K_h calculated for each of these threshers on the power required to detach the grain from the panicle, P_T, the power was calculated using the data from Wagami (1979), Gurama (1977) and P.A.U Test reports (1970-1972) on millet, sorghum and wheat threshers respectively into equation 3.32. This is presented with the design matrix of the variables in Table A2.

The result shows that the individual calculated effect of K_h for millet, sorghum and wheat threshers have no significant effect on the power required to detach the grain from the panicle. The calculated effects k_h are presented in Table 4.2

The result showed that the effect of the coefficient K_h for millet, sorghum and wheat threshers is statistically insignificant at 0.05 confidence level. Since the individual K_h for the different threshers has no significant effect, the combined value of K_h for these threshers can then be obtained using the combined mean value of K_e for the threshers.

From table A_1, the mean value of K_e = 0.91 and the standard deviation = 0.035.

from equation 3.31, $K_h = K_e \cdot K_b$

Since K_b = 0.4 (Huynh et al, 1982)

Then, $K_h = 0.91 \times 0.4 = 0.36$

Hence $K_h = 0.36$

Table 4.1: Calculated values of K_e, K_h for Millet, Sorghum and Wheat Threshers.

Crop Type	K_e (Mean Values)	K_h $(k_e x k_b)$
Millet	0.910	0.364
Sorghum	0.914	0.36
Wheat	0.907	0.363

Table 4.2: Calculated Effect of k_h

Thresher type	Estimated Effect of K_h
(millet thresher)	0.0016
(sorghum thresher)	0.0019
(wheat thresher)	0.00212

4.3 Determination of the Threshing Constant, K_T

The threshing constant or threshing factor K_T was determined by linearizing equation 3.52 using method of Least Squares. The line of best fit with regression coefficient, R = 0.90 was drawn as presented in figure 4.1, using the data from Table A3. The slope of the line gives the value of the threshing constant K_T.

The slope K_T was found to be 2.10×10^{-3}. The result of the linear regression shows that the intercept was not significant at 5% level, which indicates that equation 3.52 used in the analysis is justified.

4.4 Determination of the Damage Constant K_d

The damage constant K_d, was determined by linearizing equation 3.78 using Method of Least Square analysis. The Least Square line was drawn as presented in Figure 4.2 using the data from Table A4. The slope of the line of best fit gives the value of the damage constant K_d. The slope $K_d = 7.94 \times 10^{-3}$. Also the regression coefficient, R obtained was 0.95. The result of the linear regression shows that the intercept was significant at 5% level, which indicates that equation 3.78 used in the analysis is justified.

4.5 Determination of the Yield Factor, K_m

The yield factor, K_m in equation 3.112 was determined calculating the mean value of the Pi term using the data from Table A5. The mean value of the yield factor K_m obtained is 0.70 and the standard deviation is 0.019.

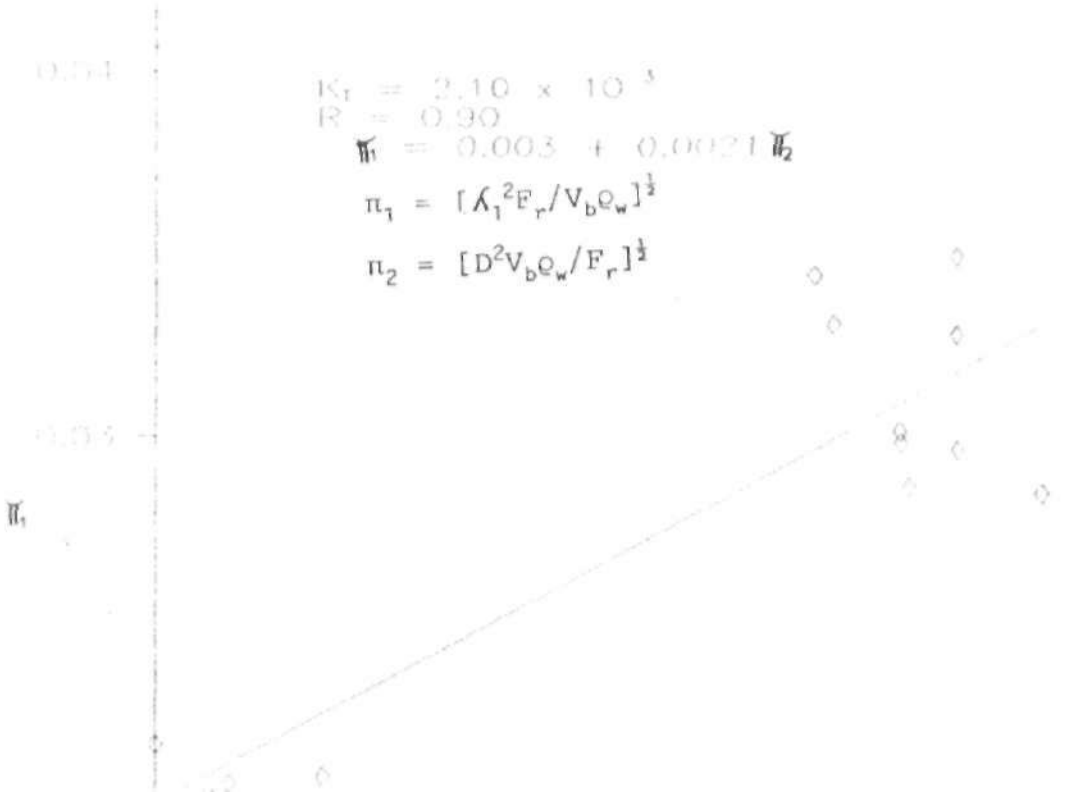
4.6 Determination of Friction Power Constant, K_f and Friction Force Coefficient, K_a

The friction power constant K_f in equation 3.37 was determined by combining equations 3.12 and 3.36 together to obtain an expression for K_f in terms of K_b and coefficient of motion resistance, μ. Substituting the values of Ka from equation 3.12 into equation 3.36 then,

$$k_f = \mu K_b^2 \qquad (4.1)$$

The average value of the coefficient of motion resistance, μ for grain crops on steel material is 0.375 (Henderson and Perry ,1976). Substituting the values of μ and K_b into equation 4.1 then,

$$K_f = 0.06$$


0.004
$K_1 = 2.10 \times 10^{-3}$
$R = 0.90$
$\pi_1 = 0.003 + 0.0021\,\pi_2$
$\pi_1 = [\lambda_1^2 F_r / V_b \varrho_w]^{\frac{1}{2}}$
$\pi_2 = [D^2 V_b \varrho_w / F_r]^{\frac{1}{2}}$
π_1

$$\Pi_1 = [\frac{K_d^2 F_r}{V_b^3 \rho_w}]^{\frac{1}{3}},$$

$$\Pi_4 = [\frac{D^2 V_b^3 \rho_w}{F_r V_d^2}]^{\frac{1}{3}}$$

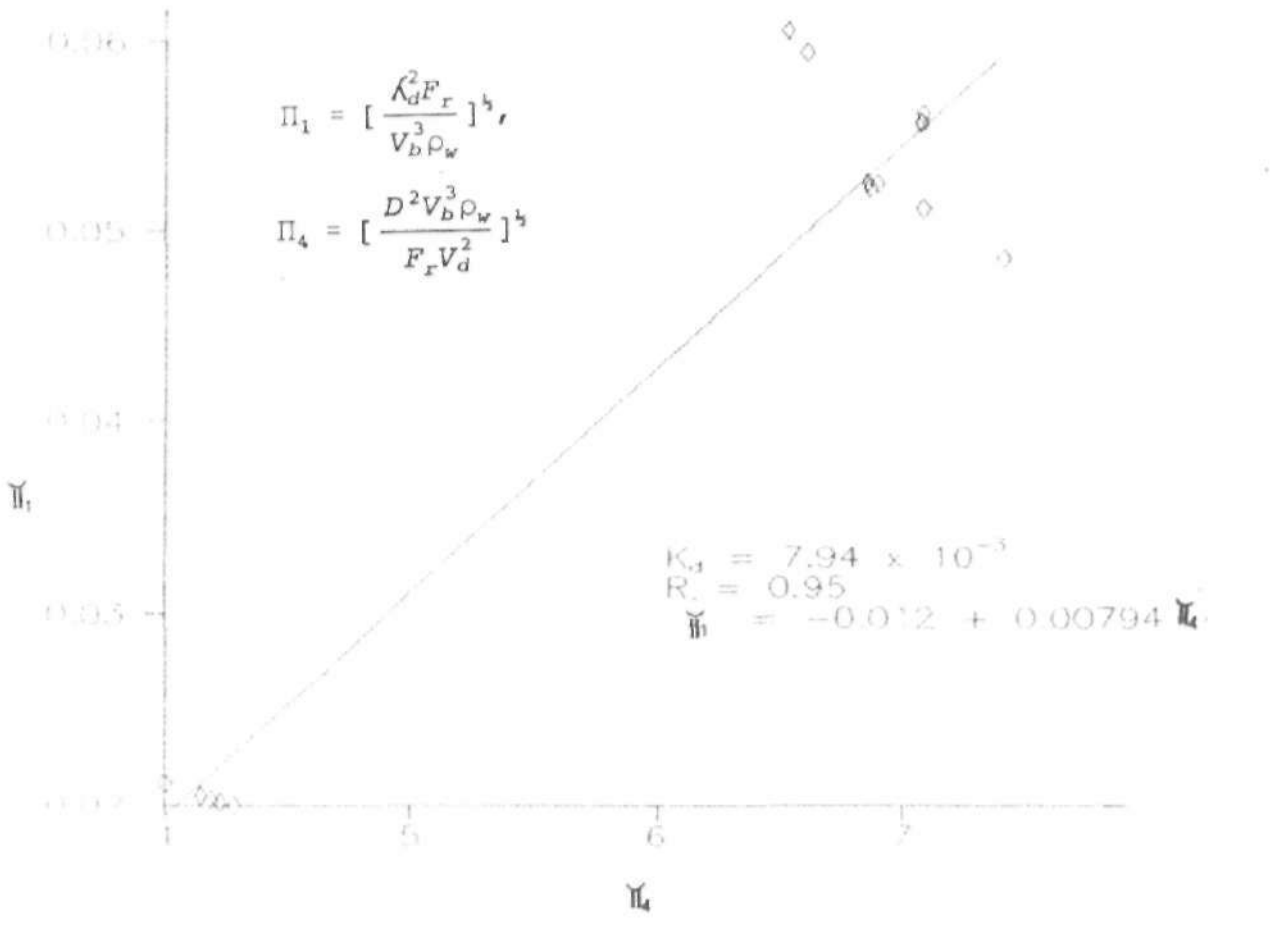


Fig. 4.2: Determination of the grain damage constant (K_d)

The friction force coefficient K_a was determined using equation 3.12. Substituting the value of μ and K_b into equation 3.12. Then, $K_a = 0.15$

4.7 Determination of the Mean Time Coefficient K_n and tThe Crop Stream Thickness Coefficient, K_s

The mean time coefficient, K_n, value determined by Huynh et al. (1982) using the data from Long et al. (1967) was used since this mean time in equation 3.100 is found to be the same when compared with Huynh's model, Therefore,

$K_n = 2.25$ (Huynh et al., 1982)

The crop stream thickness coefficient K_s was determined using equation 3.099. Rearranging the equation,

$$K_s = \tfrac{1}{2}(K_n)^2 \qquad (4.2)$$

Substituting the values of K_n established above into equation 4.2, then,

$K_s = 2.53$

CHAPTER FIVE

VERIFICATION AND VALIDATION OF THE MODELS

In order to use a developed model for either planning or design, the model should be properly verified. Model verification consists of comparing the computed model output with established result of the existing system. When verified it is furthermore optimized to select the most appropriate choices from all possible designs that are available.

The aim of this chapter is to reveal that the performance models developed are atleast consistent with the established experimental results of the existing threshers. To achieve this objective the study was conducted on two existing threshers (millet and sorghum threshers). The predicted models were compared with the experimental data and other established models. If the computed data are in close agreement with the experimental data, the model is said to be verified.

5.1 Verification of Threshing Performance Models for a Millet Thresher

The specifications of the cylinder-concave unit of the Millet thresher used for experimentation are contained in tables, 5.1, 5.2 and 5.3.

5.1.1 Measurement and evaluation

The data generated from the stationary millet thresher used in the verification of the performance models were

measured and evaluated by the following methods.

Weight measurement:

A Mettler balance with 0.01g calibrations was used for weighings.

Time measurement:

This was measured using a stop watch.

Capacity measurement:

The output capacity was measured by weighing the grains collected from the grain outlet at an hour interval of threshing operation.

Threshing efficiency evaluation:

The threshing efficiency was evaluated using the relation (Ndirika, 1993):

$$\text{Threshing Efficiency } (\%) = 100 - (Q_u/Q_T)\times 100 \qquad (5.6)$$

where,

Q_u = Quantity of unthreshed grain in sample (g)

Q_T = Total grain in sample (g)

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Power measurement:

A Wattmeter of range between 0 - 4,800 Watt rating was used for the power measurement for the millet thresher, while 0 - 12,000 Watt rating Wattmeter was used for the sorghum thresher.

Total grain loss evaluation:

The total grain loss was obtained by adding the fractions of the broken grains and the unthreshed heads. The fraction

of the damaged grain was evaluated using the relation (Ndirika, 1993):

$$\text{Fraction of damaged grain (\%)} = (Q_b/Q_T)\times 100 \qquad (5.7)$$

where,

Q_b = Quantity of broken grain in sample (g)

Q_T = Total grains in sample (g)

While the fraction of unthreshed head was evaluated using the relation:

$$\text{Fraction of unthreshed head (\%)} = (U_T/Q_T)\times 100 \qquad (5.8)$$

where,

U_T = Total unthreshed heads in sample (g)

the pictorial view of the millet thresher used for the validation of the models is shown in figure I.

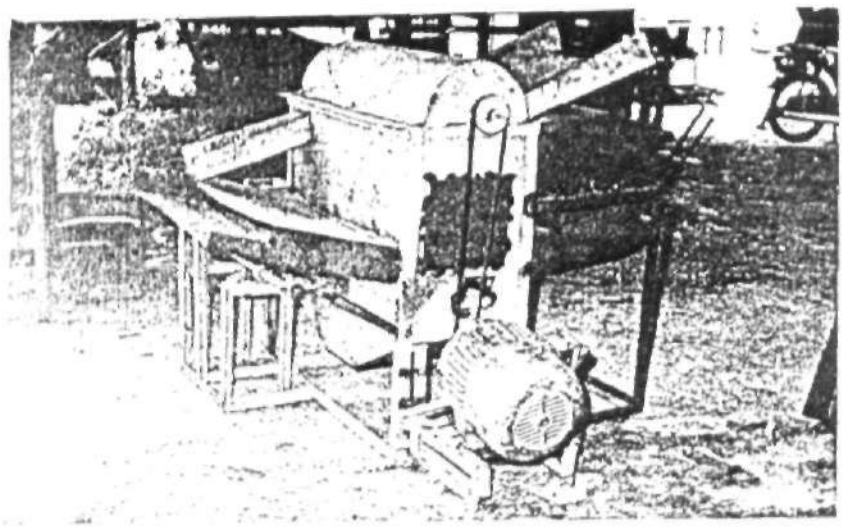


Fig. 5.1. I.A.R./A.B.U. Millet Thresher.

Table 5.1: Cylinder and Concave Data for Millet Thresher

S/N	Parameter	Dimension
1.	Effective cylinder diameter, D	0.350m
2.	Concave length, L_c	0.360m
3.	Mass of cylinder, M_c	2.50kg
4.	Cylinder concave clearance, C	0.006m
5.	Cylinder width, W_t	0.820m
6.	Centre line distance between adjacent concave rods, a_1	0.018m
7.	Concave rod diameter, a_2	0.008m
8.	Centre line distance between adjacent concave bars, b_1	0.025m
9.	Width of the concave bars, b_2	0.0085m
10.	Radius of pulley, r	0.058m

Source: IAR/ABU Millet Thresher

Table 5.2: Table of Constants used

S/N	Constant	Values
1.	Threshing constant, K_T	2.10×10^{-3}
2.	Damage constant, K_d	7.94×10^{-3}
3.	Yield factor, K_m	0.70
4.	Energy constant, K_h	0,36
5.	Friction power constant K_f	0.06
6.	Grain straw ratio (millet)	0.65
7.	Grain straw ratio 2 (sorghum)	0.58
8.	Mean time coefficient, K_n	2.25

Source: (1-5) Computed; (6) Ndirika (1993); (7) Desta and Mishra (1990); Huynh et al (1982).

Table 5.3: Crop and Operating Conditions for Millet Thresher

S/N	Parameter	Level					
		1	2	3	4	5	6
1	Feedrate F_r (kg/s)	0.02	0.03	0.04	0.05	0.06	0.07
2.	Cylinder speed with load, (V_b) m/s	3.40	3.72	3.85	4.14	4.65	5.0
3.	Cylinder speed without load, V'_b (m/s)	3.93	4.0	4.50	4.80	5.0	5.5
4.	Cylinder speed without load, N (rpm)	400	500	600	700	800	900
5.	Radius of the cylinder pulley, r (m)	0.094	0.076	0.072	0.065	0.060	0.058
6.	Mass of cylinder, M_c (kg)	2.50	2.60	2.70	2.80	2.90	3.0
7.	*Moisture content, b* (decimal)	0.09	0.10	0.11	0.12	0.13	0.14
8.	Bulk density, ϱ_d (kg/m^3)	102.0	98.6	90.2	82.83	75.8	62.12
9.	Average Grain diameter, d_1 (m): 0.003m						
10	Accleleration due to gravity of crop g': 10 m/s^2						
11	Power of prime mover used (kw): 3.7kw (5hp)						
12	Crop variety: Ex-Borno						

5.2 Techniques for Comparison of the Formulated Models

In the formulation of the predicting models, it is important to determine how well the models fit measured data and what significance the models have. Thus greater confidence in the model is gained if together a good fit and a high significance level is attained.

5.2.1 Goodness of fit:

The most common method and the one used mostly when linear models are evaluated is the correlation coefficient of regression, R or the square of this value, R^2, known as the coefficient of determination (Leabo, 1968). The correlation coefficient numerically varies between -1 and 1 indicating negative, zero or positive correlation between the model and the sample data set. The procedures for calculating R directly are limited to a linear model with one dependent and one independent variable. The coefficient of determination can be computed by squaring R or it can be computed directly by calculating the variance of the data about the mean explained by the model (Gregory and Fedler, 1986).

5.2.2 Statistical significance test:

Since the R^2 value from Equation 5.2 must also have a

the statistical significance test is done to ascertain how adequately the sample data test used for developing the model represents the whole population.

The significance level for a given R^2 can be obtained by computing Student t-test with the following equation (Snedecor and Cochron, 1980) and then looking up for the probability (significance level) in a table of 't' values:

$$t = R(DF)^{\frac{1}{2}}/(1-R^2)^{\frac{1}{2}} \qquad (5.5)$$

where,

t = Student's 't' value

R = Coefficient of regression (square root of coefficient of determination)

DF = Degrees of freeedom (number of data points minus number of constant defined in the model)

Thus, besides the usual inspection of the graphical representation of the computed versus measured results, this study considered equations B1 and B5 adequate.

5.3 Comparison Of Threshing Performance Models With Experimental Data

The performance models that were verified for a millet thresher were: The threshing efficiency (T_e), Total Grain Loss (TGL), Thresher capacity C_T and power requirement (P) as presented in equations 3.67, 3.092, 3.114, and 3.47 respectively.

Measured data from a stationary millet thresher were used to validate the performance models by plotting the graph of

measured against the predicted data for all the models and the line of best fit and the coefficient of determination (R^2) were used to measure how well the regression equation fits the data. The simulated results of each performance model obtained at variable cylinder speed (V_b) were used to compare values of each of the performance parameters obtained from experimental result.

The data used for the comparison between the values of threshing efficiency, total grain loss, output capacity, and power requirement obtained from experimental result and that obtained using the formulated performance models for the same thresher are presented in Tables 5.4, 5.5, 5.6 and 5.7 respectively. The graphical representation of the relationship between the predicted and the measured results from these tables are presented in Figures 5.2, 5.3, 5.4 and 5.5 respectively.

Table 5.4: Computed and Measured Threshing Efficiency for Millet Thresher.

Cylinder Velocity V_b(m/s)	Efficiency (T_e), %	
	Computed	Measured
3.40	95.82	95.90
3.72	96.90	96.98
3.85	97.25	97.41
4.14	97.91	98.0
4.65	98.70	98.90
5.0	99.06	99.10

Table 5.5: Computed and Measured Total Grain Loss for Millet Thresher.

Cylinder Velocity V_b (m/s)	Total grain Loss, %	
	Computed	Measured
3.40	6.7	6.88
3.72	4.88	5.0
3.85	4.29	4.40
4.14	3.22	3.35
4.65	1.95	2.02
5.0	1.38	1.45

Table 5.6: Computed and Measured Output Capacity for Millet Thresher.

Cylinder Velocity V_b (m/s)	Output capacity (C_T), kg/h	
	Computed	Measured
3.40	46.36	46.54.
3.72	47.79	48.04
3.85	48.32	48.60
4.14	49.39	49.52
4.65	50.96	51.24
5.0	51.86	52.13

Table 5.7: Computed and Measured Power Requirement for Millet Thresher.

Cylinder Velocity Vb(m/s)	P (Watt)	
(m/s)	Computed	Measured
3.40	967	970
3.72	1009	1018
3.85	1422	1450
4.14	1688	1700
4.65	1921	2004
5.0	2499	2510

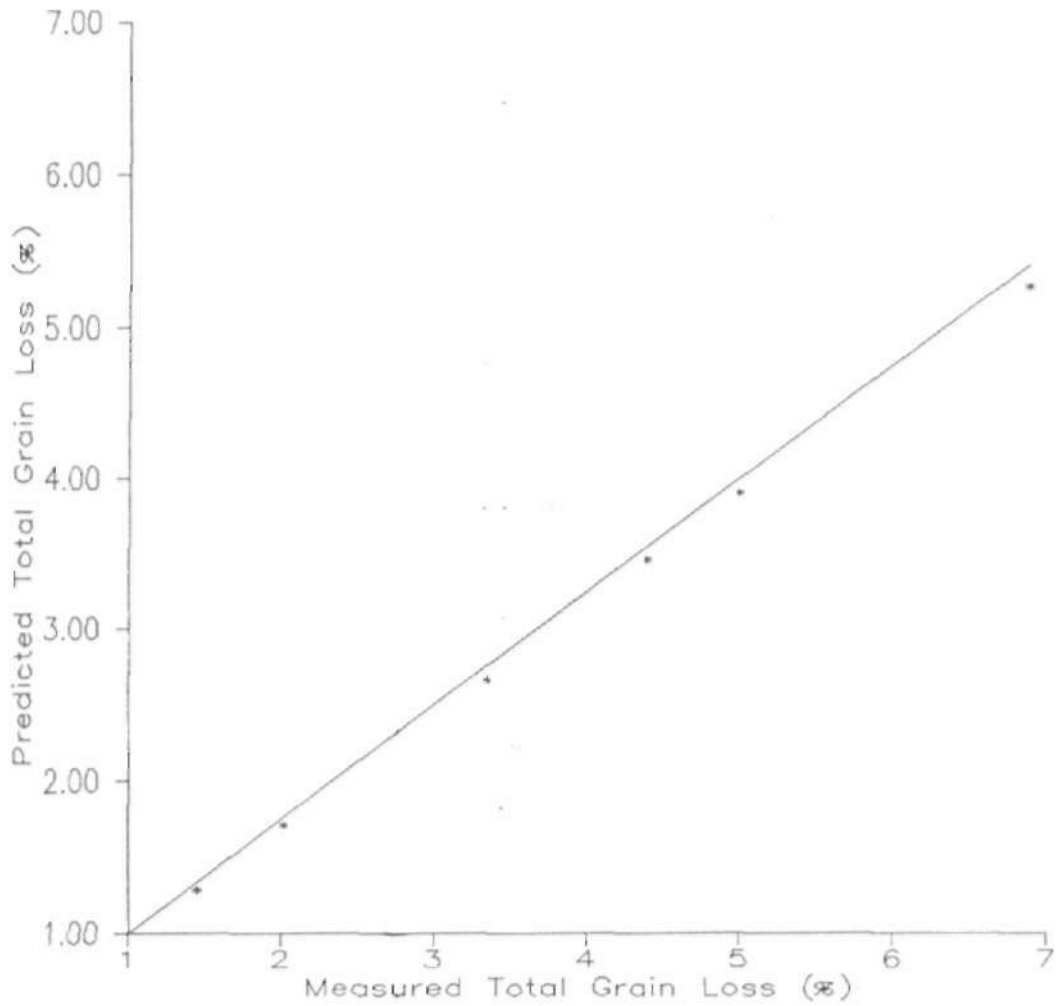


Fig. 5.3: Measured vs predicted total grain loss for a Millet Thresher

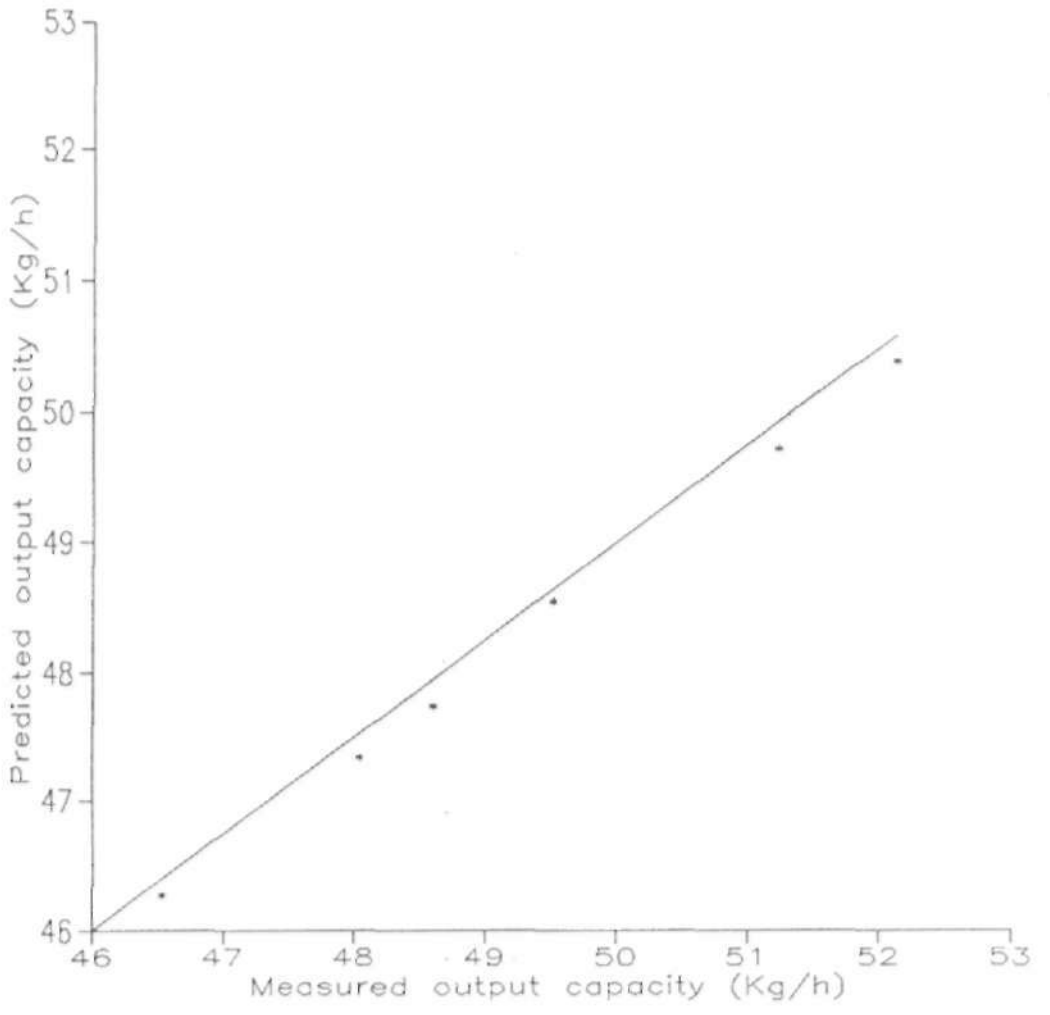


Fig. 5.4: Measured vs predicted capacity for a Millet Thresher

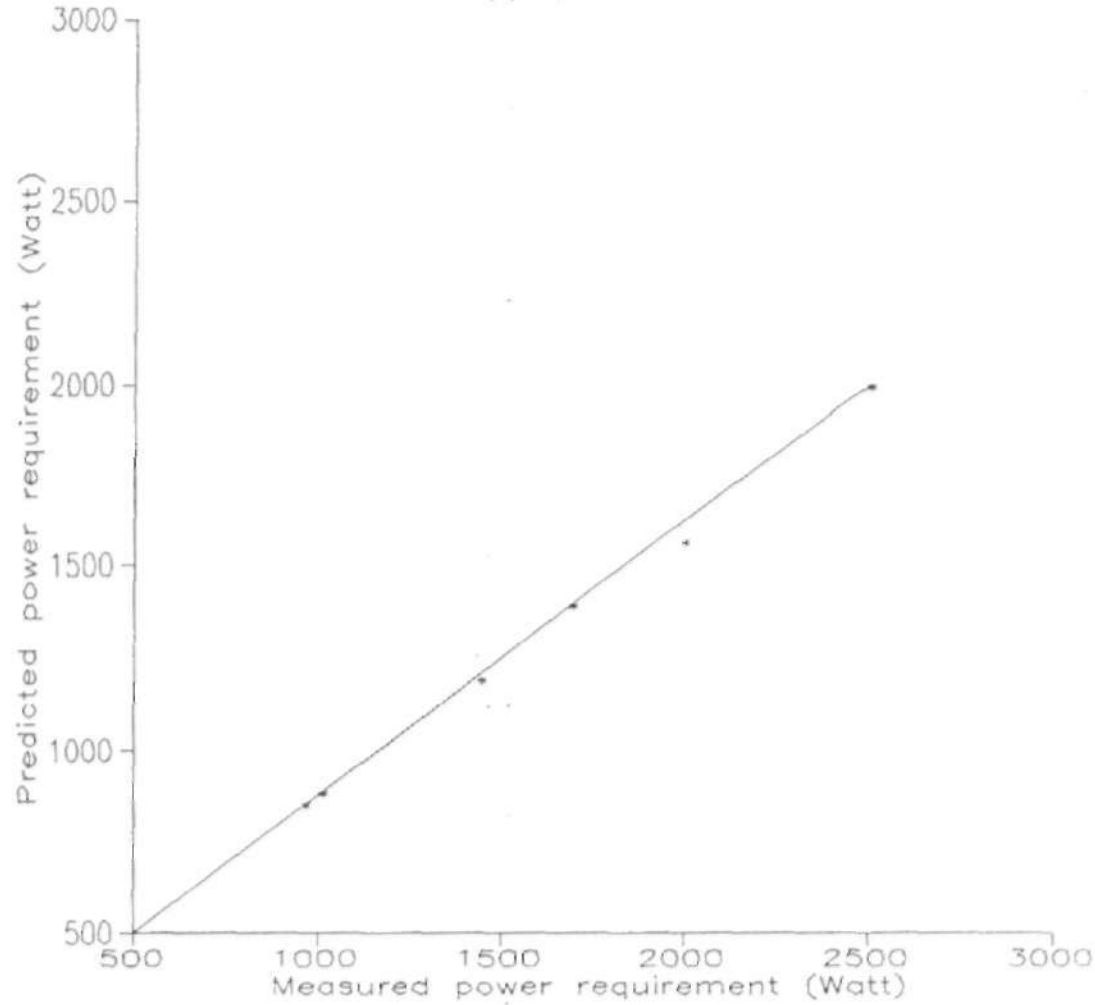


Fig. 5.5: Measured vs predicted power requirement for a Millet Thresher

Table 5.8 reveals higher calculated 't' values than the table values for all the performance models which predicts a good correlation between the models and the measured data at 0.001 level of significance.

5.4 Comparison With Huynh's Model

The threshing efficiency model developed by Huynh et al. (1982) was verified using the same measured data used for the verification of the formulated threshing performance models for millet thresher. Table 5.9 presents the data used for the comparison between computed Huynh's model and thesis model with the measured threshing efficiency. The graphical representation of the relationship between the predicted and Huynh's efficiencies are presented in figure 5.6.

Table 5.10 presents the compared R^2 and 't' values of the threshing efficiency for Huynh's and Thesis models at $p \leq 0.001$ level of significance, using the data from Table 5.9.

Table 5.10: Calculated R^2 and 't' Values Of The Compared Efficiency For Huynh's and Thesis Model with Measured Data at $P < 0.001$ Level of Significance.

Model Validation Parameters.	Huynh's Model	Thesis Model (Predicted)
R^2	0.9072	0.9880
Calculated 't' values	6.988	20.29
Table 't' values	6.869	6.869

Table 5.11 Computed Enaburekhan's, Thesis and Measured Threshing Efficiency

Cylinder velocity	Threshing Efficiency, %		
V_b (m/s)	Enaburekhan's	Ndirika's Model	Measured
3.40	96.0	95.82	95.90
3.72	97.0	96.90	96.98
3.85	97.85	97.25	97.41
4.14	98.46	97.91	98.0
4.65	99.09	98.70	98.90
5.0	99.38	99.06	99.10

Table 5.10 reveals higher correlation between the predicted and the measured efficiencies than with the Huynh's efficiency at 0.001 level of significance.

5.5 Comparison with Enaburekhan's Model

The threshing efficiency model developed by Enaburekhan (1994) was also verified using the same measured data used for the verification of the formulated threshing performance models for millet thresher. Table 5.11 presents the data used for the comparison between the predicted and Enaburekhan's model and thesis model with the measured threshing efficiency. the graphical representation of the relationship between the predicted and Enaburekhan's efficiencies are presented in Figure 5.7.

Table 5.12 presents the compared R^2 and 't' values of the threshing efficiency for Enaburekhan's and thesis models at P≤ 0.001 level of significance, using the data from Table 5.1

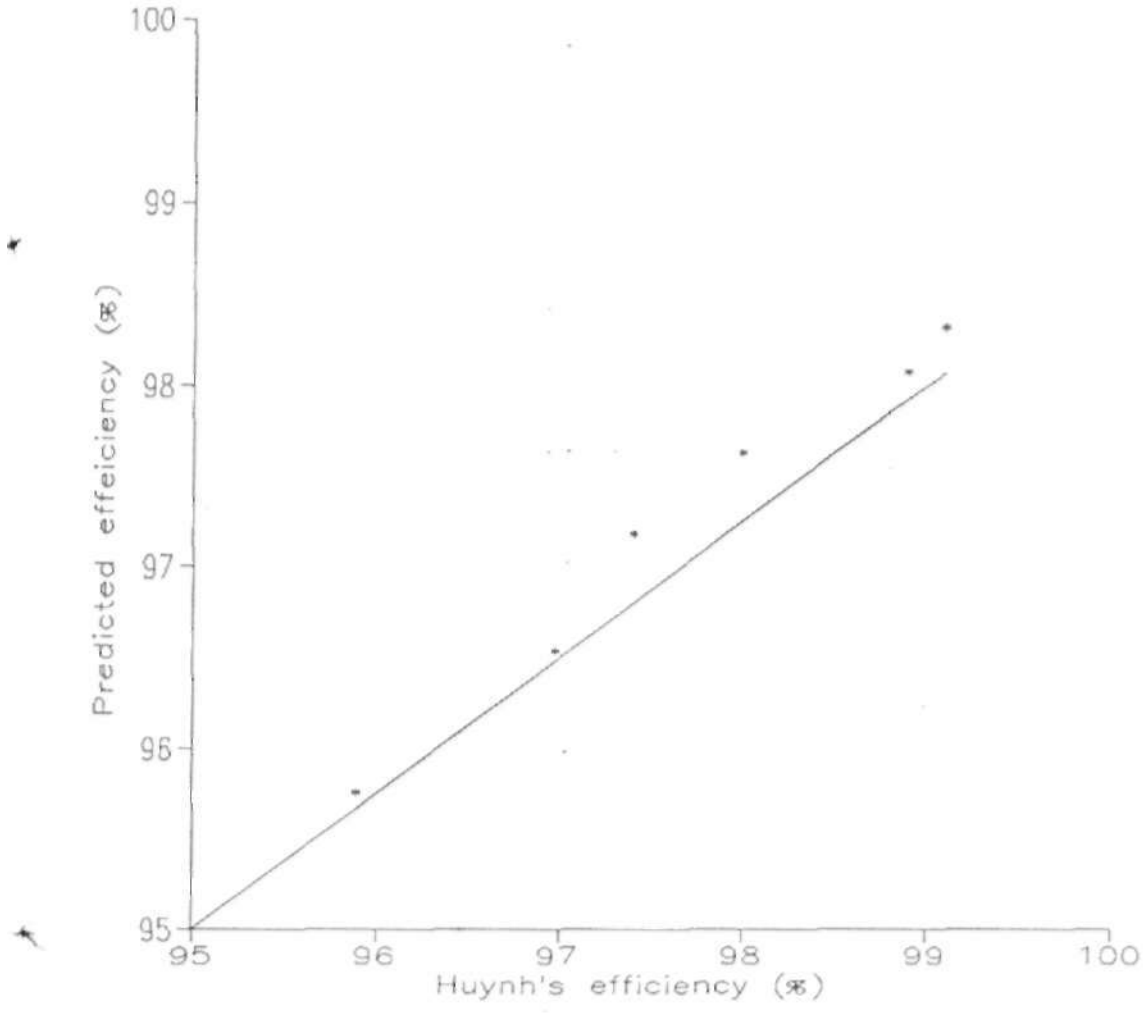


Fig. 5.6: Huynh's vs predicted efficiency

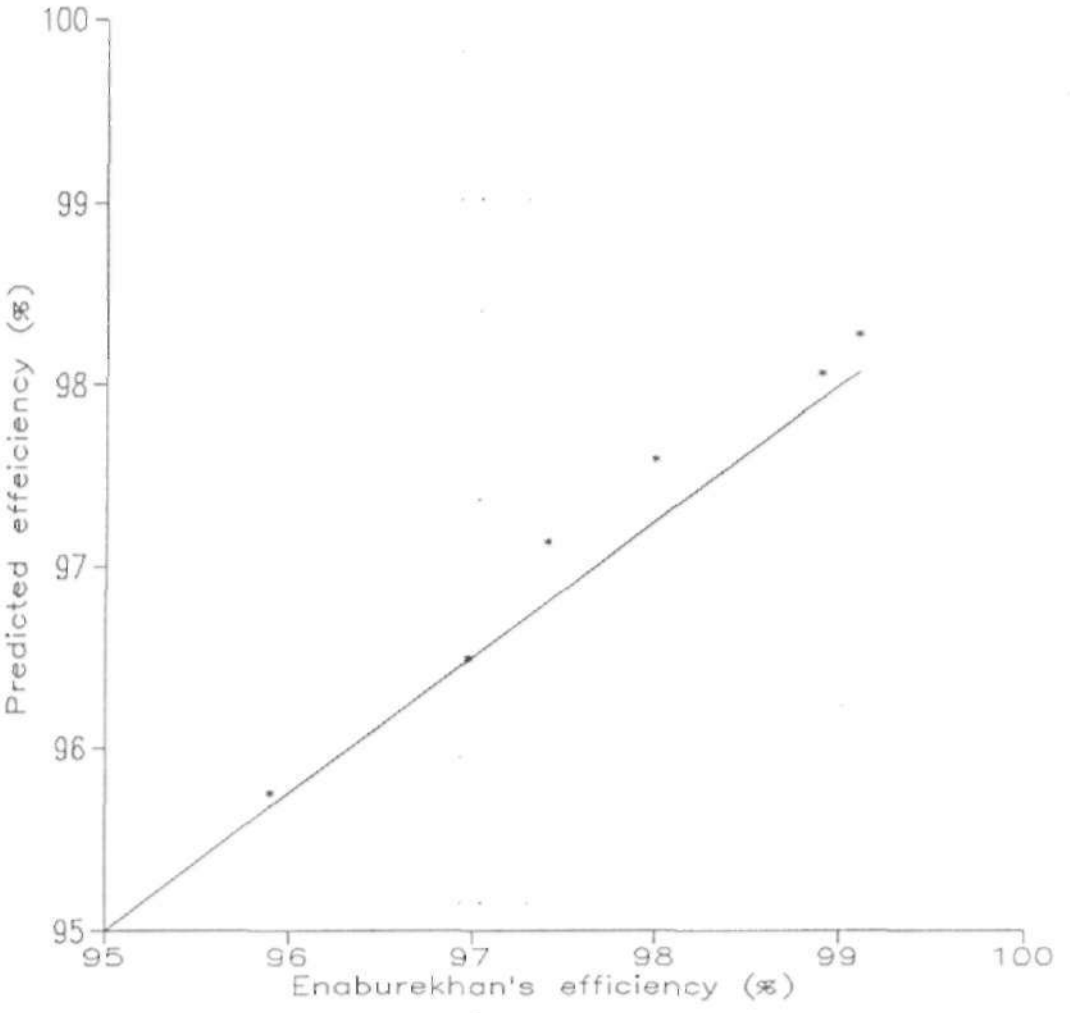


Fig. 5.7: Enaburekhan's vs predicted efficiency

Table 5.12: Calculated R^2 and 't' Values of the Compared Efficiency for Enaburekhan's and Ndirika's Model with Measured Data at P< 0.001 Level of Significance

Model validation parameters	Enaburekhan's model	Ndirika's model
R^2	0.9277	0.9880
Calculated 't' values	8.01	20.29
Table 't' values	6.869	6.869

Table 5.12 reveals higher correlation between the predicted and measured efficiencies than with the Enaburekhan's efficiency model.

The graphical comparison of the predicted, Huynh's and Enaburekhan's efficiency models with the measured efficiency is presented in Figure 5.8.

5.6 Verification of Threshing Performance Model for a Sorghum Thresher

The pictorial view of the sorghum thresher used in further verification and validation of the models is shown in figure 5.9.

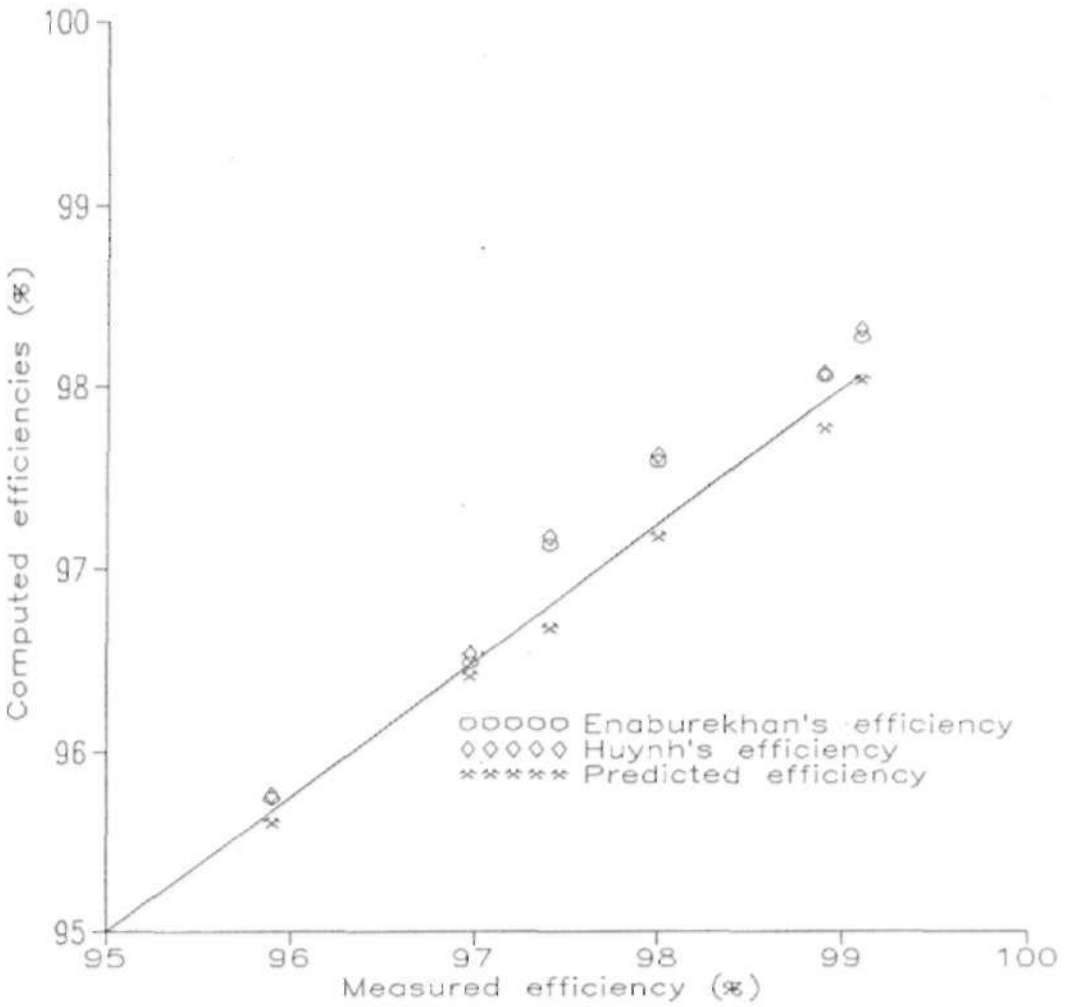


Fig. 5.8: Measured vs computed efficiencies

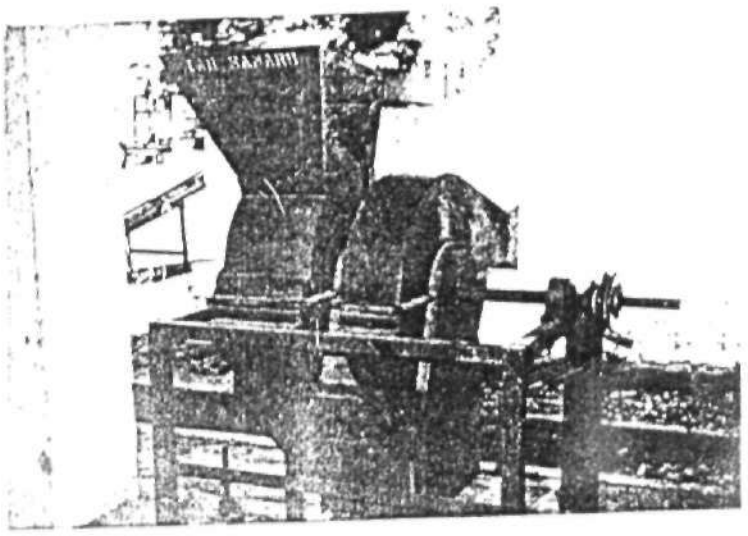


Fig. 5.9. I.A.R./A.B.U. Sorghum Thresher

5.6.1 Comparison of threshing performance models with experimental data.

Further validation of equation 3.67, 3.092, 3.114, and 3.47, for the *threshing efficiency, Total grain loss, thresher* capacity and power requirement respectively was obtained using the data from an existing sorghum thresher. The specifications of a typical cylinder concave unit (sorghum thresher), constants and operating condition used are shown in table 5.13, 5.2 and 5.14 respectively.

Table 5.13 Cylinder and Concave Data for Sorghum Thresher.

Parameter	Dimension
Effective cylinder diameter, D	0.50m
Concave length, L_c	0.48m
Mass of cylinder, M_c	7.0kg
Cylinder concave, C	0.011m
Cylinder width, W_T	0.45m
Centre line distance between adjacent concave rods, a_1	0.019m
Concave rod diameter, a_2	0.009m
Centre line distance between adjacent concave bars, b_1	0.030m
Width of the concave bars, b_2	0.0095m

Table 5.14 Crop and Operating Condition for Sorghum Thresher

S/N	Parameter	Values / Level					
		1	2	3	4	5	6
1.	Feedrate F_r (kg/s)	0.02	0.03	0.04	0.05	0.06	0.07
2.	Cylinder speed with load	4.0	4.30	4.45	4.50	4.90	5.12
3.	Cylinder speed without load	4.23	4.43	4.56	4.65	5.0	5.32
4	Cylinder speed without load, N(rpm)	400	500	600	700	800	900
5.	Radius of the cylinder, r(m)	0.01	0.085	0.073	0.063	0.059	0.056
6.	Mass of cylinder, M_c (kg)	7.0	7.10	7.20	7.30	7.40	7.50
7	Moisture content, b (dec)	0.09	0.10	0.11	0.12	0.13	0.14
8	Bulk density, ϱ_d (kg/m^3)	42.2	39.11	33.12	30.92	26.92	22.80
9	Average grain diameter, d_1 (m)	0.0035 m					
10	Acceleration due to gravity of crop g (m/s^2)	10 m/s^2					
11	Power of prime mover used	5kW (7hp)					
12	Crop variety	FARAFARA					

The simulated results of each of the performance model obtained at variable effect of cylinder speed (V_b) with all other variables kept constant was used to compare values of each of the performance parameters obtained from experimental result. The data used for the comparison between the values of threshing efficiency, total grain loss, output capacity and power requirement obtained from experimental result and that obtained using the formulated threshing performance models for the same sorghum thresher are presented in Tables 5.15, 5.16, 5.17 and 5.18, respectively. The graphical representation of the relationship between the predicted and measured results from these tables are presented in Figures 5.10, 5.11, 5.12 and 5.13 respectively.

Table 5.15 Computed and Measured Threshing Efficiency for Sorghum Thresher.

Cylinder Velocity	Total grain loss (TGL), %	
V_b (m/s)	Computed	Measured
4.0	96.26	96.40
4.30	97.07	97.16
4.45	97.41	97.68
4.50	97.52	97.70
4.90	98.21	98.41
5.12	98.51	98.60

Table 5.16 Computed and measured Total Grain Loss (TGL) for Sorghum Thresher.

Cylinder Velocity	Total grain loss (TGL), %	
V_b (m/s)	Computed	Measured
4.0	2.22	2.40
4.30	1.67	1.82
4.45	1.44	1.60
4.50	1.38	1.40
4.90	0.94	1.03
5.12	0.76	0.96

Table 5.17 Computed and Measured Output Capacity C_T for Sorghum Thresher.

Cylinder Velocity	Output capacity (CT), kg/h	
V_b (m/s)	Computed	Measured
4.0	42.04	42.24
4.30	42.99	43.28
4.45	43.60	43.90
4.50	43.68	43.83
4.90	44.99	45.29
5.12	45.38	45.68

Table 5.18 Computed and Measured Power Requirement (P) for Sorghum Thresher.

Cylinder Velocity	Power requirement (P), Watt	
V_b (m/s)	Computed	Measured
4.0	2415.768	2418.968
4.30	2744.172	2753.672
4.45	2971.114	3001.114
4.50	3139.089	3153.089
4.90	3851.157	3936.158
5.12	4584.582	4598.581

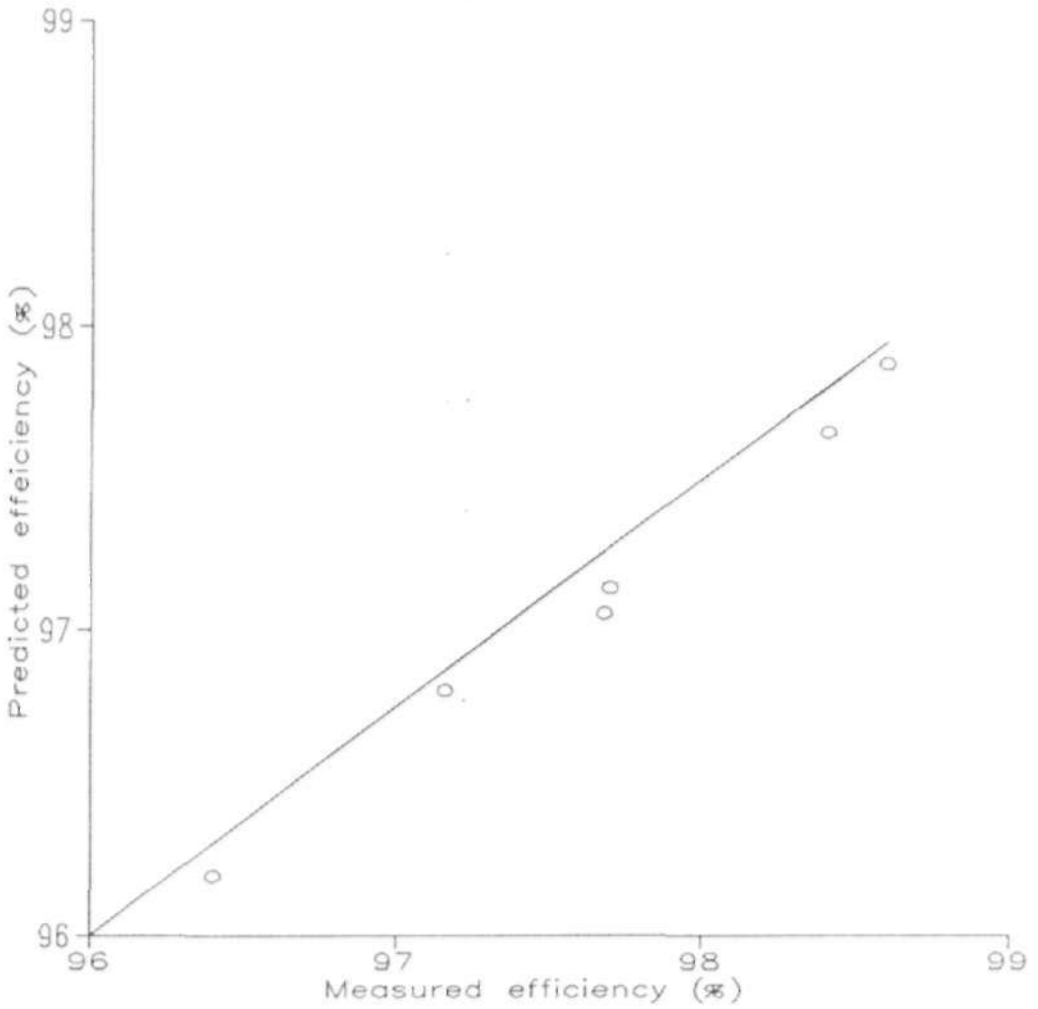


Fig. 5.10: Measured vs predicted efficiency for a Sorghum Thresher

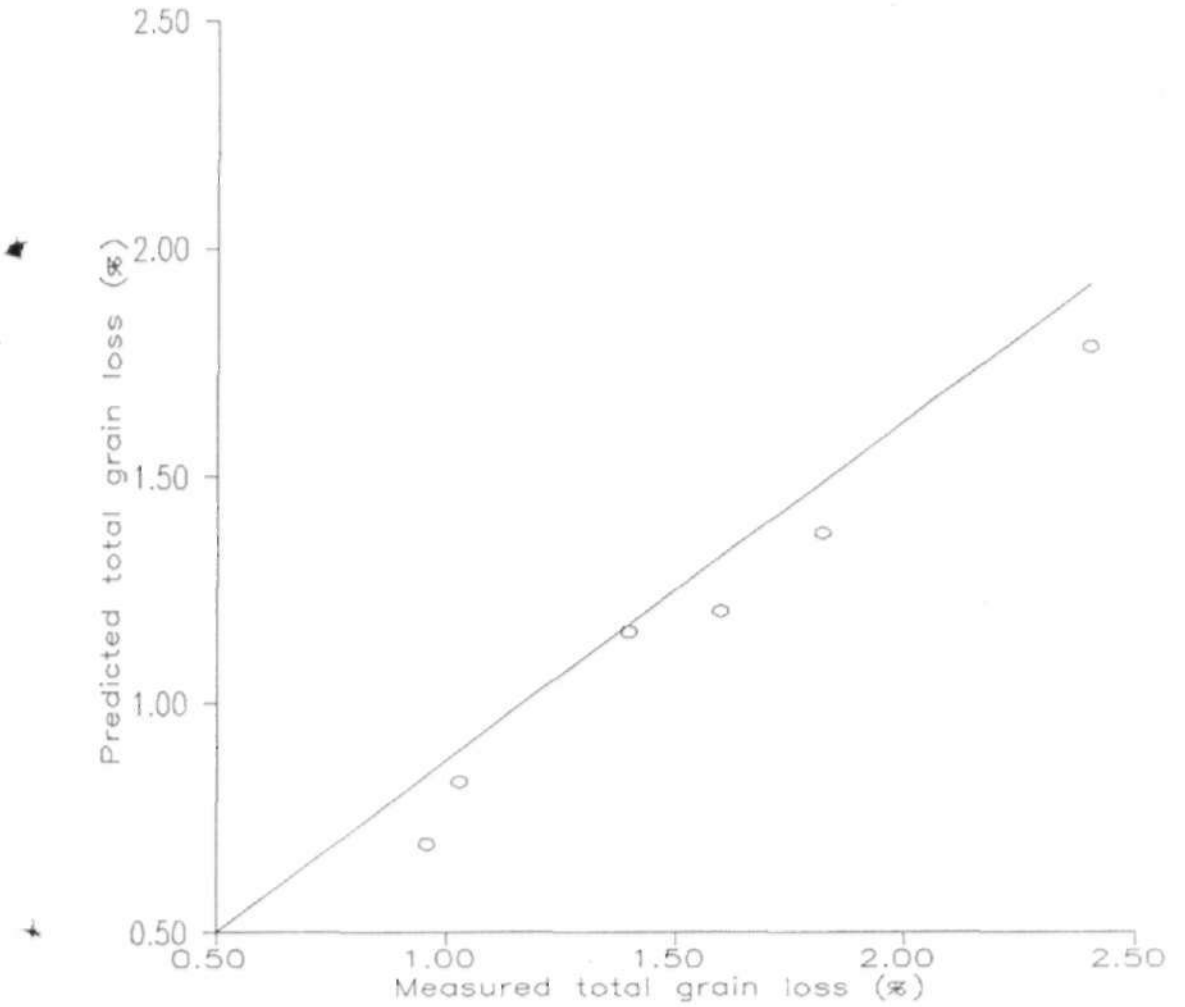


Fig. 5.11: Measured vs predicted total grain loss for a Sorghum Thresher

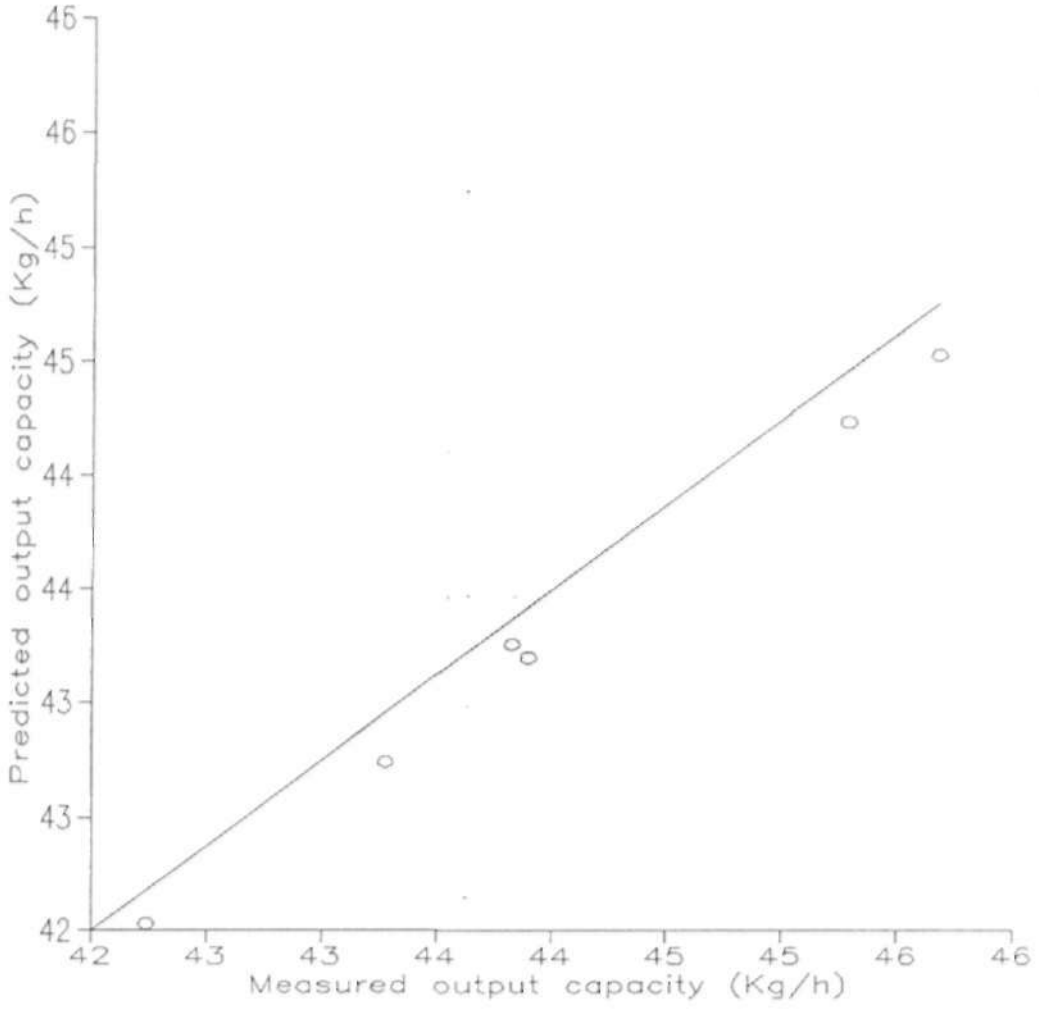


Fig. 5.12: Measured vs predicted output capacity for a Sorghum Thresher

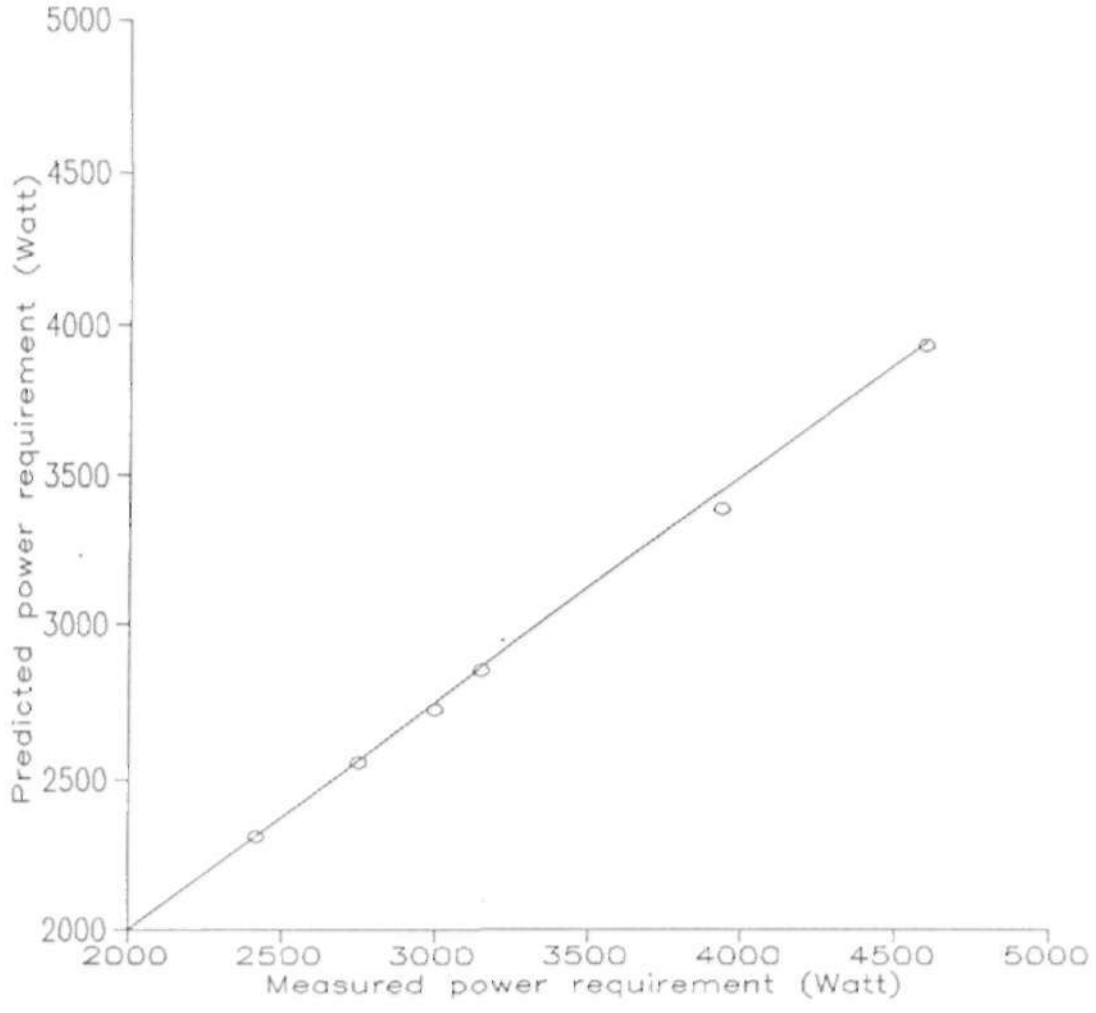


Fig. 5.13: Measured vs predicted power requirement for a Sorghum Thresher

The calculated R^2 and 't' values for each of the compared threshing performance models are presented in table 5.21.

Table 5.19: Calculated R^2 and 't' Values of the Compared Threshing Performance Models with Measured Data for Sorghum Thresher at $p \leq 0.001$ Level of Significance.

Performance Parameter	R^2 Value	Calculated 't' value	Table 't'
Threshing efficiency(T_e)	0.9449	9.259	6.869
Total Grain Loss (TGL)	0.9103	7.123	6.869
Output Capacity (C_T)	0.9488	9.625	6.869
Power Requirement (P)	0.9974	43.81	6.869

Table 5.20: Comparison of the Computed R^2 - Values for the Performance Models Between Millet and Sorghum Threshers at $P < 0.001$ Level of Significance

Type of thresher	R^2 - Values			
	T_e	TGL	C_T	P
Millet thresher	0.9880	0.9958	0.9830	0.9954
Sorghum thresher	0.9449	0.9103	0.9488	0.9974

5.6.1 Comparison of output results of the performance models between millet and sorghum threshers

The output results of all the threshing performance models computed for millet and sorghum threshers were compared using the computed R^2 Values as presented in table 5.20. The data was obtained from Table 5.8 and 5.19.

5.7 Optimization of the Performance Model

The purpose of modeling a physical system is to be able to better understand the fundamental mechanism of that system and to establish the optimum conditions for the construction and operation of the system.

Optimum conditions are those that produce the best most favourable or most beneficial result from a system (Gajda and Biles, 1978).

The interest in application of modern optimization technique is considerable, primarily as a result of development of modern computers. Most optimization techniques today are of the iterative type, that is, the optimum point is approached by a step by step method.

From review, the schemes by which optimization techniques can be classified are:

i) by number of independent variables

ii) whether derivative methods can be employed or numerical method must be applied, and

iii whether the problem is constrained or unconstrained.

These and other consideration give rise to several different approaches to optimization. It is outside the intention of the thesis to give complete development of these techniques. Excellent presentation and discussion of widely used techniques are given in books by Levi and Vol (1966), Biles and Swain (1980) and many other books.

This chapter presents an algorithm or minimization technique developed to select combination of machine variables that yield minimum grain losses for a given moisture content range and presents the best combination of machine variables that yield minimum grain losses for the millet and sorghum thresher under consideration.

5.7.1 Formulation of optimization function

Any optimization formulation is characterized by:

i) An objective function stating the quantity to be minimized or maximized and its functional dependence from design variables; and

ii) The constraints on the design variables under which an optimum is to be searched. Expressed mathematically as follows:

Optimize $y_o = g_o (x_1, x_2, \ldots, x_n)$ (5.9)

subject to:

$a_o < x_i < b_i$, i = 1, 2, 3, ... n (5.10)

where,

y_o = objective function

g_o = some relationship between y_o and x_i

x_i = design variables

a_o, b_i = lower and upper bounds respectively.

For this study, the objective function considered is the minimization of grain loss. That is, to determine if some level of the machine parameters considered would result in a minimum grain loss. A measure of the total grain loss TGL was obtained by summing the threshing loss T_L and grain damage loss D_f as established in equation 3.115b that is:

Total grain loss,

$$TGL = \exp.\ \frac{-1.5K_T\rho_d DV_b L_c}{(1-\beta)F_r} + \exp.\ \frac{-0.46K_d\rho_d DV_b L_c}{(1-\beta)F_r}$$

The design variables used in the optimization are feedrate (F_r), cylinder velocity (V_b) and moisture content (b). The lower and upper limits of the design variables which are incorporated as constraints for the different moisture content levels are as follows:

For the millet thresher:

(i) $0.03 \leq F_r \leq 0.07$ (kg/s)

(ii) $3.40 \leq V_b \leq 5.0$ (m/s)

(iii) Moisture content (b) levels: 9; 12 and 14 (%)

For the sorghum thresher:

(i) $0.03 \leq F_r \leq 0.07$ (kg/s)

(ii) $4.0 < V_b < 5.12$ (m/s)

(iii) Moisture content (b) levels: 9, 12 and 14(%)

The optimum values were computed using the computer programming flowchart Figure C1 (Appendix C)

Experimental data for the millet and sorghum threshers as presented earlier in this work were used for the computations using 3 factors, 3 x 3 x 4 levels of variable combination. Table D1 and E1 (Appendix D and E) presents the optimization simulation results of the design variables and losses for the millet and sorghum threshers, respectively. Optimum thresher parameters and corresponding threshing losses for the millet and sorghum threshers are presented in Tables 5.21 and 5.22 respectively with 5% designated as a tolerable target loss (3% threshing loss and 2% damage loss). The optimum parameters (moisture content, cylinder speed and feedrate) obtained from the simulated results for millet and sorghum threshers were experimented on the existing millet and sorghum threshers and the corresponding minimum grain losses obtained are also contained in Tables 5.21 and 5.22 respectively.

Table 5.21 Optimum Thresher Parameters and Corresponding Threshing Losses for Millet Thresher.

Moisture Content (b), %	Cylinder Speed V_b m/s	Feedrate (kg/s)	TGL (%) (simulated)	TGL (%) (measured)
9	5.0	0.03	0.085	0.10
12	5.0	0.03	0.273	0.32
14	5.0	0.03	1.23	1.33

Table 5.22 Optimum Thresher Parameters and Corresponding Threshing Losses for Sorghum Thresher.

Moisture Content (b) %	Cylinder Speed V_b (m/s)	Feedrate (kg/s)	TGL (%) (simulated)	TGL (%) (measured)
9	5.12	0.03	0.35	0.46
12	5.12	0.03	1.59	1.74
14	5.12	0.03	5.17	4.95

CHAPTER SIX

RESULTS AND DISCUSSIONS

This chapter presents discussion on the determined coefficients, and the validation of the developed models with experimental results from existing millet and sorghum threshers, Huynh's (1982) model and Enaburekhan (1994) model as presented in chapters four and five. This chapter also discusses the optimum threshing parameters for the formulated mathematical models for millet and sorghum threshers.

6.1 Predicted Coefficients

The unknown coefficients in the models were determined by linearizing the models by the Method of Least Squares using data from established experimental result from existing millet, sorghum and wheat threshers. The result reveals that the regression coefficients obtained from the regression lines of the linearised models are above 0.90 at 0.05 level of significance which gave a good fit and better correlation of the data used for the analysis. Thus the slope (constants) obtained from the regression lines can be said to be valid. Results from Tables 4.1 and 4.2 present the calculated values of Ke and K_h; and the calculated effect of K_h respectively. The result reveals that the effect of the coefficient K_e and K_h for millet, sorghum and wheat threshers are statistically insignificant at 0.05 level of significance. Since the

individual K_h for the different threshers has no significant effect, the mean value of slope Ke from table A1 for the threshers used was justified in the calculations.

6.2 Validation of Models

6.2.1 Threshing efficiency model

The threshing efficiency model (equation 3.67) was verified with measured data from existing millet and sorghum threshers by graphical and R-squared methods. From the graphical result it was established that the model describes well the measured data obtained from both threshers (Figures 5.2 and 5.10). This can also be seen from Tables 5.8, 5.19 and 5.20. The result gave R-squared values of 0.99 and 0.94 for millet and sorghum threshers respectively, at 0.001 level of significance. The difference in the values could be due to the difference in the configurations of both threshers. It was also established that the model gave better correlation and thus fits well with the measured data than with Huynh's model which have an R-squared value of 0.91 (Figure 5.8) and can also be seen in Tables 5.9 and 5.10. It was further established that the model gave better correlation and thus fits well with the measured data than with Enaburekhan's model which gave an R-square value of 0.93 (Fig 5.8). It can also be seen from tables 5.11 and 5.12. Figures 5.6 and 5.7 show that the predicted efficiency gave better correlation (R^2 =

0.8710) with the Enaburekhan's efficiency model than with Huynh's model (R^2 = 0.8377). Since the predicted efficiency model compared favourably with the previous efficiency models (Fig. 5.8) and with the measured data from existing threshers (Figs. 5.2 and 5.10), it is therefore concluded that the threshing efficiency model (equation 3.67) is valid for describing the threshing efficiency of a grain thresher.

6.2.2. Total grain loss model

The total grain loss model (Equation 3.92) was verified with measured data from existing millet and sorghum threshers. From the result it was established that the model describes well the measured data obtained from both threshers with R^2 of 0.99 and 0.91 for millet and sorghum threshers respectively at 0.001 level of significance (Figures 5.3 and 5.11). It can also be seen from Tables 5.8, 5.19 and 5.20. This reveals a higher correlation of the model with data from millet thresher than with the sorghum thresher. The difference could be as a result of the difference in the machine configurations of the thresher. It is therefore concluded that the model is valid for describing the total grain loss of a grain thresher.

6.2.3 Output capacity model

The output capacity model (equation 3.114) was verified with measured data from existing millet and sorghum threshers. From the result it was established that the model described

well the measured data obtained from both threshers with R^2 of 0.98 and 0.95 for millet and sorghum threshers respectively at 0.001 level of significance (Figures 5.4 and 5.12). It can also be seen from Tables 5.8, 5.19 and 5.20. This reveals a higher correlation of the model with data from millet thresher than with the sorghum thresher. The model is also valid for describing the output capacity of a grain thresher.

6.2.4 Power requirement model

The power requirement model (Equation 3.47) was also verified with measured data from existing millet and sorghum threshers. From the result it was established that the model describes well the measured data obtained from both threshers with R-square values of 0.99 for both millet and sorghum threshers respectively at 0.001 level of significance (Figures 5.5 and 5.13). It can also be seen from Tables 5.8, 5.19 and 5.20. The result reveals a higher correlation of the model with data from sorghum and millet threshers. The model is therefore considered valid for describing the power requirement of a grain thresher.

6.3 Optimum Threshing Parameters

6.3.1 Millet thresher

The optimization results for thresher performance parameters and corresponding threshing losses for millet

loss (MTGL) obtained by simulation and measurement for this thresher with the optimum parameters (Moisture content, cylinder speed and feedrate) are closer. The values of minimum grain loss at 9 and 12% moisture content levels are less than the tolerable value (5%) while the value of the minimum loss obtained at 14% moisture content is greater than the tolerable value. This means that the threshing operations at 14% moisture might not be favourable.

6.5 Limitation of the Present Models

The formulated performance models have the following limitations:

1. The models were developed primarily for stationary mechanical grain threshers with throw-in feedrate system.
2. The present models do not include a sub-routine to describe the grain cleaning process. Thus, they could not be used to completely simulate the thresher system.
3. The models have been verified and validated for only millet and sorghum threshers. Other crops were considered but their threshing constants were not established in this study.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATION

7.1 Conclusion

This work develops performance models for selected stationary grown threshers for evaluating and explaining the performance parameter of stationary grain threshers. The developed models were verified and validated with established experimental data from stationary mechanical threshers. The performance models were then simulated and optimized to obtain variables for minimum loss within the range of the process variables.

In Chapter three, principles of grain threshing and some of the variables responsible for the process were identified. These principles were then used to formulate models that predict threshing processes. The probabilistic theory and dimensional analysis using Buckingham's Pi theorem was introduced in deriving the threshing efficiency, and total grain loss models, the power requirement models were formulated using mechanistic theory and dimensional analysis, while the output capacity model was developed by dimensional analysis, using Buckingham's pi theorem. All the formulated models fit the conventional and axial flow type cylinders.

In chapter four, all the unknown coefficients found in the formulated models were determined using measured data

reported in literature and the determined coefficients were found to fit for millet, sorghum and wheat threshers.

In Chapter five, the formulated models, threshing efficiency, total grain loss, output capacity and power requirement were verified and validated with established experimental data from millet and sorghum threshers. The results were found generally to fit well with established experimental data, giving R-squared values greater than 0.91 which were valid at 0.001 level of significance.

The threshing efficiency model and Huynh's model were compared with measured experimental data. The result reveals a better correlation with the model than the Huynh's model. It was also established that the predicted threshing efficiency model gave better correlation when compared with the measured experimental data than with Enaburekhan's (1994) model. This chapter also presents a simulation and optimization function to obtain variables for optimum minimum loss and corresponding threshing parameter for millet and sorghum threshers.

Based on the results of the study, the following conclusions can be drawn:

(1) The threshing and separation processes can be described with mathematical models which include parameters such as feedrate, cylinder speed, concave length, moisture content, bulk density and cylinder diameter.

(2) The models conform with the general trend exhibited by the performance parameters of a typical thresher and fit well with experimental result.

(3) The predicted efficiency model compared favourably with the previous efficiency models and with the measured data from existing threshers.

(4) Minimum grain loss can be obtained at 9% moisture content, feed rate of 0.03 kg/s and cylinder speed of 5 m/s for millet and sorghum threshers.

The major contributions made in this work can be summarized as follows:

(1) The formulation of the threshing performance models for predicting Threshing efficiency, total grain loss, power requirement and output capacity of selected grain threshers, determination of threshing constants for millet and sorghum and implementation of the model on millet and sorghum threshers.

(2) Simplification of the threshing performance models from previous works by reducing the number of variables and obtaining better results.

(3) The formulation and validation of power requirement model for threshing process.

From the above conclusions, the specific objectives of this study have been met.

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APPENDICES

APPENDIX A

Table A1: Data Used to Determine Ke Values.

Vb(m/h)	Fr(kg/h)	ρ_w(kg/cm^3)	E(kWh)	$\pi_1(K_e)^+$	Thresher types/source
1.47×10^4	18.52	31	2.23	1.010	Millet thresher
1.47×10^4	21.30	31	2.98	0.910	(Wagami,1979)
1.86×10^4	25.53	31	3.40	0.885	,,
1.86×10^4	27.59	31	3.86	0.890	,,
2.10×10^4	27.35	31	4.05	0.890	,,
2.35×10^4	26.92	31	4.30	0.900	,,
2.35×10^4	29.75	31	4.75	0.885	,,
7.09×10^3	36.00	23	4.19	0.980	Sorghum thresher
7.24×10^3	36.00	23	4.80	0.890	(Gurama,1977)
7.82×10^3	36.00	23	5.29	0.900	,,
8.31×10^3	36.00	23	5.71	0.910	,,
9.00×10^3	36.00	23	5.84	0.905	,,
9.45×10^3	36.00	23	6.05	0.906	,,
9.68×10^3	36.00	23	6.52	0.908	,,
4.56×10^4	27.10	28	6.25	0.980	Wheat thresher
5.80×10^4	27.10	28	6.45	0.900	(PAU Test Reports
6.40×10^4	27.10	28	6.80	0.890	1970 - 1972)
6.90×10^4	27.10	28	7.05	0.900	,,
7.40×10^4	27.10	28	7.20	0.880	,,
8.10×10^4	27.10	28	7.60	0.900	,,
8.70×10^4	27.10	28	7.95	0.900	,,
	Mean Value:			0.910	
	Standard deviation (std) :			0.035	

$^+$ $\pi_1 = [E^2\rho_w/V_bF_r^3]^{\frac{1}{3}}$

Table A2: Design Matrix of Variables And The Power Required To Detach The Grain From The Panicle P_T

Test Number	Millet (K_h=0.344)	Sorghum (K_h=0.356)	Wheat (K_h=0.304)	$P_T x10^{-4}$ (Watt)	Interaction
1	-	+	-	$4.94x10^{-4}$	+
2	+	-	-	$9.54x10^{-4}$	+
3	-	-	+	[illegible]	+

Table A3: Data Used To Determine K_T Value.

ϱ_w (kg/m³)	D(m) (m)	L_c (m)	V_b (m/s)	Fr (kg/s)	λ_1 (sec^{-1})	π_1^+	π_2^{++}	Thresher type and source
31	0.26	0.45	4.08	$5.92x10^{-2}$	5.88	0.0312	12.020	Millet thresher
31	0.26	0.45	5.17	$7.66x10^{-2}$	7.69	0.0325	11.890	(Wagami, 1979)
31	0.26	0.45	6.53	$8.26x10^{-2}$	10.00	0.0309	12.871	"
31	0.26	0.45	6.81	$8.62x10^{-2}$	11.11	0.0330	12.867	"
31	0.26	0.45	8.17	$10.34x10^{-2}$	12.50	0.0309	12.868	"
23	0.22	0.42	2.52	$1.80x10^{-2}$	4.00	0.0280	12.484	Sorghum thresher
23	0.22	0.42	2.63	$1.88x10^{-2}$	4.22	0.0283	12.479	(Gurama, 1974)
23	0.22	0.42	3.50	$2.15x10^{-2}$	5.70	0.0266	13.462	"
23	0.22	0.42	6.30	$4.46x10^{-2}$	9.63	0.0268	12.540	"
23	0.22	0.42	7.88	$5.29x10^{-2}$	12.80	0.0278	12.877	"
24	0.32	1.5	10.05	$4.60x10^{-1}$	4.55	0.0198	7.328	Wheat thresher
24	0.32	1.5	11.73	$5.00x10^{-1}$	5.26	0.0189	8.489	(Ghaly, 1985)
24	0.32	1.5	13.40	$5.60x10^{-1}$	5.88	0.0183	7.669	"
24	0.32	1.5	15.09	$6.20x10^{-1}$	6.67	0.0183	7.729	"
24	0.32	1.5	16.76	$6.70x10^{-1}$	7.69	0.0187	7.841	"

$^{+}\pi_1 = [\lambda_1^2 F_r/V_b\varrho_w]^{\frac{1}{3}}$, $^{++}\pi_2 = [D^2 V_b \varrho_w/F_r]^{\frac{1}{3}}$

Table A4: Data Used To Determine Kd Value

ρ_w (kg/m^3)	D(m)	L_c (m)	Vb (m/s)	Vd (m/s)	Fr (kg/s)	K_d (sec^{-1})	π_1^+	π_4^{++}	Thresher type and source
31	0.26	0.45	4.08	7.34	5.92×10^{-2}	10.87	0.0576	6.680	Millet thresher
31	0.26	0.45	5.17	9.31	7.66×10^{-2}	13.89	0.0587	6.604	(Wagami, 1979)
31	0.26	0.45	6.53	11.75	8.26×10^{-2}	17.54	0.0543	7.153	"
31	0.26	0.45	6.81	12.26	8.62×10^{-2}	18.18	0.0539	7.147	"
31	0.26	0.45	8.17	14.71	10.34×10^{-2}	21.74	0.0538	7.147	"
23	0.22	0.42	2.52	4.54	1.80×10^{-2}	7.25	0.0507	6.929	Sorghum thresher
23	0.22	0.42	2.63	4.73	1.88×10^{-2}	7.52	0.0504	6.939	(Gurama, 1974)
23	0.22	0.42	3.50	6.30	2.15×10^{-2}	10.00	0.0467	7.479	"
23	0.22	0.42	6.30	11.34	4.46×10^{-2}	18.18	0.0506	6.967	"
23	0.22	0.42	7.88	14.18	5.29×10^{-2}	22.73	0.0493	7.156	"
24	0.32	1.5	10.05	18.09	4.60×10^{-1}	4.46	0.0194	4.071	Wheat thresher
24	0.32	1.5	11.73	21.11	5.00×10^{-1}	5.21	0.0187	4.219	(Ghaly, 1985)
24	0.32	1.5	13.40	24.12	5.60×10^{-1}	5.95	0.0185	4.260	"
24	0.32	1.5	15.09	27.13	6.20×10^{-1}	6.71	0.0184	4.293	"
25	0.32	1.5	16.76	30.17	6.70×10^{-1}	7.46	0.0182	4.356	"

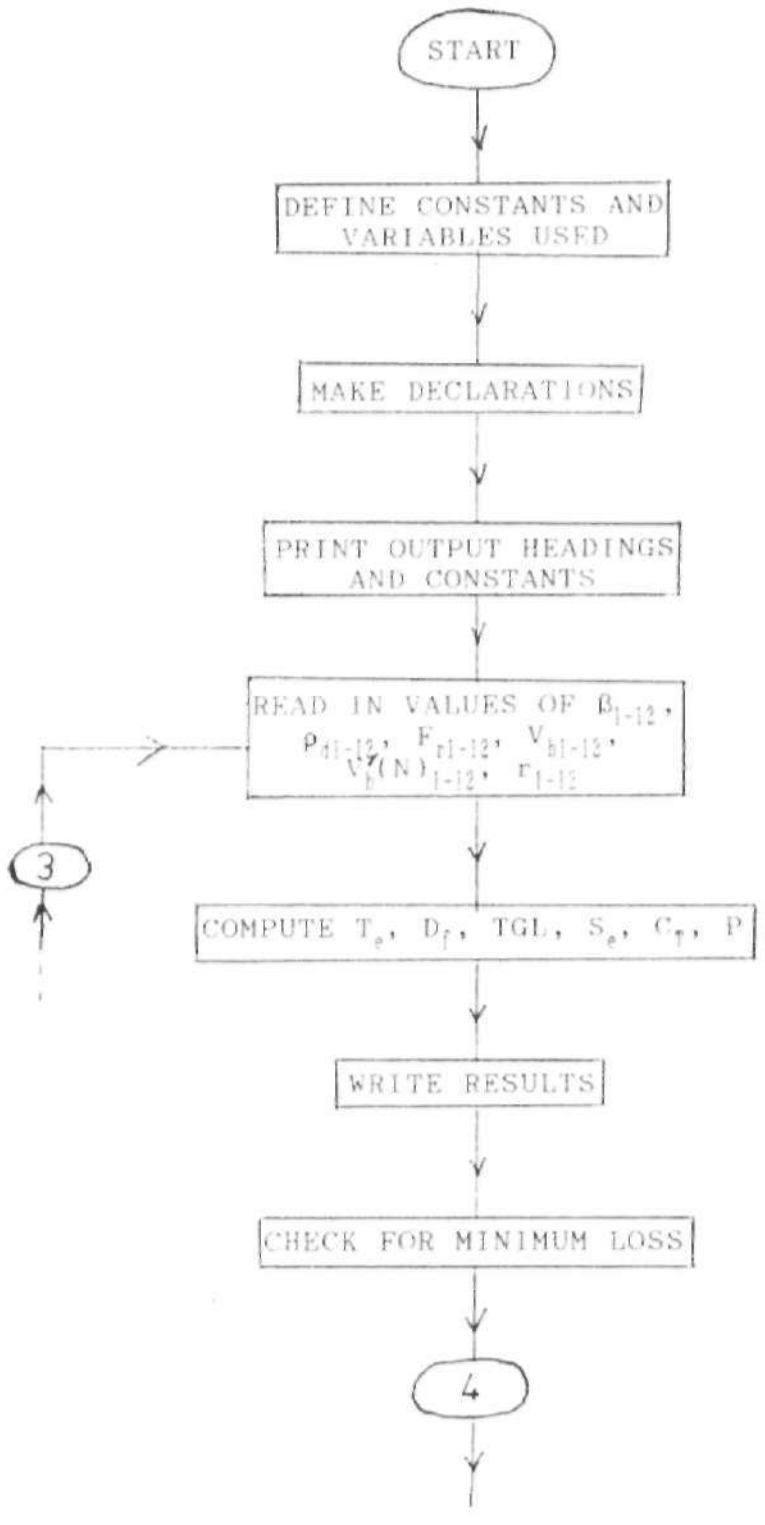
$$+\Pi_1 = \left[\frac{K_d^2 F_r}{V_b^3 \rho_w}\right]^{\frac{1}{3}}, \quad ++\Pi_4 = \left[\frac{D^2 V_b^3 \rho_w}{F_r V_d^2}\right]^{\frac{1}{3}}$$

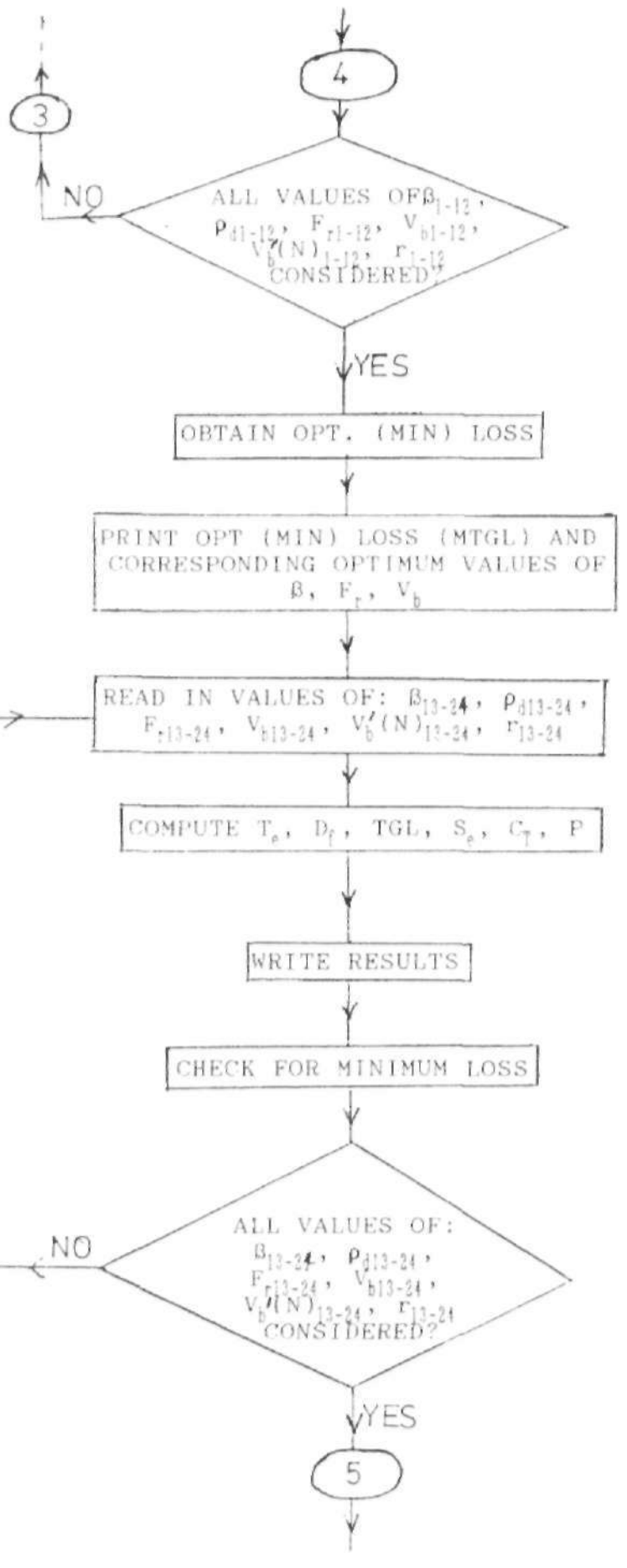
Table A5: Data Used To Determine K_m

F_r(kg/h)	Z	S_e	C_T (kg/h)	π_1' (Km)	Thresher type and source
29.87	0.66	0.965	15.03	0.701	Millet thresher
31.62	0.66	0.966	15.93	0.701	(Ajiboye, 1980)
49.66	0.66	0.968	25.07	0.701	"
57.45	0.66	0.983	29.46	0.701	"
60.67	0.66	0.984	31.12	0.701	"
360.00	0.33	0.953	109.81	0.720	Sorghum thresher
462.00	0.33	0.958	141.05	0.715	(Desta & Misra, 1970;
247.72	0.33	0.950	75.33	0.720	Singal & Thierstein,
160.60	0.33	0.940	48.50	0.721	1987)
480.00	0.33	0.963	147.89	0.720	"
960.00	0.52	0.976	340.00	0.650	Wheat thresher
365.80	0.52	0.968	129.54	0.681	(Chhabra, 1975)
302.70	0.52	0.964	107.19	0.691	"
272.57	0.52	0.960	96.52	0.691	"
197.96	0.52	0.958	70.10	0.698	"
			Mean Value:	0.700	
			Standard deviation: (std)	0.019	

$$\pi_1 = \frac{C_T}{F_r Z S_e}$$

APPENDIX E FLOW CHART FOR OPTIMIZATION SIMULATION PROGRAMME FOR MILLET AND SORGHUM THRESHER.




4
3
NO
ALL VALUES OF β_{1-12}, ρ_{d1-12}, F_{r1-12}, V_{b1-12}, $V_b'(N)_{1-12}$, r_{1-12} CONSIDERED?
YES
OBTAIN OPT. (MIN) LOSS
PRINT OPT (MIN) LOSS (MTGL) AND CORRESPONDING OPTIMUM VALUES OF β, F_r, V_b
READ IN VALUES OF: β_{13-24}, ρ_{d13-24}, F_{r13-24}, V_{b13-24}, $V_b'(N)_{13-24}$, r_{13-24}
COMPUTE T_e, D_f, TGL, S_e, C_T, P
WRITE RESULTS
CHECK FOR MINIMUM LOSS
NO
ALL VALUES OF: β_{13-24}, ρ_{d13-24}, F_{r13-24}, V_{b13-24}, $V_b'(N)_{13-24}$, r_{13-24} CONSIDERED?
YES
5

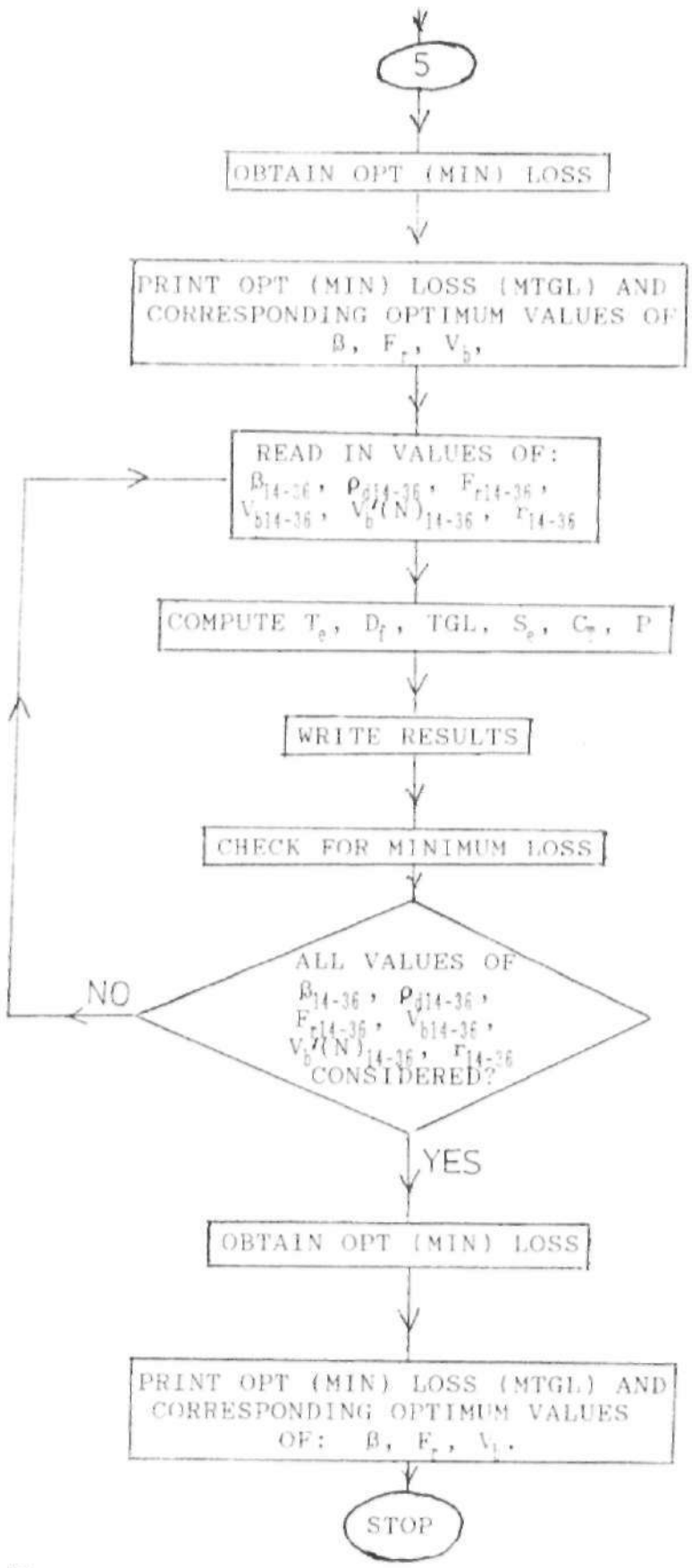

5
OBTAIN OPT (MIN) LOSS
PRINT OPT (MIN) LOSS (MTGL) AND CORRESPONDING OPTIMUM VALUES OF β, F_r, V_b,
READ IN VALUES OF: β_{14-36}, $\rho_{\beta 14-36}$, F_{r14-36}, V_{b14-36}, $V_b'(N)_{14-36}$, r_{14-36}
COMPUTE T_e, D_f, TGL, S_e, C_e, P
WRITE RESULTS
CHECK FOR MINIMUM LOSS
ALL VALUES OF β_{14-36}, $\rho_{\beta 14-36}$, F_{r14-36}, V_{b14-36}, $V_b'(N)_{14-36}$, r_{14-36} CONSIDERED?
NO
YES
OBTAIN OPT (MIN) LOSS
PRINT OPT (MIN) LOSS (MTGL) AND CORRESPONDING OPTIMUM VALUES OF: β, F_r, V_b.
STOP

Fig. p .

APPENDIX C

TABLE C1: OPTIMIZATION SIMULATION RESULT FOR MILLET THRESHER

β(dec.)	ρ_d (kg/m³)	Fr (kg/s)	Vb (m/s)	Vb (m/s)(N.rpm)	r(m)	Ce (dec.)	D (dec.)	TGL (dec.)	S_p (dec.)	C (kg/hr)	P (Watt)
0.09	102	0.03	3.40	3.93(400)	0.094	0.9940	0.00389	0.00935	0.8130	39.96	967.32
0.09	102	0.03	3.85	4.50(600)	0.072	0.9970	0.00133	0.00463	0.8290	40.68	1421.93
0.09	102	0.03	4.65	5.00(800)	0.060	0.9990	0.00037	0.00437	0.8510	41.76	1921.03
0.09	102	0.03	5.00	5.50(900)	0.058	0.9993	0.000185	0.000885	0.8600	42.26	2499.10
0.09	102	0.05	3.40	3.93(400)	0.094	0.9520	0.0299	0.0785	0.6980	57.17	967.33
0.09	102	0.05	3.85	4.50(600)	0.072	0.9680	0.0188	0.0514	0.7270	59.40	1421.95
0.09	102	0.05	4.65	5.00(800)	0.060	0.9840	0.00825	0.0243	0.7700	63.00	1921.06
0.09	102	0.05	5.00	5.50(900)	0.058	0.9880	0.00575	0.0175	0.7850	64.08	2499.14
0.09	102	0.07	3.40	3.93(400)	0.094	0.8850	0.0816	0.197	0.5970	68.40	967.35
0.09	102	0.07	3.85	4.50(600)	0.072	0.9140	0.0586	0.145	0.6280	72.00	1421.98
0.09	102	0.07	3.65	5.00(800)	0.060	0.9480	0.0325	0.0845	0.6860	78.48	1921.09
0.09	102	0.07	5.00	5.50(900)	0.058	0.9580	0.0250	0.0667	0.7060	81.00	2499.18
OPTIMUM VALUES: β = 0.09, Fr = 0.03kg/s, Vb = 5.0m/s, TGL = 0.000885											
0.12	82.83	0.03	3.40	3.93(400)	0.094	0.9860	0.00738	0.0219	0.7790	38.16	967.32
0.12	82.83	0.03	3.85	4.50(600)	0.072	0.9920	0.00385	0.0122	0.8000	39.24	1421.93
0.12	82.83	0.03	4.65	5.00(800)	0.060	0.9970	0.00121	0.00421	0.8260	40.57	1921.03
0.12	82.83	0.03	5.00	5.50(900)	0.058	0.9980	0.000732	0.00273	0.8290	40.75	2499.11
0.12	82.83	0.05	3.40	3.93(400)	0.094	0.9210	0.0523	0.1310	0.6470	52.99	967.33
0.12	82.83	0.05	3.85	4.50(600)	0.072	0.9440	0.0356	0.0916	0.6800	55.69	1421.96
0.12	82.83	0.05	4.65	5.00(800)	0.060	0.9690	0.0178	0.0488	0.7280	59.62	1921.06
0.12	82.83	0.05	5.00	5.50(900)	0.058	0.9760	0.0132	0.0372	0.7460	61.09	2599.14
0.12	82.83	0.07	3.40	3.93(400)	0.094	0.8370	0.1220	0.2850	0.5400	61.92	967.35
0.12	82.83	0.07	3.85	4.50(600)	0.072	0.8720	0.0923	0.2200	0.5800	66.60	1421.98
0.12	82.83	0.07	4.65	5.00(800)	0.060	0.9160	0.0563	0.1400	0.6340	72.72	1921.09
0.12	82.83	0.07	5.00	5.50(900)	0.058	0.9310	0.0453	0.1150	0.7560	86.76	2499.18
OPTIMUM VALUES: β = 0.12, Fr = 0.03kg/s, Vb = 5.0m/s, TGL = 0.00273											

OPTIMUM VALUES: β = 0.14, Fr = 0.03kg/s, Vb = 5 m/s, TGL = 0.0123

0.14	62.12	0.03	3.40	3.33(400)	0.094	0.3610	0.0220	0.2618	0.7200	35.28 3467.34
0.14	62.12	0.03	5.85	4.50(600)	0.072	0.9750	0.0140	0.0319	0.7450	36.58 1421.93
0.14	62.12	0.03	4.65	5.00(800)	0.060	0.9880	0.0058	0.0176	0.7850	38.56 1921.02
0.14	62.12	0.03	5.00	5.50(900)	0.058	0.9920	0.0039	0.0123	0.7940	39.02 2499.11
0.14	62.12	0.05	3.40	3.33(400)	0.094	0.6580	0.1040	0.2470	0.5650	46.26 3467.34
0.14	62.12	0.05	5.85	4.50(600)	0.072	0.8900	0.0772	0.1870	0.6010	49.21 1421.96
0.14	62.12	0.05	4.65	5.00(800)	0.060	0.9310	0.0454	0.1150	0.6600	54.07 1921.06
0.14	62.12	0.05	5.00	5.50(900)	0.058	0.9430	0.0360	0.0930	0.6780	55.51 2499.14
0.14	62.12	0.07	3.40	3.33(400)	0.094	0.7520	0.0199	0.4470	0.4570	52.56 967.29
0.14	62.12	0.07	3.85	4.50(600)	0.072	0.7930	0.1610	0.3680	0.4890	56.05 1421.98
0.14	62.12	0.07	4.65	5.00(800)	0.060	0.8510	0.1100	0.2590	0.5510	63.18 1921.10
0.14	62.12	0.07	5.00	5.50(900)	0.058	0.8710	0.0931	0.2220	0.7500	86.20 2499.18

APPENDIX D

TABLE D1: OPTIMIZATION SIMULATION RESULT FOR SORGHUM THRESHER

β(dec.)	$\mathcal{C}_d$ (kg/m³)	Fr (kg/s)	Vt (m/s)	Vb^2 (m²/s²)(N,rpm)	τ(N)	η_e (dec.)	η_b (dec.)	TGL (dec.)	η_s (dec.)	η_c (kg/hr)	P (Watt)
0.09	42.20	0.03	4.00	4.23(400)	0.1010	0.9907	0.0044	0.0137	0.7990	35.04	2415.76
0.09	42.20	0.03	4.45	4.56(600)	0.0725	0.9945	0.0024	0.0079	0.8170	35.82	2971.11
0.09	42.20	0.03	4.90	5.00(600)	0.0597	0.9967	0.0013	0.0046	0.8090	35.47	3851.14
0.09	42.20	0.03	5.12	5.32(900)	0.0564	0.9975	0.00097	0.0035	0.8380	36.75	4584.56
0.09	42.20	0.05	4.00	4.23(400)	0.1010	0.9395	0.0387	0.0992	0.6760	49.40	2415.78
0.09	42.20	0.05	4.45	4.56(600)	0.0725	0.9559	0.0268	0.0709	0.6950	50.79	2971.12
0.09	42.20	0.05	4.90	5.00(600)	0.0597	0.9678	0.0186	0.0508	0.7060	51.60	3851.18
0.09	42.20	0.05	5.12	5.32(900)	0.0564	0.9724	0.0156	0.0432	0.7520	54.96	4584.63
0.09	42.20	0.07	4.00	4.23(400)	0.1010	0.8651	0.0980	0.2329	0.5880	60.16	2415.95
0.09	42.20	0.07	4.45	4.56(600)	0.0725	0.8923	0.0755	0.1832	0.6050	61.90	2971.17
0.09	42.20	0.07	4.90	5.00(600)	0.0597	0.9141	0.0581	0.1440	0.6110	62.51	3851.21
0.09	42.20	0.07	5.12	5.32(900)	0.0564	0.9230	0.0511	0.1281	0.6470	66.20	4584.64
OPTIMUM VALUES: β = 0.09, Fr = 0.03kg/s, Vb = 5.12m/s TGL = 0.0035											
0.12	30.92	0.03	4.00	4.23(400)	0.1010	0.9710	0.0166	0.0455	0.7380	32.36	2415.76
0.12	30.92	0.03	4.45	4.56(600)	0.0725	0.9806	0.0104	0.0298	0.7640	33.50	2971.11
0.12	30.92	0.03	4.90	5.00(600)	0.0597	0.9870	0.0065	0.0195	0.7600	33.33	3851.14
0.12	30.92	0.03	5.12	5.32(900)	0.0564	0.9893	0.0052	0.0159	0.8360	36.67	4584.56
0.12	30.92	0.05	4.00	4.23(400)	0.1010	0.8806	0.0851	0.2045	0.5920	43.26	2415.78
0.12	30.92	0.05	4.45	4.56(600)	0.0725	0.9060	0.0645	0.1585	0.6220	45.46	2971.14
0.12	30.92	0.05	4.90	5.00(600)	0.0597	0.9260	0.0489	0.1229	0.6290	45.97	3851.18
0.12	30.92	0.05	5.12	5.32(900)	0.0564	0.9341	0.0427	0.1086	0.6630	48.45	4584.60
0.12	30.92	0.07	4.00	4.23(400)	0.1010	0.7808	0.1721	0.3913	0.4820	49.31	2415.81
0.12	30.92	0.07	4.45	4.56(600)	0.0725	0.8152	0.1411	0.3259	0.5150	52.69	2971.17
0.12	30.92	0.07	4.90	5.00(600)	0.0597	0.8442	0.1158	0.2716	0.5260	53.82	3851.22
0.12	30.92	0.07	5.12	5.32(900)	0.0564	0.8567	0.1051	0.2484	0.5590	57.19	4584.65
OPTIMUM VALUES: β = 0.12, Fr = 0.03kg/s, Vb = 5.12m/s, TGL = 0.0159											

CONTD.

0.14	22.80	0.03	4.00	4.23(400)	0.1010	0.4399	0.0611	0.1342	0.8610	28.98	2415.76
0.14	22.80	0.03	4.45	4.56(600)	0.0725	0.9489	0.0318	0.0629	0.8910	30.30	2971.11
0.14	22.80	0.03	4.90	5.00(800)	0.0597	0.9601	0.0225	0.0464	0.8910	30.30	3851.14
0.14	22.80	0.03	5.12	5.32(900)	0.0564	0.9673	0.0189	0.0517	0.7600	33.68	4504.87
0.14	22.80	0.05	4.00	4.23(400)	0.1010	0.7988	0.1558	0.3570	0.5870	42.90	2415.76
0.14	22.80	0.05	4.45	4.56(600)	0.0725	0.8320	0.1264	0.2944	0.5830	38.95	2971.14
0.14	22.80	0.05	4.90	5.00(800)	0.0597	0.8597	0.1025	0.2428	0.5430	39.68	3851.18
0.14	22.80	0.05	5.12	5.32(900)	0.0564	0.8716	0.0926	0.2210	0.5770	42.17	4504.61
0.14	22.80	0.07	4.00	4.23(400)	0.1010	0.6819	0.2650	0.5831	0.3940	40.31	2415.81
0.14	22.80	0.07	4.45	4.56(600)	0.0725	0.7203	0.2282	0.5079	0.4260	43.59	2971.18
0.14	22.80	0.07	4.90	5.00(800)	0.0597	0.7541	0.1966	0.4425	0.4300	44.81	3851.22
0.14	22.80	0.07	5.12	5.32(900)	0.0564	0.7692	0.1827	0.4135	0.4680	47.88	4504.65

OPTIMUM VALUES: β = 0.14, Fr = 0.03kg/s, Vb = 5.12m/s, IGL = 0.0517