UNIVERSITY OF ALBERTA

ROTARY COMBINE TECHNOLOGY - AN INVESTIGATION OF POWER REQUIREMENTS AND A METHOD TO CALCULATE GRAIN SEPARATION AND LOSSES IN REAL TIME

by

© ANDERS BJORK

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled ROTARY COMBINE TECHNOLOGY - AN INVESTIGATION OF POWER REQUIREMENTS AND A METHOD TO CALCULATE GRAIN SEPARATION AND LOSSES IN REAL TIME submitted by ANDERS BJORK in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

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ABSTRACT

Laboratory studies of grain separation characteristics and power requirements for a rotary combine were performed by running measured quantities of wheat crop through the threshing/separating components of the rotary combine.

Point grain separation (grain separation through small areas with assigned coordinates), total grain separation (combine capacity), and separation losses were measured for different MOG feed rates and rotor speeds. Power requirements were recorded for the runs, and the required power was divided into required idle power (no load power) and required net power (power for threshing and separation, idle power excluded).

A three-dimensional arithmetic model to predict grain separation through the concave and separating grate of a rotary combine is presented. The model uses point separation measured at 16 locations in a grid pattern underneath the concave and separating grate. Curve fitting techniques were used to fit equations to the point separation data. The equations then were integrated appropriately to calculate grain separation and separation losses. Point separation along the rotor axis was described well by a non-linear equation.

Idle power was found to depend on rotor speed.

Net power was found to depend on the MOG feed rate. Rotor speed did not significantly affect the net power requirement, neither was there found to be any interaction between rotor speed and MOG feed rate.

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A	coefficient determining shape of curvature	
B	coefficient determining shape of curvature	
b	attenuation coefficient	m^{-1}
C	coefficient determining shape of curvature	
c	separation attenuation coefficient	$\% \ m^{-1}$
CV	coefficient of variation	
D	coefficient determining shape of curvature	
d_1 & d_2	lower respective upper end of the interval to be integrated	m
E	coefficient determining shape of curvature	
e	the base of the natural logarithms	
F	coefficient determining shape of curvature	
FR_{MOG}	MOG feed rate	$kg \ s^{-1}$
l	axial distance from the front end ot the rotor	m
MOG	material other than grain	
n	number of observations	
P_{idle}	idle power requirement	kW
P_{net}	net power requirement	kW
r	linear correlation coefficient	
r^2	square of the linear correlation coefficient achieved by the least square fit for the regression	
S	grain separation rate	$kg \ s^{-1}$
s	standard deviation	
S_{AAX}	average point separation of grain along the rotor axis	$kg \ m^{-2} s^{-1}$
S_C	total mass of grain separated through the area of the interval	$kg \ s^{-1}$

S_{CW}	cumulative grain separation per unit width for the interval d_1 to d_2	kg m^{-1} s^{-1}
S_P	point grain separation	kg $m^{-2}s^{-1}$
$\bar{S}_{SEG}$	average point separation of grain across a segment around the concave and separating grate	kg m^{-2} s^{-1}
S_0	analytical initial separation rate	kg s^{-1}
v_t	tangential velocity of the rotor	m s^{-1}
W_A	width of the separating area	m
x	axial distance from the beginning of the concave	m
Y	observed dependent datum	
$\hat{Y}$	estimated dependent datum	
y	coordinate around concave arc or grate arc	°
y_u & y_l	coordinates for the ends of the concave arc or grate arc	°
Z	cumulative grain separated up to distance l	%

1. INTRODUCTION

The latest generation of rotary (or axial flow) combine harvesters has now been on the marketplace for more than a decade. Rotary combines have been accepted by the farmers, and they now account for a substantial share of the total combine sales.

Researchers, research institutions and test stations have shown a great interest in the rotary combine technology. No complete studies have, however, been undertaken on the behavior of the rotary combine under different field conditions. Most studies have focused on field performance comparisons of rotary combines and conventional cylinder/straw walker combines. Research projects with the aim of improving and/or developing the rotary combine technology have been carried out in a very limited number.

In the field, a combine operator has two factors to optimize; i. e., grain harvesting capacity and grain losses. In most situations, however, an increase in grain harvesting capacity is followed by an increase in grain losses. The combine operator is left to make the decision on what grain loss level is acceptable. Ideally, throughout the day he should continuously adjust the different combine settings to obtain the highest possible harvesting capacity at this acceptable grain loss level.

The combine operator obtains limited information feedback about the combine's performance. Grain harvesting capacity is usually estimated, based on the operators experience. Grain losses are, at best, monitored with a 'grain loss monitor'.

1.1 DEFINITIONS AND TERMINOLOGY

A good description of the working elements and their respective functions in different combine types is given by Kydd (1980).

The definitions and the terminology used are, as far as possible, compatible with ASAE standards, (ASAE 1988a, ASAE 1988b). Non-standard terminology is explained at the first respective occurence in each paper.

1.2 OBJECTIVES

Theoretically, if one knows the mathematical function describing grain separation through the separation elements of a combine, the function can be integrated to give total grain separation (grain harvesting capacity) and separation losses. This concept led the author to investigate grain separation through the grain separating elements of a rotary combine.

The main objective of this work was to develop a three-dimensional arithmetic model capable of calculating total grain separation and separation losses. Hence, a search for a suitable mathematical representation of the grain separation through the grain separating elements was hence undertaken. Once a suitable mathematical function was found, a computer program was developed to handle the necessary calculations.

At similar capacities, rotary combines demand more power than cylinder/straw walker combines (Spiess, 1981). A study was carried out to find the parameters influencing the required idle power (no load power) and the required net power (power for threshing and separation, idle power excluded).

1.3 THESIS FORMAT

This thesis consists of three independent papers. The first paper; ***Rotary Combines, from the Past to the Present State of Art***, is a non-technical paper describing the development of the rotary combine. The paper notes research projects undertaken at different institutions around the world, and briefly comments on their presented results. The reader will note that the results presented are sometimes incomplete, sometimes not specific and sometimes contradictory. The author has added a few personal thoughts on interesting characteristics of the rotary combine at the end of the paper. Research that the author feels should be done is briefly mentioned as well.

The second paper; ***A Three-Dimensional Arithmetic Model to Calculate Grain Separation and Separation Losses for a Rotary Combine***, first reviews attempts of other researchers to find mathematical functions that describe grain separation through different separating elements. The research done by the author to determine actual grain separation is then described. A working arithmetic procedure to calculate total grain separation and separation losses is presented. Predicted total separation and separation losses are compared with the respective measured data. A comparison of the author's results and those of other researchers is included at the end of the paper.

The third and last paper; *Power Requirement for Threshing and Separation in a Rotary Combine*, contains a literature review of research presented by others, then describes the experimental procedure used by the author to measure power requirements. The formulas found to best describe idle power and net power are further presented and discussed.

The last chapter of the thesis contains a brief summary of the authors results, together with a list of topics recommended for further studies.

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2. ROTARY COMBINES, FROM THE PAST TO THE PRESENT STATE OF ART

2.1 INTRODUCTION

Ever since man began to invent machines to help him in his daily living, he has tried to make them bigger and faster to further decrease the demand for manpower. In combine design and manufacturing, the stage has now been reached where construction of the conventional cylinder and straw walker combine cannot be further enlarged without penalty in terms of excessive costs.

Assuming that adequate cleaning capacity is available, the processing capacity of a cylinder combine is a linear function of the cylinder (and straw walker) width. A further increase in straw walker width would cause problems in straw walker crankshaft design due to large unbalanceable forces. The crankshaft bearings and the combine frame has to be given added strength to counteract those forces. It would become more difficult to obtain an even crop distribution over the cylinder, straw walker and sieve widths. An increase in cleaning shoe fan width might result in an uneven air flow across the sieves.

In Europe, where most combines are transported from the manufacturer to the retailer by railway, the increased width and height has caused transportation problems. Many of the bigger combine models now have the shape of an inverted U, to facilitate the transportation through railway tunnels.

Rotary (axial flow) combines, with rotor(s) instead of cylinder(s) and straw walkers as working elements, were chosen to be the answer to the ever-growing combine design problem by some manufacturers some 20 years ago. Available on the market today are the manufacturers' results in the form of a number of different rotary combine models.

2.2 LITERATURE REVIEW

2.2.1 The Development of the Rotary Combine Concept

There are several rotary combines on the market today. Advertisments for these combines might lead one to the conclusion that rotary combines are something new, or a principle invented by the respective manufacturer. This is, however, not true. The rotary concept for thr ʼing and separating has been around for a century, and research and development have been conducted all over the world. An exellent summary of the development of axial flow combines is given by Quick and Buchele (1978).

The very first threshing machines were built to simulate the motion of the human arm and the flail. Inventors then began to consider the rotary concept for threshing and separation, and a great number of designs appeared. As far ago as 1752 a Swede named Ljundqvist described a Swedish grain separator which used centrifugal force to separate whole grains from cracked seeds, weeds and trash.

The first threshing cylinder was patented by the Scotsman Andrew Meikle in 1788. As soon as this threshing concept was proven, rotary separation soon followed.

Possibly the earliest cylindrical rotary thresher and separator was the hand cranked twin rotor design patented in 1886 in Germany. Of the many ideas that followed, none were known to have reached the marketplace until the 1920's, when several machines where marketed in the grain belt of the central United States.

In Kansas, USA, during the early 1930's, the Rotary Farm Equipment Company manufactured and marketed a combine with a conventional threshing cylinder and an auger-type rotary separator in a very compact configuration.

In Germany, Felix Schlayer invented his 'Heliak' machine that was sold in a few numbers in Europe. German authorities reported favorable tests of this machine, even though the energy consumption was high. The Heliak machine was also tested in the USA by different combine manufacturers. Their conclusions were that the machine worked, but was not as energy efficient as the conventional cylinder machines.

In south east Asia, the agricultural engineering section of the International Rice Research Institute (IRRI) has been working since the 1960's on the development of powered rice harvesting machines. They selected the rotary threshing and separating technology for its compact and simple design. A number of companies in Asia have manufactured and marketed the IRRI rice combine, which is a small, mobile, gasoline-powered rotary unit.

An attempt to use centrifugal force for grain separation lead into production and marketing of the Western Roto Thresh combine in the latter part of the 1970's. The combine was a self-propelled unit with a transvers-mounted tangential threshing cylinder and a longitudinally-mounted axial separating drum (2.640 m long and 1.6 m in diameter). The combine was field-tested together with a conventional cylinder/straw walker equipped combine and an axial flow combine (Wrubleski and Smith, 1980). The grain separation of the drum showed no significant improvement over that of straw walkers. The Western Roto Thresh is no longer manufactured.

By 1975 a new generation of axial flow combines was introduced on the North American market by Sperry New Holland. Since then, the farm machine manufacturers have introduced new axial flow combine models almost every year.

The axial flow combines presently (1990) on the market were originally developed by Allis Chalmers, International Harvester, Sperry New Holland and White Farm Equipment, all in the USA, by Versatile in Canada, and by Fiat Laverda in Italy. However, a major restructuring of the farm machinery industry have taken place during the last decade, and some of the mentioned combines are now manufactured and/or marketed under different brand names.

2.2.2 Crop Motion

In rotary combines, the motion of the crop has two components; the velocity along the rotor axis and the tangential velocity.

Skromme (1978) stated that the spiraling motion of the crop makes it pass the threshing concave and separating grate two or three times, instead of just once as in the cylinder combine. He noted that these passes are accomplished in about three seconds, which is much faster than the time necessary to thresh and separate a crop in a conventional combine.

Murray et al. (1978) reported the peripheral speed of the crop to be about one third that of the rotor rasp bars.

Kutzbach (1983) studied the crop motions in both a cylinder combine with straw walkers and in a rotary combine. His results are given in Table 2.1 and Table 2.2. Even though the sizes of the combines he studied were not given, the results could be adapted to most combines.

Wacker (1985) noted that the crop passes approximately three to five times over the threshing concave and separating grate, with the lower number of passes occuring for low MOG (material-other-than-grain) feed rates. He also found the passes to be completed in between one and three seconds.

2.2.3 Separation Characteristics

Lalor and Buchele (1963) developed and studied an axially-fed, cone-shaped rotor rotating in an outer, stationary perforated cone. They found the threshing to be 99 % complete at all tested rotor speeds. All speeds they used gave a tangential rotor/cylinder velocity lower than those recomended today for cereal crops. They reported separation to be most efficient (75 %) at the lowest rotor speed used, and a decrease in separation with an increase in rotor speed. They concluded, however, that the orientation of the slots in the perforated outer cone was of great importance and claimed that, with another orientation of the slots, they would have been able to separate more than 98 % of the grain fed into the rotor.

Skromme (1978) and Kutzbach (1983) were both of the opinion that most of the grain is separated through the threshing concaves.

Wang et al. (1984) observed that a large percentage of the separation takes place at the threshing concave, and that this percentage increases with an increase in feed rate. They gave a mathematical expression for grain separation along the central region of the threshing concave and separating grate. The expression had the same exponentially decaying shape as the expression given by Reed et al. (1970) for separation through straw walkers. Wang et al. (1984) concluded that the separation characteristics for a rotary threshing and separating device is more complex than that of straw walkers because the characteristics depend not only on the separation process but, also, on the threshing process.

Wacker (1985) also found that most (around 95 %) grain is separated underneath the first part of the rotor.

2.2.4 Grain Losses

Three types of losses are attributed to the threshing and separation mechanism of a combine;

1. The cylinder or rotor loss, defined as the amount of seed not detached from the head, cob or pod and not isolated by the separating mechanism(s) of the combine.
2. Separation loss, defined as the amount of seed detached from the head, cob or pod but not isolated by the separating mechanism(s) of the combine.
3. The shoe loss, defined as the amount of seed detached from the head, cob or pod and isolated by the separating mechanism(s) but not isolated by the cleaning shoe(s) of the combine.

Typically, cylinder or rotor losses can be sampled from the combined straw and chaff effluents of a combine harvester. Separation losses can be sampled from the straw effluent and shoe losses can be sampled behind the shoe(s) or sieve(s). The total loss, or the processing loss, is the sum of the cylinder or the rotor loss, the separation loss and the shoe loss.

A few field tests of rotary combines have been conducted by test stations in North America and Europe. It is, however, difficult to compare tests because all test conditions have to be taken into account.

In one test (PAMI 1989), total grain losses were almost linearly proportional to the MOG (Material Other than Grain) feed rate. Other tests (SMP 1980, SJF 1980) have shown total losses that vary exponentially with MOG feed rate, similar to the total losses typically found when testing cylinder/straw walker type combines. Many tests (PAMI 1979, 1986, 1987a, 1987b) in grain seeds have, however, shown total grain losses to be low and almost independent of MOG feed rates within a wider range than that for a cylinder/ straw walker type combine. When engine power has not been the limiting factor for MOG feed rate, total grain losses have usually increased rapidly (exponentially) at some critical feed rate.

Wrubleski and Smith (1980) field-tested a rotary combine with two longitudinally mounted rotors. They found total grain losses to increase linearly with an increase in MOG feed rate. The increase in total losses was not influenced predominantly by either cylinder, shoe or rotor losses.

Fairbanks et al. (1978) reported that, in a field comparison in wheat, a rotary combine recovered more grain per unit area than a cylinder/straw walker combine. This was especially noticeable when the combines were operated near their respective maximum capacity.

Mailander et al. (1983) suggested that, when total grain losses are found to be almost linearly dependent on MOG feed rate, the combine is not tested over a sufficient range of feed rates, and that a non-linear relationship would appear at a higher MOG feed rate.

Spiess (1980) measured total grain losses (including shoe losses) in wheat for a rotary combine with one longitudinal rotor operating on a hillside. He found higher losses at right hand downhill slopes than on level land, but no significant difference in total losses when operating on left hand slopes. He concluded this to be due to the direction of rotation of the rotor (clockwise when viewed from the rear end), that delivers a higher amount grain from the right side than from the left side of the concave and separating grate. The material would hence be distributed non-uniformly across the width of the shoe. This would be further accentuated by operating on a right hand downhill slope.

2.2.5 Grain Damage

Grain damage usually is determined in tests of combines. A few tests have been conducted where rotary combines have been compared with cylinder/straw walker combines.

Fairbanks et al. (1978) found, in a field comparison, that a rotary combine consistently had less grain damage than a cylinder/straw walker combine.

Paulsen and Nave (1980), conducted a field comparison of corn damage from two makes of rotary combines and a cylinder/straw walker combine. All three combines were reported to produce satisfactory low levels of corn breakage and damage for the harvesting condition.

Soybean splits were found to be significantly higher for a cylinder/straw walker combine than for either of two rotary combines used in a test by Newberry et al. (1980). The percentage of splits increased with increased rotor/cylinder speed for all three combines, but the increase in splits was less for the rotary combines than for the cylinder/straw walker combine. A reduction in rotor and cylinder speed caused fewer splits, but the effect was offset by the increase in cylinder/rotor losses and separating losses, especially for the rotary combines.

Spiess (1980, 1981) found grain damage in corn, winter barley, spring wheat and rape seed to be several times less when harvested with a rotary combine than with a cylinder/straw walker combine. The percentage of shelled grain was larger when the grain was harvested with the rotary combine. Grain harvested with the rotary combine sometimes had a higher germination rate, thus indicating a more gentle threshing process.

Grain damage results obtained by Mailander et al. (1983) were so variable or so small that no statistically significant conclusions could be made.

2.2.6 Energy Consumption

A higher than average specific energy consumption (amount of energy used per mass unit of grain harvested) does not only lead to a higher than average cost for fuel, but also to a higher initial combine cost. The latter is due to the cost of the larger engine required to run the combine at capacity.

Wrubleski and Hill (1981) measured specific capacity (the inverse of specific energy consumption) in wheat for two different rotary combines and one cylinder/straw walker combine. They found the specific energy consumption to be approximatly 50-100% higher for the rotary combines than for the cylinder/straw walker combine.

Specific energy consumption has been measured in field tests in Canada as well as in Europe. The results differ due to different harvesting conditions, but they all indicate that rotary combines have a higher specific energy consumption than cylinder/straw walker combines.

2.2.7 Characteristics of the Straw Behind the Combine

Spiess (1980) reported that a rotary combine broke up the straw more than a cylinder/straw walker combine. After the straw had passed through the respective combines, the average straw length behind the rotary combine was two thirds of the length of that behind the cylinder/straw walker combine. The straw moisture content was 21%. The difference between the straw lengths became larger with a lower moisture content. When baling straw after the two combine types, Spiess found the bale yield after the rotary combine to be slightly less.

The swath behind the rotary combine was found to be more compact, hence needing more time to dry out before baling. In the cases where the straw was additionaly raked, the straw dried faster than that after the cylinder combine, due to the rough and cracked surface.

2.2.8 Damp Crop Conditions

Fairbanks et al. (1978) were able to 'satisfactorily' operate a rotary combine in 'conditions of straw toughness' where a cylinder/straw walker combine was 'grounded'.

Spiess (1981) highlighted the rotary combine's high operating ability. He found it possible to [illegible]ne a crop with 48% straw moisture content and a high green weed content at high feed ra[illegible] moisture content is typically in the range 10 to 30 % (wet base).

2.3 DISCUSSION

In rotary combines, both threshing and separation are accomplished by the interaction between the rotor and the rotor housing. Studies have shown threshing to be complete with lower tangential rotor velocities than those needed for complete separation of the grain. Low rotor losses have been obtained in field tests. The conventional cylinder and concave equipped combine also gives nearly complete threshing. Separation losses account for the largest amount of the total grain processing losses in a combine. Obviously there are good solutions to the threshing process whereas the separation process still can be improved.

The dominating (centrifugal) force acting on the grain in a rotary combine is much larger than the dominating force (of gravity) that separates grain from straw at the straw walkers. Hence, separation efficiency of rotary combines might be less dependent on crop conditions such as dampness. This would be a great advantage in many areas of the world. No research has, however, been done on this subject, even though there have been indications of higher separation efficiencies for rotary combines than for straw-walker-equipped combines under such conditions.

There has been limited research conducted on centrifugal separation in rotary combines. The principle of centrifugal separation of grain from straw is known to work, but it is unpublished why. This points to the necessity for further studies of the separation process.

Tests have proved that rotary combines have higher specific energy consumption than cylinder/straw walker combines. There is, however, little information on how power requirement and specific fuel consumption are affected by variables such as rotor speed, feed rate, crop moisture content etc.

The increase in total grain losses with increased MOG feed rate is less rapid for rotary combines than for cylinder/straw walker combines. Thus, rotary combines might recover more of the total amount of grain a farmer has to harvest in his fields, especially when the operator operates near the maximum capacity of the combine. The economic effect of more harvested grain added to the effect of a higher market price for less damaged grain would offset, at least in part, a higher cost for fuel due to a higher specific fuel consumption.

The straw breakage of rotary combines results in slightly lower straw yields and weaker straw bales. Typically, farmers have a surplus of straw in their fields, giving a lower straw yield minor importance. Cereal straw is a small commodity on the agricultural marketplace, and when a farmer bales and sells straw, he merely recovers his costs associated with the straw harvest (baling).

Of more concern is the effect of the intense treatment on brittle crops such as dry rapeseed. The more intense crop treatment, supported by a high centrifugal force, tends to break up a brittle crops into such small pieces that the cleaning unit becomes overloaded. This can be seen in some test reports of rotary combines as a very low capacity in oil seed compared to the capacity in cereal crops.

In the robotic era of today, the automatic grain combine is a challenge for researchers. The short crop processing time of the rotary combine, together with the constant centrifugal force separating the grain from the straw, might make it possible to build such an automatic combine. If the grain separation behaviour was known, and if there were adequate sensors to measure the amount of grain passing through the threshing concave and separating grate, it would be possible to automaticaly adjust combine settings such as rotor speed and concave clearance and to regulate the travel speed to optimize the capacity for a given grain loss level.

Farm-operated combines rarely run at their maximum capacity. The author's experience is that a good operator might reach a daily average in the swath or crop of 70 to 80 % of the rated capacity at the associated rated loss level (normally 2 to 3 %). There are several reasons for this. The operator might not feel confident with running at the high travel speed necessary to fully load the combine. He might not be willing to adjust the combine settings continuously. He might feel that losses increase rapidly (exponentially) at a certain capacity, and he prefers to be too far on the safe side of this point.

By using proper equipment and methods to monitor grain separation, and by continuously supplying information on harvesting capacity and processing losses to the operator, it would be possible for him to maximize harvesting capacity for a given grain loss level. A conservative estimate of the possible increase in harvesting capacity using such provisions would be 10-15 %. There is a tremendous potential for possible savings if farmers could buy smaller and less expensive combines and utilize them at a higher percentage of their maximum capacity.

Table 2.1 Properties of a Cylinder/Straw Walker Combine (adopted from Kutzbach, 1983)

	unit	at cylinder	at straw walker
average crop velocity	$m\ s^{-1}$	5-9	0.4-1.0
displacement of crop	m	0.5-0.8	3.5-4.4
exposure time	s	0.05-0.15	5-10
number of impacts on crop		5-15	15-40
impact frequency	Hz	85-130	2.5-6.0
straw mass per unit area at 15 t/h MOG feed rate	$kg\ m^{-2}$	0.3-0.6	2.8-6.9

Table 2.2 Properties of a Rotary Combine (adopted from Kutzbach, 1983)

	unit	at threshing concave	at separating grate
average crop velocity			
tangential	$m\ s^{-1}$	5-11	4-10
axial	$m\ s^{-1}$	1.1-1.6	1.3-2.0
displacement of crop	m	5-6	4-5
exposure time	s	0.6-0.9	0.5-0.8
number of impacts on crop		22-40	18-35
impact frequency	Hz	36-46	38-50
straw mass per unit area at 15 t/h MOG feed rate	$kg\ m^{-2}$	1.3-1.9	1.0-1.6

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3. A THREE-DIMENSIONAL ARITHMETIC MODEL TO CALCULATE GRAIN SEPARATION AND GRAIN SEPARATION LOSSES FOR A ROTARY COMBINE

A version of this paper was presented as ASAE Paper No. PNR 88-102 at the ASAE Pacific Northwest Regional meeting in Pendleton, Oregon, USA, September 28-30, 1988.

3.1 INTRODUCTION

The annual harvesting of grain crops is a stressful situation for many farmers. They have to operate one of the most expensive pieces of equipment on the farm, both in terms of initial cost and hourly cost. Also, the operator has to maximize machine harvesting capacity without exceeding a certain processing grain loss level. Unfortunately, the operators usually do not have accurate information regarding capacity and losses to base their decisions on.

Grain harvesting capacity is usually estimated by multiplying forward travel speed by estimated grain yield per unit area and by effective width of cut of the combine header or swather, while grain processing losses are most often estimated subjectively.

In recent years, so called 'grain loss monitors' have gained popularity on the market as a way of supplying information regarding processing losses to the combine operator. However, these monitors give, at best, a readout in mass loss per unit time, whereas the combine driver is more interested in losses as a percentage of harvested grain.

3.1.1 Objectives

Theoretically, if the mathematical function representing grain separation through the grain separating elements of a combine is known, the function can be integrated to give total grain separation (or harvesting capacity measured as grain feed rate if nil shoe losses and rotor losses are assumed) and separation losses. This thought led the author to investigate point separation (grain separation through small areas with assigned coordinates) through the concave and the separating grate of a rotary combine.

The main objective of this work was to develop a three-dimensional arithmetic model capable of calculating total grain separation and separation losses. Hence, a search for suitable mathematical representations of the grain separation through the grain separating elements was undertaken. Once suitable matemathical functions were found, a computer program was developed to handle the necessary calculations.

Also, by measuring the total mass of grain separated through the concave and separating grate, and by measuring the separation losses behind the combine, verification of the chosen model was thought to be possible.

3.1.2 Literature Review

Grain separation through the concave in a rotary combine

Researchers Lo et al. (1978) did experiments with a stationary rotary corn thresher. The concave area was partitioned perpendicular to the rotor axis into eight equal sections. Corn separation was found to be low underneath the first part of the rotor, peak separation to occur halfway along the rotor and separation to decay exponentially underneath the last part of the rotor.

Wang et al. (1984), in field tests, measured point separation with piezo-electric grain sensors mounted underneath one rotor on a rotary combine with two parallel rotors. The sensors were mounted on a frame underneath the concaves, without any special provision to catch separated grain from a specific area of the concaves. They reported separation of wheat to decay exponentially with axial distance from the rotor front end, but only if the center region of the concave grate arc was considered. The mathematical representation of grain separation was reported as

$$S=S_0e^{-b\,l} \tag{3.1}$$

where: S = grain separation rate, mass per unit time

S_0 = analytical initial separation rate, mass per unit time

e = the base of the natural logarithms

b = attenuation coefficient, m^{-1}

l = axial distance from the front end ot the rotor, m

They found more grain to be separated through the center portion of the threshing concave arc than towards either side. The separation distribution along the separating grate arc was reported to be uniform since no distinct peak separation rate existed.

Wacker (1985) used an experimental rotary combine to measure grain separation. The rotor had a diameter of 0.51 m and a total length of 3.3 m. The crop to be processed was fed by a conveyor belt to a table auger, then by an intake chain conveyor to the rotor. The crop was fed tangentially to the 1.0 m long vane section of the rotor, passed through the 1.0 m long threshing section, then the 1.0 m long separation section and finally the residues were discharged by the 0.3 m long discharge beater. The separated grain was collected in twelve boxes spaced evenly, axially, underneath the threshing and separating sections.

Using whole and prethreshed crop, Wacker found that prethreshing the crop as a pretreatment only slightly increased the amount of grain separated through the threshing concave. Significant threshing occurs due to the action of the table auger, the intake chain elevator and the rotor vanes. Thus, according to Wacker, a nontreated crop will become prethreshed on the way to the threshing part of the combine rotor.

By assuming the threshing process to have only a small influence on the separation process, grain separation was found to be well described by the equation

$$Z=(1-e^{-c\,l})100 \qquad (3.2)$$

where: Z = cumulative grain separated up to distance l, %

e = the base of the natural logarithms

c = separation attenuation coefficient, % m^{-1}

l = axial distance from the front end of the threshing concave, m

Grain separation through the concave in a concave/straw walker type combine

Klenin et al. (1970) noted that the greatest quantity of grain is separated through the central part of the concave.

Mahmoud and Buchele (1975) investigated kernel separation through the concave and concave extension of a corn sheller (a cylinder/concave unit). They collected the separated kernels in five boxes; three boxes underneath the concave, the fourth box underneath the concave extension and the fifth box behind the concave extension. Mahmoud and Buchele suggested an exponentially decaying equation to best describe the kernel separation through the concave and concave extension used.

Mathematical models to predict grain separation through a concave were developed by Huynh et al. (1982) and Trollope (1982). Huynh et al. based their model on probabilistic theory combined with the three physical phenomenas detatchment of kernels from the the stalks, penetration of kernels through the straw mat and passage of kernels through the concave grate. Huynh et al. suggested a separation function that peaks near the entrance of the concave and then decays exponentially towards the end of the concave. Trollope derived a set of differential equations that lead to an equation to approximate cumulative grain separation through the concave, similar to the equation used by Wacker (1985).

Grain separation through straw walkers

Klenin et al. (1970) and Reed et al. (1970) both used an exponentially decaying function, similar to the equation used by Wang et al. (1984), to describe grain separation through straw walkers. Reed et al. noted, however, that separation through the very first part of the walker increases with distance along the walker and then peaks before decaying exponentially. Non-uniform separation across the width of the straw walker also was noted by Reed et al..

Boyce et al. (1974) approximated grain separation through straw walkers with a normal-type distribution, i. e. a bell-shaped curve.

Gregory and Fedler (1986) used Fick's Law of Diffusion to predict a grain separation that decays exponentially with straw walker length.

3.2 MATERIALS AND METHODS

3.2.1 Experimental Unit

An experimental unit was fabricated using the rotor (complete with housing, concaves, variable speed drive and intake elevator) from a 1978, model 1460, International Harvester rotary combine. The rotor and assemblies were mounted into a steel structure totally enclosed in plywood. This allowed collection of the material separated through the concave and the separating grate. Sixteen sheet metal ducts were welded in a grid pattern (Figure 3.1) on to the concave and separating grate to enable measurement of point separation of grain. The material coming through the ducts was collected in removable fabric bags held up by steel supports mounted on a slider underneath the rotor housing. With the slider in the front position, sheet metal deflectors prevented material from falling into the bags. As a result, the material separated through the ducts fell freely on to the bottom of the plywood enclosure (Figure 3.2a). With the slider in the rear position, the material coming through the ducts was collected in the bags (Figure 3.2b). The slider was manually operated by a lever. Two microswitches, one switching at each end of the slider path, were connected to a data aquisition board (MetraByte Dash-16) in a personal computer (IBM PC/XT). The computer sampled the voltage across each switch 100 times per second. By analyzing the voltage data for the high-to-low changes and vice versa, the location of the slider relative to time could be obtained. Hence, the duration of the time that grain was collected in the bags could be calculated.

A plywood box was attached to the discharge end of the experimental unit to collect the residual material. The box had two sections, one to allow for easy removal of the straw, the other one to enable measurements of grain separation losses. The latter section was equipped with a hinged lid that opened when the slider underneath the rotor housing was moved to the rear position. Thus, the material not separated through the concaves or separating grate and the material separated through the ducts was collected simultaneously.

The rotor assembly was driven from the 1000-rpm power-take-off on a 130-kW diesel tractor. An emergency stop control for the rotor was obtained by connecting a solenoid fuel valve on the tractor to emergency stop switches on the experimental unit.

The crop to be threshed was fed, heads first, by a 15 m long and 0.9 m wide conveyor belt assembly straight into the intake elevator of the experimental unit. The canvas conveyor belt was driven by a three phase, 3.7 kW asynchronous motor. The conveying speed was 1.0 m s^{-1}

3.2.2 Sampling Duct Locations and Cross-Sectional Areas

The locations of the sampling ducts along the rotor axis where chosen to give as even a spacing as possible. The locations along the concave arcs and grate arc were a compromise between avoiding edge effects from the interface of nonperforated area and perforated concave and grate area, and the wish to place the ducts as far apart as possible (Figure 3.1).

Due to the design of the concave and separating grate, equal cross-sectional sampling areas for all of the ducts could not be achieved and the areas ranged from 4836 mm^2 to 7650 mm^2.

3.2.3 Experimental Crop

Spring wheat (**Katepwa**), selected for it's relative easiness to thresh, was harvested with a binder in September 1986, stacked and protected from the environment by tarpaulins. Each bundle had an average mass of 4.0 kg as used. The average MOG (Material Other than Grain)/grain ratio was 1.2 with a standard deviation of 0.063. The moisture contents (wet basis), as used, of the straw and grain were in the range 7 to 13 % and 11 to 14 % respectively with average moisture contents at 10.6 % and 12.7 % respectively. These parameters are good representatives of the conditions farmers experience in their fields during the grain harvesting season. They are all within the accepted range for combine testing in North America (ASAE, 1986a).

3.2.4 Experimental Design

Initial test runs led to the design of a randomized block experiment with four replicates, three feed rates (6, 8 and 10 kg of crop per second) and five rotor speeds (700, 800, 900, 1000 and 1100 rpm). Malfunctioning peripheral equipment delayed and halted the experiments, that were carried out during April and May 1987. A major driveline failure concluded the experiments at run number 34, giving a total of two completely replicated blocks plus four odd runs. Each run lasted ten seconds, of which two thirds were used to stabilize the threshing and separating process and the remaining time was used for data aquisition.

3.2.5 Experimental Procedure

The threshing concave clearance was set initially at 56 mm at the inlet side and 8 mm at the outlet side of the concave and held constant throughout the experiments.

The transport vanes inside the rotor housing were mounted in their middle position, giving a vane angle of 22° relative to the tangent of the rotor housing.

The necessary number of crop bundles for each feed rate were taken from the stack, weighed on a platform balance and evenly distributed onto the conveyor belt. The rotor speed was adjusted according to a hand-held contact tachometer (Power Instruments, Tak-ette Model 1707) that was previousely calibrated against a line-synchronized stroboscope (Pioneer DS303). When the rotor speed was correct (within ± 5 rpm), the conveyor belt was started. When two thirds of the material on the conveyor belt had been fed into the experimental unit, the slider underneath the rotor housing was instantly moved to the rear position. Slightly before the last bundle disappeared into the experimental unit, the slider was instantly moved to the forward position. This procedure enabled collection of grain into the bags underneath the concave and the grate for an interval of three to four seconds.

Once the dust had settled, the contents of the bags and the material collected on the bottom of the rotor housing enclosure were cleaned to remove straw and chaff and the grain masses were measured. The loose grain kernels collected in the lid-covered section behind the experimental unit were recovered and their mass determined. A random sample was taken during each run from the straw and separated grain respectively. The moisture content of the grain sample was determined according to standard procedures, ASAE (1986b). Moisture content of the straw was determined using the same procedure.

All data were recorded manually and stored on computer diskettes for later analysis.

3.3 A THREE-DIMENSIONAL ARITHMETIC MODEL TO CALCULATE GRAIN SEPARATION AND GRAIN SEPARATION LOSSES FOR A ROTARY COMBINE

Point separation of grain was approximated by measuring the flow of separated grain through a small cross-sectional area. Mathematical functions were fitted to the point separation data. The mathematical representations then were integrated over the full concave and separating grate area.

Grain separation through the concave and separating grate was assumed to be uniform relative to time. Hence grain separation rate was calculated as the total mass of grain collected divided by the collection time.

The author believes that the future rotary combine will be equipped with an on-board microcomputer. The microcomputer will be collecting grain separation information from sensor-pads, similar to the pads presently used as so-called grain loss sensors. The sensor-pads will be located in a similar X-Y pattern as used in the presented experiment. The micro-computer will perform mathematical operations to calculate not only grain separation, separation losses and relative grain separation losses, but also use the information from these calculations to inform the combine operator about combine effiency. The computer will compare the coefficients obtained when fitting curves to the separation data from the sensor-pads, to coefficients stored in the computer memory during previous, similar conditions. With such information, the computer will be able to recommend, to the operator, changes in combine settings that will increase productivity. Primary parameters to be adjusted will include rotor speed and concave clearance.

The practical suitability of the described computer-system totally depends on the accuracy that the system can achieve. At present, there are no guide-lines or recommendations regarding what error would be allowable or tolerable when predicting grain separation or grain separation losses.

In order to quickly and reliably produce all this information, the micro-computer program must be based on separation functions being versatile, relatively easy to mathematically fit, and with as few coefficients as possible. Thus, these restrictions have been applied to the author's search for suitable mathematical functions representing grain separation along and across the grain seprating elements of a rotary combine.

3.3.1 Mathematical Procedure

Point grain separation around the concave arc and grate arc on a rotary combine can not be represented with a sample taken midways around the arc, similar to the method applied to some 'grain loss monitors' where grain separation through straw walkers is sampled underneath the middle walker(s). Grain separation around the concave and grate arc is non-uniform, as noted by Wang et al. (1984). Neither would an average of three samples around the arc be representative, since the separation around the arc is non-linear (Wang et al. 1984).

By visually looking at the sampled point grain separation data (Table 6.1) a second degree polynomial equation appeared to adequately describe point grain separation around the concave arc and the grate arc. The three coefficients generated for each curve-fit by that equation would be of use in a study of grain separation behaviour, as noted earlier. However, such study is beyond the scope of this work.

Hence, the function chosen to represent point grain separation around the concave arcs and grate arc is

$$S_P = A + By + Cy^2 \qquad (3.3)$$

where: S_P = point grain separation, kg m^{-2} s^{-1}

A, B & C = coefficients determining shape of curvature

y = coordinate around concave arc or grate arc, °

This function will represent three distinct grain separation patterns, depending on the sign and/or magnitude of the coefficients B and C;

1. an initial peak separation decaying convex along the concave or grate arc (B is negative, C is negative),
2. an initial peak separation decaying concave along the concave or grate arc (B is negative, C is positive), and

3. a peak separation occurring somewhere in the mid-region of the concave or grate arc (B is negative, C is negative).

The coefficient A remains positive for all three patterns. Refer to Figure 3.3 for a graphical explanation.

Average point separation across a segment around the concave and separating grate is then calculated by integrating equation 3.3 around the entire concave or grate arc length and dividing by the respective arc length. Hence,

$$\bar{S}_{SEG} = [(Ay_u + (B/2)y_u^2 + (C/3)y_u^3) - (Ay_l + (B/2)y_l^2 + (C/3)y_l^3)] / (y_u - y_l) \qquad (3.4)$$

where: $\bar{S}_{SEG}$ = average point separation of grain across a segment around the concave and separating grate, kg m^{-2} s^{-1}

y_u & y_l = coordinates for the ends of the concave arc or grate arc, °

A, B & C = coefficients determining the shape of curvature of the separation function

The data from the three ducts on each of the five rearmost segments were used to calculate values of A, B, and C for each segment according to equation 3.3. Equation 3.4 was then used to calculate average point separation for each segment.

Average point separation of grain across the segment where the first (single) duct was located had to be estimated differently. Based on data presented by Wang (1984), the author believed that the first (single) measurement would be an over-estimate of the average point separation of grain across this segment. Thus, a trial-and-error approach was used to find what fraction of the measured separation should be used in the model to give the highest number of computed values within the least error range. Best results were obtained when taking 80 % of the measured separation as average point separation. Refer to Figure 3.4 for a graphical explanation.

The average point separation of grain across the respective segments around the concave and separating grate were then fitted (using an APL-based non-linear regression program, Appendix B) with an equation as follows:

$$S_{AAX} = D(x-E)^2 e^{-Fx} \tag{3.5}$$

where: S_{AAX} = average point separation of grain along the rotor axis, kg m^{-2} s^{-1}

D, E & F = coefficients determining the shape of curvature of the separation function

x = axial distance from the beginning of the concave, m

e = the base of the natural logarithms

This function was chosen because it peaks sharply near the entrance of the rotor, and then decays exponentially with the distance along the rotor axis, thus closely following the point separation data obtained by the author as well as grain separation data obtained by researchers Wacker (1985), Lo et al. (1978), Boyce et al. (1974) and Reed et al. (1970).

To obtain cumulative grain separation per unit width of the concave and separating grate for an axial interval, equation 3.5 is integrated with respect to axial distance along the concave and separating grate:

$$S_{CW} = \left[(-x^2-(2/F)x-2/F^2+2Ex+2E/F-E^2)(D/F)e^{-Fx} \right]_{d_1}^{d_2} \tag{3.6}$$

where: S_{CW} = cumulative grain separation per unit width for the interval d_1 to d_2, kg m^{-1} s^{-1}

D, E & F = coefficients determining the shape of curvature of the separation function

d_1 & d_2 = lower respective upper end of the interval to be integrated, m

By multiplying equation 3.6 by the circumferential width of the separating area, total grain separated through the area can be calculated:

$$S_C = S_{CW} W_A \tag{3.7}$$

where: S_C = total mass of grain separated through the area of the interval, kg s^{-1}

S_{CW} = cumulative grain separation per unit width for the interval, kg m^{-1} s^{-1}

W_A = width of the separating area, m

Hence, the mass of grain separated per unit time through the concave area of the experimental unit is given by multiplying the concave circumferential width by equation 3.6 for the interval from zero to the end of the concave/beginning of the separating grate.

Separation through the separating grate is calculated using the grate circumferential width and the interval from the end of the concave/beginning of the separating grate to the end of the separating grate. Separation losses are calculated by using the separating grate width and the interval from the end of the separating grate to infinity. Refer to Figure 3.5 for a graphical explanation.

All calculations were carried out by a personal computer running software written in APL (Appendix B).

3.4 RESULTS

3.4.1 Errors and Omissions

Due to a computer disk error, the measured results from run no. 4 were not available for further analysis. A manual error made the measured separation losses for run no. 23 too large.

The reader should bear in mind that the so-called measured grain separation and measured grain separation losses are true values only if grain separation is uniform relative to time. The effect of non-uniform grain separation, in time, is unknown.

3.4.2 Curve Fitting of the Average Point Separation Data Along the Rotor Axis

The standard deviation, s, of the fit, is a standard measurement used to describe how well an equation is fitted to data (Steel and Torrie, 1980). The standard deviation is calculated according to Steel and Torrie, (1980) as:

$$s = \sqrt{\frac{\Sigma(Y - \hat{Y})^2}{n - 2}} \tag{3.8}$$

where: s = standard deviation of the fit

Y = observed dependent datum

$\hat{Y}$ = estimated dependent datum

n = number of observations

The standard deviation, s, of the fit for equation 3.5 is given in Table 3.1, column 4, for the individual runs.

The coefficients A, B and C (equation 3.3) and the coefficients D, E and F (equation 3.5) are listed in Appendix B, Table 7.1 repective Table 7.2.

3.4.3 Computed Grain Separation

The relative deviations of computed grain separation from measured grain separation are plotted versus measured grain separation in Figure 3.6. The linear correlation coefficient, r, for computed and measured grain separation is r = 0.83. The coefficient of variation, CV, of the ratio computed/measured grain separation is 13 %. Grain separation was computed within ±15 % of the measured separation for 26 runs out of a total of 33 valid runs.

3.4.4 Computed Grain Separation Loss

Grain separation losses calculated by the computer model were consistently too low (Figure 3.7). By using linear regression techniques, the computer calculated losses were adjusted as follows.

Adjusted computer calculated grain separation loss = 0.02 + 1.33 S_C (3.8)

where: S_C = total mass of grain separated through the area of the interval (here: the interval from the end of the separating grate to infinity), kg s^{-1}

The loss from run no. 5 was not used in the regression, due to the large deviation between this loss and the data from the other runs. The square of the linear correlation coefficient achieved by the least square fit is r^2 = 0.93, standard deviation for the fit, s = 0.024 kg s^{-1}.

The relative deviations of adjusted computer calculated losses from measured grain separation losses are plotted versus measured separation losses in Figure 3.8. Adjusted computer calculated and measured losses have a r = 0.88 and their ratio a CV = 36 %. Grain separation losses were computed within ±15 % of measured grain separation losses for 10 runs out of a total of 32 valid runs.

Adjusting the computed grain separation losses by applying a 'scale factor' to them might appear unorthodox. However, this method shows that there in fact is a linear correlation between computer calculated and measured grain separation over the grain separation (capacity) range used. The method also facilitates a meaningful comparison of computed relative grain separation losses and measured relative grain separation losses, as follows.

3.4.5 Computed Relative Grain Separation Loss

Relative grain separation loss is obtained when grain separation loss is divided by grain separation. This loss, on a percentage base, is the loss a farmer would be most interested in. The relative deviations of adjusted computed relative losses from measured relative grain separation losses are plotted in Figure 3.9. Relative computed grain separation losses and relative measured grain separation losses have $r = 0.83$ and their ratio a $CV = 36$ %. Relative grain separation losses were computed within ± 15 % of relative measured grain separation losses for 12 runs out of a total of 32 valid runs.

3.5 DISCUSSION

3.5.1 Mathematical Representation of the Average Point Separation Along the Rotor Axis

The equation chosen to represent average point separation along the rotor axis (equation 3.5) has not previously been cited in literature seen by the author. However, the exponentially decaying tail produced by the equation agrees with previously presented grain separation characteristics of rotary combines, threshing cylinders and straw walkers. Furthermore, the initially increasing grain separation suggested by the equation is similar to data presented by researchers Wacker (1985), Lo et al. (1978), Boyce et al. (1974) and Reed et al. (1970). The theoretical approach by Huynh et al. (1982), also supports an initially increasing separation.

A comparison can be made between Equation 3.5 and Equation 3.1. The latter equation was used to describe grain separation for a rotary combine (Wang 1984), but was also used in a similar format by Reed et al. (1970) to describe separation through straw walkers. The first coefficient (S_0) in Equation 3.1 does not allow for an initial increase in grain separation with axial distance (x) from the beginning of the concave. By replacing that coefficient with a function depending on x, such as $D(x-E)^2$ in Equation 3.5, initial grain separation along the rotor axis is better described.

In some cases (Figure 3.10a) the modeled grain separation is initially high and rapidly decreasing to nil, then increasing and finally exponentially decaying. Such initial grain separation will not be achieved by any grain separating mechanism, but is merely a result of extending Equation 3.5 beyond experimental data. The discrepancy did not significantly influence the computed grain separation.

Since grain separation depends on preceding threshing, it follows that when threshing is insufficient or inefficient in the first part of a rotary threshing mechanism, initial grain separation has to be low or delayed. This can clearly be seen in the initial part of the modeled grain separation computed at low feed rates and high rotor speeds (Figure 3.10a). Here, the density of the straw mat between the rotor and the rotor cage might be too low to allow early threshing by efficient rubbing of the grain heads. However, prethreshing by the table auger and intake elevator might offset poor initial threshing, as noted by Wacker (1985). This might explain the initially high or initial peak grain separation found for a rotary combine by Wang et al. (1984).

The author has two theories that would explain why the computer calculated grain separation losses consistently were underestimated. The first theory is that there is a discontinuity in the separating pattern between the end of the concave and the beginning of the sparating grate. The second theory involves the curve-fitting computer software, that fitted Equation 3.5 by minimizing the unweighted residual sum-of-squares. This method assignes little consideration to the normally very low point separation levels at the rear end of the separating grate, that significantly influence the separation losses.

3.5.2 Monitoring Grain Loss

Some more or less successful grain loss monitoring systems have been developed throughout recent years. All commercially available models the author is aware of treat separation across the width of the concave, straw walker, sieves, concave arc and separating grate arc as being uniform. This is not a valid assumption, however. The non-uniform separation across the concave arc and separating grate arc presented here agrees with data on separation through straw walkers presented by Reed et al. (1970), and separation through the concave arc on a rotary combine presented by Wang et al (1984). A three-dimensional approach to calculate grain separation losses, similar to the method suggested here, was proven feasible by Liu and Leonard (1989). They used Equation 3.3 and Equation 3.4 to calculate average point separation of grain across three segments around the separating grate, but then used a simple exponentially decaying equation to estimate separation losses.

3.6 CONCLUSIONS

Two mathematical functions with three coefficients each can be used to describe point grain separation along and across the concave and separating grate of a rotary combine.

A three-dimensional arithmetic model, based on integration of the two mathematical separation functions, can be used to calculate grain separation and separation losses for a rotary combine. The arithmetic model was tested with experimental data, and estimated most computed separation values within ± 20 % of the measured values. The model under-estimated the grain losses in most runs by 20 % to 85 %, with the highest percentage obtained for the runs with the lowest measured losses.

By applying size-restrictions to the cofficients in the non-linear equation, (equation 3.5), the performance of the three-dimensional arithmetic model might improve. The small set of data presented here, and the large variation within that data, deams a further refinement of the non-linear equation meaningless. Financial restraints of the the author's research budget prevented the extension of the research beyond run number 34, where the drive-line of the experimental unit failed.

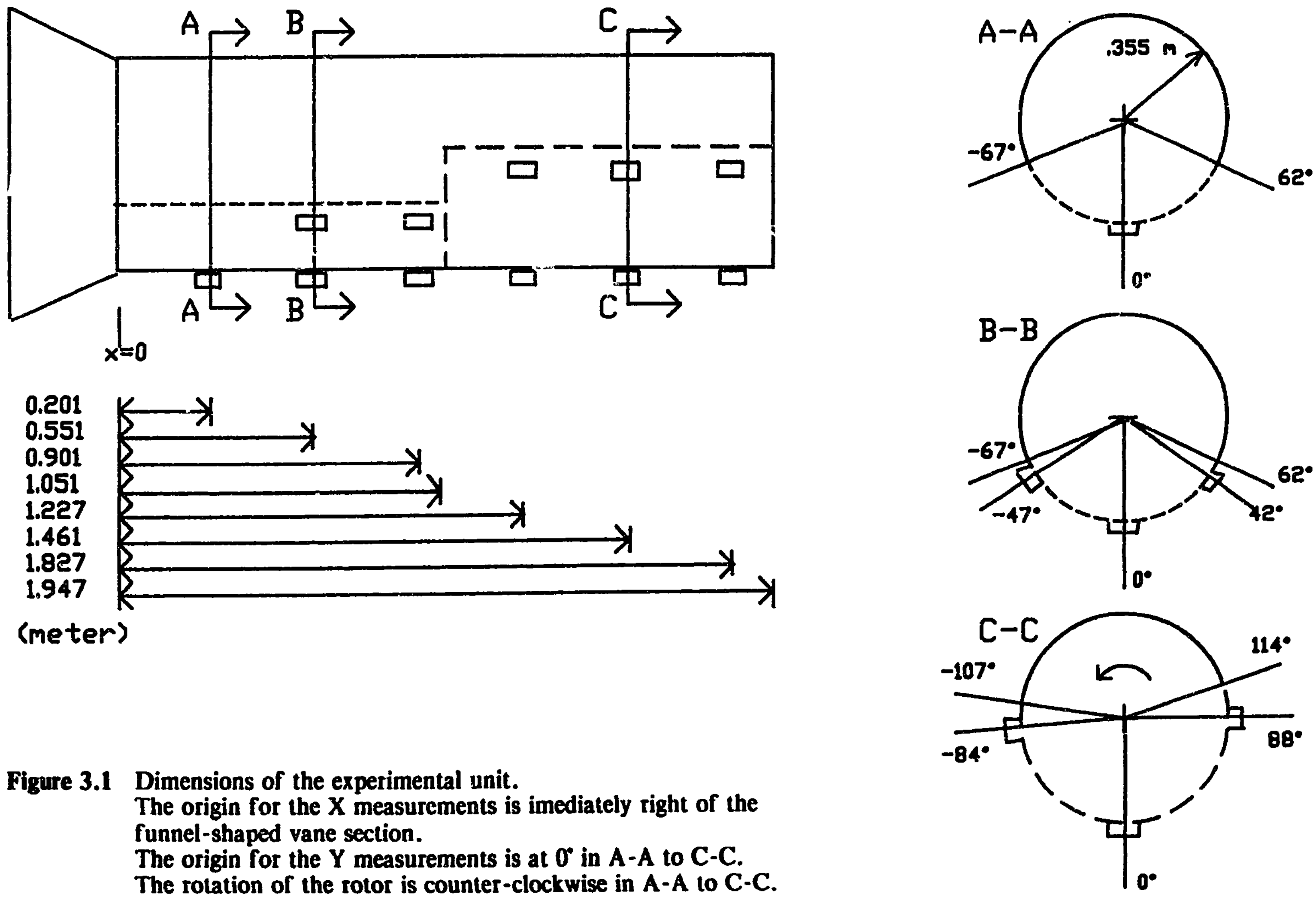

Figure 3.1 Dimensions of the experimental unit.
The origin for the X measurements is imediately right of the funnel-shaped vane section.
The origin for the Y measurements is at 0° in A-A to C-C.
The rotation of the rotor is counter-clockwise in A-A to C-C.

(a)

(b)

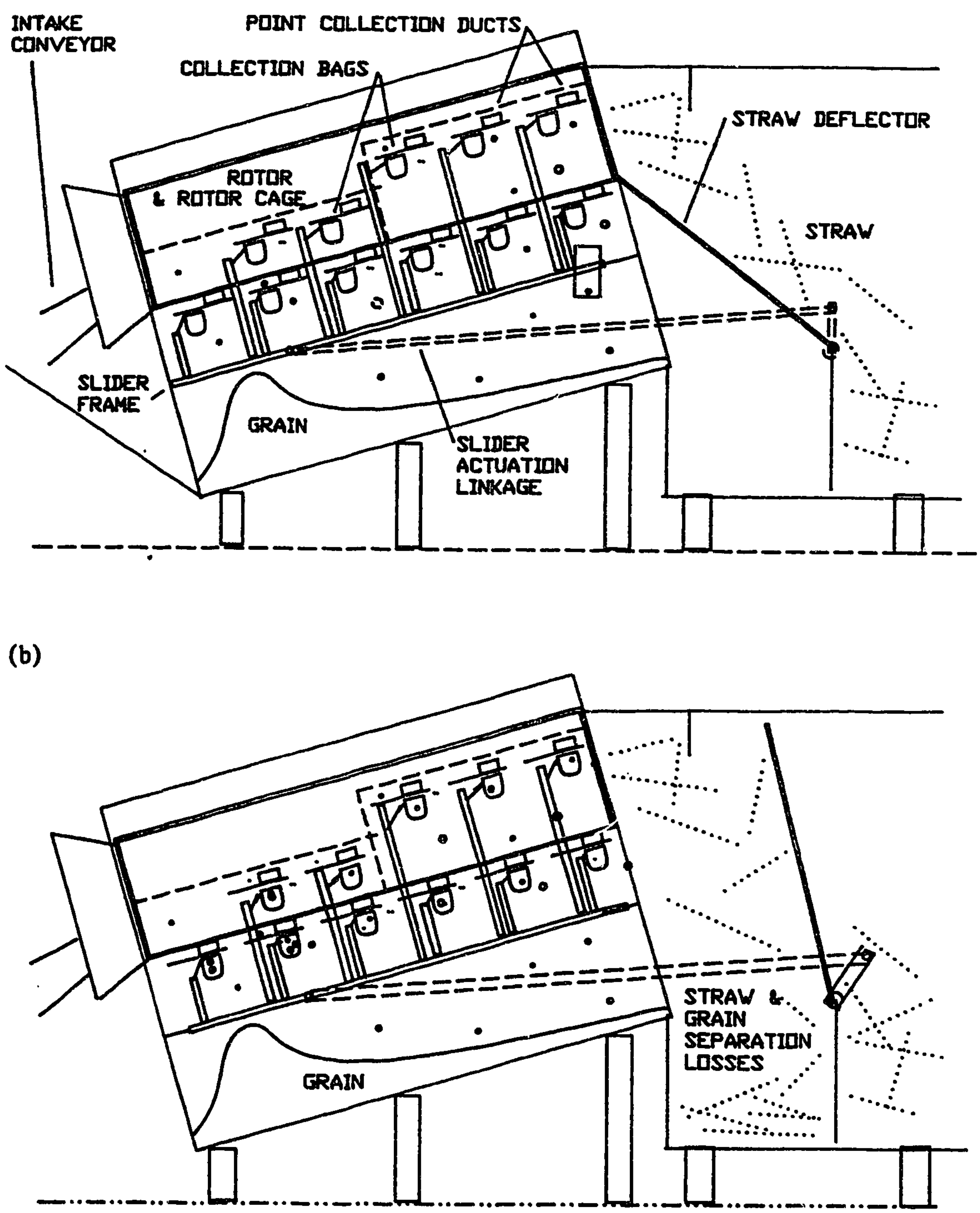

Figure 3.2 Side view of the experimental unit.
(a) Initial part of run, separation is stabilizing, slider in front position, point separation is not measured.
(b) Final part of run, slider in rear position, point separation and grain separation losses are measured.

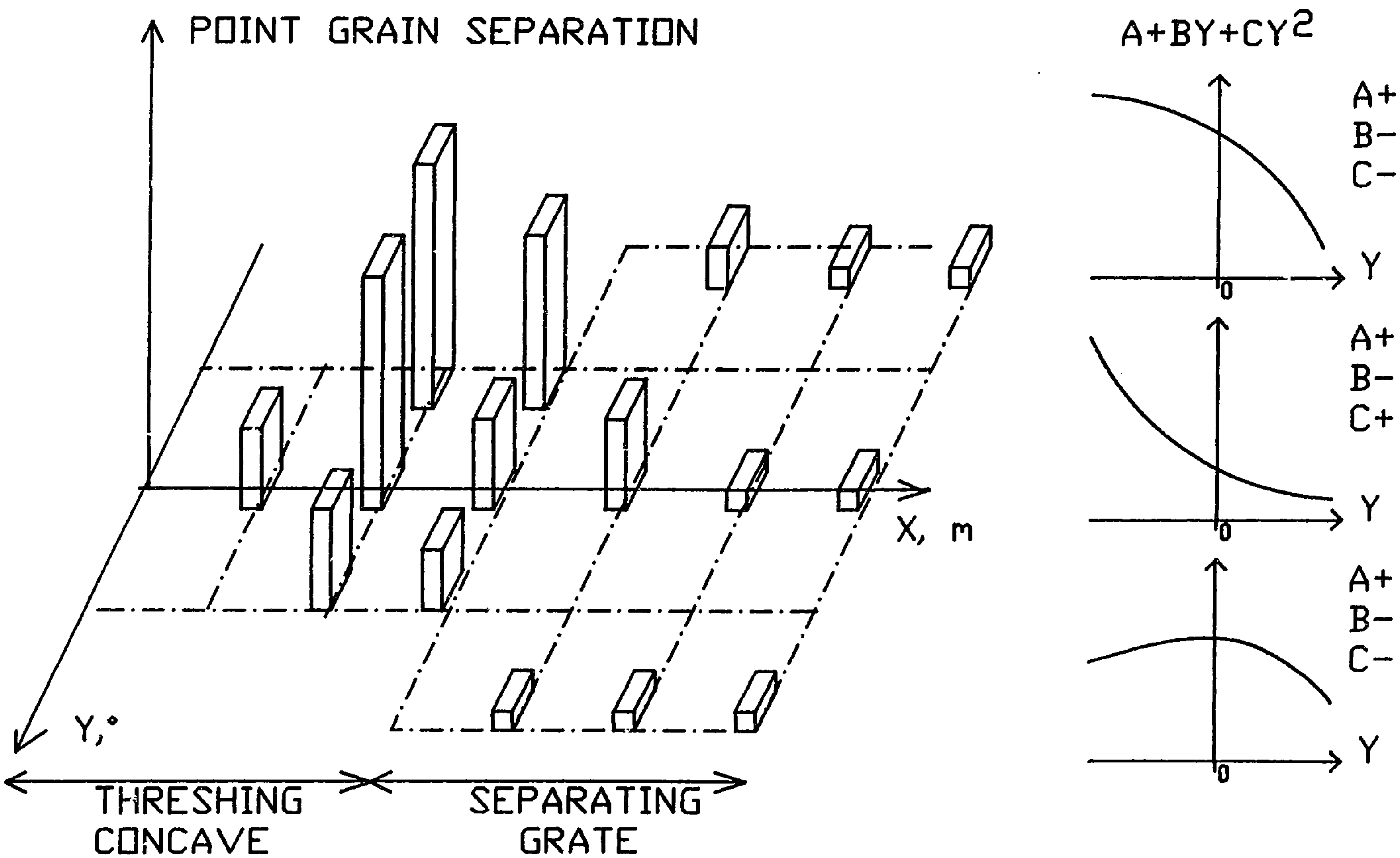

Figure 3.3 Graphical explanation of the three-dimensional arithmetic model. Step 1.

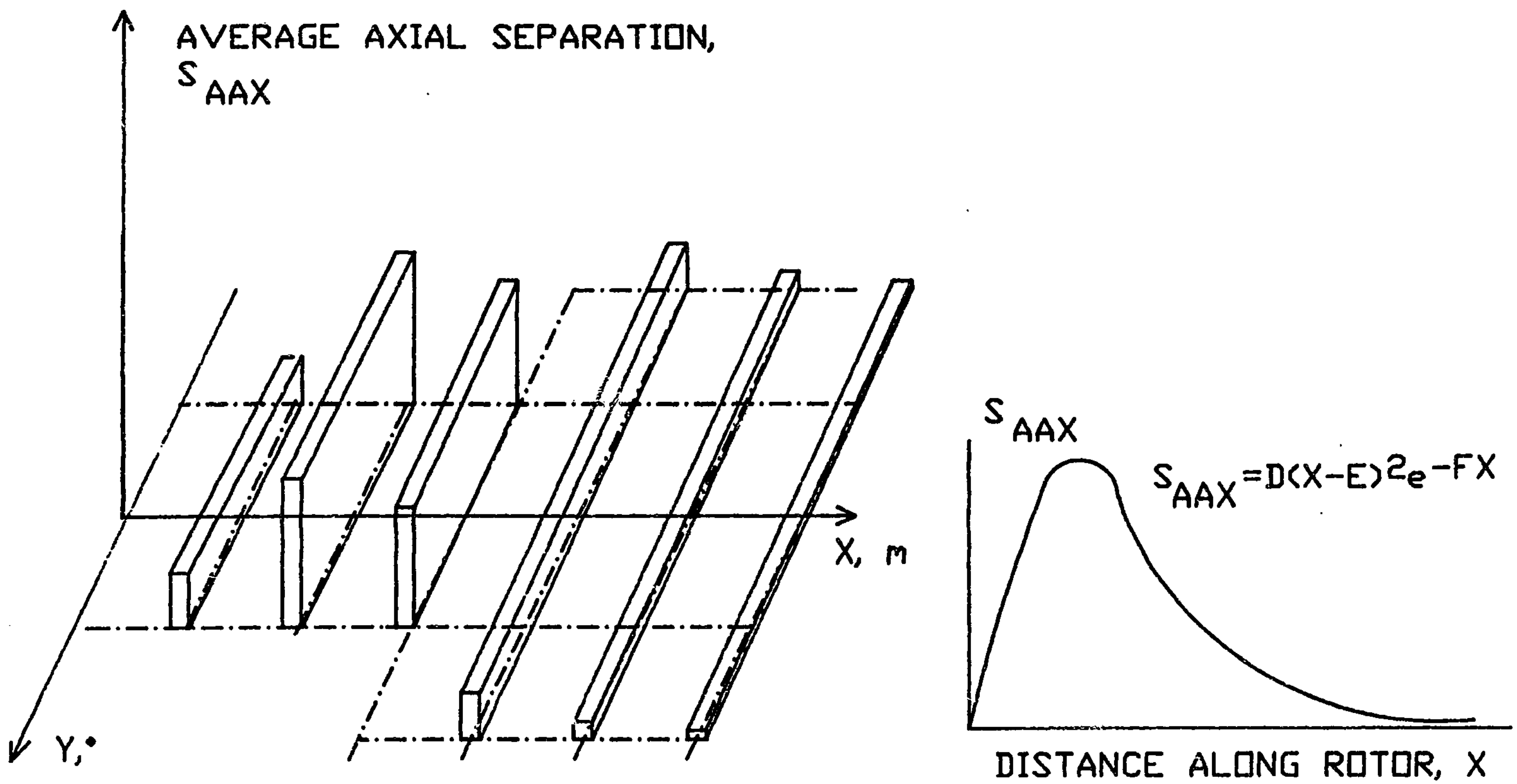

Figure 3.4 Graphical explanation of the three-dimensional arithmetic model. Step 2.

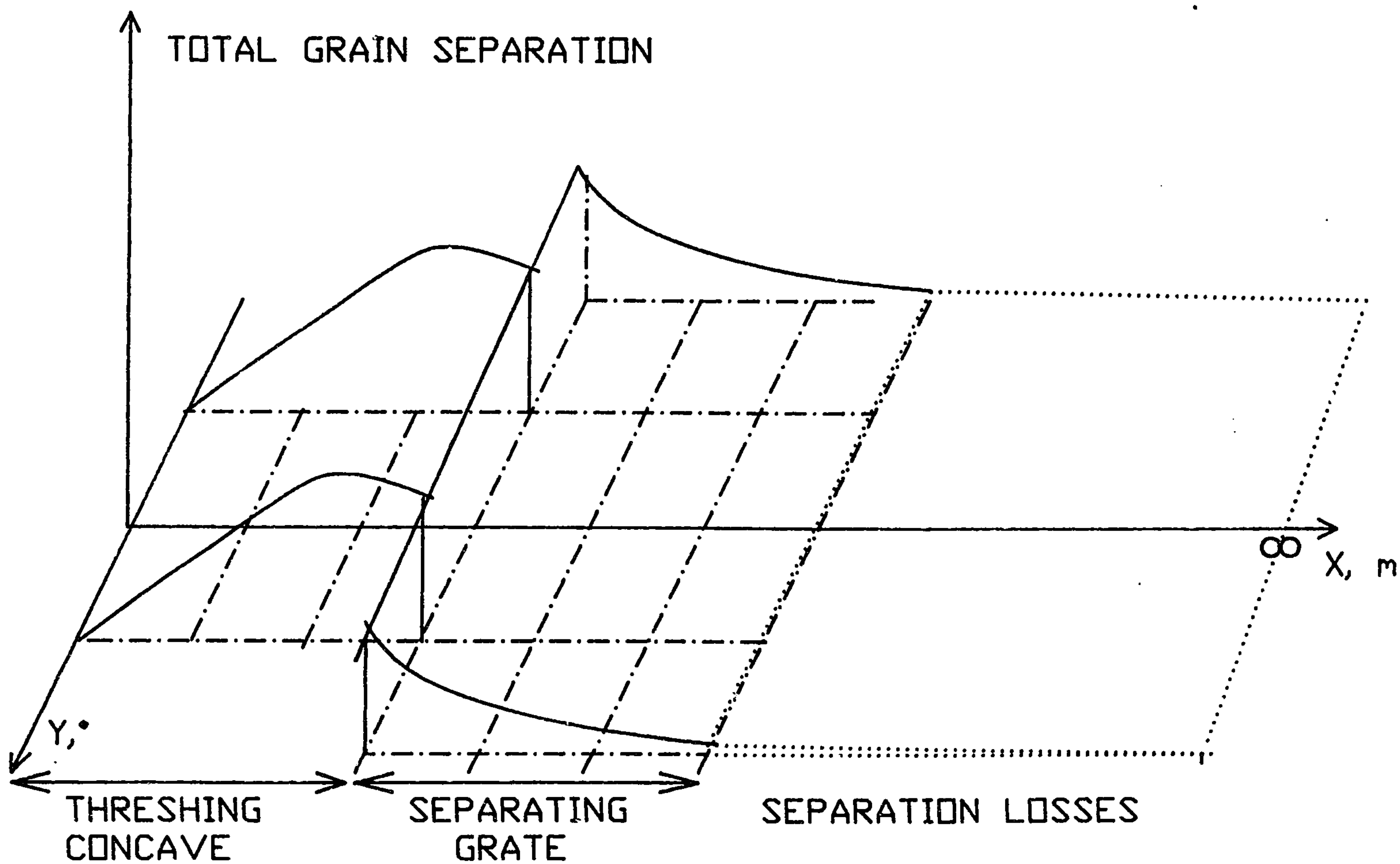

Figure 3.5 Graphical explanation of the three-dimensional arithmetic model. Step 3.

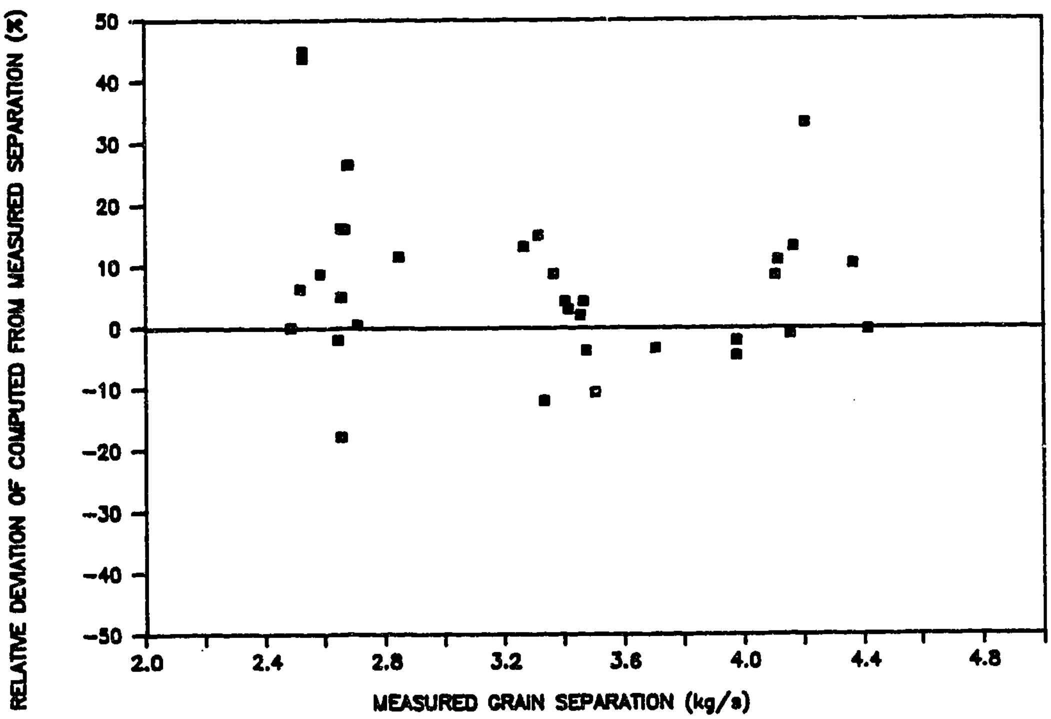

Figure 3.6 The relative deviations of computed grain separation from measured grain separation.

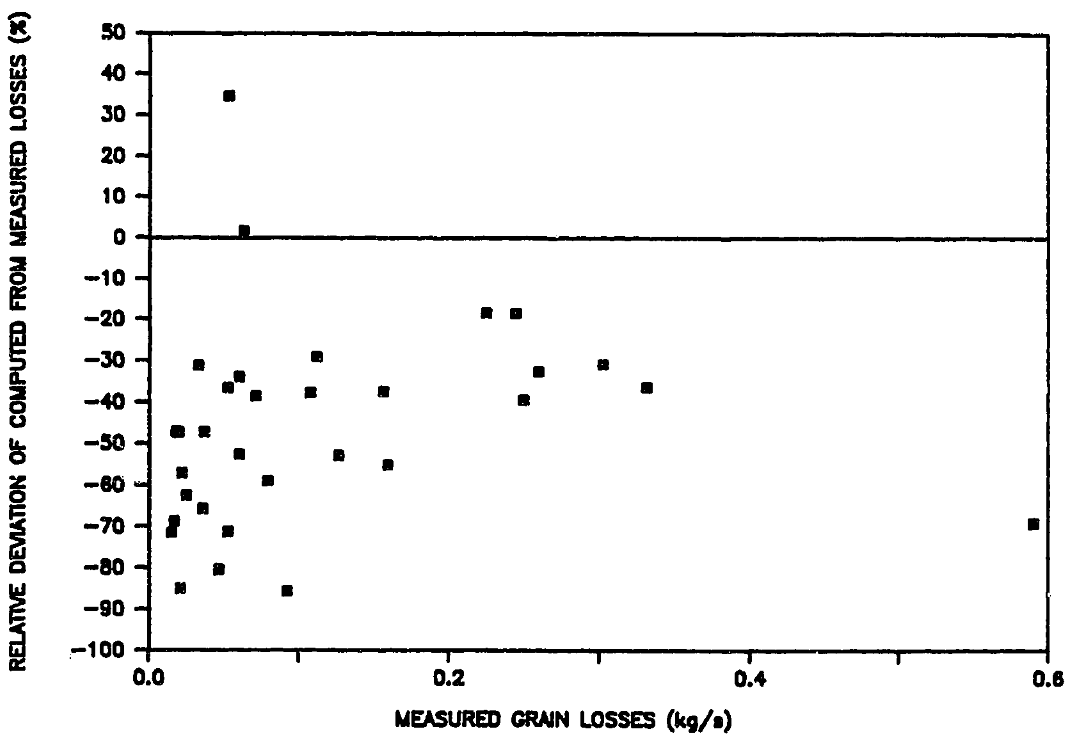

Figure 3.7 The relative deviations of computed grain separation losses from measured grain separation losses.

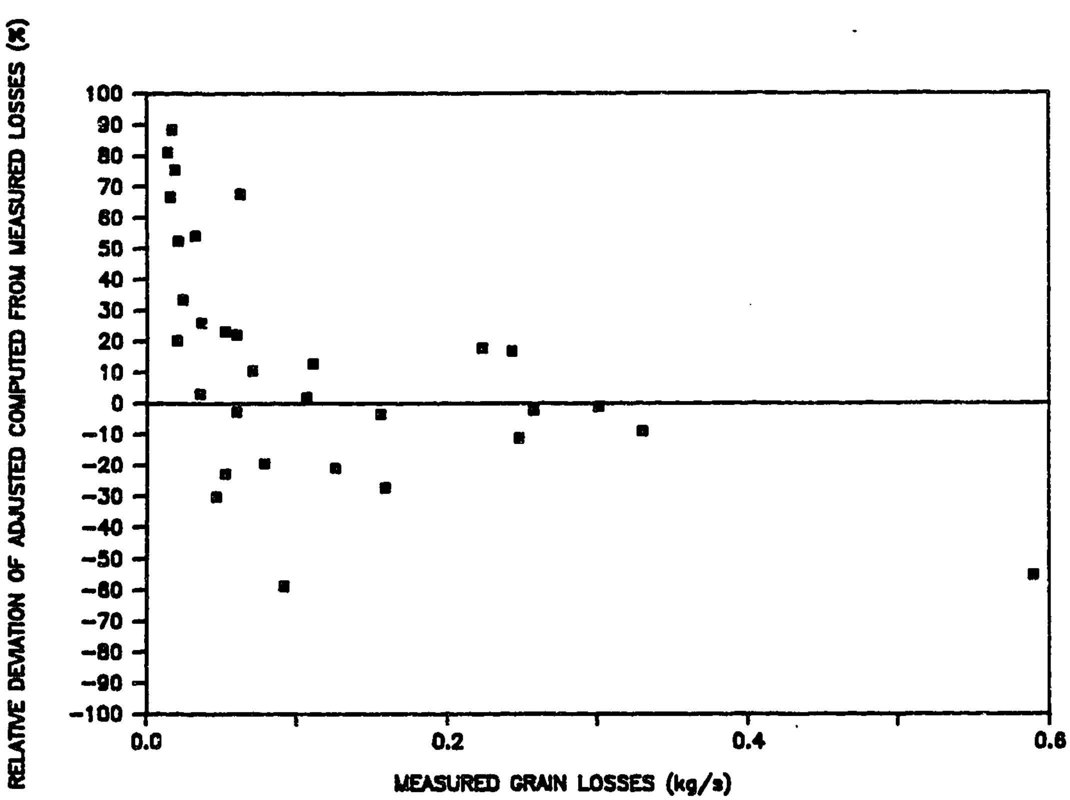

Figure 3.8 The relative deviations of adjusted computed grain separation losses from measured grain separation losses.

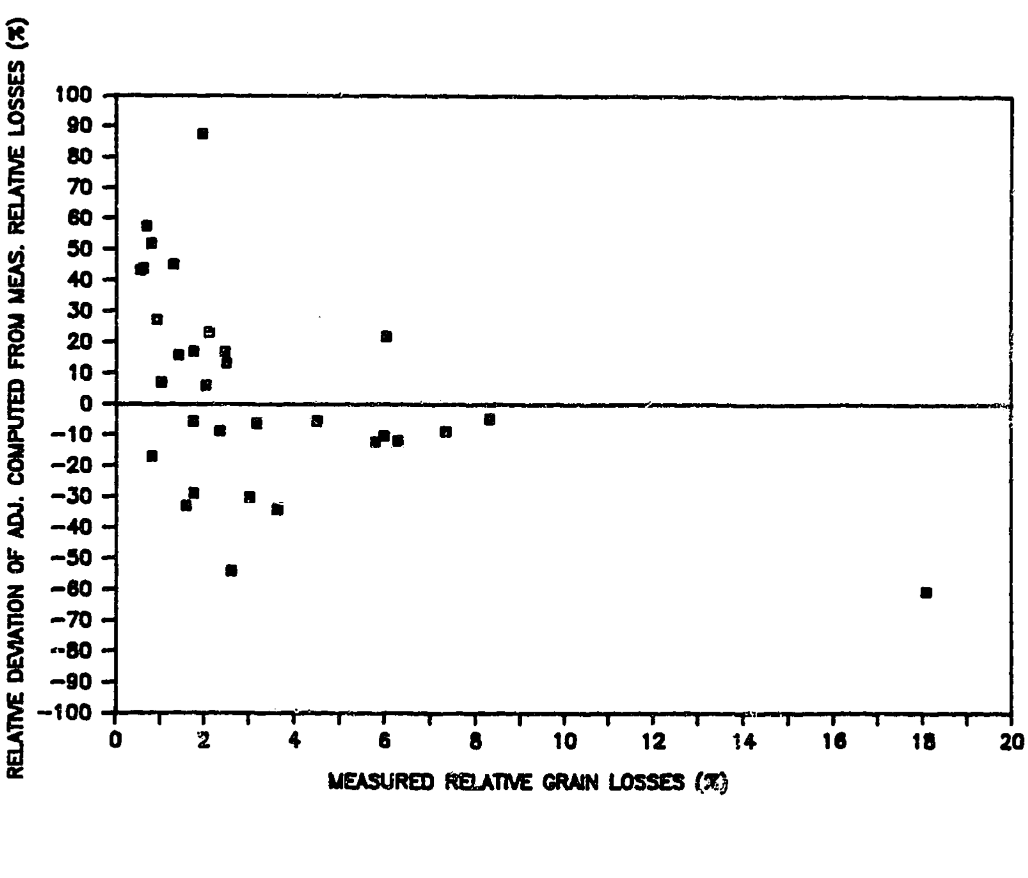

Figure 3.9 The relative deviations of the ratios adjusted computed relative grain separation loss from the ratios measured relative grain separation loss.

(a)

(b)

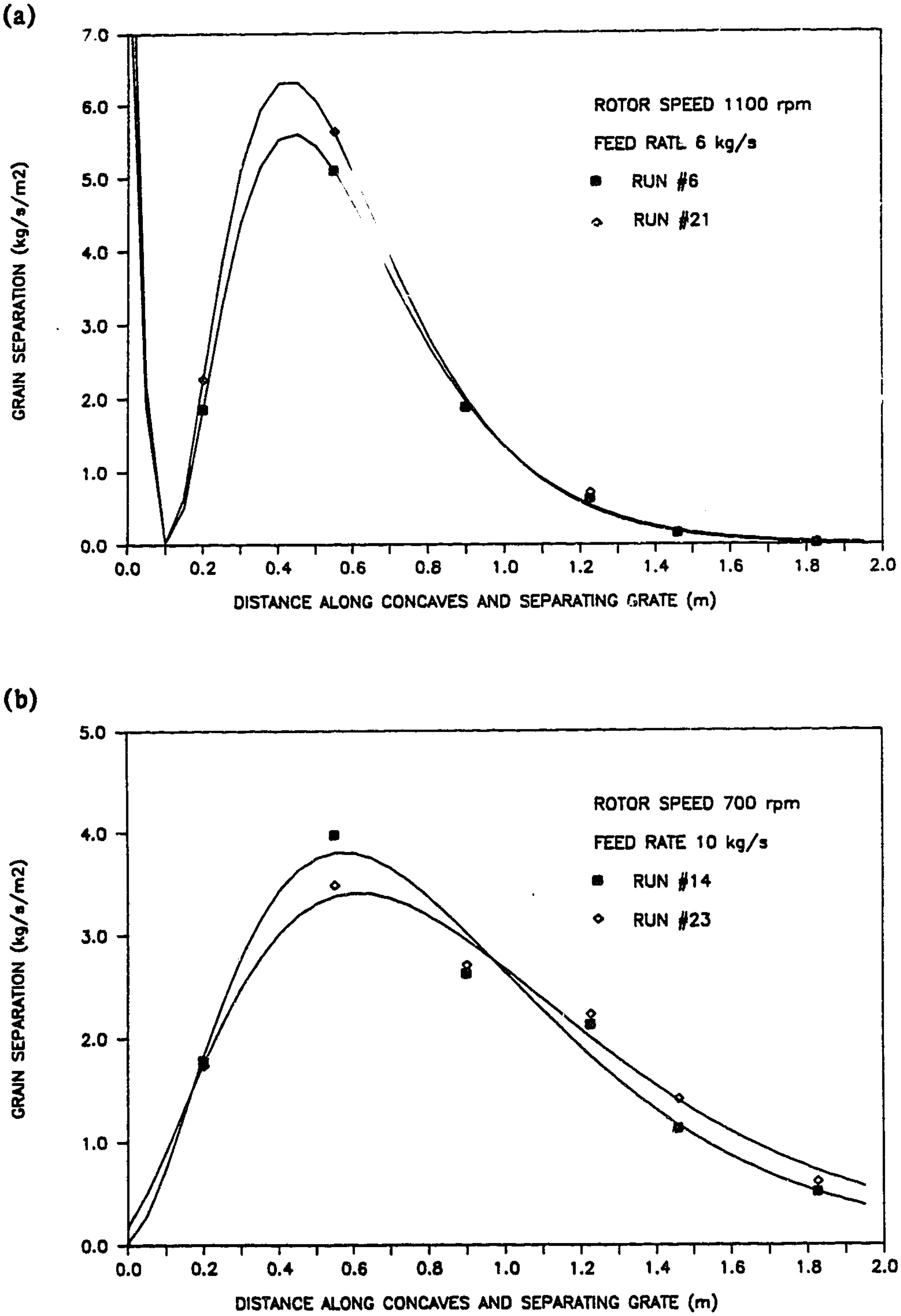

Figure 3.10 Point separation of grain along the concave and separating grate. Symbols represent the average point separation across a segment along the concave and separating grate. Lines represent average point separation of grain along the rotor axis, fitted to the average point separation for each segment.
(a) rotor speed 1100 rpm, feed rate 6 kg/s
(b) rotor speed 700 rpm, feed rate 10 kg/s

Table 3.1 Measured and Computer Modeled Data for the Individual Experiments

Run #	Rotor speed	Feed rate, crop	s of regression*	Grain separation** computed	Grain separation** measured	Grain separation loss adjusted computed	Grain separation loss measured
	(rpm)	(kgs^{-1})	($kgm^{-2}s^{-1}$)	(kgs^{-1})	(kgs^{-1})	(kgs^{-1})	(kgs^{-1})
10	700	6	0.180	3.08	2.65	0.113	0.052
29	700	6	0.059	2.59	2.64	0.320	0.046
34	700	6	0.199	2.48	2.48	0.064	0.052
5	700	8	0.168	3.69	3.26	0.262	0.589
30	700	8	0.089	2.93	3.33	0.063	0.078
14	700	10	0.307	3.78	3.97	0.299	0.330
23	700	10	0.209	3.88	3.97	0.508	<0.506
7	800	6	0.169	3.62	2.52	0.104	0.062
28	800	6	0.151	2.80	2.58	0.045	0.036
31	800	6	0.114	2.67	2.51	0.049	0.032
1	800	8	0.125	3.57	3.70	0.262	0.223
27	800	8	0.115	3.52	3.45	0.149	0.155
13	800	10	0.144	4.44	4.10	0.297	0.301
24	800	10	0.328	4.10	4.15	0.220	0.248
11	900	6	0.076	3.65	2.52	0.024	0.020
25	900	6	0.013	2.18	2.65	0.032	0.017
15	900	8	0.048	3.65	3.36	0.108	0.106
16	900	8	0.174	3.54	3.40	0.072	0.059
12	900	10	0.120	5.59	4.20	0.283	0.243
18	900	10	0.093	4.55	4.11	0.251	0.258
2	1000	6	0.059	2.71	2.70	0.032	0.021
17	1000	6	0.024	2.78	2.65	0.032	0.024
33	1000	6	0.057	3.17	2.84	0.033	0.019
9	1000	8	0.036	3.51	3.41	0.057	0.059
26	1000	8	0.039	3.80	3.31	0.040	0.052
32	1000	8	0.081	3.33	3.47	0.036	0.035
4	1000	10	n/a	n/a	n/a	n/a	n/a
19	1000	10	0.215	4.39	4.41	0.123	0.110
6	1100	6	0.071	3.08	2.66	0.027	0.016
21	1100	6	0.132	3.37	2.67	0.025	0.014
3	1100	8	0.189	3.13	3.50	0.037	0.091
20	1100	8	0.194	3.60	3.46	0.077	0.070
8	1100	10	0.054	4.70	4.16	0.098	0.125
22	1100	10	0.019	4.81	4.36	0.114	0.158

* Standard deviation for the non-linear regression of the average point separation of each segment, in direction parallel to the rotor axis.

** Grain separated through the concave and separating grate.

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4. POWER REQUIREMENT FOR THRESHING AND SEPARATION IN A ROTARY COMBINE

A version of this paper was presented as ASAE Paper No. PNR 88-204 at the ASAE Pacific Northwest Regional meeting in Pendleton, Oregon, USA, September 28-30, 1988.

4.1 INTRODUCTION

New combine harvester models with increased capacity have been developed throughout the years. With this increase in capacity, an increase in engine power for these combines has followed.

The specific fuel consumption cost (or cost of fuel per processed unit mass of grain) is very low, typically less than one percent of the value of the processed grain. This cost is affected insignificantly by engine size, and is usually of little concern for farmers.

Of more concern, however, is the high initial cost of the engine of today's high capacity combine. Furthermore, since a typical combine is only used some 100 hours per year, the hourly cost of the combine engine alone is excessive.

A better understanding of the power transmission through the combine would possibly lead to more energy-efficient design and more efficient use of the combine harvester.

4.1.1 Objectives

The power required to drive the rotor in a rotary combine might be divided into two parts:

1. the required idle power (no throughput, no load power), and
2. the required net power (power for threshing and separation, idle power excluded).

This paper presents research undertaken to describe idle power and net power in terms of rotor speed and material-other-than-grain (MOG) feed rate.

4.1.2 Literature Review

The results of most previous combine energy consumption measurements available are presented in test reports published in North America (PAMI, 1979) and Europe (SMP, 1982). Different crops, moisture contents, combine designs and other variables make comparisons of test reports difficult. In general, however, rotary combines have a 50 to 100 % higher specific fuel consumption than cylinder/straw walker type combines.

Effects of rotor/cylinder speed on power requirement

Wacker (1985), using an experimental rotary combine, found idle power to be proportional to the cube of the tangential velocity at the periphery of the rotor. Specific energy consumptions for threshing and separating both winter and summer wheat showed a small linear increase with rotor tangential velocity.

Arnold and Lake (1964) found a linear increase in power requirement with an increase in tangential velocity for a threshing cylinder.

Effects of feed rate on power requirement

Wacker (1985) found specific energy consumption to be independent of crop (winter and spring wheat, spring barley) at low MOG feed rates. At higher feed rates, the specific energy consumption increased at different rates for the different crops, but all increases were linearly proportional to the MOG feed rate.

PAMI (1987), in a test of a pull-type combine equipped with a threshing cylinder and two separating rotors, reported power requirement for the unit to increase linearly with an increase in MOG feed rate.

Hill and Frehlich (1985) noted that the power requirement for a cylinder/straw walker combine depends mostly on the MOG feed rate. Fuel consumption closely followed the changes in MOG feed rate.

Arnold and Lake (1964) found power requirement to increase linearly with an increase in MOG feed rate if the crop was fed to the cylinder at a constant stream thickness. When the crop was fed to the cylinder at a constant stream speed, the increase in power requirement was exponentially dependent on the MOG feed rate.

Effects of torque and rotor/cylinder speed on power

Results presented by Wacker (1985) indicated a high variation, with time, in power requirements for a rotary combine. The variation depended mostly on the torque necessary to turn the rotor. The frequency of the torque oscillations seemed to be in the range of 0.5

to 1 Hz at a rotor speed of 1000 rpm. Variations in rotor speed were small and only slightly influenced the power requirement. The torque necessary to turn the rotor was reported to have a 0.6 s phase lag relative to the power absorbed by the intake conveyor.

The changes in direction and velocity of the crop, when in transition from the vane section to the threshing section of the rotor, were suggested to cause uneven material transportation and, hence, the uneven torque demand.

Arnold and Lake (1964) found similar variations in torque necessary to drive a threshing cylinder. Torque variations were found to increase with MOG feed rate. Variations were less marked when the MOG feed rate was increased by an increased crop stream speed, than when the MOG feed rate was increased by an increased stream thickness.

4.2 MATERIALS AND METHODS

4.2.1 Experimental Unit

An experimental unit was fabricated using the rotor (complete with housing, concaves, variable speed drive and intake elevator) from a 1978, model 1460, International Harvester rotary combine. The rotor and assemblies were mounted into a steel structure totally enclosed in plywood. This enabled collection of the material separated through the concave and the separating grate. A plywood box was attached to the discharge end of the experimental unit to collect the residual material.

The rotor assembly was driven from the 1000 rpm PTO of a 130 kW diesel tractor. An emergency stop for the rotor was obtained by connecting an solenoid fuel valve on the tractor to emergency stop switches on the experimental unit.

A torque meter (Lebow Associates, model no. 1105-10K) with a built-in tachometer was mounted in the drive train of the experimental unit (Figure 4.1). The electrical signals from the torque meter (a Wheatstone bridge circuit of strain gauges mounted on the torque meter shaft) and the tachometer (a magnetic pick-up) were fed to signal conditioners (Honeywell Accudata 105 and Accudata 104DC for the torque-meter respective ITT Barton

Model [illegible] for the tachometer). The signal conditioners were interfaced via a data aquisition board (MetraByte Dascon-16) to a personal computer (IBM PC/XT). The signals were sampled by the computer 100 times per second, and the data were stored on diskettes for later analysis.

The crop to be threshed was fed, heads first, by a 15 m long and 0.9 m wide conveyor belt assembly straight into the intake elevator of the experimental unit. The canvas conveyor belt was driven by a three phase, 3.7 kW asynchronous motor. The conveying speed was 1.0 m s^{-1}

4.2.2 Experimental Crop

Spring wheat (**Katepwa**), selected for relative easiness to thresh, was harvested with a binder in September 1986, stacked and protected from the environment by tarpaulins. Each bundle had an average mass of 4.0 kg as used. The average MOG/grain ratio was 1.2 with a standard deviation of 0.063. The moisture contents (wet basis), as used, of the straw and grain were in the range 7 to 13 % and 11 to 14 % respectively with average moisture contents 10.6 % and 12.7 % respectively. These parameters are representative of the conditions farmers experience in their fields during the grain harvesting season. They are all within the accepted range for combine testing in North America (ASAE, 1986a).

4.2.3 Experimental Design

Initial test runs led to the design of a randomized block experiment with four replicates, three feed rates (6, 8 and 10 kg of crop per second) and five rotor speeds (700, 800, 900, 1000 and 1100 rpm). A major driveline failure concluded the experiments at run number 34, giving a total of two completely replicated blocks plus four odd runs. Each run lasted ten seconds.

4.2.4 Experimental Procedure

Estimates of electrical noise sampled by the computer were obtained by sampling the torque and speed signals with all peripheral electrical equipment running, but with the PTO shaft disconnected from the tractor. The noise obtained from the torque meter (average and peak noise reached 0.5 % respective 3 % of the voltage read by the data aquisition board at full calibration load) then was averaged and subtracted from all calibration and experimental torque data. The signal-conditioner used with the tachometer had a built-in filter that offset the incoming noise. Hence, the outgoing signal was used unchanged.

The torque meter and the tachometer were calibrated by increasing the torque and the speed repectively in steps. When the maximum values (1012 Nm and 1037 rpm) were reached, torque and speed were decreased in steps. For calibration refer to Appendix A, Figure 6.1 (torque) and Figure 6.2 (speed). The torque was applied as combinations of weights hung at the end of a one-meter long arm attached perpendicular to the input shaft of the torque meter while the output shaft was held fixed. The speed was measured with a line-synchronized stroboscope (Pioneer, model DS303). At the same time, a hand-held, contact tachometer (Power Instruments, Tak-ette Model 1707) used to set the rotor speed was checked and found satisfactory relative to the stroboscope.

The transport vanes inside the rotor housing were mounted in their middle position giving a vane angle of 22° relative to the tangent of the rotor housing.

The threshing concave clearance was initially set using a feeler gauge at 56 mm at the inlet side of the concave and at 8 mm at the outlet side. The clearances were held constant throughout the experiments.

The necessary number of bundles for each feed rate was taken from the stack, weighed on a platform balance and evenly distributed onto the conveyor belt. The rotor speed was adjusted according to the previously mentioned hand-held tachometer and, when correct, the data sampling was initialized and the conveyor belt was started.

Once the dust had settled the material collected on the bottom of the rotor housing enclosure was cleaned and the grain mass was determined. A random sample was taken during each run from the straw and separated grain. The moisture content of the grain sample was determined according to a standard procedure, ASAE (1986). Moisture content of the straw was determined using the same procedure.

The average MOG/grain ratio for each individual run was determined using the mass of crop processed and the total mass of grain collected. This included separation losses estimated by sampling the straw behind the experimental unit.

4.2.5 Data Processing

The raw torque and speed data were converted into power data, and the power data for each run were plotted versus a time scale. From the plots, a subjectively chosen part of the power data was selected to calculate average power requirement for the individual run. The criteria for chosing a representative part of the plot were:

- to average over as long a period of time as possible (usually about five seconds),
- not to include the initial increase and the final decrease in power found at the ends of the run, and
- since the power was oscillating, to average over full cycles.

Idle power (no load power) for each run was obtained by averaging the power data recorded prior to when the crop entered the rotor housing.

Net power was calculated by subtracting idle power from the average power requirement for each run.

Analysis of variance (ANOVA) were performed on idle power (Table 4.1) and net power (Table 4.3).

4.3 RESULTS

4.3.1 Errors and Omissions

The MOG feed rate was calculated throughout using the respective crop feed rate (6, 8 and 10 kg/s), and the average MOG/grain ratio that was 1.2 with a standard deviation of 0.06. Since the true MOG/grain ratio of the crop varied, both between and within each run, the MOG feed rates all contain an error of unknown magnitude.

Straw and grain moisture contents were not considered variables in these experiments. Hence, the moisture contents that varied both between and within each run also contributed with an unknown magnitude to an error in the MOG feed rate and, hence, net power.

4.3.2 Idle Power

Figure 4.2 shows a plot of idle power requirements and Table 4.5 gives the results from the individual runs. An ANOVA table of the two completed replicates (run # 1 - 30) is found in Table 4.1 and the means in Table 4.2.

Tangential rotor velocity significantly ($F(4,25\ d.f.)=14.6$, $\alpha = 0.005$) influenced the idle power requirement. By regression techniques, idle power was found to be best represented by the equation

$$P_{idle} = 0.022\, v_t^{1.72} \qquad (4.1)$$

where: P_{idle} = idle power requirement, kW

v_t = tangential velocity of the rotor, m s^{-1}

The data from run no. 2, 3, 31 and 34 were not used in the regression due to their large deviation from the mean at the respective velocities. The square of the linear correlation coefficient achieved by the least square fit for the regression was $r^2 = 0.99$ and the standard deviation of the fit was $s = 0.63$ kW. The results from run nos. 2, 3, 31 and 34, were not used in the regression due to their large deviation from the mean value at the respective speed.

4.3.3 Net Power

Figure 4.3 shows a plot of net power requirements and Table 4.5 gives the results from the individual runs. An ANOVA table of the two completed replicates (run # 1 - 30) is found in Table 4.3 and the means in Table 4.4. A three-dimensional plot of net power versus MOG feed rate and tangential rotor velocity is found in Figure 4.4.

MOG feed rate significantly ($F(2,15\ d.f.)=116$, $\alpha = 0.005$) influenced the net power requirement. The tangential velocity of the rotor had no significant effect on net power ($F(4,15\ d.f.)=0.54$). No significant interaction between tangential rotor velocity and MOG feed rate was found to influence the net power requirement ($F(8,15\ d.f.)=0.71$).

By regression techniques, net power was found to be best represented by the equation

$$P_{net} = 5.02\ FR_{MOG}^{\ 1.60} \qquad (4.2)$$

where: P_{net} = net power requirement, kW

FR_{MOG} = MOG feed rate, kg s^{-1}

The regression had $r^2 = 0.99$, $s = 5.32$ kW.

4.3.4 Effects of Torque and Speed on Power Absorbed by the Rotor

As can be seen from Figure 4.5, the torque necessary to turn the rotor was oscillating. Since the PTO speed supplied by the tractor was fairly constant at 1000 rpm, power necessary to turn the rotor closely followed the torque oscillations.

4.4 DISCUSSION

4.4.1 Idle Power

Idle power consists of two main components. Friction in bearings, universal joints and between gears form the first component. Friction power is directly proportional to speed. The second component is the power absorbed by the air pumping action of the rotor vanes. Power requirement for a fan or a pump is theoretically proportional to the speed cubed. Idle power was found to be proportional to rotor speed to the power of approximately 1.7, thus indicating friction to be the main component in idle power requirement for the experimental unit.

The experiments done by Wacker (1985) indicated a more rapid increase in idle power requirement with rotor speed than what was found here. Differences in the design of the power trains and the rotors of the respective experimental units might account for the difference in power requirement.

4.4.2 Net Power

The net power requirement increased progressively with MOG feed rate according to Equation 4.2. Hence, in theory, the absolute increase in specific energy consumption will be less at high MOG feed rates than at low MOG feed rates.

Results presented by Wacker (1985) do not fully support this theory. According to his data, the specific energy consumption (including both net and idle power) will be linearely proportional to the MOG feed rate.

This study indicates no significant change in net power requirement with rotor speed, whereas Wacker notes that power requirement increases slightly with rotor speed. The different results might be attributed to the large variation in the experimental data from this study. This gives a large error-sum-of-square that makes rotor speed statistically not significant.

4.4.3 Torque Variations

The torque oscillations are built up by at least three superimposed frequencies. One frequency (range 1.5 - 3 Hz) noticeable in Figure 4.5 closely follows the inverse of the number of bundles fed to the rotor per second. It is obvious that even though the crop was distributed as uniformly as possible onto the conveyor belt, a homogeneous feeding was not obtained.

The highest fluctuations in amplitude have a frequency in the range of 0.5 to 1 Hz. The author has no theoretical explanation for these torque variations, but the data corresponds to findings by Wacker (1985) for a rotary combine and by Arnold and Lake (1964) for a threshing cylinder. However, the author finds it logic to believe in the theory that the torque variations are caused by uneven material flow through the rotor, as suggested by Wacker (1985).

The author has no explaination for the torque variations noticeable in the range 14 - 17 Hz.

It is beneficial to have as small a variation in torque demand as possible. Small variations in torque put less stress on the engine and the drive-train, hence giving them a longer life expectancy. Small variations in torque demand also mean that a smaller flywheel could be used, and/or possibly a smaller, and hence less costly engine.

4.5 CONCLUSIONS

1. Idle power was found to be exponentially dependent of the tangential velocity of the rotor.
2. Net power was found to be exponentially dependent of the MOG feed rate.
3. Neither the tangential velocity of the rotor nor any interaction between tangential rotor velocity and MOG feed rate influenced the net power requirement.
4. The torque necessary to turn the rotor was found to oscillate at a high amplitude. Some of the oscillations could be attributed to uneven feeding of the rotor. However, the major cause of the torque variations remains unknown.

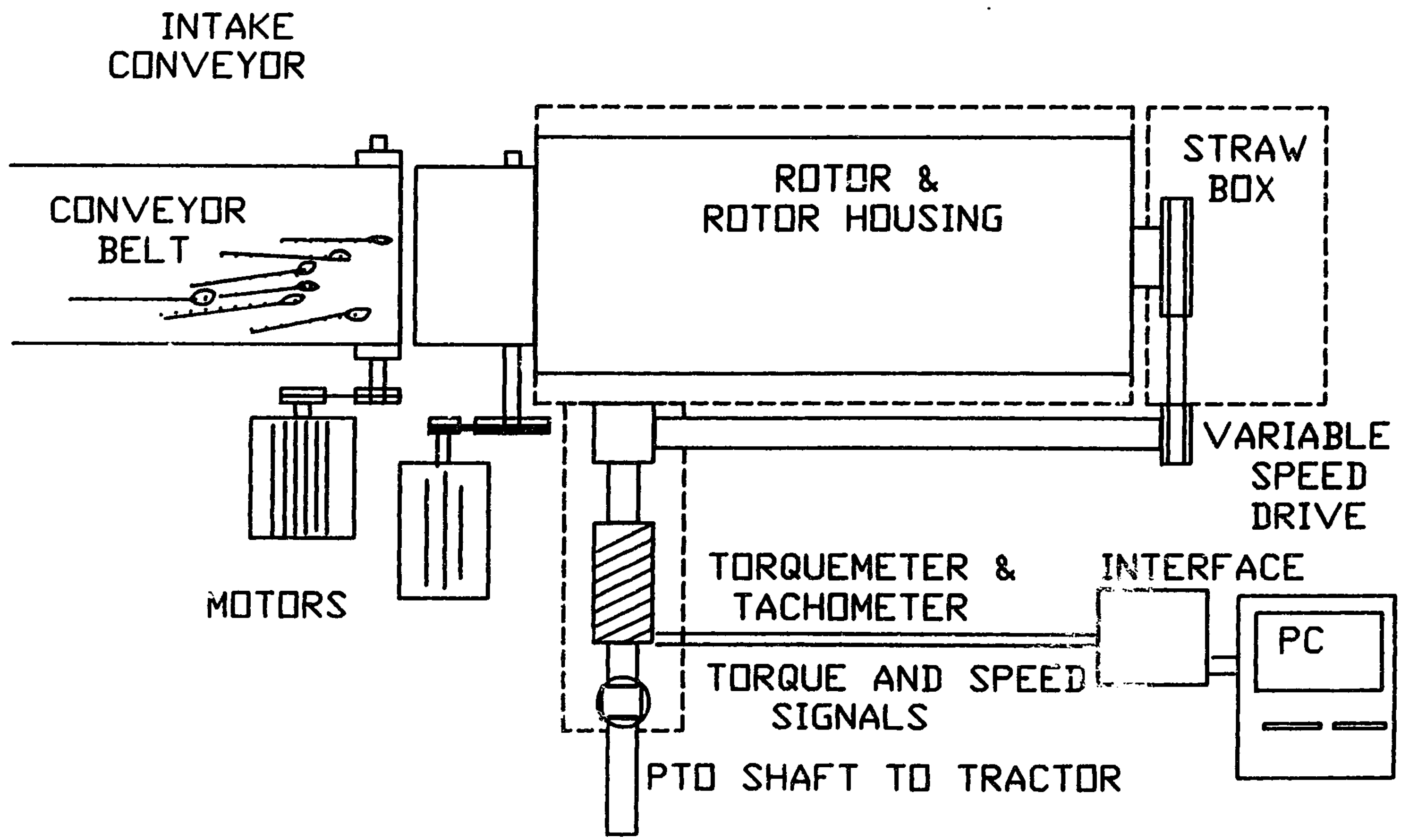

Figure 4.1 Top view of the experimental unit.

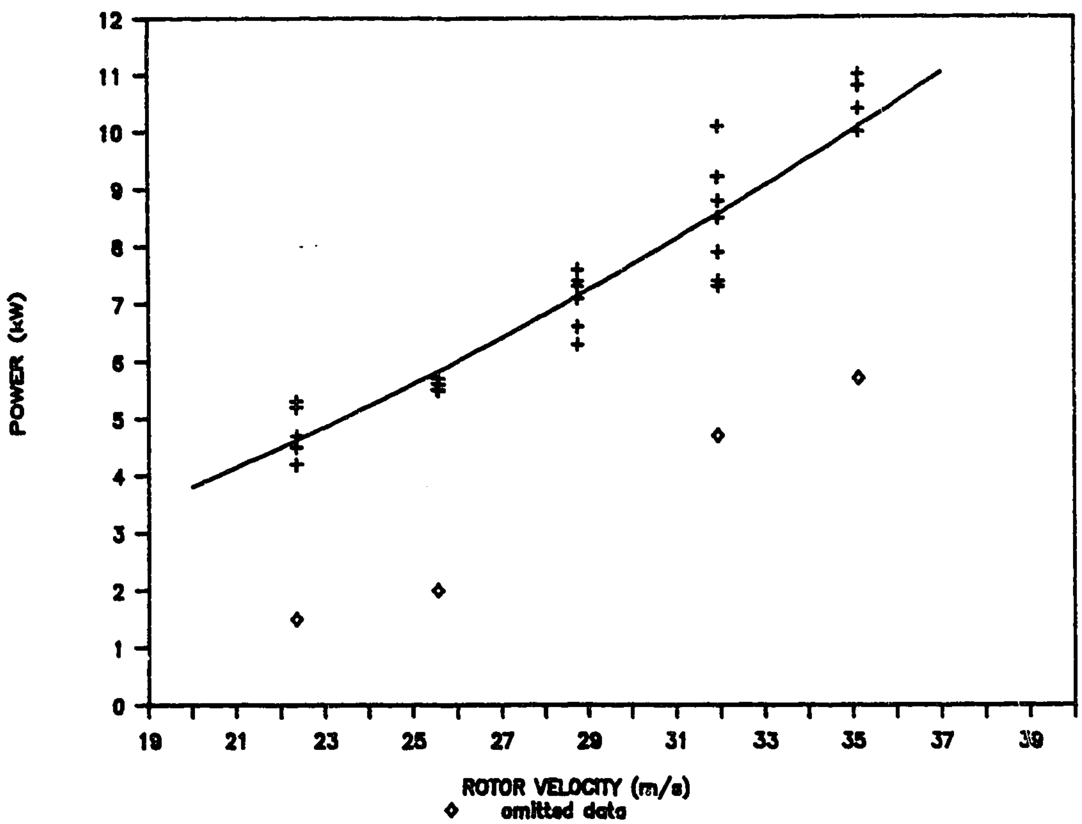

Figure 4.2 Idle power versus tangential rotor velocity.

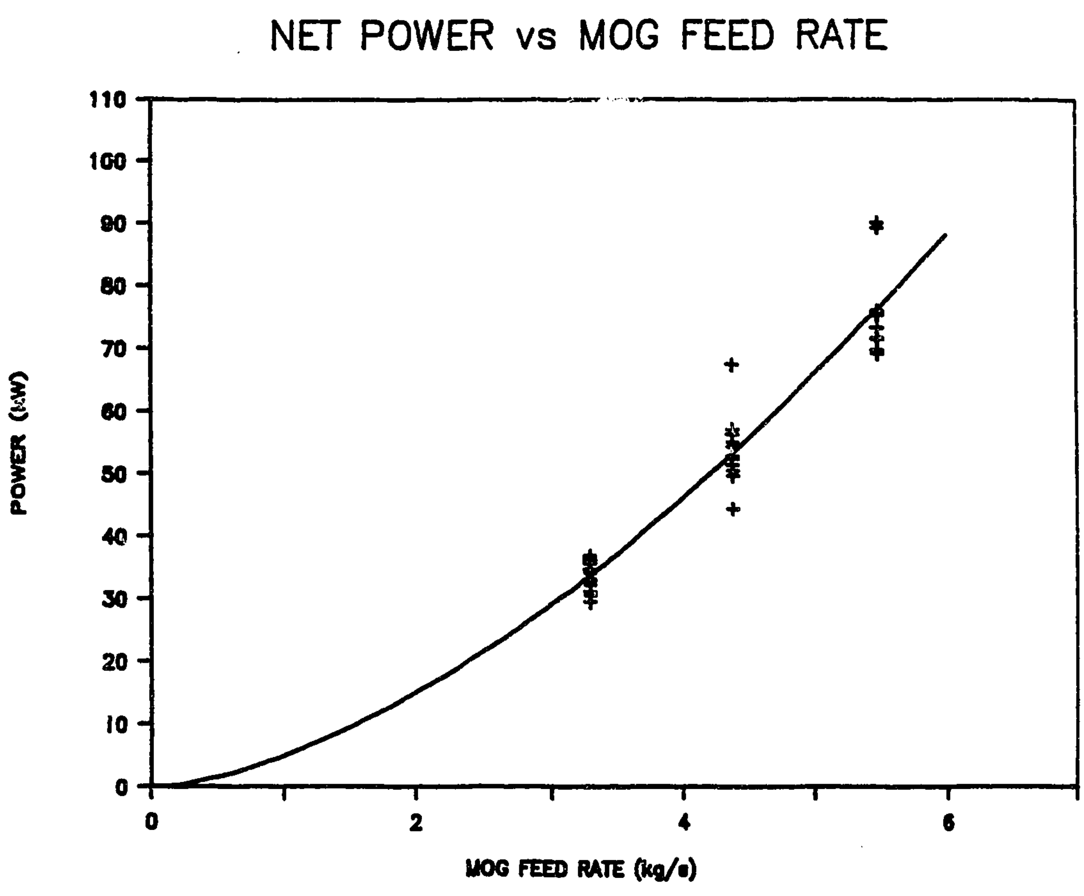

Figure 4.3 Net power versus MOG feed rate.

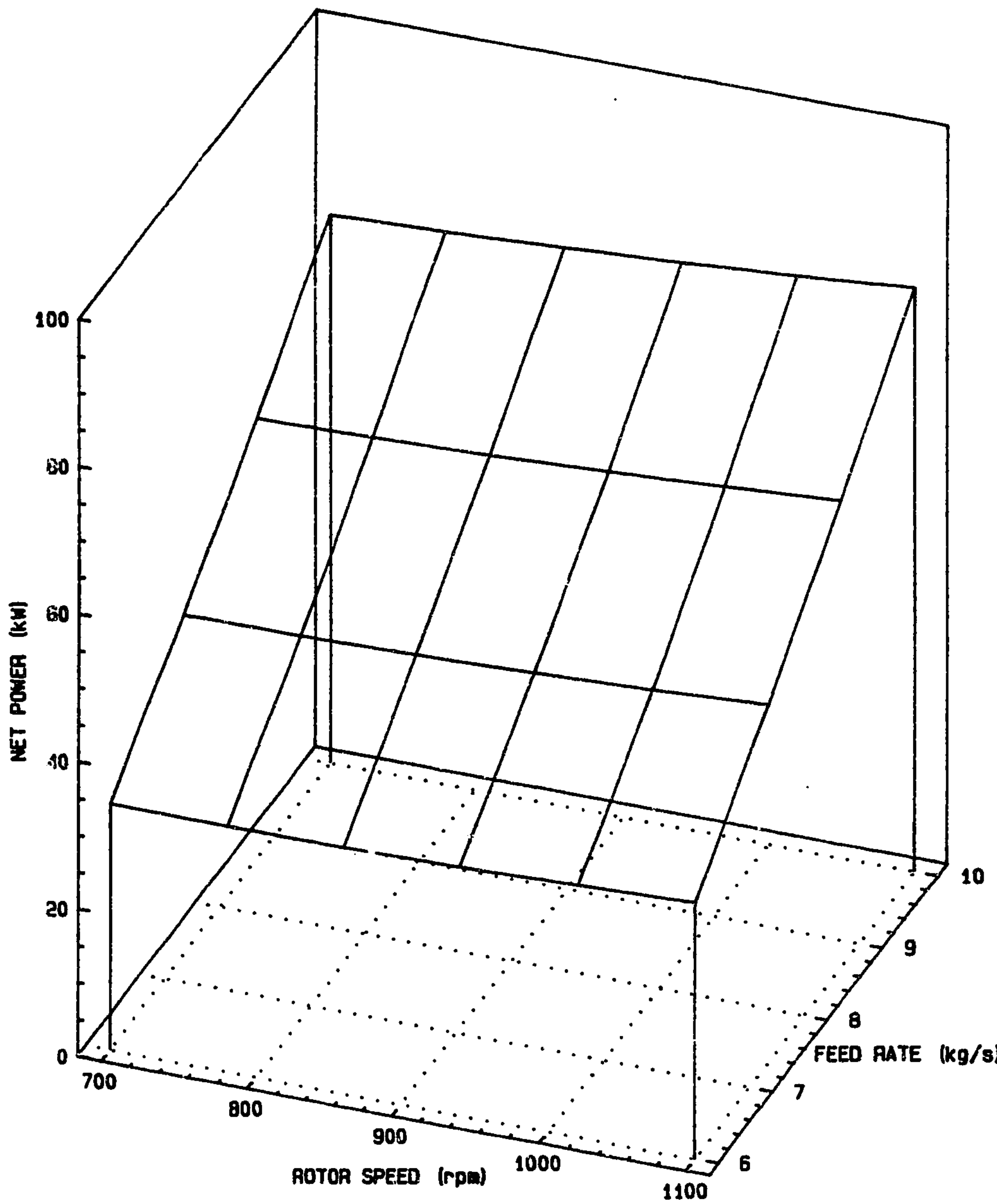

Figure 4.4 Net power versus MOG feed rate and tangential rotor velocity.

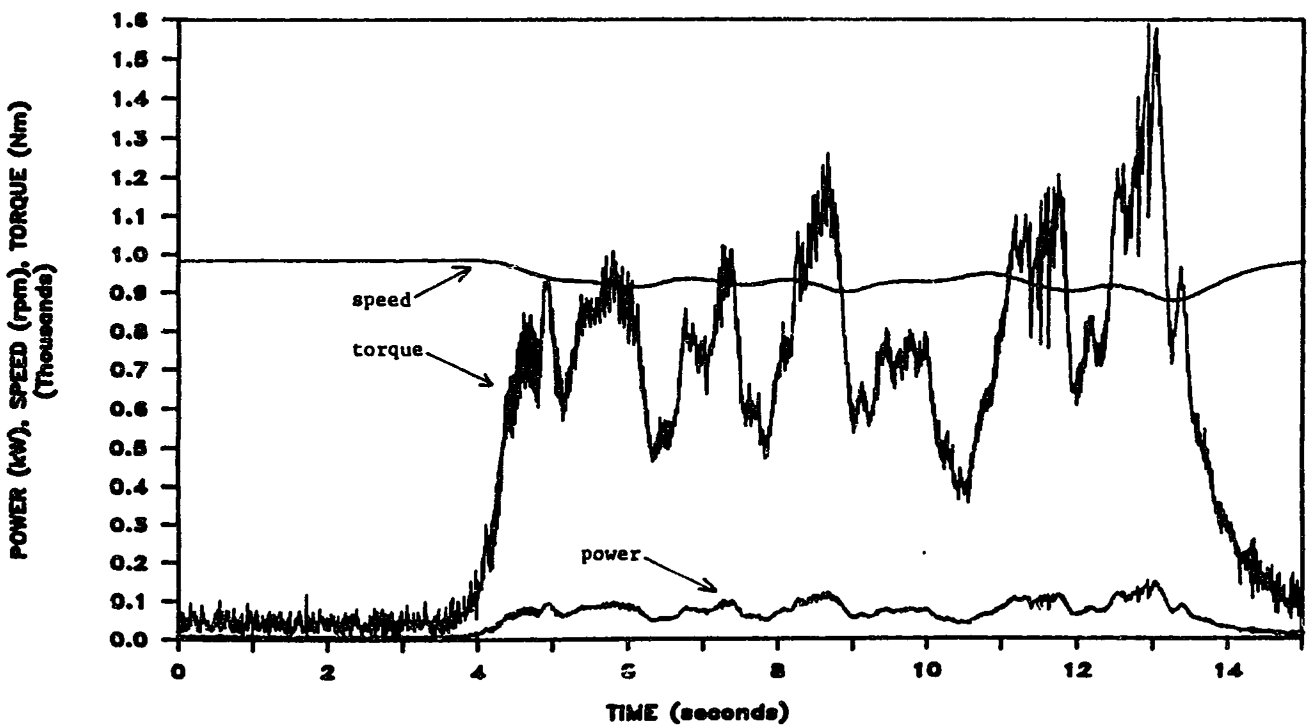

Figure 4.5 Effects of PTO torque and PTO speed on power.
Run #14, rotor speed 700 rpm, crop feed rate 10 kg/s

Table 4.1 Analysis of Variances in Idle Power Requirements

Source	d. f.	S.S.	M. S.	F	
Rotor Speed	4	94.5	23.6	14.6	***
Error	25	40.4	1.6		
Total	29	134.9			

*** significant at $\alpha = 0.005$

Table 4.2 Means of Idle Power Requirements

Rotor Speed (rpm)	Mean Idle Power (kW)
700	4.4
800	5.1
900	7.1
1000	8.0
1100	9.8

Table 4.3 Analysis of Variances in Net Power Requirements

Source	d. f.	S.S.	M. S.	F	
Block	1	10.7	10.7	0.3	
MOG Feed Rate (F)	2	9012.4	4506.2	110.3	***
Rotor Speed (S)	4	84.1	21.0	0.5	
F x S	8	220.8	27.6	0.7	
Error	14	571.8	40.8		
Total	29	9899.8			

*** significant at $\alpha = 0.005$

Table 4.4 Means of Net Po[illegible]r Requirements

Rotor Speed (rpm)	Mean Net Power (kW)
700	49.7
800	52.4
900	53.8
1000	51.4
1100	57.1

MOG Feed Rate (kgs^{-1})	Mean Net Power (kW)
3.27	33.6
4.36	53.8
5.45	76.3

Table 4.5 Idle Power and Net Power for the Individual Experiments

Run #	Rotor speed (rpm)	Feed rate, crop (kgs^{-1})	Idle power (kW)	Net power (kW)
10	700	6	5.2	34.6
29	700	6	5.3	32.8
34	700	6	1.5	32.2
5	700	8	5.3	56.3
30	700	8	4.7	44.5
14	700	10	4.5	71.8
23	700	10	4.2	76.0
7	800	6	5.5	34.1
28	800	6	5.6	34.7
31	800	6	2.0	31.1
1	800	8	5.5	67.4
27	800	8	5.6	55.2
13	800	10	5.7	69.2
24	800	10	5.5	75.3
11	900	6	7.1	33.1
25	900	6	6.3	29.5
15	900	8	7.6	51.4
16	900	8	7.3	49.7
12	900	10	7.4	69.9
18	900	10	6.6	89.4
2	1000	6	4.7	30.5
17	1000	6	10.1	35.6
33	1000	6	7.3	36.1
9	1000	8	9.2	52.8
26	1000	8	8.8	52.6
32	1000	8	7.4	54.5
4	1000	10	8.5	73.4
19	1000	10	7.9	75.7
6	1100	6	11.0	36.9
21	1100	6	10.4	36.4
3	1100	8	5.7	57.2
20	1100	8	10.0	50.5
8	1100	10	10.8	71.6
22	1100	10	10.8	90.2

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5. SUMMARY AND RECOMMENDATIONS

5.1 SUMMARY

1. Point grain separation around the concave arc and separating grate arc can be approximated with an equation as follows:

$$S_p = A + By + Cy^2 \quad (3.3)$$

where:

S_p = point grain separation, kg m^{-2} s^{-1}

A, B & C = coefficients determining shape of curvature

y = coordinate around concave arc or grate arc, •

2. The average point separation of grain along the rotor axis can be described by a non-linear equation:

$$S_{AAX} = D(x-E)^2 e^{-Fx} \quad (3.5)$$

where:

S_{AAX} = average point separation of grain along the rotor axis, kg m^{-2} s^{-1}

D, E & F = coefficients determining the shape of curvature of the separation function

x = axial distance from the beginning of the concave, m

e = the base of the natural logarithms

3. Once *equation 3.5* has been established from point separation data, the mass of grain separated through the threshing concave and separating grate areas, per unit time, can be calculated by integrating the equation over the length of the threshing concave respectively the separating grate, and by multiplying by their respective width. The total mass of grain separated through these two areas, per unit time, is the equivalent of the havesting capacity of the combine.

4. Separation losses, in mass of grain per unit time, can theoretically be calculated by integrating *equation 3.5* from the rear end of the separating grate to infinity, and by multiplying by the width of the separaing grate. However, separation losses calculated from the experimental data of this work were consistently lower than measured separation losses.

5. Relative separation losses, as a percentage of harvesting capacity, can be calculated by dividing the result from *pt. 4* by the result from *pt. 3*.
6. Idle power (no load power) was found to depend on rotor speed.
7. Net power (power for threshing and separation, idle power excluded) was found to depend on the MOG feed rate. Rotor speed did not significantly effect the net power requirement. No interaction between rotor speed and MOG feed rate was found to affect the net power requirement.
8. Torque necessary to drive the rotor was found to oscillate, sometimes at an amplitude in excess of ± 50 % of the average torque. A minor part of the oscillations could be traced to uneven feeding of the rotor. However, the source of the major part of the oscillations remains unexplained.

5.2 RECOMMENDATIONS FOR FURTHER STUDIES

1. A more extensive study of point grain separation should be carried out. This study should include different crop varieties, MOG feed rates, grain/MOG ratios, rotor speeds, vane angles and crop moisture contents.
2. The influence of the variables in *pt. 1* on the coefficients of *equation 3.5* should be analyzed. It might then be possible to find a set of equations that could be used to optimize combine settings under different conditions.
3. Equipment and methods should be developed where point grain separation is measured with piezo electric pads (grain sensors) mounted underneath the separating areas. The piezo electric pads should be interfaced with a computer that gives an instant readout of capacity and losses. The market potential for such procuct would be large.
4. Point grain separation studies should be carried out for different designs of rotary separators. For example, what does the separation function look like for a separating grate that has a 360° wrap?
5. The source or cause of the large low frequency torque oscillations should be

determined. Possibly, engines with less extra (spare) power could be used if the torque oscillations were minimized.

6. APPENDIX A

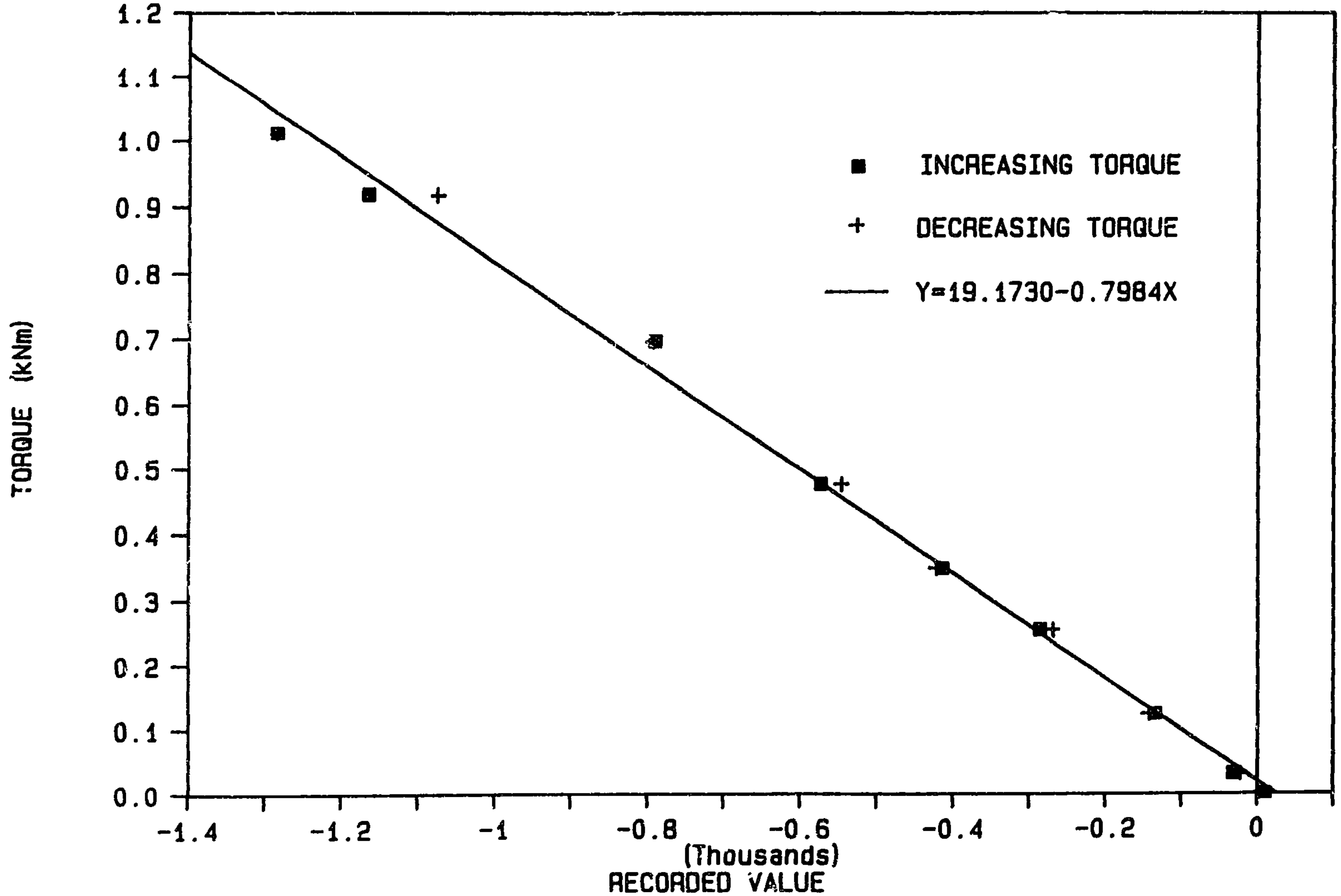

Figure 6.1 Calibration of torque meter.

$r^2 = 0.994$, $s = 28.4$ Nm

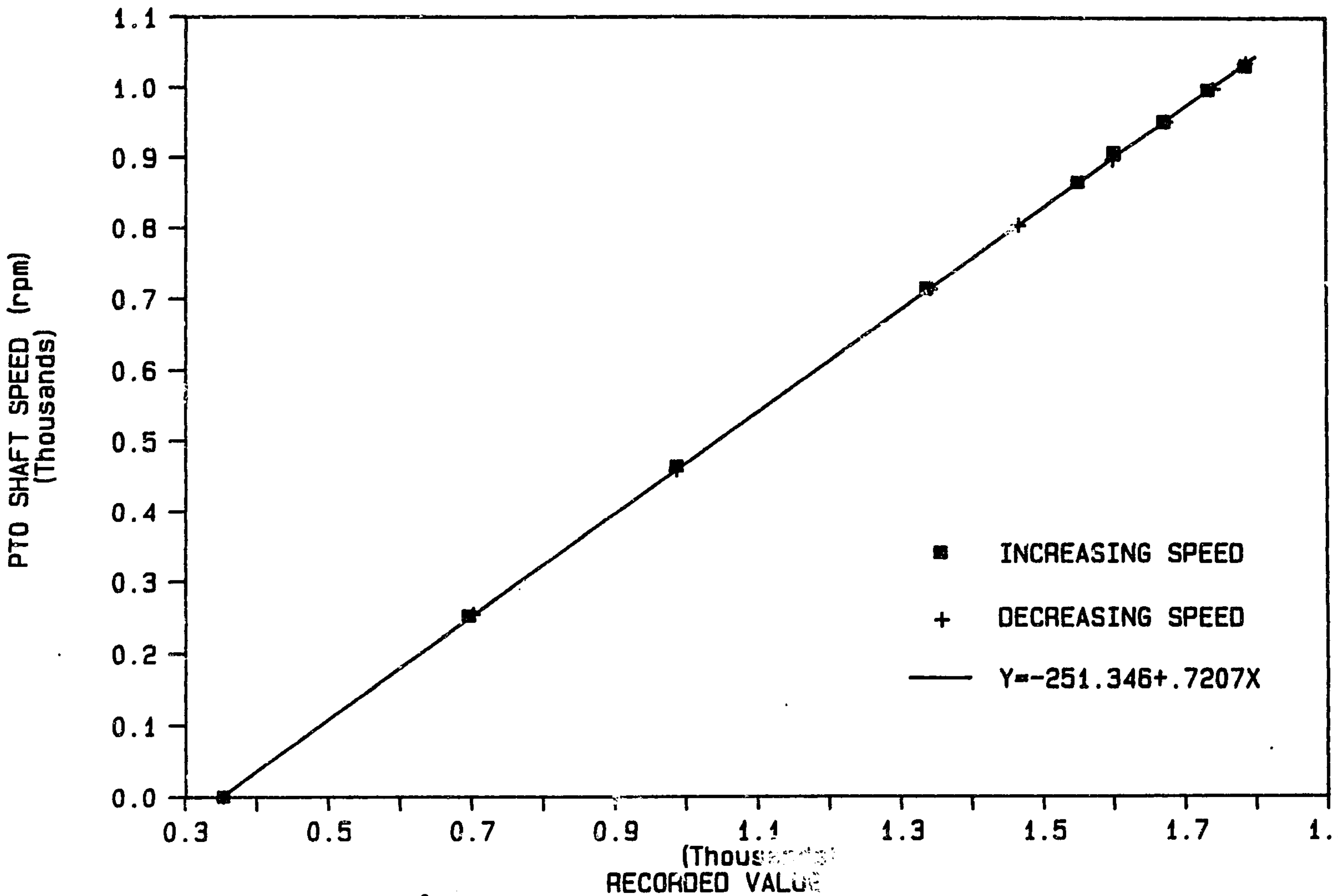

Figure 6.2 Calibration of tachometer. $r^2 = 0.999$, $s = 2.08$ rpm

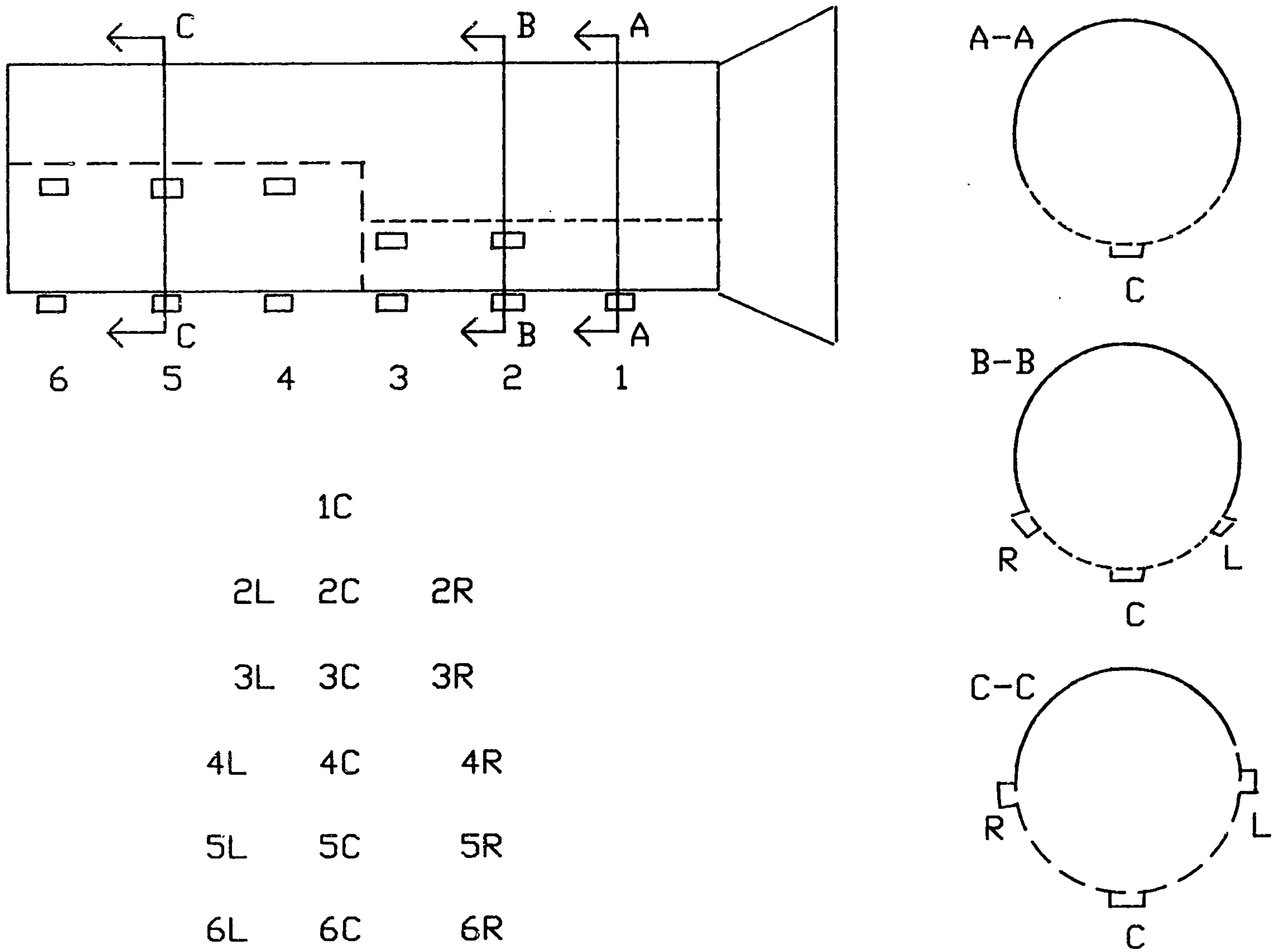

Figure 6.3 Nomenclature for duct location used in the tables of point separation data.

Table 6.1 Measured Grain Separation at the Individual Ducts.

Run No.	Axial Location	Grain Separation ($kg\ m^{-2}\ s^{-1}$) L	C	R
1	1		3.099	
	2	2.530	3.858	4.056
	3	0.771	2.593	3.856
	4	1.261	1.387	2.231
	5	0.485	0.970	1.164
	6	0.194	0.336	0.582
2	1		2.491	
	2	2.164	3.409	7.100
	3	0.852	1.049	3.791
	4	0.302	0.654	0.654
	5	0.050	0.201	0.352
	6	0.050	0.044	0.101
3	1		3.137	
	2	2.353	4.640	7.557
	3	1.176	1.438	3.[illegible]58
	4	0.551	1.042	1.353
	5	0.251	0.451	0.451
	6	0.100	0.130	0.200
4	1		n/a	
	2	n/a	n/a	n/a
	3	n/a	n/a	n/a
	4	n/a	n/a	n/a
	5	n/a	n/a	n/a
	6	n/a	n/a	n/a
5	1		2.366	
	2	2.433	3.785	5.258
	3	1.690	2.839	3.837
	4	1.088	2.021	2.799
	5	0.570	1.244	0.985
	6	0.259	0.359	0.622
6	1		2.331	
	2	2.558	4.036	8.427
	3	0.966	1.137	3.407
	4	0.218	0.680	1.046
	5	0.044	0.174	0.305
	6	0.017	0.038	0.044

Run No.		Grain Separation ($kg\ m^{-2}\ s^{-1}$)		
	Axial Location	L	C	R
7	1		2.547	
	2	2.264	3.325	7.959
	3	1.627	2.547	5.132
	4	0.651	1.364	2.007
	5	0.217	0.705	0.651
	6	0.054	0.141	0.217
8	1		3.990	
	2	4.200	5.530	9.272
	3	2.170	3.010	5.593
	4	1.020	1.861	1.986
	5	0.429	0.966	0.698
	6	0.161	0.279	0.376
9	1		2.893	
	2	2.748	3.977	8.363
	3	1.446	2.169	4.485
	4	0.444	1.057	1.553
	5	0.166	0.555	0.721
	6	0.055	0.144	0.222
10	1		1.951	
	2	2.195	3.089	5.725
	3	1.626	2.520	4.101
	4	0.686	1.350	1.558
	5	0.249	0.623	0.686
	6	0.062	0.162	0.125
11	1		2.510	
	2	2.685	4.319	10.431
	3	0.875	1.284	3.498
	4	0.269	0.582	0.627
	5	0.045	0.313	0.403
	6	0.045	0.078	0.090
12	1		4.721	
	2	3.719	6.151	8.196
	3	2.503	4.649	6.015
	4	1.536	2.519	2.578
	5	0.713	1.700	1.645
	6	0.329	0.428	0.603

Run No.	Axial Location	Grain Separation (kg m^{-2} s^{-1}) L	C	R
13	1		3.512	
	2	2.986	4.742	6.031
	3	1.932	3.630	4.246
	4	1.167	2.529	2.604
	5	0.584	1.481	1.077
	6	0.269	0.428	0.808
14	1		2.237	
	2	2.697	4.671	4.634
	3	1.908	2.631	3.320
	4	1.059	2.492	2.724
	5	0.706	1.261	1.412
	6	0.303	0.481	0.858
15	1		2.970	
	2	2.838	4.356	6.592
	3	1.320	2.178	5.135
	4	0.506	1.360	2.075
	5	0.253	0.860	1.063
	6	0.152	0.219	0.304
16	1		2.294	
	2	2.850	3.823	7.891
	3	1.321	2.224	5.553
	4	0.480	1.247	1.279
	5	0.213	0.533	0.693
	6	0.107	0.139	0.160
17	1		3.429	
	2	2.265	3.365	7.074
	3	0.971	1.165	3.129
	4	0.248	0.688	0.893
	5	0.050	0.298	0.397
	6	0.050	0.043	0.099
18	1		3.187	
	2	3.132	5.000	6.873
	3	2.198	3.736	4.621
	4	1.264	2.118	3.033
	5	0.548	1.559	1.432
	6	0.211	0.365	0.758

Run No.	Axial Location	Grain Separation (kg m^{-2} s^{-1}) L	C	R
19	1		3.588	
	2	3.402	4.948	7.998
	3	1.794	3.031	6.242
	4	0.759	1.398	2.372
	5	0.332	0.806	0.901
	6	0.190	0.288	0.332
20	1		3.233	
	2	2.630	4.109	7.949
	3	1.534	2.027	4.032
	4	0.672	1.602	2.017
	5	0.210	0.504	1.050
	6	0.084	0.146	0.210
21	1		2.820	
	2	2.751	4.677	9.182
	3	0.894	0.963	3.615
	4	0.211	0.686	1.318
	5	0.053	0.158	0.316
	6	0.021	0.046	0.053
22	1		3.853	
	2	3.312	5.205	10.304
	3	2.095	3.312	5.969
	4	0.726	1.842	2.488
	5	0.363	1.037	1.140
	6	0.207	0.270	0.363
23	1		2.172	
	2	2.655	4.646	3.298
	3	2.172	3.137	2.854
	4	1.249	2.406	3.007
	5	0.648	1.712	1.758
	6	0.370	0.601	0.925
24	1		2.599	
	2	2.481	4.607	7.141
	3	1.890	3.131	3.664
	4	1.268	2.120	2.536
	5	0.679	1.585	1.540
	6	0.317	0.510	0.770

Run No.		Grain Separation (kg m^{-2} s^{-1})		
	Axial Location	L	C	R
25	1		1.807	
	2	1.738	2.572	5.772
	3	0.626	1.043	2.923
	4	0.213	0.647	0.746
	5	0.107	0.266	0.320
	6	0.053	0.046	0.053
26	1		3.026	
	2	2.763	4.408	10.512
	3	1.184	1.908	4.979
	4	0.404	1.006	1.312
	5	0.151	0.504	0.454
	6	0.101	0.175	0.151
27	1		2.428	
	2	2.365	3.112	6.609
	3	1.867	2.428	4.515
	4	0.907	1.655	1.862
	5	0.382	0.859	0.716
	6	0.191	0.248	0.477
28	1		2.090	
	2	2.090	3.135	7.044
	3	0.799	1.352	4.653
	4	0.330	0.613	1.084
	5	0.141	0.283	0.330
	6	0.047	0.082	0.094
29	1		1.477	
	2	2.488	3.032	6.620
	3	0.700	1.088	3.514
	4	0.417	0.723	0.835
	5	0.119	0.417	0.238
	6	0.060	0.103	0.119
30	1		1.811	
	2	2.310	3.185	6.630
	3	1.124	1.998	4.267
	4	0.575	1.079	1.053
	5	0.192	0.479	0.527
	6	0.096	0.166	0.192

Run No.	Axial Location	Grain Separation $(kg\ m^{-2}\ s^{-1})$ L	C	R
31	1		2.028	
	2	1.905	2.705	6.720
	3	0.922	1.168	4.330
	4	0.377	0.735	1.225
	5	0.094	0.283	0.330
	6	0.047	0.082	0.094
32	1		2.664	
	2	2.664	4.308	8.760
	3	0.850	1.644	4.291
	4	0.391	0.942	1.174
	5	0.130	0.522	0.522
	6	0.043	0.113	0.130
33	1		2.775	
	2	2.466	3.823	8.686
	3	0.863	1.295	4.149
	4	0.284	0.902	1.135
	5	0.095	0.284	0.331
	6	0.019	0.082	0.047
34	1		1.859	
	2	1.626	2.478	5.536
	3	0.852	1.549	4.152
	4	0.416	0.772	0.950
	5	0.119	0.297	0.416
	6	0.059	0.154	0.178

7. APPENDIX B

7.1 APL PROGRAMS

Where not otherwise noted in the beginning of the APL program, the programs listed are developed by and are the property of Computing Services, University of Alberta, Edmonton, Alberta.

```
     ∇CALCSEP[⎕]∇
   OUT←N CALCSEP DATA;N;DATA;YT;YS;X;XSEP;XY;INIT;FIRST;FINAL;R2;S;VAL;RES;SPS
   ⍝ EDITED 880929                    ANDERS BJORK
   ⍝ CALCULATES GRAIN SEPARATION AND GRAIN LOSSES PER TIME UNIT
   ⍝ REQUIRES THE FOLLOWING FUNCTIONS:
   ⍝    SEPWRAP, DEFAULTNONLINSQ, NLLSQCK, INTEGSEP
   ⍝    NLLSQCK REQUIRES:NLLSQ, DIAGMAT, EPS, FUNC
   ⍝ REQUIRES THE FOLLOWING VARIABLES:
   ⍝    ⍵EIGHT
   ⍝    NLLSQ REQUIRES: ⍳INIT
    YT← ¯47 0 42 ¯67 62 ⍝[∘] DUCT LOCATION AND BOUNDARIES C/C, THRESH. WRAP
    YS← ¯84 0 88 ¯107 114 ⍝[∘] DUCT LOCATION AND BOUNDARIES C/C, SEP. WRAP
    X← 0.201 0.551 0.901 1.227 1.461 1.827 ⍝ DUCT LOCATION C/C, ROTOR AXIS
   ⍝ FIND AVERAGE SEPARATION
    XSEP←6⍴0
    XSEP[2]←(⌽DATA[N;8;])SEPWRAP YT
    XSEP[3]←(⌽DATA[N;9;])SEPWRAP YT
    XSEP[4]←(⌽DATA[N;10;])SEPWRAP YS
    XSEP[5]←(⌽DATA[N;11;])SEPWRAP YS
    XSEP[6]←(⌽DATA[N;12;])SEPWRAP YS
    XSEP[1]←DATA[N;7;2]×⍵EIGHT
   ⍝ FIND SEPARATION EQUATION
    XY←(6 1 ⍴X),[2](6 1 ⍴XSEP),(6 1 ⍴1)
    INIT←⍳INIT ⍝INITIAL VALUES (INIT←)A B C, FOR NLLSQ
    DEFAULTNONLINSQ
    FIRST←XY NLLSQCK INIT
    FINAL←XY NLLSQ FIRST
    'NLLSQ DIFFERENCES: ',⍕(FIRST-FINAL)
   ⍝ STATISTICS
    S←s
   ⍝ FIND TOTAL SEPARATION BY INTEGRATION
    VAL← 0 1.051 1.947 ⍝ AXIAL BOUNDARIES
    RES←VAL INTEGSEP FINAL
    TRSEP←((RES[2]-RES[1])×((YT[5]-YT[4])×○1×0.71÷360))
    SPSEP←((RES[3]-RES[2])×((YS[5]-YS[4])×○1×0.71÷360))
    TOTSEP←TRSEP+SPSEP
   ⍝ FIND SEPARATION LOSSES
    LOSSES←(0-RES[3])×((YS[5]-YS[4])×○1×0.71÷360)
   ⍝ RESULTS
    OUT←DATA[N;1;],FINAL,S,TRSEP,SPSEP,TOTSEP,DATA[N;6;1],LOSSES,DATA[N;3;2]+1
    ⍴0
```

```
      ∇NLLSQCK[⎕]∇
    B←XY NLLSQCK INITIAL
     →((2≠ρρXY),1≠ρρINITIAL)/ERR2,ERR1
     →ERR2×ι3≠(ρXY)[2]
     →ERR3×ι(ρINITIAL)>1↑ρXY
     →ERR4×ι1≠+/(⎕NL 3)[;ι5]∧.='FUNC '
     B←XY NLLSQ INITIAL
     →0
    ERR1:'RIGHT ARGUMENT MUST BE A VECTOR OF INITIAL ESTIMATES OF'
     'THE PARAMETERS OF THE THEORETICAL FUNCTION FUNC'
     →0
    ERR2:'LEFT ARGUMENT MUST BE A N BY 3 MATRIX'
     →0
    ERR3:'THERE ARE MORE PARAMETERS FOR THE THEORETICAL'
     'FUNCTION THAN DATA'
     →0
    ERR4:'THERE MUST BE A USER DEFINED FUNCTION IN THE ACTIVE WORKSPACE CALLED
```

```
      ∇NLLSQ[⎕]∇
    B←XY NLLSQ INITIAL;Z;D;S;T;A;L;SW;IT;dELTA;iTER
     →OPT×ιDEFAULTNLLSQ≠1
     dELTA←1E¯5
     iTER←10
     →LA
    OPT:dELTA←DELTA
     iTER←ITER
    LA:eI←1+(SW←XY[;3]*0.5)
     S←+/((XY[;2]-D←XY[;1]FUNC B←T←INITIAL)×SW)*2
     Z←((1↑ρXY),ρT)ρIT←0
    AGAIN:L←0
    LOOP:Z[;L]←((XY[;1]FUNC T+dELTA×(L←L+1)=ιρT)-D)÷dELTA
     →LOOP×ιL<ρT
     Z←(DIAGMAT SW)+.×z←Z
     T←T+(⌹Z)+.×(XY[;2]-D)×SW
     D←XY[;1]FUNC T
     →AGAIN×ιiTER>IT←IT+1
     rES←XY[;2]-D
     B←((2,ρB)ρB,T)[1+A=S←(A←+/(rES×SW)*2)⌊S;]
     y←XY[;1]FUNC B
     dEG←(1↑ρXY)-(ρINITIAL)
     rES←XY[;2]-y
     rSS←S
     s←(rSS)*0.5
     →0×ιdEG≤0
     s←s÷dEG*0.5
     ePS←EPS
```

```
      ∇DEFAULTNONLINSQ[⎕]∇
    DEFAULTNONLINSQ
     DEFAULTNLLSQ←1
     'OK'
```

```
      ∇FUNC[⎕]∇
[0]   Y←X FUNC PAR;PAR;X;Y
[1]    Y←(PAR[1]×(X-PAR[2])*2)××(¯1×PAR[3]×X)
```

```
      ∇DIAGMAT[⎕]∇
[0]   Z←DIAGMAT V;N
[1]    N←ρV
[2]    Z←(N,N)ρ⍉((N+1),N)ρV,(N×N)ρ0
```

```
      ∇EPS[⎕]∇
[0]   Z←EPS;R
[1]    R←⌹((DIAGMAT+eI)+.×z+s)
[2]    Z←R+.×⍉R
```

```
      ∇SEPWRAP[⎕]∇
[0]   AVE←SEP SEPWRAP YLOC;AVE;SEP;YLOC;ABC;X;INT;AVE
[1]   ⍝ REVISED 880513          ANDERS BJORK
[2]   ⍝ CALCULATES THE AVERAGE SEPARATION ALONG THE WRAP
[3]    ABC←SEP⌹(3↑YLOC)∘.* 0 1 2
[4]    X←YLOC[4 5]
[5]    INT←(ABC[1]×X)+(0.5×ABC[2]×X*2)+((÷3)×ABC[3]×X*3)
[6]    AVE←(INT[2]-INT[1])÷(YLOC[5]-YLOC[4])
```

```
      ∇INTEGSEP[⎕]∇
[0]   RES←VAL INTEGSEP PAR;VAL;PAR;A;B;C;X;RES
[1]   ⍝ REVISED 880513          ANDERS BJORK
[2]   ⍝ EVALUATES THE INTEGRAL '|(A(X-B)*2×e*(-CX))dx' FOR THE VALUE 'VAL'
[3]   ⍝  USING THE PARAMETERS A, B, C IN 'PAR'.
[4]    A←PAR[1] ⋄ B←PAR[2] ⋄ C←PAR[3]
[5]    X←VAL
[6]    RES←((¯1×X*2)+(¯2×X÷C)+(¯2÷C*2)+(2×B×X)+(2×B÷C)+(¯1×B*2))×(A÷C)×(*(¯1×C×X)
```

7.2 REGRESSION COEFFICIENTS

Table 7.1 Regression Coefficients for Equation 3.3

Run No.	Axial Location	Coefficient		
		A	B	C
1	2	3.86E+00	-1.87E-02	-3.08E-04
	3	2.59E+00	-2.30E-02	8.21E-05
	4	1.39E+00	-5.84E-03	5.01E-05
	5	9.70E-01	-3.87E-03	-1.86E-05
	6	3.36E-01	2.29E-03	7.61E-06
2	2	3.41E+00	-5.27E-02	5.49E-04
	3	1.05E+00	-3.00E-02	6.03E-04
	4	6.54E-01	-1.95E-03	-2.33E-05
	5	2.01E-01	-1.76E-03	4.75E-07
	6	4.36E-02	-3.10E-04	4.39E-06
3	2	4.64E+00	-5.80E-02	8.55E-05
	3	1.44E+00	-2.20E-02	3.75E-04
	4	1.04E+00	-4.62E-03	-1.09E-05
	5	4.51E-01	-1.11E-03	-1.32E-05
	6	1.30E-01	-5.94E-04	2.87E-06
4	2	n/a	n/a	n/a
	3	n/a	n/a	n/a
	4	n/a	n/a	n/a
	5	n/a	n/a	n/a
	6	n/a	n/a	n/a
5	2	3.79E+00	-3.18E-02	-9.47E-06
	3	2.84E+00	-2.45E-02	-6.87E-05
	4	2.02E+00	-9.91E-03	-7.83E-06
	5	1.24E+00	-2.16E-03	-6.25E-05
	6	3.59E-01	-2.16E-03	1.16E-05
6	2	4.04E+00	-6.27E-02	6.54E-04
	3	1.14E+00	-2.49E-02	4.97E-04
	4	6.80E-01	-4.79E-03	-5.18E-06
	5	1.74E-01	-1.52E-03	4.11E-07
	6	3.78E-02	-1.48E-04	-9.42E-07
7	2	3.33E+00	-5.99E-02	8.24E-04
	3	2.55E+00	-3.75E-02	3.72E-04
	4	1.36E+00	-7.88E-03	-2.51E-06
	5	7.05E-01	-2.38E-03	-3.60E-05
	6	1.41E-01	-9.44E-04	-4.78E-07

Run No.	Axial Location	Coefficient A	Coefficient B	Coefficient C
8	2	5.53E+00	-5.43E-02	5.39E-04
	3	3.01E+00	-3.65E-02	3.93E-04
	4	1.86E+00	-5.43E-03	-4.69E-05
	5	9.66E-01	-1.34E-03	-5.40E-05
	6	2.79E-01	-1.24E-03	-1.11E-06
9	2	3.98E+00	-5.95E-02	7.19E-04
	3	2.17E+00	-3.23E-02	3.60E-04
	4	1.06E+00	-6.42E-03	-6.26E-06
	5	5.55E-01	-3.17E-03	-1.41E-05
	6	1.44E-01	-9.65E-04	-4.88E-07
10	2	3.09E+00	-3.77E-02	3.91E-04
	3	2.52E+00	-2.71E-02	1.39E-04
	4	1.35E+00	-4.95E-03	-2.95E-05
	5	6.23E-01	-2.45E-03	-2.04E-05
	6	1.62E-01	-3.26E-04	-9.18E-06
11	2	4.32E+00	-8.19E-02	1.02E-03
	3	1.28E+00	-2.74E-02	4.20E-04
	4	5.82E-01	-2.01E-03	-1.76E-05
	5	3.13E-01	-2.04E-03	-1.15E-05
	6	7.76E-02	-2.55E-04	-1.34E-06
12	2	6.15E+00	-5.11E-02	-1.62E-04
	3	4.65E+00	-4.07E-02	-2.47E-04
	4	2.52E+00	-5.81E-03	-6.09E-05
	5	1.70E+00	-5.14E-03	-6.90E-05
	6	4.28E-01	-1.62E-03	5.63E-06
13	2	4.74E+00	-3.50E-02	-1.62E-04
	3	3.63E+00	-2.75E-02	-3.07E-04
	4	2.53E+00	-8.01E-03	-8.48E-05
	5	1.48E+00	-2.52E-03	-8.73E-05
	6	4.28E-01	-3.20E-03	1.58E-05
14	2	4.67E+00	-2.44E-02	-5.37E-04
	3	2.63E+00	-1.60E-02	-2.91E-05
	4	2.49E+00	-9.36E-03	-7.86E-05
	5	1.26E+00	-4.00E-03	-2.62E-05
	6	4.31E-01	-3.28E-03	1.43E-05

Run No.	Axial Location	Coefficient		
		A	B	C
15	2	4.36E+00	-4.15E-02	1.28E-04
	3	2.18E+00	-4.05E-02	4.77E-04
	4	1.36E+00	-9.09E-03	-6.89E-06
	5	8.60E-01	-4.60E-03	-2.61E-05
	6	2.19E-01	-8.88E-04	1.38E-06
16	2	3.82E+00	-5.31E-02	7.12E-04
	3	2.22E+00	-4.48E-02	5.54E-04
	4	1.25E+00	-4.45E-03	-4.85E-05
	5	5.33E-01	-2.75E-03	-1.01E-05
	6	1.39E-01	-3.07E-04	-6.37E-07
17	2	3.36E+00	-5.11E-02	5.93E-04
	3	1.16E+00	-2.22E-02	4.18E-04
	4	6.88E-01	-3.69E-03	-1.49E-05
	5	2.98E-01	-1.98E-03	-9.52E-06
	6	4.30E-02	-3.06E-04	4.33E-06
18	2	5.00E+00	-4.23E-02	-5.18E-05
	3	3.74E+00	-2.82E-02	-2.00E-04
	4	2.12E+00	-1.03E-02	6.96E-06
	5	1.56E+00	-4.84E-03	-7.56E-05
	6	3.65E-01	-3.25E-03	1.70E-05
19	2	4.95E+00	-5.01E-02	3.15E-04
	3	3.03E+00	-4.78E-02	4.37E-04
	4	1.40E+00	-9.48E-03	2.52E-05
	5	8.06E-01	-3.21E-03	-2.48E-05
	6	2.88E-01	-8.14E-04	-3.41E-06
20	2	4.11E+00	-5.72E-02	5.22E-04
	3	2.03E+00	-2.63E-02	3.47E-04
	4	1.60E+00	-7.69E-03	-3.27E-05
	5	5.04E-01	-4.96E-03	1.84E-05
	6	1.46E-01	-7.34E-04	3.88E-07
21	2	4.68E+00	-6.95E-02	5.62E-04
	3	9.63E-01	-2.75E-02	6.16E-04
	4	6.86E-01	-6.49E-03	1.24E-05
	5	1.58E-01	-1.55E-03	3.98E-06
	6	4.57E-02	-1.79E-04	-1.14E-06

Run No.	Axial Location	Coefficient		
		A	B	C
22	2	5.20E+00	-7.50E-02	7.13E-04
	3	3.31E+00	-4.20E-02	3.10E-04
	4	1.84E+00	-1.01E-02	-2.90E-05
	5	1.04E+00	-4.37E-03	-3.73E-05
	6	2.70E-01	-9.13E-04	2.35E-06
23	2	4.65E+00	-1.15E-02	-8.55E-04
	3	3.14E+00	-9.30E-03	-3.26E-04
	4	2.41E+00	-1.01E-02	-3.48E-05
	5	1.71E+00	-6.19E-03	-6.71E-05
	6	6.01E-01	-3.26E-03	7.13E-06
24	2	4.61E+00	-5.22E-02	3.69E-05
	3	3.13E+00	-2.09E-02	-2.04E-04
	4	2.12E+00	-7.26E-03	-2.74E-05
	5	1.59E+00	-4.75E-03	-6.30E-05
	6	5.10E-01	-2.65E-03	5.21E-06
25	2	2.57E+00	-4.26E-02	5.42E-04
	3	1.04E+00	-2.41E-02	3.38E-04
	4	6.47E-01	-3.01E-03	-2.18E-05
	5	2.66E-01	-1.21E-03	-6.87E-06
	6	4.62E-02	-3.85E-06	9.61E-07
26	2	4.41E+00	-8.20E-02	1.02E-03
	3	1.91E+00	-3.99E-02	5.41E-04
	4	1.01E+00	-5.20E-03	-1.86E-05
	5	5.04E-01	-1.65E-03	-2.68E-05
	6	1.75E-01	-2.67E-04	-6.52E-06
27	2	3.11E+00	-4.45E-02	6.36E-04
	3	2.43E+00	-2.80E-02	3.49E-04
	4	1.65E+00	-5.41E-03	-3.51E-05
	5	8.59E-01	-1.78E-03	-4.14E-05
	6	2.48E-01	-1.71E-03	1.21E-05
28	2	3.13E+00	-5.24E-02	6.55E-04
	3	1.35E+00	-4.01E-02	6.41E-04
	4	6.13E-01	-4.44E-03	1.39E-05
	5	2.83E-01	-1.07E-03	-6.08E-06
	6	8.17E-02	-2.68E-04	-1.41E-06

Run No.	Axial Location	Coefficient		
		A	B	C
29	2	3.03E+00	-4.29E-02	7.12E-04
	3	1.09E+00	-2.92E-02	4.76E-04
	4	7.23E-01	-2.38E-03	-1.25E-05
	5	4.17E-01	-5.65E-04	-3.21E-05
	6	1.03E-01	-3.39E-04	-1.79E-06
30	2	3.18E+00	-4.56E-02	5.90E-04
	3	2.00E+00	-3.38E-02	3.09E-04
	4	1.08E+00	-2.64E-03	-3.51E-05
	5	4.79E-01	-1.89E-03	-1.57E-05
	6	1.66E-01	-5.45E-04	-2.87E-06
31	2	2.70E+00	-5.04E-02	7.46E-04
	3	1.17E+00	-3.48E-02	6.90E-04
	4	7.35E-01	-4.97E-03	1.03E-05
	5	2.83E-01	-1.33E-03	-9.19E-06
	6	8.17E-02	-2.68E-04	-1.41E-06
32	2	4.31E+00	-6.54E-02	6.25E-04
	3	1.64E+00	-3.66E-02	4.20E-04
	4	9.42E-01	-4.47E-03	-2.03E-05
	5	5.22E-01	-2.17E-03	-2.58E-05
	6	1.13E-01	-4.92E-04	-3.39E-06
33	2	3.82E+00	-6.59E-02	8.00E-04
	3	1.29E+00	-3.41E-02	5.67E-04
	4	9.02E-01	-4.85E-03	-2.47E-05
	5	2.84E-01	-1.34E-03	-9.22E-06
	6	8.20E-02	-1.39E-04	-6.56E-06
34	2	2.48E+00	-4.14E-02	5.03E-04
	3	1.55E+00	-3.49E-02	4.36E-04
	4	7.72E-01	-3.06E-03	-1.12E-05
	5	2.97E-01	-1.71E-03	-3.55E-06
	6	1.54E-01	-6.72E-04	-4.63E-06

Table 7.2 Regression Coefficients for Equation 3.5

Run No.	Coefficient		
	D	E	F
1	5.32E+01	-9.95E-02	3.34
2	4.04E+02	7.88E-02	5.51
3	3.82E+02	6.23E-02	5.33
4	n/a	n/a	n/a
5	8.13E+01	-1.61E-02	3.49
6	7.41E+02	1.09E-01	6.08
7	2.01E+02	4.63E-02	4.33
8	2.97E+02	3.73E-02	4.55
9	3.21E+02	6.20E-02	4.91
10	1.49E+02	4.69E-02	4.16
11	1.19E+03	1.22E-01	6.55
12	1.31E+02	-4.42E-02	3.67
13	8.23E+01	-6.08E-02	3.46
14	7.75E+01	-1.59E-02	3.41
15	1.73E+02	2.15E-02	4.26
16	3.01E+02	7.60E-02	4.72
17	3.43E+02	4.61E-02	5.46
18	1.21E+02	-9.62E-03	3.68
19	2.13E+02	2.33E-02	4.27
20	2.25E+02	3.09E-02	4.57
21	9.07E+02	1.07E-01	6.28
22	2.77E+02	3.65E-02	4.43
23	4.62E+01	-6.21E-02	2.97
24	1.22E+02	8.07E-03	3.74
25	3.04E+02	8.25E-02	5.39
26	5.63E+02	8.77E-02	5.44
27	1.32E+02	2.12E-02	3.97
28	3.11E+02	7.94E-02	5.07
29	4.66E+02	1.13E-01	5.59
30	2.54E+02	7.99E-02	4.73
31	2.53E+02	7.03E-02	4.91
32	5.17E+02	8.93E-02	5.50
33	5.10E+02	8.53E-02	5.59
34	1.64E+02	5.21E-02	4.53