THRESHING PEA BEANS WITH ROUGH-SURFACE BELTS HAVING SPEED DIFFERENTIALS

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ABSTRACT

THRESHING PEA BEANS WITH ROUGH-SURFACE BELTS HAVING SPEED DIFFERENTIALS

By

Mehmet Yener Tulu

A threshing belt system was designed and constructed by using strong textured rubber belts with a rough surface and four flat pulleys. The main objective was to reduce the threshing losses which are encountered in conventional combines' cylinders, by replacing impact methods of threshing that are used in conventional combines, with rubbing action of threshing belts. The threshing belt system which was tested in this study was assumed a model with small capacity and small dimensions. The width of the belt was 12 inches, and contact length of belts was 33 $\sim$ 34 inches. Diameters of the drums were 4 1/2 inches.

Tests were made for 36 bean samples taken from storage, and the samples were dry, harvesting moisture, and damp moisture content groups. Bean samples were artificially treated by water to get the above mentioned moisture content groups.

Speed ratios are defined as upper belt speed over lower belt speed, and were established at 1.5, 2.0, 2.5 and 3.0. The same direction of movement was provided for both

belts. Upper belt speeds were adjusted to the values of 1.25 ft/sec, 2.5 ft/sec, and 4.33 ft/sec by using variable speed device.

Four speed ratios gave four different lower belt speeds for each upper belt speed. Thus there were 12 different speeds for three different moisture contents. Clearance was 1/4 inch for all the tests.

The damp beans (30% or more moisture content) had poor efficiencies for all speed ratios and belt speeds. Nevertheless, with proper design of the system, efficiency for damp beans could be increased.

It was decided that the speed ratios for threshing belts should begin from 2.5 as a lower limit, since the efficiencies for all moisture contents were unsatisfactory for practical purposes for the values of speed ratios lower than 2.5.

The efficiencies of harvesting moisture content, and storage-dry beans were high (100% or near to 100%) for speed ratios 2.5 and 3.0, even for high values of belt speeds, at which the system had more capacity than the lower values of belt speeds.

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CHAPTER I

INTRODUCTION AND OBJECTIVE

Harvesting of the crops is one of the most important aspects of our civilization's oldest industry, agriculture, from the earliest time of its appearance. Harvesting is composed of two main actions, namely, cutting of the crops, and threshing.

Old conventional means of cutting was sickle and scythe. Threshing used to be done by flails. These devices are still used in some countries of the Old World and, mostly in underdeveloped countries. In the United States, which has the most advanced technology of the 20th century, they were used to a limited extent until 1912 (9). In our days, the greater part of the world's grain and other agricultural products are still harvested by the old means.

In the first quarter of this century, like other agricultural machines, combines have become one of the most important benefactors of the farmers.

Combines were used mainly in harvesting of cereals in their early days. Later, the necessity arose for other crops and agricultural products, such as clover, cotton, corn, potatoes, beets, cucumbers, etc. For these crops and products, investigators either have built new machines or adapted the combines for required purposes.

Adaptation of combines for new products have brought many changes and new ideas, but threshing and separating mechanisms have not undergone essential changes. These adaptations of combines have caused some deficient operations of threshing mechanisms, while they were sufficiently efficient for cereals. The main problem of the threshing mechanism was the high losses of the threshing process.

Some work has been done to adapt the combines for beans; but these have the same deficiency, i.e., high loss rate, as other adapted machines for other agricultural products.

There are mainly four ways to obtain threshing force:

1. Impact (Impulsive Acceleration)
2. Stripping
3. Non-Impulsive Acceleration
4. Rubbing.

The objective of this study was to develop information for bean threshing, evaluate design factors by using different speeded rubber belts, in which rubbing action takes place. These rubber belts will replace the cylinder in conventional combines.

The author hopes that his findings would contribute to develop efficient and improved threshers in the future.

CHAPTER II

REVIEW OF LITERATURE

History of Combines

As indicated in the introduction, the first tools used for threshing were staffs and flails. The farmers in early times used to work by hand in agricultural operations. They harvested their agricultural crops differently, that is, they used to have different operations for different crops. However, principles of these operations did not differ too much. In some primitive societies, even animals were used to take off the seeds from the heads by simply treading the material to be threshed.

Of course the flail was more advanced than the staff, since, the free swinging shorter member resulted in more threshing capacity than the staff. Its invention dates back, but when, is unknown.

The flail is still used in many countries. Church and Dieffenbach (1949) mention about sledge type threshers. It is described as a thick plank or sledge drawn by oxen or horses, and having inserted upon its under surface pieces of stone, flint or iron, projecting from three-quarters to half an inch, by which the ears of grain are torn asunder. This type of threshing method is still used in Spain and other Middle East countries. In Turkey this type of threshing is very common.

Turkish farmers still prefer to use sledge type threshers rather than combines. In Turkey, straw is the main fodder to feed the animals. Combines were first introduced in 1950 on a large scale in Turkey. Farmers accepted combines with great enthusiasm, but they could not feed their animals with combined straw, since it has sharp edges, whereas, the sledge type threshers used to give soft straw. And now, farmers who have combines use a sledge type thresher to soften the straw after the combine's operation. This situation is unthinkable for modern countries.

Church and Dieffenbach (1949) say that the first threshing machine was made by Jethro Tull of Shelborne, England, and was not successful. Michael Menzies' threshing machine was successful which was built in 1732 and water powered.

The Industrial Revolution, which is defined as the change in social and economic organization resulting from the replacement of hand tools by machine and power tools and development of large-scale industrial production, has brought some changes in agriculture and in harvesting processes.

In the nineteenth century many people worked on threshing machines. They tried to use horse, water, and steam power. These early machines were huge, and unmovable stationary threshers. However, some inventors produced portable machines, but these were only stationary machines built on wheels to move the threshers from one place to another. They were not operating in the field like today's combines (6).

Nyberg (1957) indicates that the first patent on reaping and threshing machine was issued to Samuel Lane of Hallowell, Michigan, in 1828. This shows that the idea of combined reaping and threshing machines is 140 years old.

Moore and Hascall of Kalamazoo, Michigan, built a combine which was pulled by twenty horses and cut a fifteen-foot swath in 1835. This machine was patented in 1836. Moore and Hascall tested their machine which harvested 800 acres during the 1854 season and finally burned from an overheated bearing.

These early types of combines could not make progress and gain popularity among the farmers. They were pulled by horses and were ground-driven from a bull-wheel.

The new harvesting method by using combines did not become commercially established until 1880.

In 1887 a twenty-two foot steam powered machine was built in California by Berry. It was capable of harvesting fifty acres a day with a six man crew. When it was rebuilt and equipped with a forty-foot cutter-bar, its capacity was increased to ninety-two acres with the same crew (22).

Khan (1952) says that the combine was not considered useful in its early days because of the belief that the weather conditions would not permit its usage in any other place than the Pacific Coast. The machines which were used in the Pacific Coast and Great Plain states were large and much more suited to the large scale farming of the West. The great demand for the combines from the Eastern states which had small acreages pushed the manufacturers to produce new machines suitable for those states. As a result, small size combines ranging from five to eight feet of cutter-bar were manufactured.

In 1912 internal combustion engines were used in combines. Power-driven machines first appeared in 1939.

Lalor (1962) mentions a combine which was built in Australia around 1920 and brought to the United States and Canada in 1924. This machine merely stripped the heads from the standing crop and left the straw after it. Lalor also states that such a mechanism was described by Pliny in the first century as being at work in the fields of Gaul, and Palladus also mentioned a similar machine in the fourth century.

Khan (1952) reports that the combines were introduced to Midwestern states between 1925 and 1928. In

Michigan it was in 1927. Their number increased very rapidly in Michigan. In 1927 there were seven, in 1928 thirty-three, and in 1929 fifty-four combines in Michigan. In these first three years combining was not promising. Small fields and grain acreages, diversified crops, the need of straw for livestock bedding, and unfavorable weather conditions were the main reasons for this result.

Development and Studies

Lalor (1962) indicates that it is difficult to determine the exact time when the combine was first used to harvest crops other than the cereals. However there are many references about the usage of combines for peas, beans, clover, the grasses, and corn. To be able to use combines for these crops many modifications had to be made on the mechanism of the machines. Namely, the straw rack was enlarged to handle greater volumes of straw, pick up attachments were developed to harvest windrowed crops, and the cleaning system was adapted to handle the larger amounts of damp, green material often associated with some of the crops harvested.

Most of these modifications were the result of the great demand of small farmers. They had small capital and had to confine one type of crop to reduce the machinery investments. This situation was not wide spread, therefore there was a need for universal combines which would be suitable for several crops. Such a machine was built by Harry Ferguson Company (10). This "multipurpose, semi-self-propelled harvester" was tractor mounted, designed for quick attachment, and was intended to perform the functions of corn, grain, and forage harvesters.

Many research studies have been conducted by Americans and Europeans on threshing. Some of them were new designs, and some of them factorial studies of the existing machines to improve their performances.

Wessel (1960) worked on a conical rotor threshing mechanism. Buchele (1959) built and patented a machine called "Threshing Cone" similar to this conical rotor mechanism. At the same time he also developed a machine that achieved threshing by rubbing the material along the inside of a perforated cone by means of flaps attached to a rotating shaft and pressed against the material by the resulting centrifugal force.

Lalor (1962) evaluated the design parameters of Buchele's Threshing Cone. He states that the hundred per cent efficiency could be expected if correct selection of the slot angle was made. The feeding mechanism was found to be functionally deficient at low speeds (350 rpm), and improvement should be done in this mechanism if the machine will be used in practice. This machine is not versatile, and it is not economical to have different cones for different crops.

Lalor and Buchele (1963 and 1963) have published two articles about the threshing cone, and Lamp and Buchele (1960) analyzed impulsive and non-impulsive methods of threshing.

Lamp (1959) studied the threshing of wheat by centrifugal forces. He made extensive laboratory tests to determine the factors affecting the threshing of grain. The research shows that there are numerous factors to be determined and functions should be improved. In his machine, damage rate to the grain was high.

Some research has been done on damage to grain. Kolganov (1952) showed that the mature grains are much more vulnerable to damage than the immature ones. Kolganov says that the greatest damage was caused to that grain which had a large absolute and specific weight, which means to the good quality grain.

DeLong (1942) found that more mechanical damage was done to grain by rasp-bar cylinders than by either angle-bar or spike-tooth types. The spike-tooth cylinder was found to do the least harm. He concluded that the rubber-faced angle-bar had a slight advantage, in that it accomplished adequate threshing without causing excessive kernel damage.

Bunelle _et al_. (1953) found that the peripheral speed of the cylinder was the most important variable affecting seed damage for small seed legumes. The amount of seed damage was found to decrease when the cylinder-load increased; when the straw was leafy and had a high moisture content, similar results were found. The threshing efficiency was found to be low at cylinder speeds of 5000 feet per minute which did not damage the seed.

There have been some work done on bean harvesting by combines. These researches mostly aimed to reduce the harvesting losses of combines.

Asher (1951) conducted a research on the adaptation of the combine to the harvesting of navy beans. He found that for bush-type beans the direct harvesting method is the best, since it minimizes weather risk, reduces labor cost, and for the vine-type bean the best method to be used under good weather conditions is the pulling, wind-rowing, and combining method. Under unfavorable conditions the direct combining method may be used to an advantage on vine-type beans, because the losses incurred are beans which would ordinarily be picked, since they are in contact with the soil and mold readily, or are subjected to weather damage. He concludes that the use of the flat guards was found to be advantageous since the threshing losses at the cutter-bar were reduced. He suggests the use of the Hume reel for the combine in forcing the feeding of the material to the machine.

Khan (1952), in his study about the efficiency of harvesting navy beans with a combine, gives loss characteristics of the combine in detail. Efficiency and loss are given as follows:

$$\text{Per cent Efficiency} = \frac{\text{Net Yield X100}}{\text{Preharvest Yield}}$$

$$\text{Per cent Loss} = \frac{\text{Loss X100}}{\text{Preharvest Yield}}$$

His experiments showed that the wet crop had a very poor net yield, recovering only 50.74 per cent preharvest. The cutter-bar loss was 0.9 per cent in wet and 0.41 per cent in dry crops. The cylinder loss increased in the windrow method by 3.15 per cent. Although the Hume reel has a higher shatter loss, he suggests its use since it balances this amount by picking up more pods.

Asrar (1967) and Tabiszewski (1968) worked on converted Lilliston Peanut Combine for pea beans. The purpose of their studies were to develop the threshing characteristics of this machine for pea beans.

Gunkel and Anstee (1962) conducted direct-harvesting experiments at Cornell University, Ithaca, New York in 1961 and 1962. They used various mechanisms designed to pull the plant from the soil.

Bolen (1968) worked on the application of hydraulics to the direct harvesting of edible beans.

His mechanism consisted of two hydraulicly-driven, virtually horizontal, overlapping 13 1/2 inch disks, in opposite directions at speeds ranging from 400 to 700 rpm and 500 to 1000 rpm.

This mechanism provided minimum shattering losses of the pods. Gathering losses were proportional to operating height and decreases as operating height was lowered. Also the horsepower required to operate the disks was directly proportional to the operating height, so that as the operating height was lowered, the required horsepower increased.

McColly (1958) states that the fall rains and foggy weather are major hazards for bean harvesting operations. He also indicates that the reciprocating cutter-bar cut into too many pods, and any bean pod cut into immediately pops open hence most of the beans are lost. The finger type reel will lift some pods above the sickle and reduce bar loss by fifty per cent.

Perry and Hall (1965) conducted experiments to determine the mechanical properties of pea beans under impact loading. The important result that they have found is less amount of permanent deformations to the beans (2.7 per cent), temporary deformations averaged 21 per cent.

Saul and Hukill (1968) (23) designed and built an experimental corn shelling mechanism at Iowa State University. The key components of the new shelling unit are dual rubber belts and floating springs. The rubber belts turn in opposite directions, rolling the ears of corn through the unit and shelling the ears with a squeezing action.

It is expected to reduce damage by ninety to one hundred per cent by using this mechanism. The floating springs automatically adjust the sheller to the diameter of the ears of corn as they pass between two rubber belts.

This unit gave very good results in laboratory tests, in which corn with 15 per cent moisture was shelled. If it proves as successful for 20 to 30 per cent moisture range which is the harvesting moistures for fresh corn, the principle can be easily incorporated in mechanical corn pickers.

LeBaron (1968) (22) explains their machine as more efficient than the machines presently being used for bean seed plot harvester.

This machine has two rubber belts, one of which travels at a slightly faster speed than the other, but both of them in the same direction. With these characteristics, this machine is similar to the device constructed at Michigan State University than any other.

LeBaron says that this new machine is able to thresh the "peanuts," and increase the efficiency of the threshing operation. "Peanuts" are defined by the industry as the broken segments of bean pods containing seed.

Bean Production in Michigan and the United States

Khan (1952) and Bolen (1968) give some statistical data about the bean production in Michigan and in the United States.

Pea beans is one of the most important cash crops for Michigan's farmers. Between 1959 and 1964, 40 per cent of the national edible bean acreage was harvested in Michigan, and 39 per cent of the national edible bean production was produced in Michigan.

For the same period (1959-1964) Michigan produced 99.4 per cent of all pea or navy beans, 58.5 per cent of all cranberry beans, and 27.8 per cent of all red kidney beans of the United States. In the state 91 per cent of the total production was navy beans, and 6 per cent of the total production was red kidney beans.

Average production of the six-year period for the United States was 18,481,000 cwt and for Michigan 7,267,000 cwt. These figures show the importance of bean production for Michigan and the United States.

CHAPTER III

TEST APPARATUS

Test apparatus was constructed in the Research Laboratory of Michigan State University Agricultural Engineering Department.

It mainly consists of two belts and four flat pulleys, two of which are drivers (F in Figure 1), and the other two driven (G in Figure 1). Three supporter rollers were placed before the tests (Figure 1). This system was mounted on a wooden frame (Figure 2).

A thin metal feeding mechanism was placed before the driver flat pulleys (A in Figure 2 and Figure 3). It was positioned on an incline, so that it would allow the material to slide down to the space between the belts by gravitation. However, this proposed functioning of the feeding mechanism was poorly achieved, so it merely helped to prevent any probable accident during experiments.

A collecting pan, made of wood, was placed under the lower belt (G in Figure 2 and Figure 4). An additional inclined wood plate was placed before the driven flat pulleys to prevent the scattering of the beans during tests. A sack was attached to the collecting pan to gather the threshed material (F in Figure 2 and Figure 5).

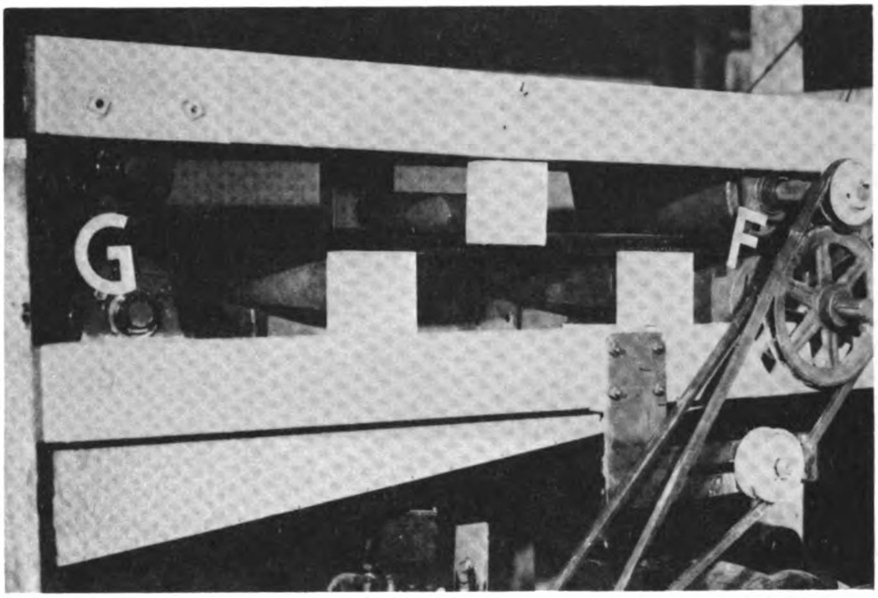

Figure 1.--Main Part of the Threshing Mechanism

F = Driver Flat Pulleys
G = Driven Flat Pulleys

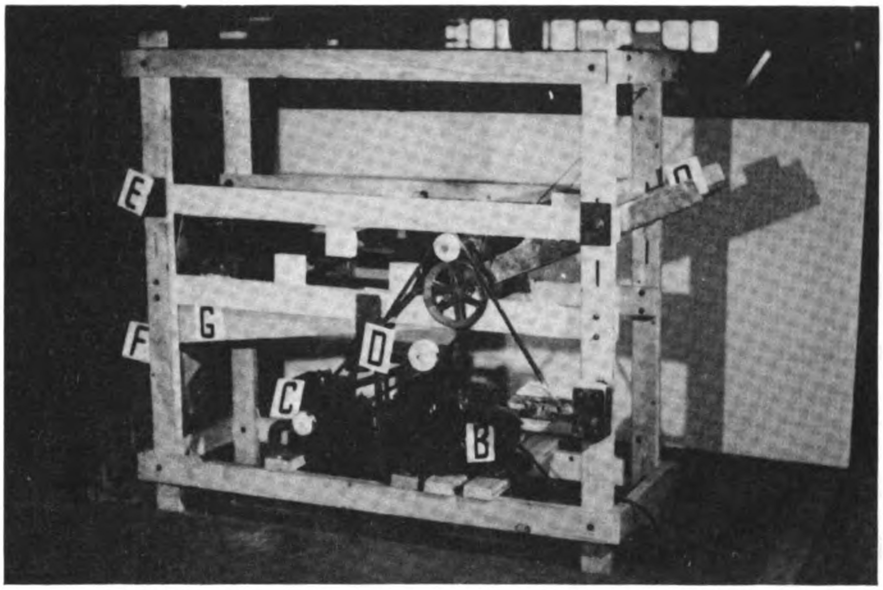

Figure 2.--General View of the Threshing Mechanism

A = A Thin Metal Feeder
B = Auxiliary Motor
C = Electric Motor with a Variable
    Speed Device
D = Transmission Mechanism
E = One of the Four Bolts to Adjust the
    Clearance
F = Sack
G = Collecting Pan

Since it was a necessity to have different speeds for the tests, an electric motor with a variable speed device was used as a power source (C in Figure 2). In addition to this, an auxiliary electric motor was placed beside the previous one, but never has been used in the tests (B in Figure 2).

Power transmission was provided by using pulleys and V-Belts. It was desired to have movement of the threshing belts in the same direction, therefore open and crossed-belt drive were used to limit ourselves to only one power source (D in Figure 2, and Figure 6).

Flat pulleys were attached to the frame by using rolling bearing shafts. Driver flat pulleys have 7 inches extension of shaft on which to attach the pulleys. Diameter of the flat pulleys is 4 1/2 inches, and diameter of the shaft is 1 inch (Figure 7).

Threshing belts which were the main elements of the threshing mechanism were made of rubber and have a strong texture and rough surface (Figure 8). Width B of the belt was 12 inches (Figure 9), and contact length L was 33 or 34 inches (from center of driver flat pulley to the center of driven flat pulley. Thickness of the belt was 3/8 inches, 3/16 of this thickness was constituted by tooth-like projections. Contact length depends upon the tightness of the belt. Figure 10 gives the detailed dimensions of the belt design.

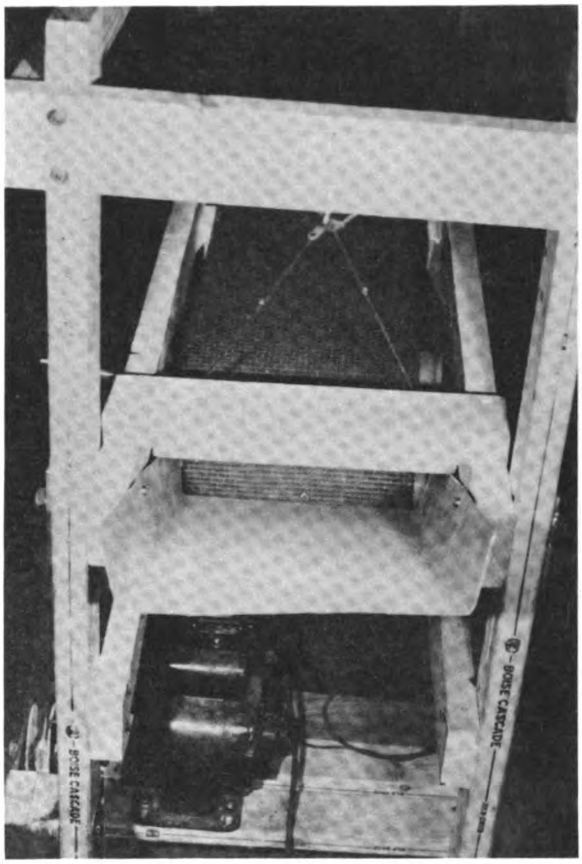

Figure 3.--A Thin Metal Feeding
Mechanism

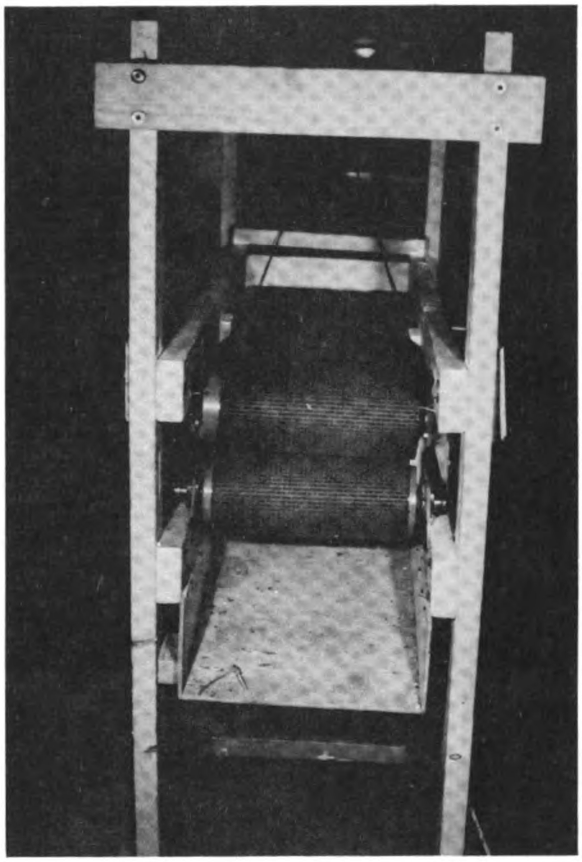

Figure 4.--Collecting Pan

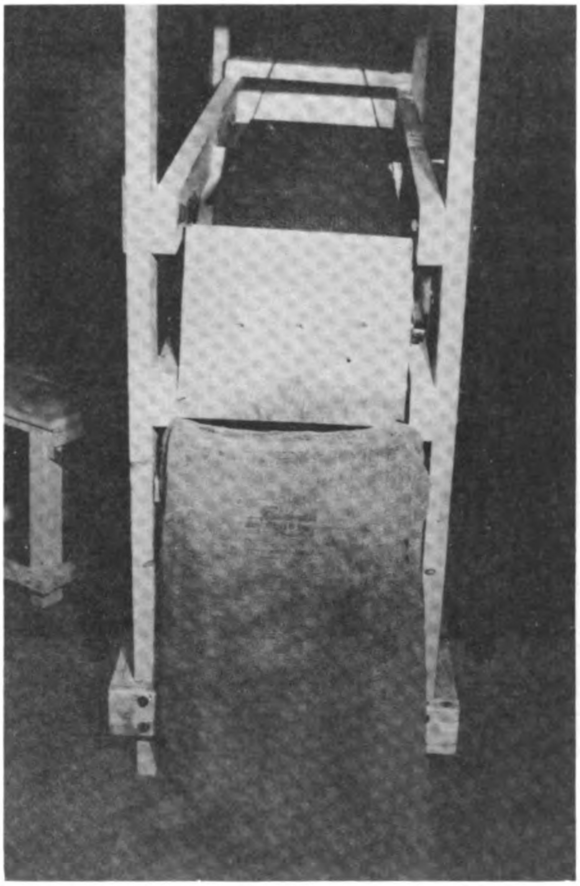

Figure 5.--An Inclined Wood Plate and a Sack Attached to the Collecting Pan

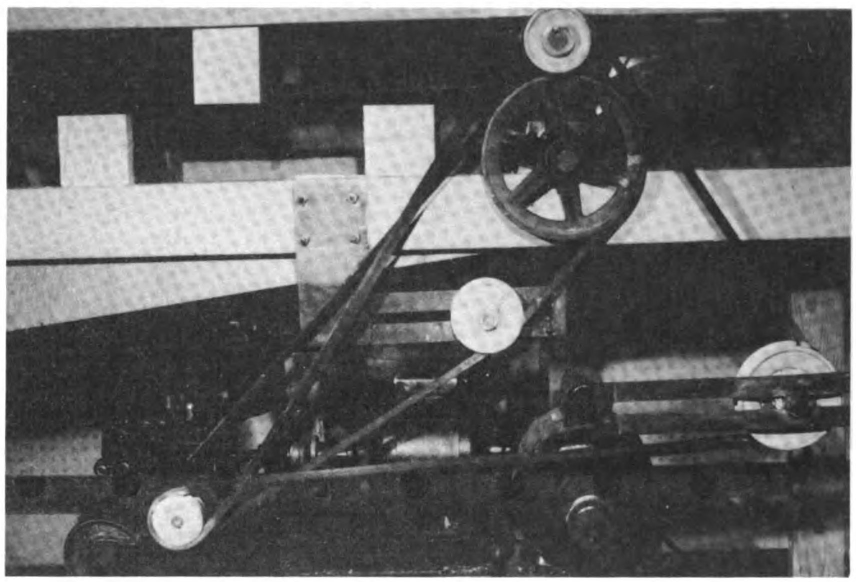

Figure 6.--Transmission Mechanism: Open and Crossed-Belt Drive, Pulleys, and Idle Pulleys
(In this arrangement n = 2.5)

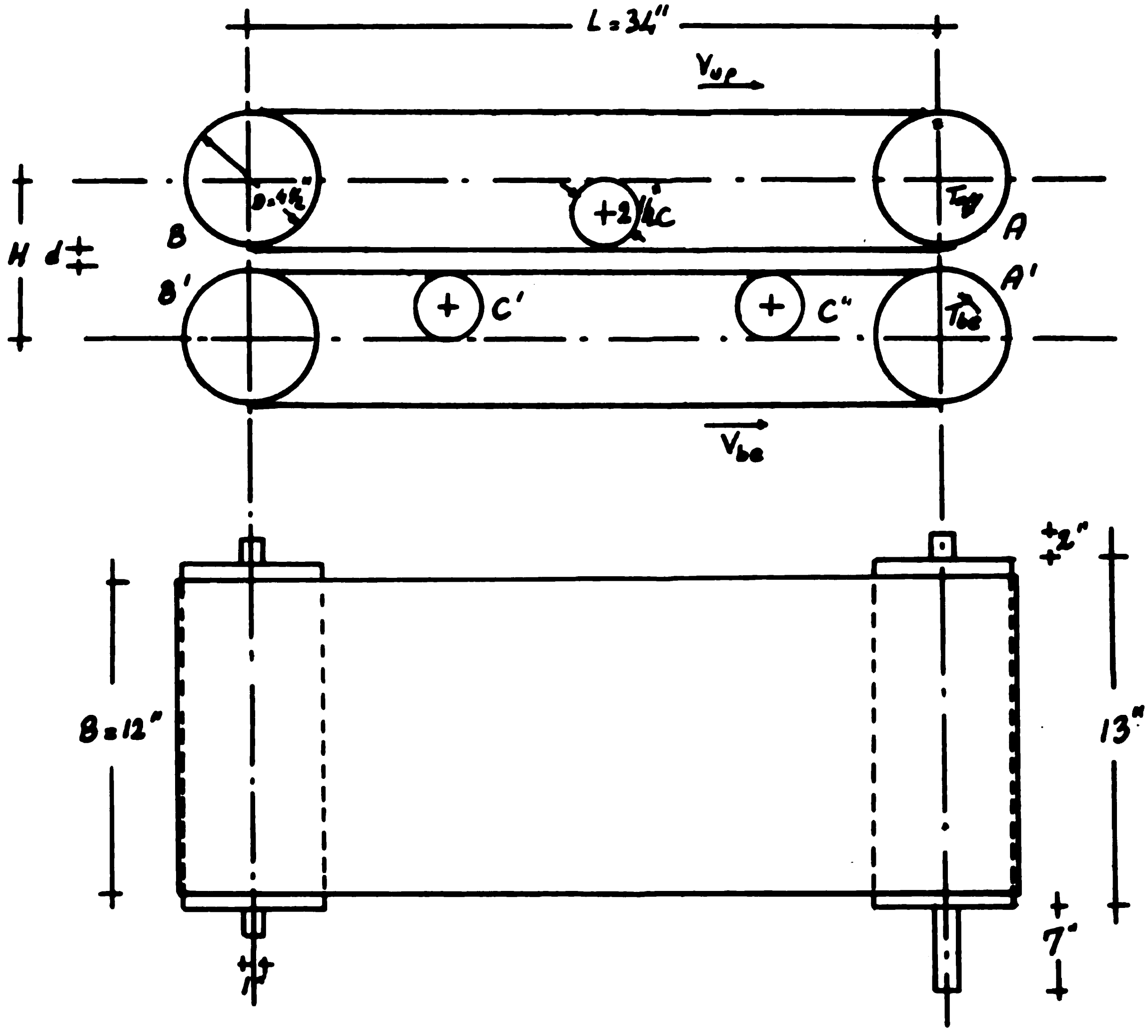

Figure 7.--Dimensions of Belt System

L = Contact Length of Belts
D = Diameter of Flat Pulleys
A&A' = Driver Flat Pulleys
B&B' = Driven Flat Pulleys
V_{up} = Velocity of Upper Belt
V_{be} = Velocity of Lower Belt
C,C',&C" = Supporter Drums
d = Clearance
T_{up} = Torque of Upper Driver Flat Pulley
T_{be} = Torque of Lower Driver Flat Pulley
H = Distance Between Upper and Lower Flat Pulley Axes

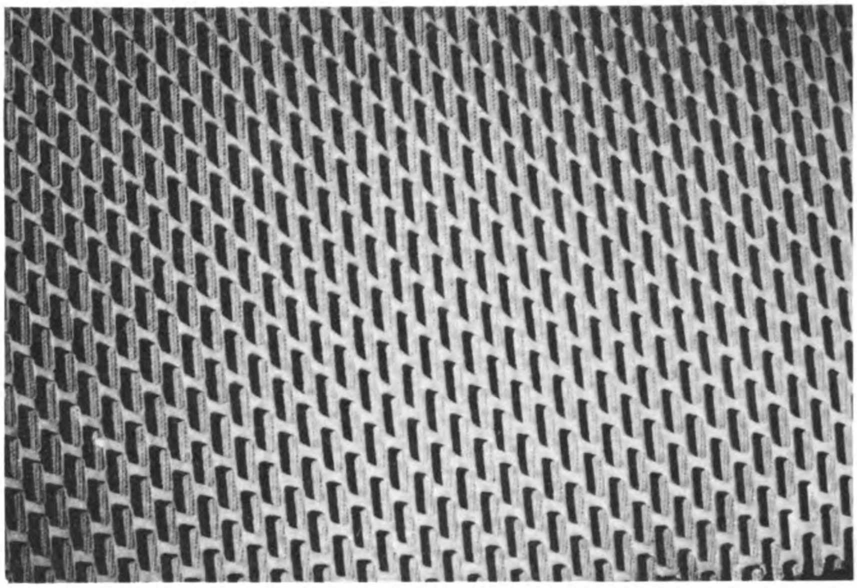

Figure 8.--Design of Belt Surface (Long sides of projections perpendicular to the direction of travel)

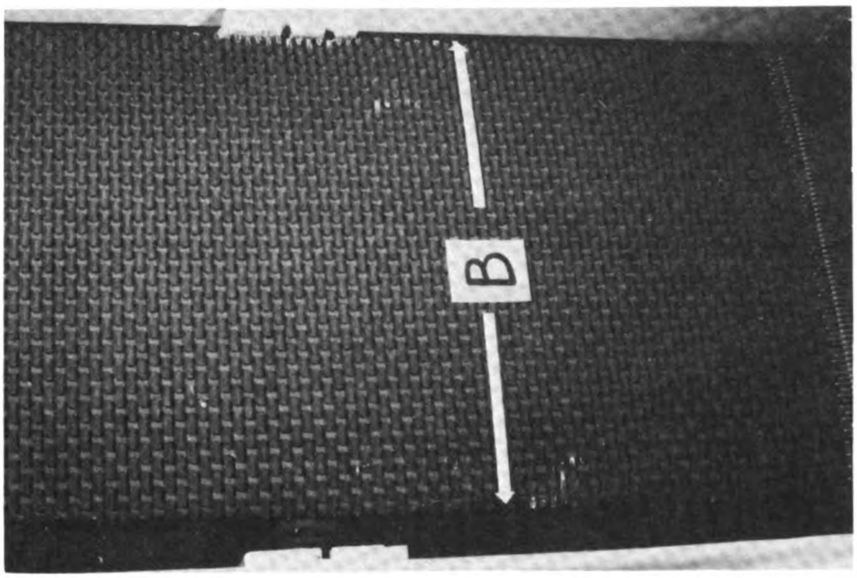

Figure 9.--Width of Belt
(B = 12")

The lower belt was fixed, it was immovable, but the upper belt was adjustable vertically, to be able to change d = clearance (distance between the adjacent surfaces of the lower and upper belts). This simply is done by loosening the bolts, and moving the wood beams up or down. E in Figure 2 shows one of the four bolts to do this.

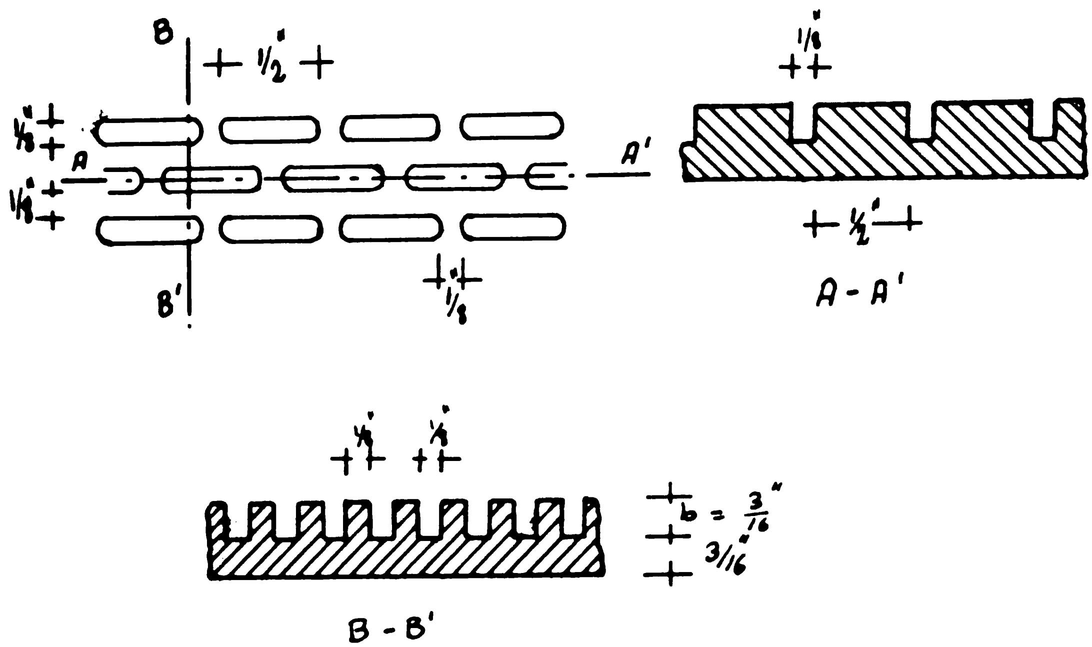

Figure 10.--Details and Dimensions of Belt Design

CHAPTER IV

MODE OF OPERATIONS OF THRESHING BELTS

Threshing belts with speed differentials are proposed for use in combines, in place of cylinders, for beans (Figure 11).

In a conventional combine, the cylinder is the threshing unit. It causes high losses for beans and some other crops. Some studies have been conducted on combines and their cylinders on how to reduce these high losses. Since the threshing principle of a cylinder is impact (Impulsive Acceleration), high loss rates prevail and thus remain the unsolved problem.

Some other principles rather than impact are required to get a more efficient threshing device. The idea of threshing belts has arisen upon the belief that the rubber action, instead of impact would give sufficient results for bean threshing and with some modifications for the other crops.

Threshing belts move in the same direction; one of which is slower than the other (Figure 7). The upper belt moves faster than the lower. While the belts move, material to be threshed is fed in the direction of the movement of belts. This material is squeezed by the

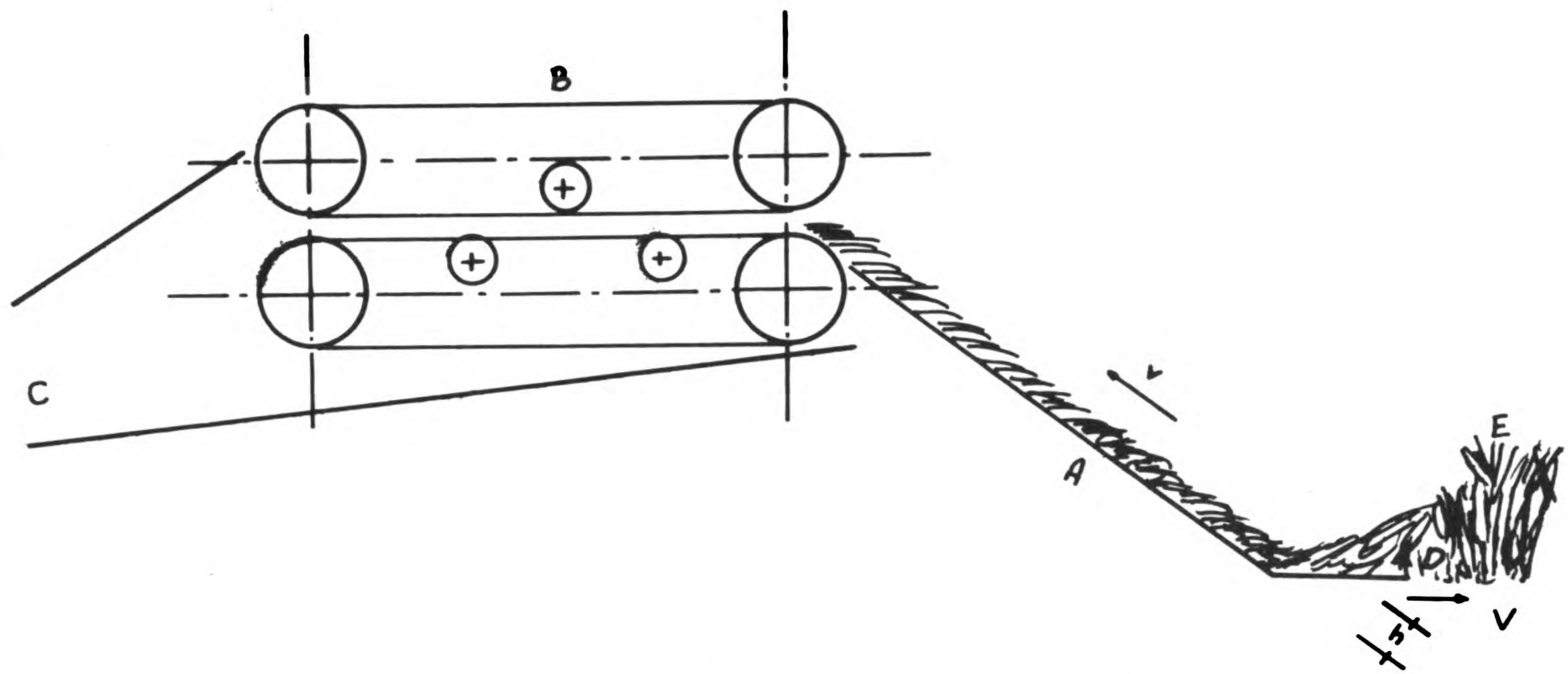

Figure 11.--Schematic View of the "Threshing Belts" in a Combine

A = Feeding Platform
B = Threshing Unit
C = Collector
D = Cutter

h = Thickness of Oncoming Material to the Threshing Belts
V = Velocity of a Combine
v = Velocity of Oncoming Material to Threshing Belts

compression of the belts. This compression, assumed to be uniform throughout and normal to the contact surfaces of the belts, causes a friction force between the material to be threshed and the rubber belts due to the high friction coefficient between rubber belts and beans.

The rubbing action of belts on the material opens the bean pods, while the material is conveyed toward the outlet. Thus threshing is completed.

There are three possibilities for the direction of movement of belts:

1. Belts are moving in the same direction with speed differential,
2. One belt is stationary, the other is moving,
3. Both of the belts are moving, one of which is in an opposite direction, provided with speed differential.

The last two arrangements of direction of movement have more rubbing action than both belts moving in the same direction, which was handled in this study.

In these two later cases rubbing action lasts longer. Longest is the opposite directed motion of the belts. Of course we can say this, if we have comparable speed values for the three cases.

Our tests were conducted with two belts moving in the same direction, since it is required to have an aggressive system. The other two possibilities have more rubbing action with less capacity, but ours has less rubbing action with a comparatively larger capacity.

If the belts move with equal speeds, then the system will not thresh the material. It will work like a conveyor, without a rubbing action.

At this point it is necessary to define a speed ratio (n) as,

$$n = \frac{\text{Speed of upper belt}}{\text{Speed of lower belt}} = \frac{V_{up}}{V_{be}} \qquad (1)$$

provided $n > 1$.

Where:

V_{up} = Speed of upper belt

V_{be} = Speed of lower belt.

The speed ratio (n) will be one of the most characteristic variables of threshing belts.

Another definition is effective speed (V_{ef}), which is the difference between V_{up} and V_{be},

$$V_{ef} = V_{up} - V_{be},$$

by using Equation (1)

$$V_{ef} = V_{up}\left(1 - \frac{1}{n}\right) \qquad (2)$$

The speed of the material (V_{pa}) between the belts relative to some point outside the system would be,

$$V_{pa} = \frac{V_{up} + V_{be}}{2} \quad \text{and Equation (1) gives}$$

$$V_{pa} = \frac{1}{2} V_{up} \left(1 + \frac{1}{n}\right). \tag{3}$$

Equations (2) and (3) show that the duration of the rubbing action is mainly a function of n for a fixed V_{up}. More generally, since V_{up} is adjustable, it is a variable, Equations (2) and (3) are the functions of V_{up} and n.

Increasing n values give increasing V_{ef}'s and decreasing V_{pa}'s or vice versa. This shows that n itself constitutes a big role in the threshing mechanism.

For different n values, separation of beans from the pods occurs at different places from the initial feeding position of the material.

In practice combine's speed will be the main governing factor. The speed of the oncoming material (v) to the threshing belts is a function of the speed of the combine (V) (Figure 11). It will effect the thickness of the oncoming material to the belts, and amount of material to be threshed (Q).

For a fluctuating amount of material (Q) the clearance (d) will be either small or large, and this will result in nonefficient threshing. Irregular feeding will cause accumulation of material between the belts and nonuniform compression of belts.

Since the purpose of the threshing is to remove the bean seeds from the pods, it is important to know how much resistance beans have.

In actual field conditions, the machine will be fed bean pods and stalks, or in other words, with a whole crop. This situation makes the problem more complicated.

CHAPTER V

VARIABLES INVOLVED

As indicated before, speed ratio (n), effective speed (V_{ef}), and V_{pa} were important variables.

If we consider a combine with a threshing belt, then speed of combine (V), speed of oncoming material to the threshing belts (v), and thickness of oncoming material to the threshing belts (h), and the capacity of cutting mechanisms of the combine's cutter (Q) will be the main limiting and governing variables of the system.

The constant dimensions of the threshing belts system are:

L -- Contact length of belts,

B -- Width of belts,

A = L x B -- Contact surface area of belts

D -- Diameter of flat pulleys.

Although these are constant in our system they should be considered as variables, since they are the governing factors of capacity, and performance of our system.

Clearance (d), defined as the distance between the adjacent surfaces of belts, is an important variable, which effects the performance and capacity of threshing belts.

The various speeds of the belts and the material, namely, V_{ef}, V_{pa}, V_{up}, V_{be} and depending on the V_{up} and V_{be}, n, are the significant variables as mentioned before.

The material passed through the belts, which is sometimes called a feeding rats, and sometimes, amount of material to be threshed (Q) is the function of variables, which were mentioned. Besides these variables, μ_γ (rolling friction coefficient between the material and belts), the compression of the belts (P), moisture content of the material (θ), and the resistance of the beans (R_a) (Attachment Resistance), are the other variables which effect the Q.

R_a, attachment resistance is defined as,

$$R_a = \Sigma \text{ (Forces exerted on beans by pods)} \qquad (4)$$

which is an inherent characteristic of the beans.

The forces exerted on the material being fed must be in the sense to overcome R_a to accomplish the threshing.

If we consider a particle between the belts as shown in Figure 12, we can see the forces which are opposite to the R_a are F_u, and F_b, which are the friction force exerted upon a particle by the upper belt, and the friction force exerted upon a particle by lower belt, respectively.

In Figure 12,

$$F_u = \mu_\gamma P \qquad (5)$$

$$F_b = \mu_\gamma N, \tag{6}$$

where $N = P + W$, and

P - Compression of belts

W - Weight of a particle (bean).

It is useful to define a parameter, which is called "Relative Roughness" of the belts system (Figure 13). It is defined as,

$$\varepsilon = \frac{b}{d} \tag{7}$$

Where, ε - Relative Roughness,

b - Height of tooth-like projections of belts

d - Clearance between interior belt surfaces

Relative roughness is a dimensionless parameter, which express the characteristic of belts for a given d (clearance).

Efficiency of threshing belts defined as,

$$\eta = \frac{\text{Amount of threshed bean pods x100}}{\text{Amount of pods oncoming to the threshing belts}} \tag{8}$$

The variables dealing with the power source of the system are the torque of upper driver drum (T_{up}), and the torque of lower driver drum (T_{be}) (Figure 7).

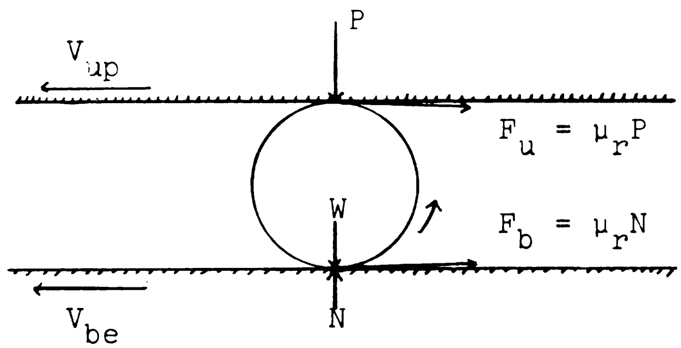

Figure 12.--Forces on a particle between the belts.

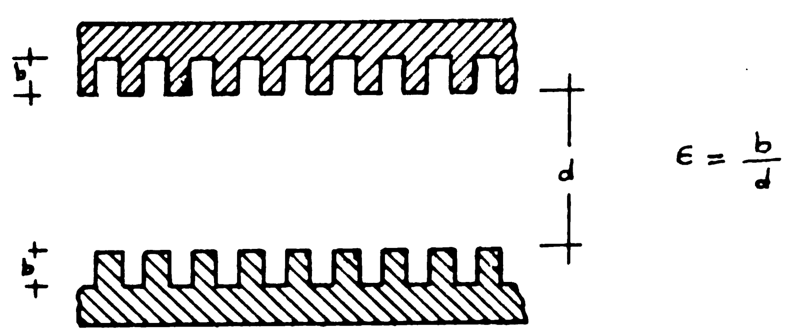

Figure 13.--Definition of "Relative Roughness of Belt System."

CHAPTER VI

FUNCTIONAL RELATIONSHIPS OF VARIABLES

Effective Speed

Effective speed (V_{ef}) is a function of V_{up}, and n as implied by Equation (2). But V_{up} is a function of Q (capacity of cutting mechanism of combine). Therefore V_{up} is a composite function of Q.

$$V_{ef} = f(n,V_{up}) \tag{9}$$

$$V_{up} = f(Q) \text{ gives} \tag{10}$$

$$V_{ef} = F(n,Q). \tag{11}$$

Similarly, Equation (3) gives,

$$V_{pa} = F(n,Q). \tag{12}$$

Moisture Content

Moisture content is an independent variable for our operations with threshing belts. It is a porperty of the crop, which changes with environmental conditions and time. Its value for the beans, normally 24 per cent for harvesting conditions, 14 per cent in a storage, 30 per cent or more when the beans are damp. These values are for the Michigan climate.

$$\theta = f(T, t, \lambda) \text{ where,} \tag{13}$$

T - Temperature of environment,

t - Time,

λ - Relative moisture content of environment.

Relative Roughness and Rolling Friction Coefficient

Equation (7) implies that the relative roughness is a function of d.

$$\varepsilon = f(d)$$

but, $d = f(h)$, and $h = f(Q)$ gives

$$\varepsilon = F(Q) \tag{14}$$

Rolling friction coefficient is the function of belt surface, and the condition of beans' surface which is controlled by moisture content.

$$\mu_\gamma = f(\theta, \varepsilon) \tag{15}$$

Attachment Resistance

This variable is almost undefined. It is a function of many unknown factors. Moisture content is the most predominant one.

$$R_a = f(\theta, \ldots\ldots)$$

Equation (13) gives,

$$R_a = f(T, t, \lambda, .) \qquad (16)$$

Friction Forces

Friction force exerted upon a particle by the upper belt is a function of P and μ_γ. Equation (5) implies,

$$F_u = f(P, \mu_\gamma)$$

Equation (15) implies,

$$F_u = f(P, \theta, \varepsilon). \qquad (17)$$

Similarly for the lower belt, Equations (6) and (15) gives

$$F_b = f(P + W, \mu\gamma), \text{ and}$$

$$F_b = f(P + W, \theta, \varepsilon). \qquad (18)$$

Discharge-Feeding Rate

Discharge is proportional to the product of V_{pa}, clearance, width of belt, density of material, and time.

$Q \sim V_{pa} \times d \times B \times \rho \times \frac{1}{t}$, where ρ is density of material to be threshed.

$$Q = f(V_{pa}, d, B, \rho, h, \mu_\gamma, t).$$

Equation (12), $h = f(V)$, $d = f(V)$, and (15) results in,

$$Q = F\ (V,\ n,\ B,\ \rho,\ \theta,\ \varepsilon,\ t). \tag{19}$$

Efficiency

Efficiency depends on the performance characteristics of the machine. Generally it is a function of effective speed, rolling friction coefficient, and compression.

$$\eta = f(V_{ef},\ \mu_{\gamma},\ P)$$

Equations (11) and (15) gives,

$$\eta = F(n,\ V,\ \theta,\ \varepsilon,\ P). \tag{20}$$

CHAPTER VII

MOVEMENT OF THE BEAN PODS AND BEAN POD-SHAPED OBJECTS BETWEEN THE BELTS

It was desirable to observe how the bean pods and bean pod-shaped objects moved and behaved between the belts, when the belts were in motion.

To do this, storage-dry bean pods and 3/8 inch diameter, 2 1/2 inch long rubger and wood cylinders were run through the belts. The clearance was 1/4 inch (from a tooth-like projection to the other), and the movement of the upper belt was manual, while the lower belt was stationary.

When the rubber and wood pieces were perpendicular to the direction of movement, they smoothly turned, without changing their direction. When they were parallel to the direction of movement, the wood piece did not change its orientation, but due to the compression of belts, it slid on the lower belt, whereas the rubber piece assumed very complicated positions, and finally its position became perpendicular to the direction of movement.

A wood prism 3/8 inch square by 2 1/2 inch long was run through the belts. It showed the same situations as the cylindrical wood pieces did.

Storage-dry bean pods were easily opened between 5 to 10 inches from the beginning point. At the outlet end of the belts, the pods were found to be broken into pieces and the seeds were free. Orientation of pods did not make so much difference, but the pods which were parallel to the direction of movement took a little longer time and distance to be opened from the beginning point (about 20 inches from the beginning). The pods, which were parallel to the direction of movement behaved the same as the wood pieces, but later they became folded and then cracked, to let the seeds free.

The pods, which were neither perpendicular nor parallel to the direction of movement, changed their position to the perpendicular case and were threshed. Wood and rubber pieces proved the same situation. Not one of the objects or beans fell from the sides of the belts, when either perpendicular or parallel to the direction of movement. While they were changing their position to the parallel case, they moved on a parallel line to the direction of movement. This situation was undoubtedly a result of the belt design.

CHAPTER VIII

PROCEDURE FOR THE TESTS

Tests were run for three different moisture contents (θ) of one variety of pea beans at four different speed ratios (n), for three different values of speed of upper belt (V_{up}). This resulted in 36 runs.

Moisture Content (θ) Determinations

Moisture content (θ) of the beans was determined by using wet basis,

$$\theta = \frac{\text{Wet Weight - Dry Weight}}{\text{Wet Weight}} \times 100 \qquad (21)$$

with results in per cent.

Since the harvesting time for beans was over, the moisture content values corresponding to the harvesting and damp conditions of the beans were constituted artificially. To simulate these moisture contents, the beans were moistened by soaking them in the water and keeping them in containers covered by plastic sheets. They were left for 12 hours in the containers and then left open to the atmosphere to evaporate the excess moisture from the crop before the tests.

The samples taken for bean seeds and straw from storage-dry, harvesting dampness, and damp beans were weighed to have their wet weights, and put into the oven for 72 hours to get the dry weights of each group.

The values of dry and wet weights can be seen in Table 1.

TABLE 1.--Wet Weights and Dry Weights of Samples.

	Wet Weights (lb)	Dry Weights (lb)	
Storage-dry	0.163	0.139)	
Harvesting	0.157	0.122)	--- Bean Seeds
Damp	0.150	0.109)	
Storage-dry	0.130	0.108)	
Harvesting	0.135	0.102)	--- Straw
Damp	0.140	0.099)	

By using Equation (21) and the values in Table 1 we found the moisture contents (Table 2).

TABLE 2.--Moisture Content of Bean Seeds and Straw.

	Moisture Content (θ), Per Cent	
	Bean Seeds	Straw
Storage-dry	14.7	16.9
Harvesting	22.3	24.5
Damp	27.3	29.3

Speed Ratio (n)

It was assumed that there would be no threshing of consequence for n = 1.0. Therefore tests began with n = 1.5 and proceed with n = 2.0, n = 2.5, and n = 3.0. These speed ratios were provided for by changing the pulley size of the lower belt's driver flat pulley for each n. As can be understood from the statement just made, the upper belt's speed remained unchanged throughout the tests.

Measurement of Speed of Belts

Speeds of the upper belt pulley shaft were measured by using "BIDDLE" tachometer.

The relationship given by "BIDDLE" is,

$$S = \frac{1}{2} \times r \text{ ft/min or } S = \frac{1}{120} \times r \text{ ft/sec}, \qquad (22)$$

where,

S - Peripheral Speed (Speed of upper belt in our case), (V_{up}),

r - rpm shown by tachometer.

The variable speed device was adjusted to give r = 150, r = 300, and r = 520 rpm for the upper belt.

Equation (22) led the V_{up} values as,

$r = 150 \quad : \quad V_{up} = 1.25$ ft/sec

$r = 300 \quad : \quad V_{up} = 2.50$ ft/sec

$r = 520 \quad : \quad V_{up} = 4.33$ ft/sec

Table 3 shows the corresponding values of V_{be}, V_{ef}, and V_{pa} for V_{up} s at four different n values.

Clearance (d)

Although clearance is one of the important variables of the system, it was kept essentially constant during tests. The value of clearance (d) was 1/4 inch (from a tooth-like projection to the other). For the values of d smaller than 1/4 inch, the beans were cracked, and greater than 1/4 inch, there were no threshing. The reason for this was the inconvenience of the feeding mechanism, which was manual and non-uniform for consistent feedings.

TABLE 3.--Corresponding Values of V_{be}, V_{ef}, and V_{pa} for V_{up}s at Different n Values.

V_{up} (ft/sec)	1.250				2.500				4.330			
n	1.5	2.0	2.5	3.0	1.5	2.0	2.5	3.0	1.5	2.0	2.5	3.0
V_{be} (ft/sec)	0.833	0.625	0.500	0.416	1.660	1.250	1.000	0.833	2.900	2.160	1.730	1.440
V_{ef} (ft/sec)	0.417	0.675	0.750	0.840	0.340	1.250	1.500	1.667	1.430	2.170	2.600	2.890
V_{pa} (ft/sec)	1.041	0.938	0.875	0.833	2.080	1.875	1.750	1.666	3.610	3.240	3.030	2.835

CHAPTER IX

DATA FOR THE TESTS

For 36 tests, the material passed between the rough belts, and the times for this amount were determined for the harvesting moisture content groups. Q, discharge or feeding rate values were found to be fairly reliable, since the uniform and continuous feeding was not established.

Q and V_{pa} values are tabulated in Table 4. As indicated before Q is the function of V_{pa} ($Q \sim V_{pa} \times d \times \rho \times \frac{1}{t}$).

TABLE 4.--Values of Q Corresponding to the Values of V_{pa}s.

V_{pa} (ft/sec)	Q (lb/sec)
0.833	0.052
0.875	0.073
0.938	0.085
1.041	0.104
1.666	0.150
1.750	0.174
1.875	0.185
2.080	0.198
2.885	0.220
3.030	0.245
3.240	0.260
3.610	0.290

Values in Table 4 show that the relationship between V_{pa} and Q have a linear characteristic.

The efficiencies of each run have been found according to the Equation (8). These values of efficiencies tabulated in Tables 5, 6, 7, 8 and 9 for different factors, n, θ, V_{pa}, V_{ef}, and V_{up} for comparison purposes.

TABLE 5.--Efficiencies Corresponding to the Values of n for Three Different Upper Belt Speeds and Moisture Contents.

θ \ n	1.0	1.5	2.0	2.5	3.0	V_{up}
SD	0.0	7.1	79.0	100.0	100.0	1.25
H	0.0	5.1	59.0	100.0	100.0	ft/sec
D	0.0	0.0	0.0	9.4	28.2	
SD	0.0	3.4	62.0	100.0	100.0	2.50
H	0.0	3.0	43.0	92.0	100.0	ft/sec
D	0.0	0.0	0.0	5.2	20.5	
SD	0.0	0.0	49.0	94.0	100.0	4.33
H	0.0	0.0	34.0	87.0	100.0	ft/sec
D	0.0	0.0	0.0	3.2	14.0	

TABLE 6.--Efficiencies Corresponding to the Values of Moisture Content for Different Speed Ratios and Upper Belt Speeds.

θ	SD			H			D		
V_{up}	1.25	2.50	4.33	1.25	2.50	4.33	1.25	2.50	4.33
n 1.5	7.1	3.4	0.0	5.1	3.0	0.0	0.0	0.0	0.0
η 2.0	79	62	49	59	43	34	0.0	0.0	0.0
2.5	100	100	94	100	92	87	9.4	5.2	3.2
3.0	100	100	100	100	100	100	28.2	20.5	14

TABLE 7.--Efficiencies Corresponding to the Values of V_{ef} and V_{pa} for Three Different Belt Speeds and Moisture Contents.

θ \ V_{ef}	0.417	0.625	0.750	0.834	V_{up}
SD	7.1	79.0	100.0	100.0	
H	5.1	59.0	100.0	100.0	1.250 ft/sec
D	0.0	0.0	9.4	28.2	
θ	1.041	0.938	0.875	0.833	V_{pa} \ V_{up}

TABLE 8.--Efficiencies Corresponding to the Values of V_{ef} and V_{pa} for Three Different Belt Speeds and Moisture Contents.

θ \ V_{ef}	0.840	1.250	1.500	1.667	V_{up}
SD	3.4	62.0	100.0	100.0	
H	3.0	43.0	92.0	100.0	2.500 ft/sec
D	0.0	0.0	5.2	20.5	
θ	2.080	1.870	1.750	1.666	V_{pa} \ V_{up}

TABLE 9.--Efficiencies Corresponding to the Values of V_{ef} and V_{pa} for Three Different Belt Speeds and Moisture Contents.

θ \ V_{ef}	1.430	2.170	2.600	2.890	V_{up}
SD	0.0	49.0	94.0	100.0	
H	0.0	34.0	87.0	100.0	4.330 ft/sec
D	0.0	0.0	3.2	14.0	
θ	3.610	3.240	3.030	2.885	V_{up} \ V_{pa}

CHAPTER X

RESULTS AND DISCUSSIONS

Efficiency Curves

We have made an assumption before about n. It was said that there would be no threshing of consequence for the values of n = 1.0. This can be seen from Table 5. Even for n = 1.5 the efficiencies are very small or equal to zero.

To visualize the effect of n, on the performance of the system, n versus η diagrams were drawn (see Figures 14, 15, and 16), based upon the values of Table 5.

Damp beans give unsatisfactory results. Efficiencies are zero for n = 1.5 and n = 2.0, and higher speeds of upper belt decrease the efficiency. This is due to the large values of V_{pa}s at high speeds of upper belt. When V_{pa} increases, the duration of material between the belts decreases, and this causes the rapid movement of material through the belts. Rapid movement of material lessens the rubbing action.

This fact is also true for the harvesting and storage-dry group beans. Small efficiency values for n - 2.5 at V_{up} = 2.5 ft/sec for harvesting group beans, and for n = 2.5 at V_{up} = 4.33 ft/sec for harvesting and storage-dry beans show this fact.

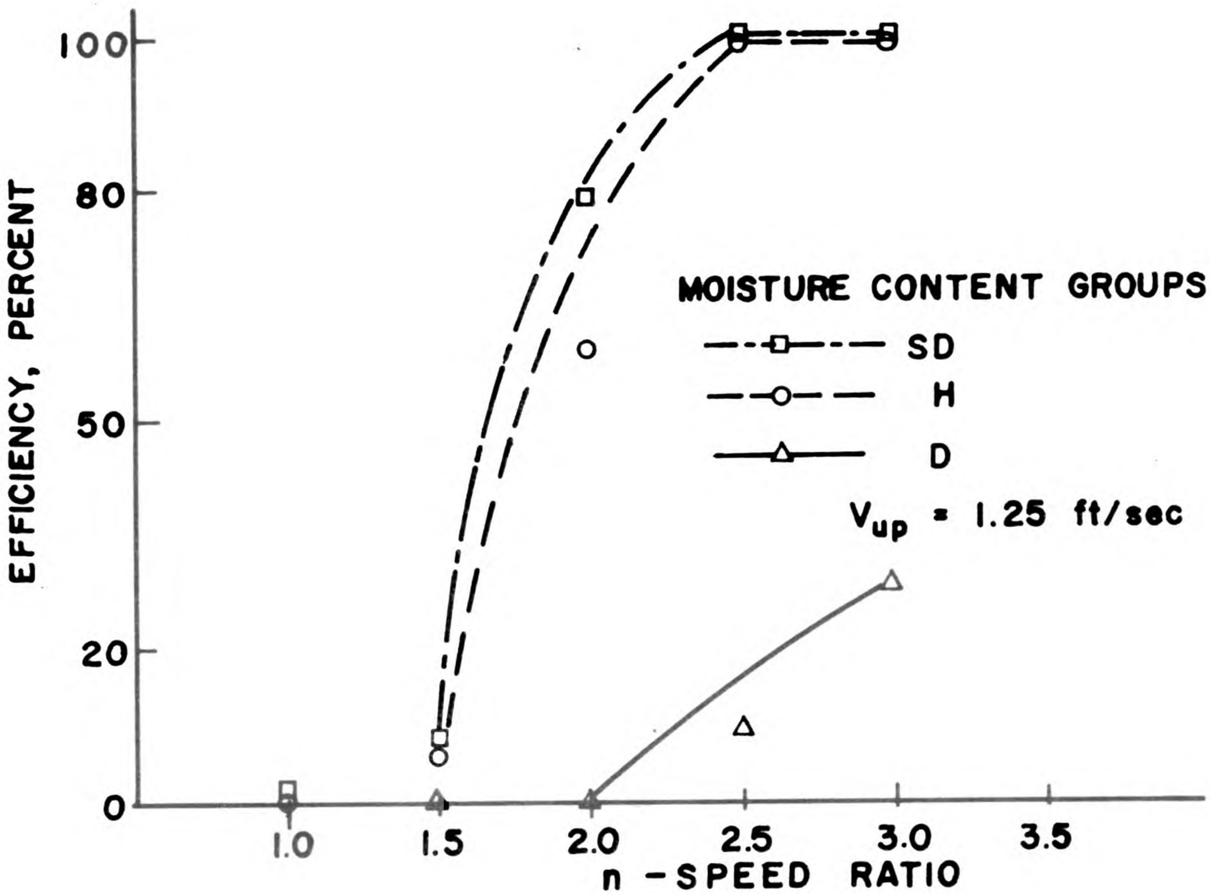

Figure 14.--Speed Ratio vs. Efficiency Relationships for V_{up} = 1.25 ft/sec and Three Different Moisture Contents (θ)

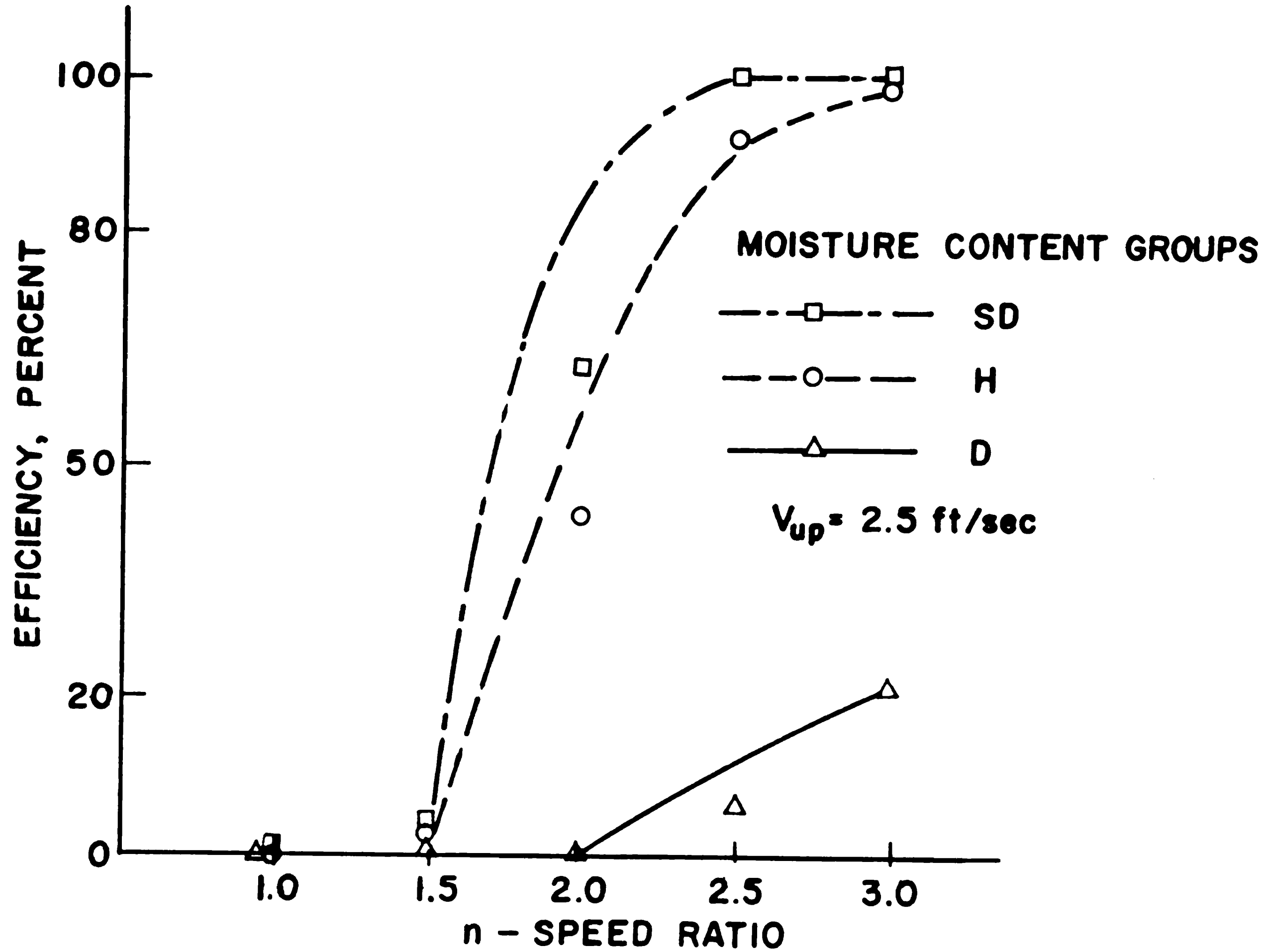

Figure 15.--Speed Ratio vs. Efficiency Relationships for V_{up} = 2.50 ft/sec and Three Different Moisture Contents (θ)

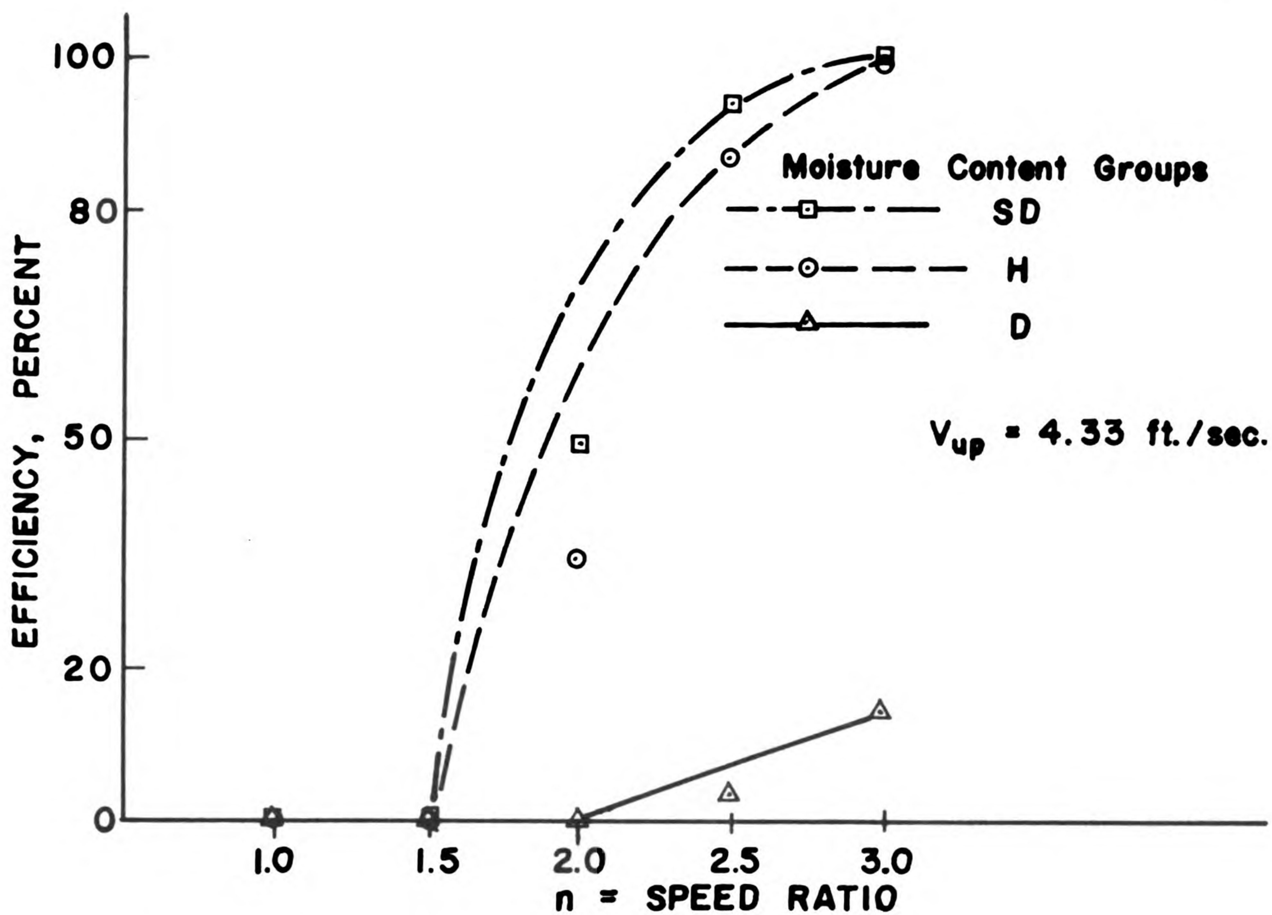

Figure 16.--Speed Ratio vs. Efficiency Relationships for V_{up} = 4.33 ft/sec and Three Different Moisture Contents (θ)

Storage-dry and harvesting group beans have good efficiency values (100% or less) for $n = 2.5$ and $n = 3.0$. For $n = 1.5$ and $n = 2.0$ the efficiencies decrease.

For $n = 3.0$ and $V_{up} = 1.25$ ft/sec, storage-dry and harvesting group beans gave 100% efficiencies. No visible damage was observed when the material left the apparatus, but straw consisted of broken stalks and very small pieces. These values of n and V_{up} correspond to the value of $V_{pa} = 0.833$ ft/sec, which is the smallest. If we increase the speed ratio to some higher value than the 3.0, then we may encounter some damage for storage-dry and harvesting group beans. It may not be occurred, also, because of the soft handling of the material by threshing belts.

To improve the performance of the system for damp beans, the best solution seems to be to increase the speed ratio to more than 3.0, for $V_{up} = 1.25$ ft/sec, since, at this speed of upper belt, efficiency curve has the steepest slope for damp beans. Or this can be achieved by using other ways, such as making the lower belt stationary or changing its direction of movement opposite to the upper belt having a slower speed than the upper belt.

By using these possible arrangements of the belt movement directions, even for the higher values of the upper belt's speeds, the system can be efficient for damp beans. The threshing capacity of the belts was lower at lower upper belt speeds since decreasing values of V_{up}'s give smaller values of V_{pa}'s which effects the capacity of the system. In practice high capacity threshing systems will be preferred.

If this threshing method were used in the field or in practice, the speed ratios should begin from 2.5, since the efficiencies corresponding to the smaller values of n, are unsatisfactory even when compared with conventional combine's cylinders.

Although the efficiencies for (1) harvesting-moisture content and (2) storage-dry group beans were high at V_{up} = 1.25 ft/sec for n = 2.5 and n = 3.0. V_{up} = 4.33 ft/sec should be tried with larger n values, to have higher capacities for these moisture content groups.

The threshing belt system seems to be inconvenient for beans having moisture content higher than or equal to 30%. This shows that the R_a (Attachment Resistance) is a direct function of moisture content (θ). However in the tests conducted, it was observed that the damp beans were accumulated between the belts, and caused to move the belts together without any speed differential. This was due to the nonuniformity of feeding and different values of rolling friction coefficients for damp beans-belts and damp stalk-belts. High moisture content and nonuniform feeding causes the material to be wound and formed into a roll between the belts, which causes high compression of the belts and the belts to move with equal speed.

In practice, the capacity of the cutting mechanism of a combine and crop density are limiting factors of the capacity of the threshing belts. The speed of the material between the belts (V_{pa}), because of being dependent on other variables, cannot be fundamental to the capacity of the system.

V_{ef} versus η curves were also plotted (Figures 17, 18, and 19), by using the values in Tables 7, 8 and 9. It was noticed that the V_{pa} versus η curves were the same as V_{ef} versus η s.

The V_{ef} versus η curves are similar to the n versus η curves. They can be used to find the V_{ef} values at the best efficiency for three different moisture contents.

Another important set of efficiency curves are moisture content versus efficiency curves for four values of n and three different upper belt speeds (Figures 20, 21, 22 and 23), which are based on Table 6.

These curves easily can show the inconvenience of speed ratios n = 1.5 and n = 2.0.

If a threshing belts system combine is to be built, moisture content versus efficiency curves are the best characteristics to determine efficiency, speed ratio, and upper belt's speed for a known moisture content.

Deflection of Belts

Several trials of the threshing belts showed that the deflection of belts would be greater than expected. To

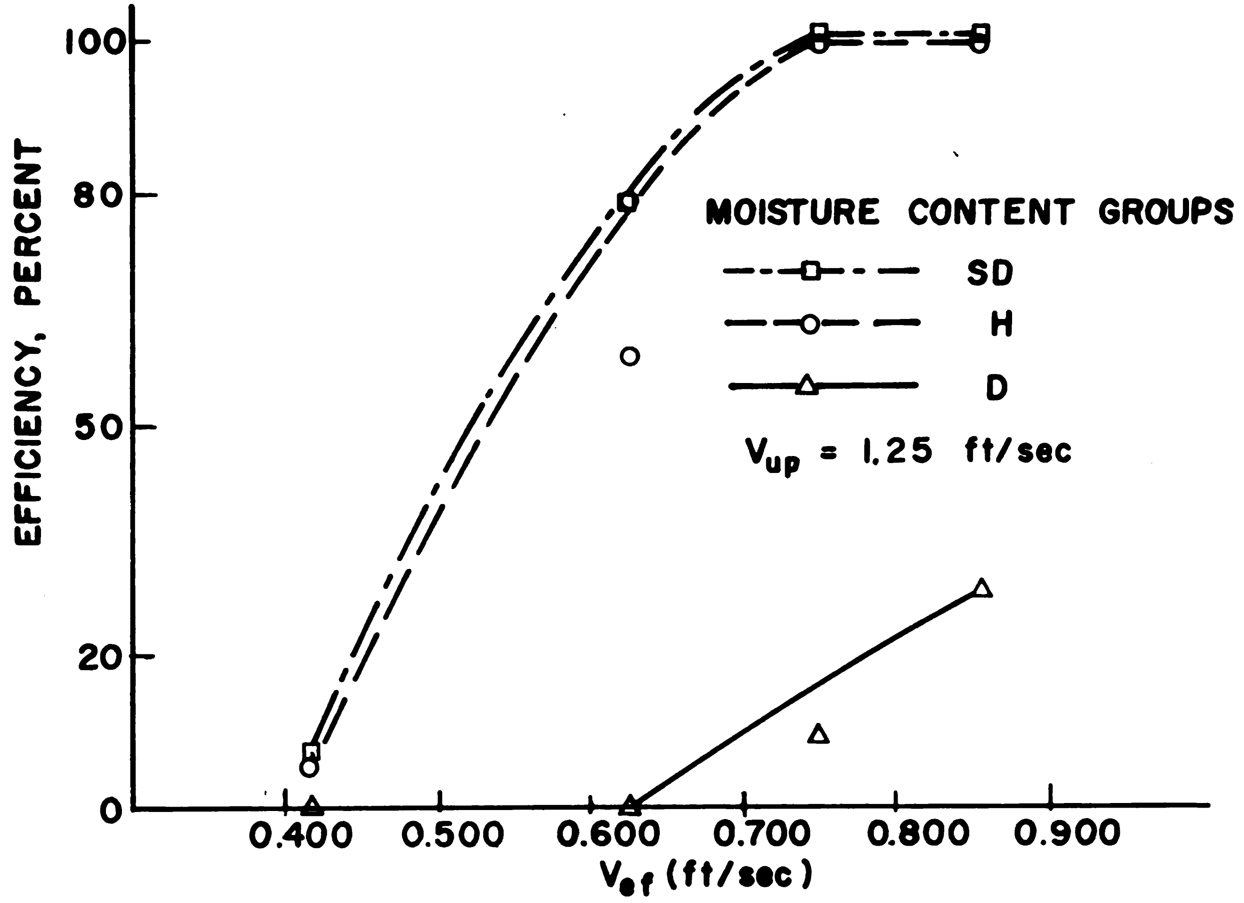

Figure 17.--Effective Speed vs. Efficiency Relationships for V_{up} = 1.25 ft/sec and Three Different Moisture Contents (θ)

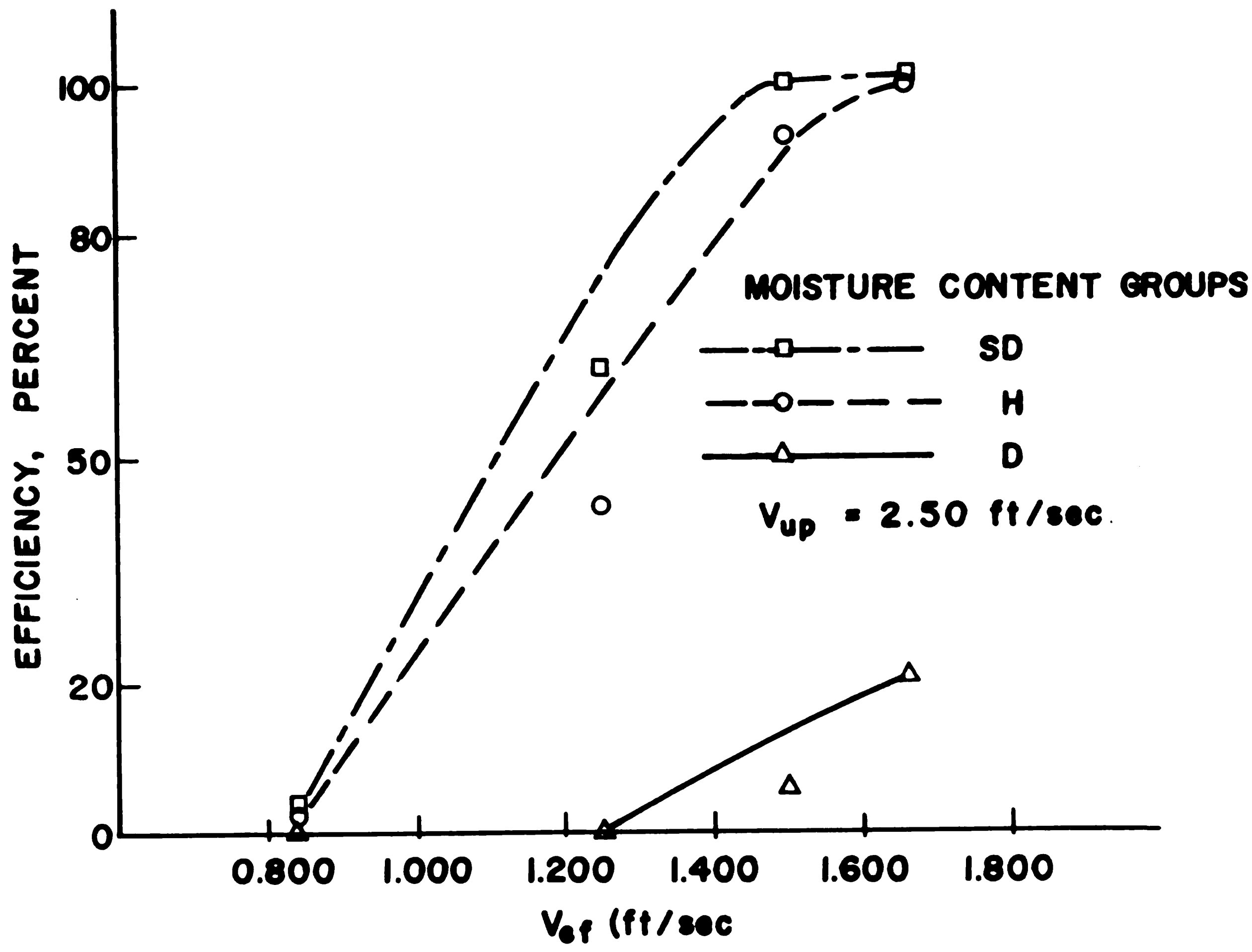

Figure 18.--Effective Speed vs. Efficiency Relationships for V_{up} = 2.50 ft/sec and Three Different Moisture Contents (θ)

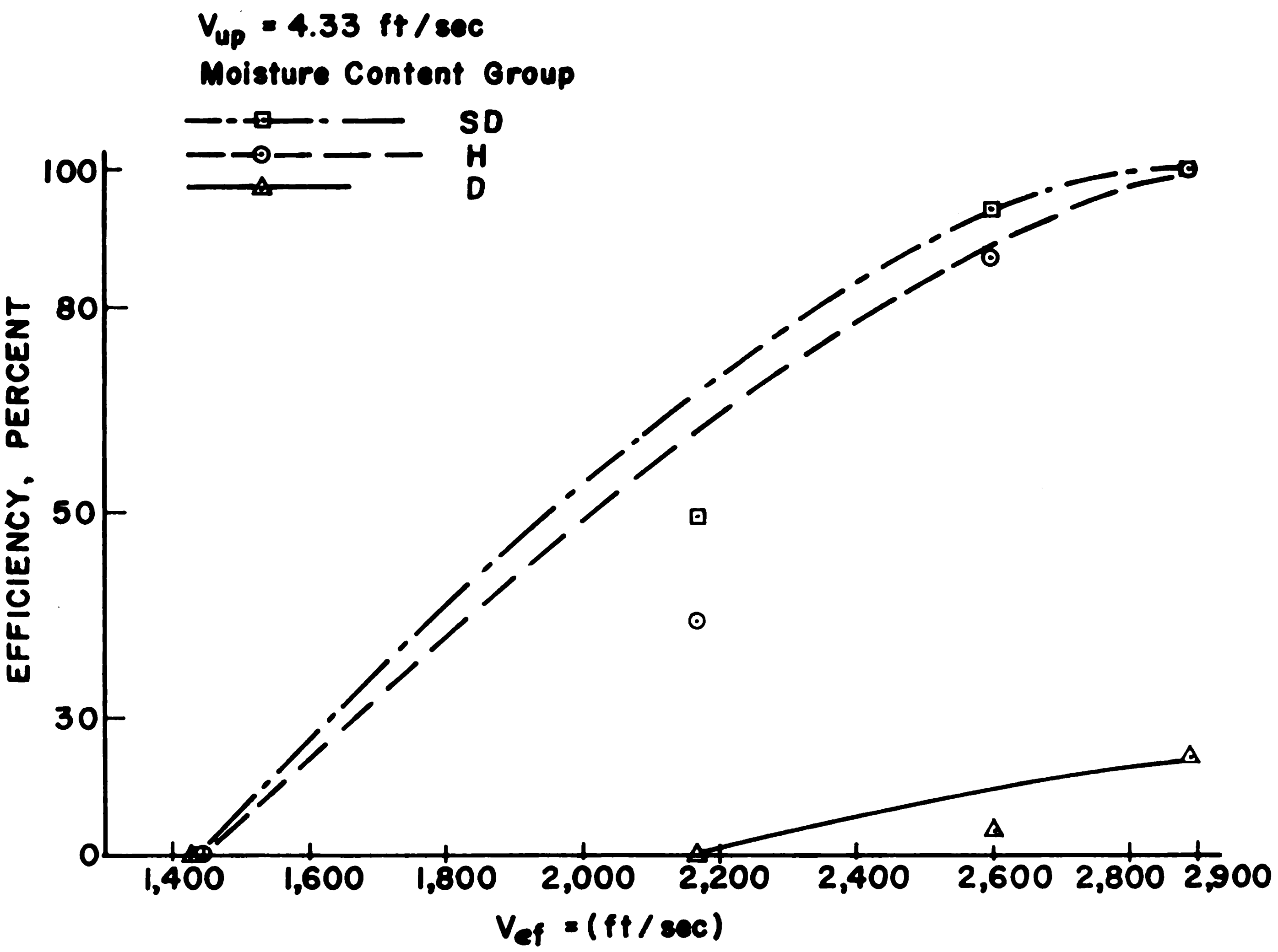

Figure 19.--Effective Speed vs. Efficiency Relationships for V_{up} = 4.33 ft/sec and Three Different Moisture Contents (θ)

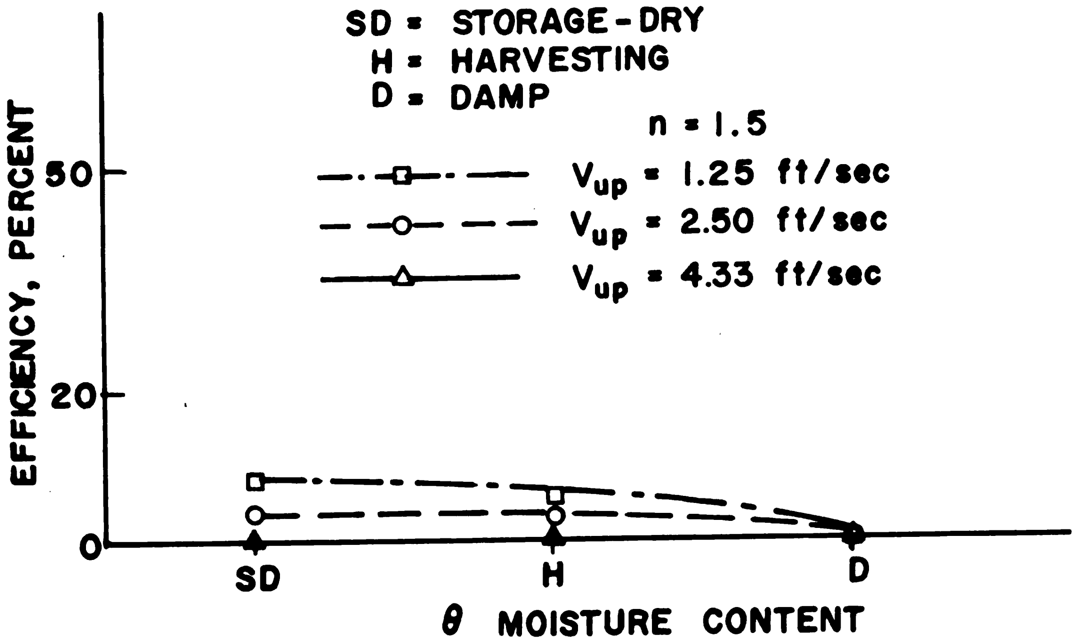

Figure 20.--Moisture Content vs. Efficiency Relationships for n = 1.5 and Three Different Upper Belt Speeds

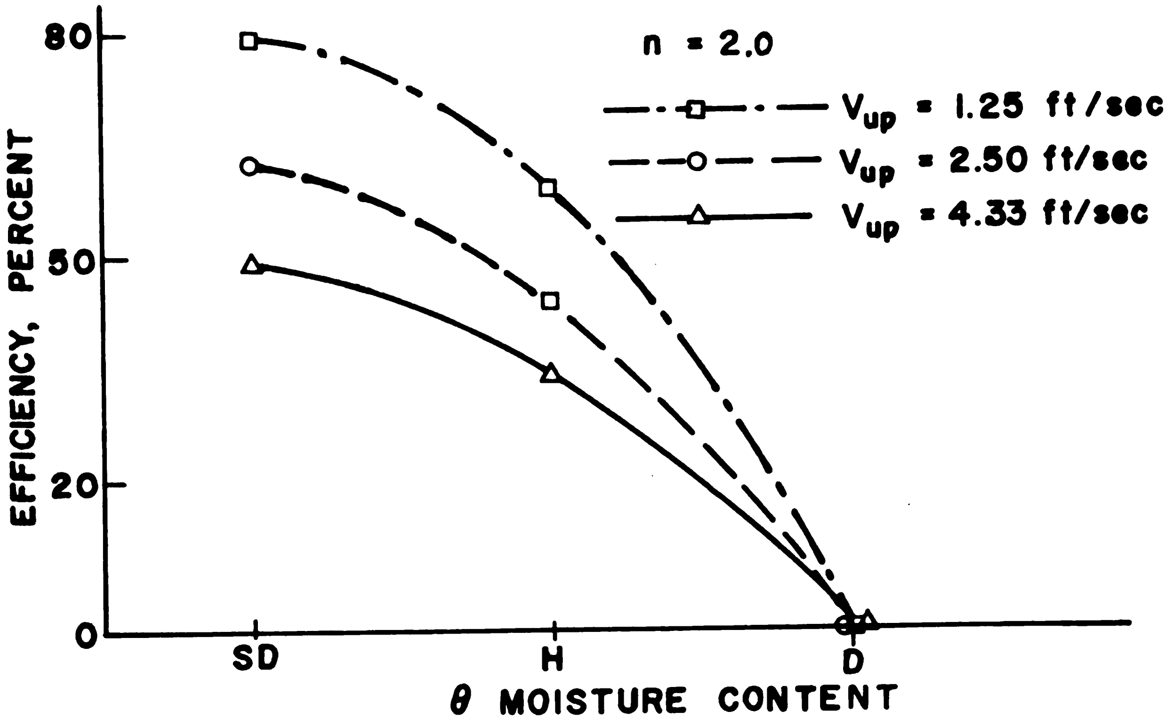

Figure 21.--Moisture Content vs. Efficiency Relationships for n = 2.0 and Three Different Upper Belt Speeds

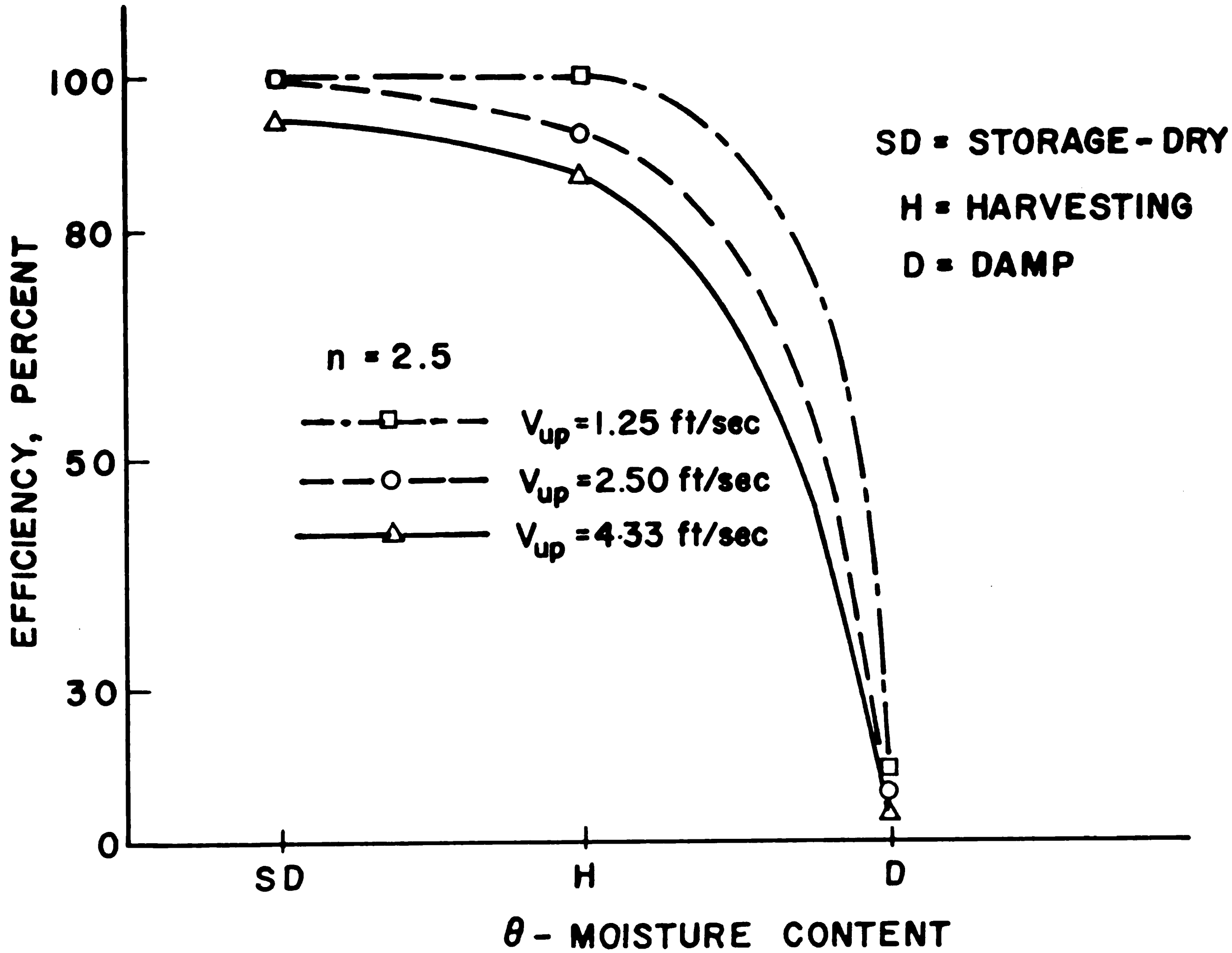

Figure 22.--Moisture Content vs. Efficiency Relationships for n = 2.5 and Three Different Upper Belt Speeds

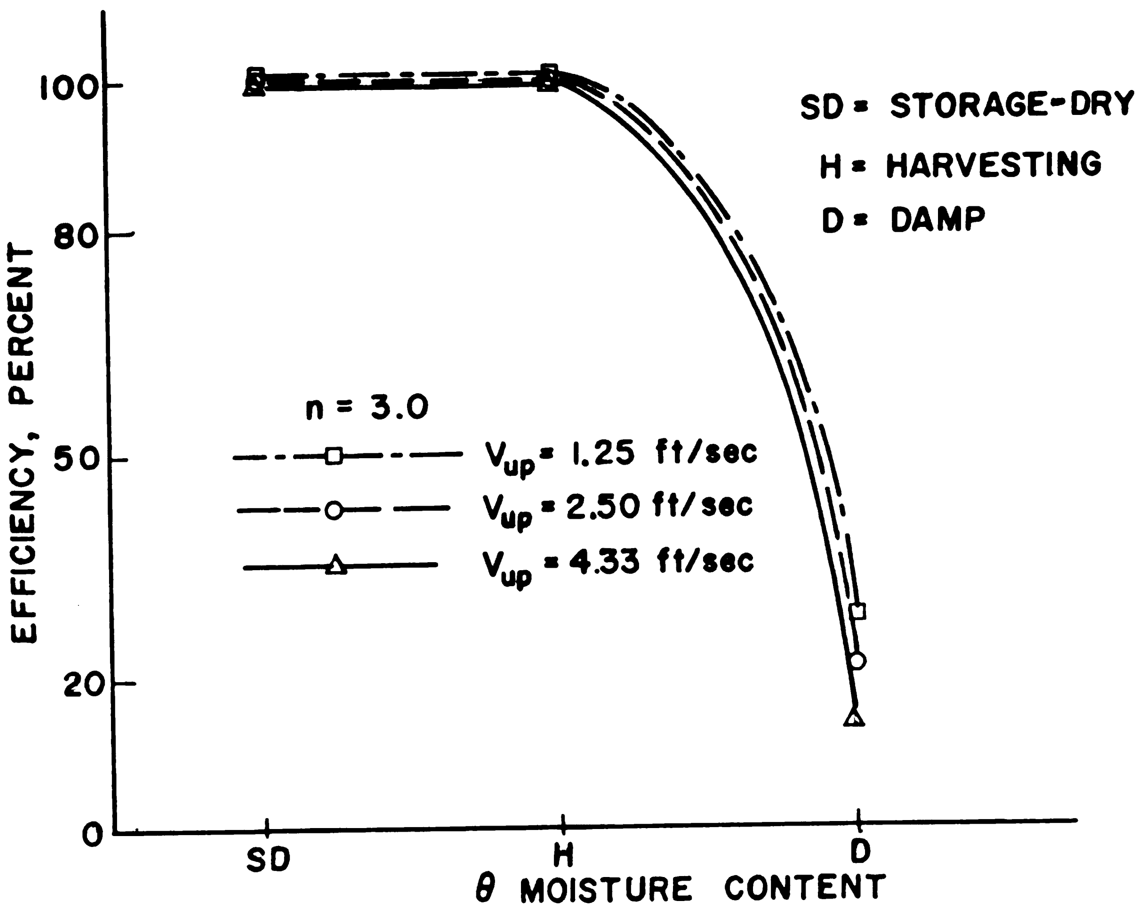

Figure 23.--Moisture Content vs. Efficiency Relationships for n = 3.0 and Three Different Upper Belt Speeds

prevent the deflections, tightening the belts was tried, but this was not satisfactory.

To have a good system performance it was decided to put a sheet of metal underneath the lower belt. This did not work, because of the overloading of electric motor due to the high friction between belt and the metal sheet.

Placement of supporter rollers on the back sides of adjacent surfaces of each belt gave good results. Two supporter rollers for the lower belt, and one for the upper belt were positioned, and tests were made.

CHAPTER XI

SUMMARY

Threshing belts with speed differentials for beans were built and tested in the Research Laboratory of Agricultural Engineering Department of Michigan State University.

Tests were run for different speed ratios, at different speeds for three different moisture content values of beans.

Performance of the belts was found to be excellent for harvesting-dryness and storage-dry beans for the speed ratio 2.5 and greater. Although damp beans revealed poor efficiencies, it was possible to improve the design by judicious selection of the speed ratios and speeds to increase the threshing efficiency for damp beans.

The effect of belt clearance on the performance of threshing belts could not be studied because of the unsuitability of the feeding mechanism.

CHAPTER XII

CONCLUSIONS

1. Threshing belts must be mounted on a steel frame. This will allow having easily adjustable flat pulleys and placing of metal sheets to support the belts. Although supporting rollers gave satisfactory results, the metal sheet supports will be the best solution.

2. A variable speed device should allow the values of speeds in large ranges, and a powerful motor should be used as a power source.

3. By using chains, which are attached to the sides of the belts and sprockets attached to the driver and driven flat pulleys, the slippage and movement of the lower belt according to the upper belt, which was encountered in damp bean tests, can be prevented, i.e., speed differential can be provided to increase the efficiency for damp beans. Although this proposed design would take some additional mechanical work, the performance of the system is improved completely.

4. With its good efficiency values and the practically nonexistence of seed damage, threshing belts can replace the cylinder in conventional combines for beans. To do this, improvement of the system and adaptation of combines are imperative.

CHAPTER XIII

SUGGESTIONS FOR FURTHER STUDY

1. The feeding mechanism should be improved and redesigned. An automatically regulated feeding mechanism will be the best.

2. The effect of clearance (d) on performance should be studied.

3. Other possibilities of movement directions of belts should be tested, i.e., one belt stationary, other belt moving, and oppositely moving belts, to improve the efficiency for damp beans.

4. Functional relationships should be developed theoretically, and confirmed by the test.

5. A prototype combine with threshing belts should be built and tested in the actual field conditions.

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