FLOW CHARACTERISTICS OF SHELLED CORN THROUGH CHUTES

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ABSTRACT

FLOW CHARACTERISTICS OF SHELLED CORN THROUGH CHUTES

By

Joseph Aiken McCurdy

It is important that all parts of a grain handling system function smoothly and with a precision that the design engineer can predict. Considerable work has been done on discharge of semi-fluids through orifices in storage bins. Flow equations have been established for various sizes and shapes of orifices. Very little has been determined on the flow of grains through transporting devices such as chutes.

The purpose of this work was to study the mechanical behavior of shelled corn flowing through chutes and to develop a test procedure utilizing suitable equipment so that the flow rates of the grain could be accurately measured. Next, the effect of chute length on flow characteristics was studied. Also the relationship between size and shape of grain chutes constructed of different materials and flow characteristics was studied. Finally the effect of chute angles on flow rates of grains was determined.

Apparatus was used that had been constructed principally for the study of grain flow. It was selected to accommodate chute lengths as short as $1\frac{1}{2}$ ft and as long as $7\frac{1}{2}$ ft. The basic equipment consisted of a storage bin suspended about 5 ft above the floor. This made it possible to move a balance beam platform scale under the storage bin for gravity flow. A second bin was made portable so that it could be elevated on pivoted channel iron beams and powered by an electric motor driving

a winch. This portable bin also served as a storage bin for the longer ($7\frac{1}{2}$ ft) chutes since it could be elevated about 9 ft above the floor. Yellow dent shelled corn that ranged in moisture content from 10.19% to 8.38% w.b. (wet basis) was used throughout the tests.

It was found that the flow rate varied but was essentially unaffected by the chute length. The relationship describing the flow of shelled corn through rectangular orifices was determined. The flow rate was found to be proportional to the sine of the chute angle. The proportionality constant was determined for the various chute angles and was found to be constant only for the same size orifices. The flow rates at the various chute angles were found to be equal to flow rates through orifices placed horizontally in bins, as determined by Ewalt, multiplied by the sine of the angle.

It became apparent during the tests that semi-fluids flowing from a storage bin are influenced by the velocities prior to flowing through the orifice in the chute. With the orifice placed in the chute 6 in. from the storage bin the resulting approach velocity increased the flow by 1.42 over the flow with the orifice in the end of the chute.

The depth of corn flowing in a chute varied with the length of the chute and was independent of the chute angle. Different chute materials did not appear to influence the depth of shelled corn flowing in chutes at various angles beyond 25 deg.

Approved F H Buelow

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The author would also like to express his appreciation to his wife Dorothy and family for their patience, encouragement and typing assistance which helped make completion of the investigation possible.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES - Continued

LIST OF FIGURES

The author is shown timing the rate of flow of shelled corn through a short ($1\frac{1}{2}$ ft) wood chute using a $1\frac{1}{2}$ x 6 in. orifice in the chute.

INTRODUCTION

Whenever grain is made to move from one point to another a flow pattern is established. In transporting grains from the harvest field to final processing this flow pattern is reestablished many times. It is important that all parts of a grain handling system function smoothly and with a precision that the design engineer can predict.

Cereal grains can neither be classified as a solid nor a liquid. Previous work has shown that flow from a bin through an orifice is independent of the grain depth. Flow formulas have been established for various sizes and shapes of orifices. Very little has been determined on the flow of grains through transporting devices such as chutes. For automatic control, it is important that information be available for designing all parts of a grain handling system.

Considerable work has been done in the chemical engineering field where there is interest in the flow of cracking catalysts, fertilizers, concentrates and other materials. All of these works relate to discharge through orifices in storage bins. Very little, if any, information is available on the flow of semi-fluids in chutes.

This study was conducted to determine the different flow characteristics of shelled corn through chutes. Corn ranks third in world grain production and about half of the total world corn crop is harvested in the United States. With the increased use of picker-sheller type corn harvesters, grain handling has become a task of considerable magnitude. Specific information is needed on the performance of different chute materials, the effect of location and angle of the orifice and the effect of angle on grain velocities and flow depths in the chutes.

The objectives of this investigation were: (1) To investigate the mechanical behavior of corn flowing through chutes, (2) To study the relationship between length of grain chutes and flow characteristics, (3) To study the relationship between size and shape of grain chutes and flow characteristics, (4) To study the relationship between the slope of grain chutes and flow characteristics.

Since flow through grain chutes is dependent on the flow through the orifices in the storage bin it should be possible to determine these relationships. This information would supplement existing knowledge of grain flow through orifices and provide design parameters for chutes. These same parameters should be valuable in further studies of specific characteristics and rheological properties of corn.

REVIEW OF LITERATURE

Considerable information is available on semi-fluid flow from various storages such as bins, bunkers and silos. Flow from storage is an important step in moving semi-fluids to final processing but it is equally important that design information be available for chutes and other transporting devices. Lack of knowledge of flow characteristics of semi-fluids in chutes often necessitates a trial and error approach.

Hudson (1950) in his contribution to the Chemical Engineers' Handbook stated that the simplest chute--the straight through--by trial may be found to be on too flat a slope so that the material will back up or on too steep a slope so that the material will accelerate. If the slope is too flat the difficulty may be corrected by flooring the chute with a thin sheet of stainless steel or aluminum or with plate glass. If it is too steep the equivalent of a reduced slope may be secured by bolting cross angles to the bottom of the chute. Sometimes the available head is altogether too small to permit an inclined chute that will permit flow. The correction may be a vibrating chute, usually by an electromagnetic unit. The chute then may be horizontal.

Hudson commented further that long inclined straight chutes may be objectionable because they scatter dust. Thus bituminous coal when dry flows readily on an incline of 36 deg, but if it is damp or if the chute is rusted it will not flow. So it is usual to specify a 43 to 45 deg slope. Coal will flow on this slope even when quite damp but will build up speed and shatter or scatter dust. Because this difficulty holds true for many granular materials, long straight chutes are avoided when it is possible to do so where degradation or dust is to be prevented.

An alternative frequently used for anthracite coal is a vertical box chute with steps projecting alternately from two opposite sides. The material cascades with little degradation. Spiral chutes are also applicable to vertical lowering where gentle handling is desired. They are suited to either bulk or packaged materials.

One of the first mathematical expressions of laws governing the flow of solid particles was the result of investigations by Deming and Mehring (1929). The flow of fertilizers, lead shot, glass beads, and some varieties of seed through truncated cones was investigated to provide data for the design of fertilizer distributors, seed drills and storage bins. Their equation was the following:

$$T = \frac{\mu}{D_o^{2.5} d} \left[0.201 + (0.392 - 2.58 \sin \tfrac{1}{2} \phi)\left(\frac{D_p}{D_o} + 0.130 + 0.161\mu\right)\right] \quad (1)$$

Where:

- T = time of flow (hr/ton)
- μ = tan θ; θ = static angle of repose (deg)
- D_o = orifice diameter (ft)
- D_p = particle diameter (ft)
- ϕ = angle of the cone (deg)
- d = density of the material (lbs/ft^3)

This equation was found applicable for cone angles up to $(\pi - 2\alpha)$ where α was the angle of repose in radians.

Takahasi (1934) developed an empirical equation for the flow of spherical forms of equal size as follows:

$$V \doteq \frac{1}{g} \left[f(\mu_1)\, d^{-2.5} + a\,\overline{D}\, d^{-3.5}\right] \quad (2)$$

Where:

- V = time for flow of unit volume (min/ft^3)
- $\overline{D}$ = mean diameter of particles (in)

d = orifice diameter (in)

a = constant

g = gravitational acceleration (32.2 ft/sec^2)

$f(\mu_1)$ = Tan θ; θ = kinetic angle of repose (deg)

This equation is limited to a ratio of $\overline{D}/d$ equal to three or greater and no specific accuracy was claimed for this equation.

Further experiments on the flow of catalyst particles were conducted by Newton, et al. (1945). They observed the flow toward an orifice in vertical models using multicolored pellets. When the depth exceeded 1.5 times the diameter of the orifice there was an apparent angle of repose equal to 71 deg as compared to a static angle of repose of 34 deg. The following simplified equation was found for the rate of flow of the catalyst:

$$F = 8.50\ D^{2.96}\ H^{0.04} \qquad (3)$$

Where:

F = flow rate (lb/min)

H = head (ft)

D = orifice diameter (in)

This formula was considered valid as long as the diameter of the orifice was greater than 6 times the particle diameter.

Work on the development of equipment to measure the flow properties of bulk solids was undertaken by Jenike (1958). He suggested that bulk solids such as ore, coal, cement, flour, cocoa and soil can be represented by a frictional, cohesive, plastic-solid. He derived a mathematical theory of flow leading to flow, no-flow criteria. The theory was applied to the design of bins, hoppers and storage piles for gravity flow. He suggested that while there are, and always will be, solids which are not suitable for gravity flow, the vast majority of them will flow if the bins and feeders are designed correctly. Jenike (1962) is continuing his work on a mathematical study of the steady state flow of bulk solids.

Further work on the rate of discharge through orifices has been reported by Franklin and Johanson (1955). An equation was derived for flow of glass beads, lead shot, cracking catalyst and puffed rice.

Their equation for horizontal orifices was:

$$W = \frac{P_S\, D^{2.93}}{(6.288 + 23.16)\ (d + 1.889) - 44.9} \tag{4}$$

Where:

W = flow rate (lb/min)

P_S = true density (lb/ft^3)

μ = tan θ; θ = kinetic angle of friction (deg)

D = diameter of orifice (in)

d = average screen size of particles (in)

Particle size ranged from 0.03 to 0.2 in. with densities ranging from 7.3 to 676 lb/ft^3. Orifice diameters ranged from 0.236 to 2.28 in. An accuracy of $\pm$ 7% was found between theoretical and experimental data.

Initial work on the effect of inclining the orifice was reported. A flow rate for an inclined orifice was given as:

$$W_\theta = \frac{W_O \cos \alpha - \cos \theta}{\cos \alpha - 1} \tag{5}$$

Where:

W_θ = discharge rate at angle θ (lb/min)

W_o = discharge rate at $\theta = 90^\circ$ (lb/min)

θ = inclination of orifice to horizontal (deg)

α = internal kinetic angle of repose (deg)

Internal kinetic angle of repose was defined as the angle formed by the plane at which particles change direction of motion with the horizontal when rotated in a cyclinder. The surface static angle of repose was defined as the maximum angular deviation from horizontal of the surface of a static pile of granular material. Surface kinetic angle of repose was defined as the slope of a continuously moving surface of a pile of granular material.

The apparatus consisted of a rotating drum 1 ft in diameter and 8 in. long, with axis fixed in a horizontal position and a plastic window through which surface static, surface kinetic and internal kinetic angles of repose were observed. The use of internal kinetic angle of repose gave better correlation of the flow rate data than did use of either static or surface kinetic angle.

Two formulae, based on dimensional analysis, have been proposed for calculating the rate of discharge of granular materials through orifices. The equation proposed by Fowler and Glastonbury (1959) is:

$$\frac{W}{\rho_B A \sqrt{2g D_h}} = 0.236 \left(\frac{D_h}{d_s}\right)^{0.185} \qquad (6)$$

Where:

W = weight discharged per second (lb/sec)

ρ_B = bulk density (lb/ft^3)

A = orifice area (sq in)

D_h = hydraulic diameter, $\left(\frac{4 \text{ x area of orifice}}{\text{perimeter}}\right)$

d_s = spherical diameter of particle (in)

Granular materials such as sand, sugar, rape seed, wheat and rice were tested using circular, rectangular, triangular, hexagonal, pentagonal and square orifices. The accuracy was found to be ± 10%.

A simplified form of the Fowler's equation was proposed by Rose and Tanaka (1959):

$$\frac{W}{D^{2.5} \rho g^{0.5}} = 0.16 \left(\frac{D}{d} - 3\right)^{0.3} \phi(\theta) (Z-5)^{-0.5} \qquad (7)$$

Where:

W = rate of flow (lb/min)

D = diameter of orifice (in)

d = diameter of particles (in)

ρ = density (lb/ft^3)

g = acceleration of gravity (32.2 ft/sec^2)

θ = angle of the cone (deg)

Z = shape factor of the particles

ϕ = coefficient that depends on the material and the cone angle θ

The shape factor Z was not defined by Rose and Tanaka but was considered equal to 6 for spheres and 8 to 25 for discs.

Tests were made on steel balls, silica sand, steel discs and some fertilizers. Bridging was noted when the minimum dimension of the opening was approximately equal to 3 particle diameters. Results indicated that the rate of discharge was independent of the true value of the coefficient of friction of the material but dependent upon the cohesive strength and proportional to $D^{2.5}$ (D = orifice diameter). Flow was also independent of the nature of the material provided the particle shapes were substantially similar.

Brown and Hawksley (1953) made a thorough examination of the mechanism of flow of solids through orifices. They showed that there were at least five distinct regions of movement near the orifice and that the upper surface of the solids did not move until a considerable dilation of the packing had occurred. They did not however give any equation to explain the flow.

Later Brown and Richards (1959) made further tests on the flow of glass beads and sand through orifices and developed the following equations:

Flow through rectangular orifice:

$$Q = 2.72\ A\ H^{\frac{1}{2}}\ \psi \qquad (8)$$

Flow through a circular orifice:

$$Q = 2.24\, D^{2.5}\psi \qquad (9)$$

Where:

Q = flow (gm/sec)

A = orifice area (cm^2)

H = perimetral diameter, $\left(\frac{4 \times \text{area of orifice}}{\text{perimeter}}\right)$ cm

$\psi = \frac{V}{gH^{\frac{1}{2}}}$ (dimensionless unit)

g = acceleration of gravity (cm/sec^2)

D = diameter of orifice (cm)

With ψ equal to 0.3 the accuracy was ± 50%. The ratio of D/P was limited to 20 to 30. (D = diameter of a circular orifice in cm, P = mean particle diameter in cm.) Contrary to Jenike's theory, these experiments indicated that the flow rate was independent of the tightness or the original packing. Flow from narrow vessels was influenced by friction on walls and interlocking of particles owing to the proximity of the walls. Other conclusions were:

1. Fine particles discharge more ràpidly than coarse particles.
2. Spherical particles flowed more rapidly than angular particles.
3. Rectangular orifices discharged at about the same rate as an elliptical orifice of the same area but both were appreciably slower than flow from a circular orifice.

Ketchum (1919) was one of the earliest to investigate the flow of agricultural grains. His work showed that the rate of discharge of wheat through an orifice was independent of the head over the orifice and varied in direct proportion to the cube of the orifice diameter. This flow phenomenon was explained by Ketchum as follows: The wheat grains in the bin tend to form a dome over the orifice which supports the weight above it. The surface of this dome is actually the surface of rupture. When the orifice is opened the grain flows out of the space below the dome and the space is filled up by grains dropping from the top of the dome. As these grains drop, others take their place in the dome. Experiments with glass bins showed that the grain from the center of the bin discharges first. This drops through the top of the dome while the grain in the lower part of the dome discharges last.

Further work by Ketchum on grain flow showed that the coefficient of friction of wheat on wheat was 0.501; the coefficient of friction of wheat on the bin wall was 0.307, while the tangent of the angle of repose of wheat was 0.421. Other conclusions drawn were:

1. The pressure of grain on bin walls and bottoms follows a law which is entirely different from the law of the pressure of fluids.
2. The lateral pressure of grain on bin walls is less than the vertical pressure and usually ranges from 0.3 to 0.6 of the vertical pressure.
3. The ratio of lateral to vertical pressures is not a constant, but varies with different grains and bins.
4. The pressure of moving grain is only slightly greater than the pressure of grain at rest.
5. Discharge gates in bins should be located at or near the center of the bin.
6. If the discharge gates are located in the sides of the bins the lateral pressure due to moving grain is decreased near the discharge gate and is materially increased on the side opposite the gate.
7. The maximum lateral pressures occur immediately after filling and are slightly greater in a bin filled rapidly than a bin filled slowly. Maximum lateral pressures occur in deep bins during filling.

Hinkley (1926) classified dry sand, wheat and other granular materials as semi-fluids and confirmed Ketchum's observation that flow of grain from an orifice is proportional to the cube of the area of the orifice and is independent of the head.

Anderson and Alcock (1954) described grain flow into and out of storage. Grain tends to separate into heavier and lighter components when poured into or drawn from a bin. When entering a bin the grain falls freely to the surface of the pile, but the heavier grains fall straight down, whereas, the lighter material floats outward. This tends to cause chaff, dust and lighter particles to accumulate near the bin walls. When the stream of heavy grain reaches the pile, smaller particles are trapped between the larger kernels and remain at the center of the conical pile, while the kernels of grain flow away down the slope. This produces a core of high-dockage grain in the center of the pile. When the grain is drawn from the bin, the lighter particles tend to lose their places in the flowing stream and thus leave the bin last.

Barre (1958) further described the action of emptying a bin of grain. The column of grain directly over a discharge leaves first and gradually widens as it reaches the funnel-shaped grain surface. The bulk of grain then turns itself inside out. This pattern of flow is referred to as funnel flow. In a very steep sloped hopper the whole mass of grain flows down simultaneously. The flowing core increases in diameter until all the material in the hopper is included. This flow pattern is referred to as mass flow.

Common grains under some circumstances and conditions can very easily become relatively non-free flowing owing to the presence of dust, cracked grain and foreign material. Damp grain exhibits poorer flow properties than dry grain. To make material flowable its bulk strength must be overcome and the material allowed to become loose. Bulk strength can be kept to a minimum by using vertical partitions at the center of the bin, by using supporting shelves at vertical intervals on the bin wall and by using a supporting shelf in the center of the hopper. Spreaders under the filling spout reduce impact and keep pressures to a minimum.

O'Callaghan (1960) distinguished two modes of flow in beds of grain under the action of gravity. One mode has been associated with "shallow" and the other with "deep" beds. He observed that in a flat-bottomed bin some of the grain remains stationary at the walls of the container, when grain flows continuously in a moving bed between inlet and discharge orifices. The rupture line between the stationary and moving grain was found to be represented by a logarithmic spiral.

Other conclusions were:

1. The proportion of the total grain volume that is occupied by stationary grain is greater in a shallow bed than in a deep bed, when the inlet and discharge orifices are on the center-line of the container.
2. Inclined hopper sides at the approach to the discharge orifice do not alter the general shape of the rupture line from that which develops in a flat bottomed container.
3. In a shallow bed grain flows more freely at the center than at the sides and mixing of the grain takes place.
4. In a deep bed, moving vertically downward, grain flows uniformly except near the discharge orifice, where doming takes place.
5. Flow of grain from two sources to a common discharge orifice is influenced by the action of the wedge of grain formed by one source on that formed by the other.
6. Flow of grain around an obstruction is influenced by the wedges of grain formed below the obstruction.

Lorenzen (1959) investigated the moisture effect on granular friction of small grains. In the normal moisture range of 7 to 13% there was found in general no major change in the mean static coefficients of friction. The same was found true of kinetic coefficients of friction. In the high moisture range from 13 to 20% the influence of moisture on the mean coefficient was more pronounced and is especially apparent for wheat and corn. The angle of repose for wheat in this moisture range increases by 31% and for corn by 20%.

In these tests the steel surface used was unquestionably smoother than the wood surface, however, the coefficient for corn on wood was lower than for corn on steel. It was surmised that cohesion influenced this coefficient for corn on steel because of the flat form of the kernel. Cohesion is an elusive factor in that there is at present no practical method of determining where friction ends and cohesion begins.

It was also determined that grain running shallow will produce more drag per unit weight of the given grain than grain running deep. It was apparent that a state of smoothness is reached beyond which further polishing has little effect.

Welschof (1961) measured the rate of flow of oats, wheat, granular fertilizers and dry sand. Circular and rectangular orifices were tested where the orifice diameters varied from 5 to 100 mm and the particle diameters varied from 0.1 to 5.0 mm. Equations for the flow of wheat were developed by Welchof for both circular and rectangular orifices.

Attempts were made to measure the static pressure in the openings. The equations given applied only to wheat and were not valid for other grains or other semi-fluid materials. The use of these equations required the measurement of physical properties which would be difficult to obtain. A coefficient of discharge, the angle of internal friction of the grain, bulk density and a correction for the orifice diameter which accounted for the constriction of the orifice during flow were all needed for application of the equations. The values obtained for wheat agreed closely with the formulas as long as the ratio of the orifice diameter to the grain diameter remained large.

Stahl (1950) developed equations for the rate of flow of grains through horizontal discharge openings.

For circular orifices:

$$Q = 0.1753\ D^3 \tag{10}$$

For rectangular orifices:

$$Q = 0.2232W\ (WL) \tag{11}$$

Where:

Q = flow rate (bu/min)

D = diameter of orifice (in)

W = width of orifice (in)

L = length of orifice (in)

These relationships were printed in a technical bulletin published by the American Society of Agricultural Engineers (1948). Stahl also stated that the flow through vertical openings was one-third the rate through horizontal apertures. This appears to be based on the ratio of lateral to vertical pressures in a bin.

Work by Ewalt (1962) produced some equations that are unique for corn. The derived relationships were found to have a maximum standard deviation of difference of $\pm$ 3.24% when compared with experimental measurements for widths greater than 1.5 inches. The equations formulated for shelled corn of the moisture content listed follow:

Horizontal Openings:

$$\begin{aligned} &\text{Round orifice } Q = 0.1196D^{3.10};\ MC = 8.4\%\ \text{d.b.} \\ &\text{Rectangular orifice } Q = 0.1531W^{1.62}L^{1.40};\ MC = 12.1\%\ \text{d.b.} \end{aligned} \tag{12}$$

Vertical openings:

$$\begin{aligned} &\text{Round orifice } Q = 0.0351D^{3.30};\ MC = 12.72\%\ \text{d.b.} \\ &\text{Rectangular orifice } Q = 0.0573W^{1.75}L^{1.50};\ MC = 12.72\%\ \text{d.b.} \end{aligned} \tag{13}$$

Since none of the equations have exponents of the same power, a fixed ratio could not be determined between the horizontal and vertical openings. This refutes the assumption made by Stahl that flow from a vertical orifice is one-third of the flow from a horizontal orifice of the same size and shape. Also the assumption that the area affects the flow rate appears invalid in light of the results found in this research. The effect of both the width and length appeared more important.

Tests on the increase in the slope of the bottom of the bin showed a slight increase in the flow rate of the grain. This held true as long as the flow remained funnel flow. At 52.5 deg mass flow, as defined by Barre (1958), occurred and the flow rate decreased below that recorded at 40 deg.

The moisture content appeared to have a bearing upon the flow rate of the grain. As the moisture content increased, the flow rate tended to decrease. Increased moisture content appeared to increase the friction coefficient of corn on corn. Thus, the flow rate of the corn decreased.

Two tests were conducted to evaluate the effect of head on the flow of grain. Little, if any, variation occurred in the flow rate at different grain depths. This confirmed previous results that flow rate is not affected by the depth of grain.

No definite tests were conducted to determine the ratio of the orifice diameter to the mean particle size that would cause bridging. However, bridging did occur when the minimum dimension of the orifice was less than approximately three particle diameters.

Although the literature review produced some equations for semi-fluid flow there was a lack of information on the flow characteristic through transporting devices such as chutes. No equations were found relating the size of the orifice opening, chute length or chute angle to the rate of semi-fluid flow. Much of the information available requires parameters that are not readily available for shelled corn.

APPARATUS

In choosing equipment for this research problem several considerations were kept in mind. The apparatus was selected to accommodate chute lengths as short as 2 ft and as long as 8 ft. To eliminate product variations and minimize a storage problem a small batch was tested over and over again many times. Only very minimum damage to the grain could be tolerated and therefore samples were discarded when damage appeared.

Storage was provided in an 8 ft^3 bin (1 x 2 x 4 ft) supported 5 ft off the floor. See Figure 1. This support made it possible to place a balance beam Toledo scale on a moveable base under the storage bin. The bin was framed with 2 x 4 in. lumber and lined with $\frac{1}{2}$ in. plywood. The front and back panels (12 x 48 in) were removable. Rods through the sides at top and bottom held these panels in place. An opening in the front panel was provided with a sliding door to retain the corn while the bin was being loaded and the various chutes installed.

A second (24 x 30 x 24 in) portable bin alternately received the discharge from the shorter chutes and returned the shelled corn to the storage. See Figure 2. Elevation was accomplished by attaching this bin to the ends of a pair of 3 in. channel iron beams pivoted 81 in. off the floor. A steel cable, from a power winch attached at the opposite end of the beams, raised and lowered the portable bin. The steel beams were detached during weighing. A double-pole, double throw switch was used to control the $\frac{1}{2}$ horsepower motor.

To provide additional height for the longer chutes the portable bin was raised on the steel beams. The longer chutes were then attached and the flow was measured into a third bin set on the scales. See Figures 3 and 4. When the portable bin was lowered it was refilled by manually dumping the scale bin.

Fig. 1 - An over-all view of the apparatus showing the storage bin, portable bin and platform scales.

Fig. 2 - The portable bin is raised on pivoted channel beams to dump the shelled corn into the storage bin.

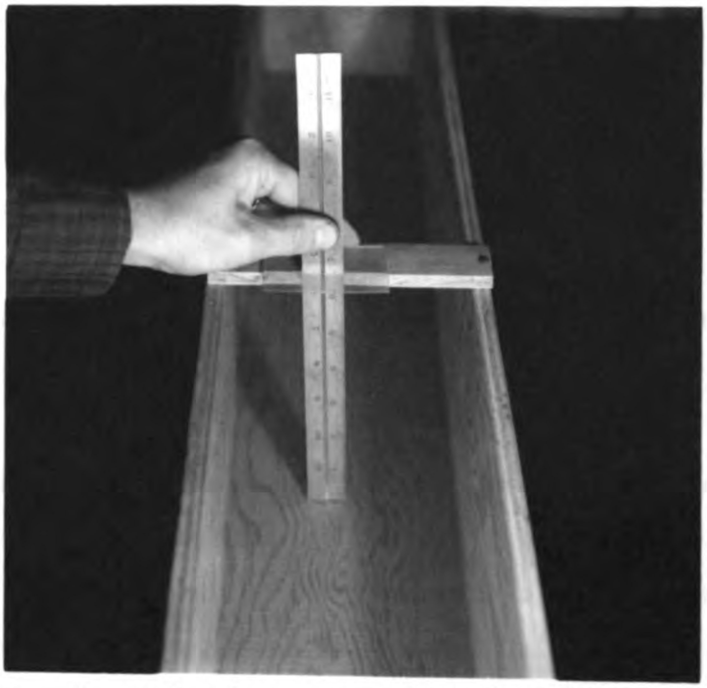

Fig. 3 - A depth gage graduated in 0.01 in. was used to measure the depth of corn flowing in the chutes.

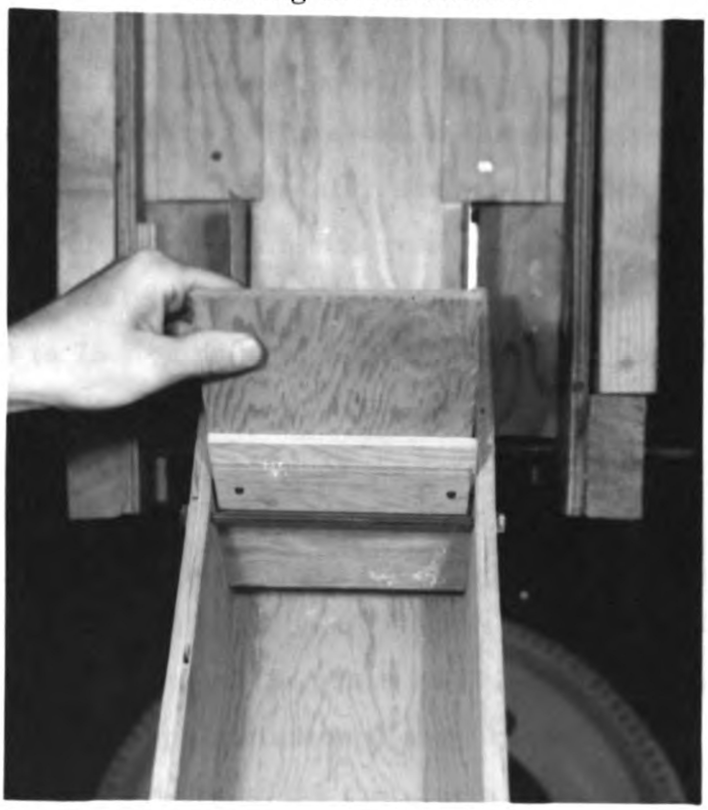

Fig. 4 - A plywood gate was used to control the flow of corn through the chute orifice.

All angles were carefully measured before each run using a protractor head for a combination square with attached level. An angle of 25 deg from horizontal was selected as the shallowest angle to measure flow, and the equipment restricted the steepest angle to 72 deg. Care was taken to clamp the bins and chutes in place firmly to insure that the angle did not change during a test.

The corn flow was controlled in the chutes with a plywood orifice 6 in. from the inlet end of the chutes. This orifice was formed by clamping a $\frac{1}{4}$ in. plywood block so that the desired opening was provided. The resulting orifice was kept perpendicular to the chute bottom and the size of the opening was checked before each flow trial. Care was taken to keep the leading edge of the plywood orifice square. The sliding door from the storage bin was kept open wide enough to insure that the chute orifice was covered with corn at all times. Flow through the orifice was manually started and stopped by sliding a plywood gate up and down to open and close the orifice. Time was measured with a stop watch.

The balance beam Toledo scale, used to weigh the corn, had a capacity of 200 lb. It was possible to read weights to the nearest 1/8 lb. Calibration of this scale showed readings of 1 oz light at 1 to 6 lb; 2 oz heavy at 50 to 75 lb; and 4 oz light at 100 to 175 lb. Tare weights of the portable bin allowed runs of 100 to 125 lb of corn.

A depth gage was used to measure the depth of corn at various locations along the chute. This gage was graduated in 0.01 in. and could be read $\pm$ 0.02 in. See Figure 5. Depth was judged at the point where corn would just strike the end of the depth gage.

The moisture content of the grain was checked periodically by using a Steinlite capacitance type moisture meter, model 400G. Air temperatures and relative humidities of the test room were determined using a sling psychometer and psychrometric chart.

Fig. 5 - Corn flowing from the portable bin through the long wood chute and into the scale bin.

Fig. 6 - A long steel chute mounted to measure the flow rates and the depths of corn flowing in the chutes.

METHOD OF PROCEDURE

Yellow dent shelled corn that had been dried with heated air was obtained from the Swine Farm of Michigan State University. This corn was cleaned to remove most of the cracked kernels and crushed cob. Thorough cleaning was not attempted, however, to more closely simulate normal operating conditions. The resulting density was 56.0 pounds per bushel. Moisture content for the grain ranged from 10.19 to 8.38% w.b. (wet basis) throughout the tests.

A flow pattern for the shorter (2 ft) chutes was established from the portable bin, to the storage bin, through the chutes and into the lowered portable bin. After the corn was elevated in the portable bin it flowed by gravity into the storage bin. The portable bin was then lowered to the platform scale and the scale was adjusted to read zero. The chutes were attached and the angle was adjusted. The retaining door on the storage bin was opened and the corn was allowed to fill the end of the chute to the gate at the orifice. A stop watch was started when the orifice gate was opened and stopped when it was closed.

For the longer ($7\frac{1}{2}$ ft) chutes the flow pattern was from the raised portable bin, through the chutes, into a scale bin and then hand dumped into the lowered portable bin. Before the chutes were attached the portable bin was clamped securely to prevent tipping. Approximately 115 lb of shelled corn was used for each run.

As the corn was used repeatedly, damaged kernels and small dirt particles tended to collect in the bottom and corners of the bins. Periodically the used corn was discarded and replaced with new corn.

Chute Lengths

The first tests were to find what effect chutes of different lengths had on the flow rate of the grain. Wood chutes (6 x 6 in inside dimensions) were constructed of 3/8 in. plywood in 2 and 8 foot lengths. The plywood was interior grade with surfaces graded A and B. The A surface was used for the interior of the chutes and the plywood was cut so that the corn flowed parallel with the grain of the wood.

To insure accurate metering of the corn flow, plywood blocks were installed 6 in. from the top ends of the chutes. This formed an orifice that could easily be adjusted and manually opened and closed. The effective lengths of the chutes were therefore reduced from 2 ft to 1.5 ft and from 8 ft to 7.5 ft. The plywood orifices were held in place by ¼ in. clamping rods through the sides of the chutes. See Figure 6. Care was taken to keep the orifices perpendicular to the bottom of the chutes and running full during the tests.

The chutes were attached to the bins. The angle from the horizontal was carefully measured using a protractor head for a combination square with an attached level. The various slopes were set on the protractor and the chute angle adjusted until the bubble on the level was centered. Flow rates were taken at 25, 20, 45, 60 and 72 deg for 2 ft and 8 ft wood chutes. The orifice opening was kept constant at 1½ x 6 in. Three replications were made for each angle. These data of flow rate versus angle from horizontal were plotted for the two chute lengths. See Figures 7 and 8.

Chute Angles

The investigation of the influence of chute angle on discharge rates was extended to include steel chutes. Twenty gage black steel sheets were formed into chutes (6 x 6 in., inside dimensions) 2 ft and 8 ft long. Plywood blocks were again used to form the orifices 6 in. from the top end of the chutes. Wood spacers were attached across the top of the chutes to insure that they would retain their shape.

Tests were made at the various angles with $1\frac{1}{2}$, 2 and 3 in. orifice openings. The flow patterns were accomplished as before. Three replications were made for each change in orifice opening and angle.

Corn Depth in Chutes

To measure the depth of the corn flowing in the chutes a depth gage was developed. This consisted of a steel rule graduated in 0.01 in. and a clear plastic slide. The slide was made of rigid plastic 3 in. by 2 in. with an opening in the center through which the rule could move up and down. See Figure 5.

As the corn flowed through the $7\frac{1}{2}$ ft chutes the depth was measured at the wood spacers placed at 2 in., 6 in., 2 ft, 5 ft and $7\frac{1}{2}$ ft along the chute. Full depth from the top of the brace to the bottom of the chute was carefully measured. As the corn flowed through the chute the depth from the top of the brace to where the corn just touched the bottom of the depth gage was recorded. The resultant corn depth was found by subtracting the reading with the corn flowing, from the full measured depth. Three replications at the various angles and orifice openings were made at each location along the chutes. These data of corn depth versus distance along the chute were plotted for $1\frac{1}{2}$ and 2 in. orifice openings at 25, 30, 45 and 60 deg.

The angle where the corn reached zero velocity was measured by allowing the corn to flow and decreasing the angle to the point where the corn would not move in the chute. Normally the corn would flow at a depth approximately equal to 2 kernels deep at angles over 25 deg and at a distance of 2 to 5 ft from the orifice. It tended to run slightly deeper as the angle was decreased. Measurements of the chute angle was taken at the point where the corn ceased to flow. Both the wood and steel chutes were tested for zero velocity.

ANALYSIS OF DATA

Results of Tests on Effect of Chute Length

Tests were conducted to determine the effect of chute length on the discharge through an orifice in rectangular wood and steel chutes. Shelled corn with a moisture content of 10.19 to 8.48% w.b. (wet basis) was used. Flow measurements were made with orifice openings $1\frac{1}{2}$ x 6 in and 2 x 6 in. for chute lengths of $1\frac{1}{2}$ and $7\frac{1}{2}$ ft. These chutes were tested at angles of 25, 30, 45, 60 and 72 deg.

These results indicate there is little or no difference between the discharge of a $1\frac{1}{2}$ x 6 in. orifice in the short ($1\frac{1}{2}$ ft) wood chute as compared to the long ($7\frac{1}{2}$ ft) chute. See Figures 7 and 8. The percent difference from the mean discharge ranged from 0.19 to 1.42% as shown in Table 1. The discharge through the $1\frac{1}{2}$ x 6 in. orifice in the steel chutes was slightly higher in the short chutes compared to the long chute with the percent difference from the mean ranging from 0.50 to 3.05% as shown in Table 2.

Using the 2 x 6 in. orifice the discharge was higher through the long wood chute with the percent difference from the mean ranging from 0.97 to 2.88% as shown in Table 3. The discharge was higher in the short steel chute using the 2 x 6 in. orifice with the percent difference ranging from 0.20 to 2.77% as shown in Table 4. The data used in plotting the curves in Figures 7 and 8 are found in Tables 9-14, Appendix A.

All of the runs were made over a period of weeks and during this time the temperature and relative humidity fluctuated. Thus, the moisture content varied from 10.19 to 8.38% w.b. as determined by a Steinlite moisture tester. There was a slope of about 10 deg to the bottom of the portable bin used to elevate the grain for the longer chutes.

TABLE 1

Percent difference from the mean flow rate between short ($1\frac{1}{2}$ ft) and long ($7\frac{1}{2}$ ft) wood chutes at various angles with the chute orifice $1\frac{1}{2}$ x 6 in.

Angle (deg)	Flow Rates (lb/min)		Percent Difference from mean
	Short Chute	Long Chute	
25	108.3	108.9	0.28
30	128.4	128.9	0.19
45	181.5	180.5	0.28
60	222.0	223.8	0.40
72	245.5	252.6	1.42

TABLE 2

Percent difference from the mean flow rate between short ($1\frac{1}{2}$ ft) and long ($7\frac{1}{2}$ ft) steel chutes at various angles with the chute orifice $1\frac{1}{2}$ x 6 in.

Angle (deg)	Flow Rates (lb/min)		Percent Difference from mean
	Short Chute	Long Chute	
25	107.7	106.5	0.50
30	140.6	132.3	3.05
45	193.3	181.9	3.04
60	236.8	223.0	3.00
72	255.4	244.9	2.10

TABLE 3

Percent difference from the mean flow rate between short ($1\frac{1}{2}$ ft) and long ($7\frac{1}{2}$ ft) wood chutes at various angles with the chute orifice 2 x 6 in.

Angle (deg)	Flow Rates (lb/min)		Percent Difference from mean
	Short Chute	Long Chute	
25	170.3	180.4	2.88
30	212.7	218.7	1.39
45	307.5	315.1	1.22
60	392.8	400.5	0.97
72	430.0	441.0	1.26

TABLE 4

Percent difference from the mean flow rate between short ($1\frac{1}{2}$ ft) and long ($7\frac{1}{2}$ ft) steel chutes at various angles with the chute orifice 2 x 6 in.

Angle (deg)	Flow Rates (lb/min)		Percent Difference from mean
	Short Chute	Long Chute	
25	205.7	184.9	5.25
30	233.5	225.9	1.66
45	330.5	312.7	2.77
60	390.2	386.6	0.46
72	442.3	440.5	0.20

Flow limitations from the side of the storage bin would not permit tests with the short chutes using a 3 x 6 in. orifice. Tests were made, however, on the long chutes using 3 x 6 in. orifices and angle versus discharge rate was plotted as shown in Figures 7 and 8.

From the results of this investigation of the effect of chute length on the discharge rate of shelled corn, it appeared that the flow rate was essentially unaffected by the chute length.

Effect of Chute Angle on Rate of Flow

The relationship describing the flow of shelled corn through rectangular orifices placed in chutes at different angles was determined. Orifice openings 6 in. wide and $1\frac{1}{2}$, 2 and 3 in. high were used with chute angles of 25, 30, 45, 60 and 72 deg. A plot of chute discharge (lb/min) versus angle (deg) for the various orifices, Figures 7 and 8, showed that discharge increased as the angle increased. Several attempts were made to describe the curved lines mathematically. It was observed that the curves are similar to sine curves; that is, the flow rate appeared to be a function of the chute angle θ. The equation then is of the following form;

$$F = KA \sin \theta \qquad (14)$$

Where:

F = flow rate (lb/min)

K = constant for a given orifice size and shape

A = orifice area (in^2)

θ = chute angle (deg)

The constant K was determined for the various orifice openings and chute angles. See Tables 5 and 6. The coefficient of variation ranged from 1.08 to 4.22% for the different sizes and types of chutes. See Table 7.

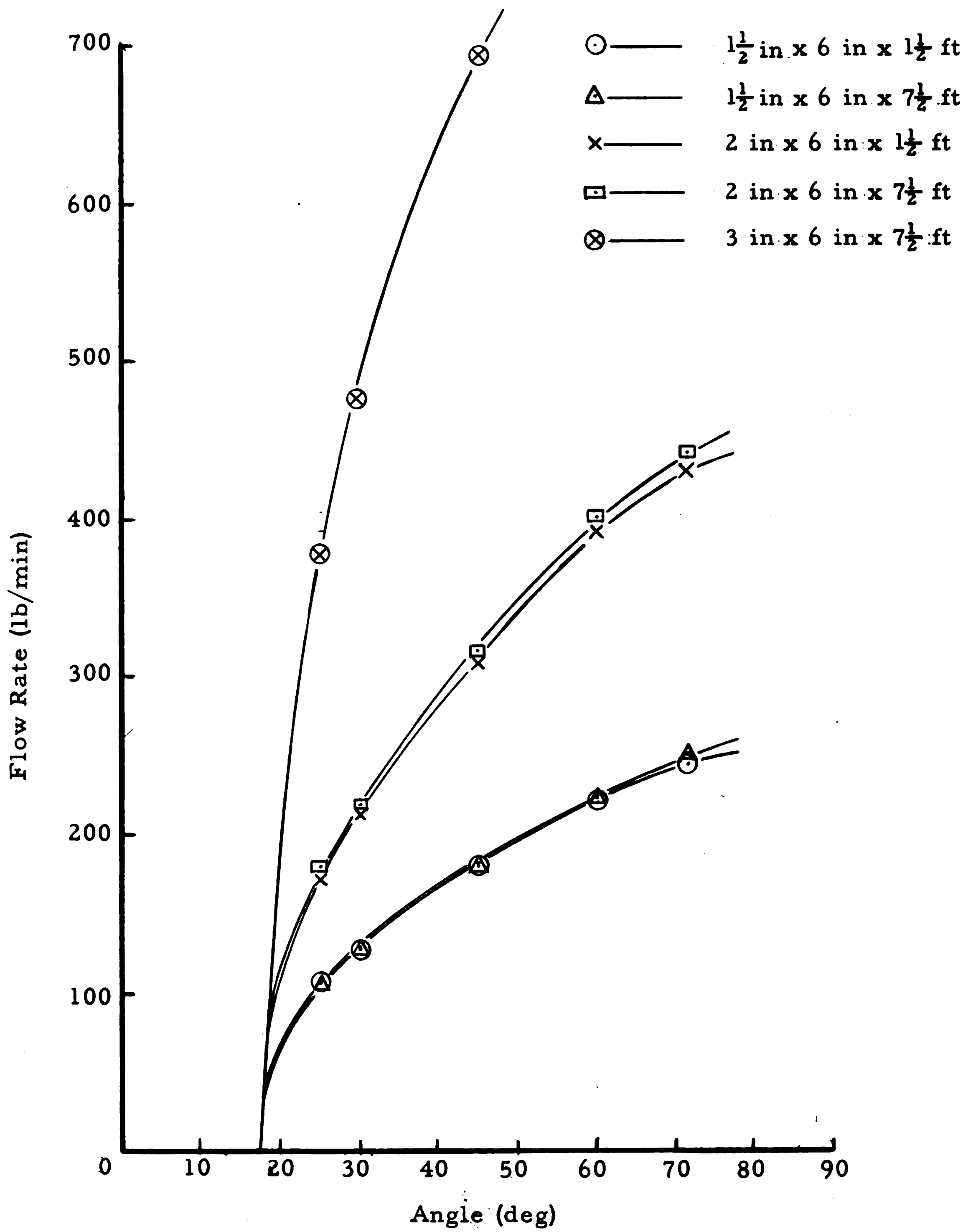

Fig. 7 - Flow rate of shelled corn through wood chutes $1\frac{1}{2}$ ft and $7\frac{1}{2}$ ft long with various orifice sizes and chute angles.

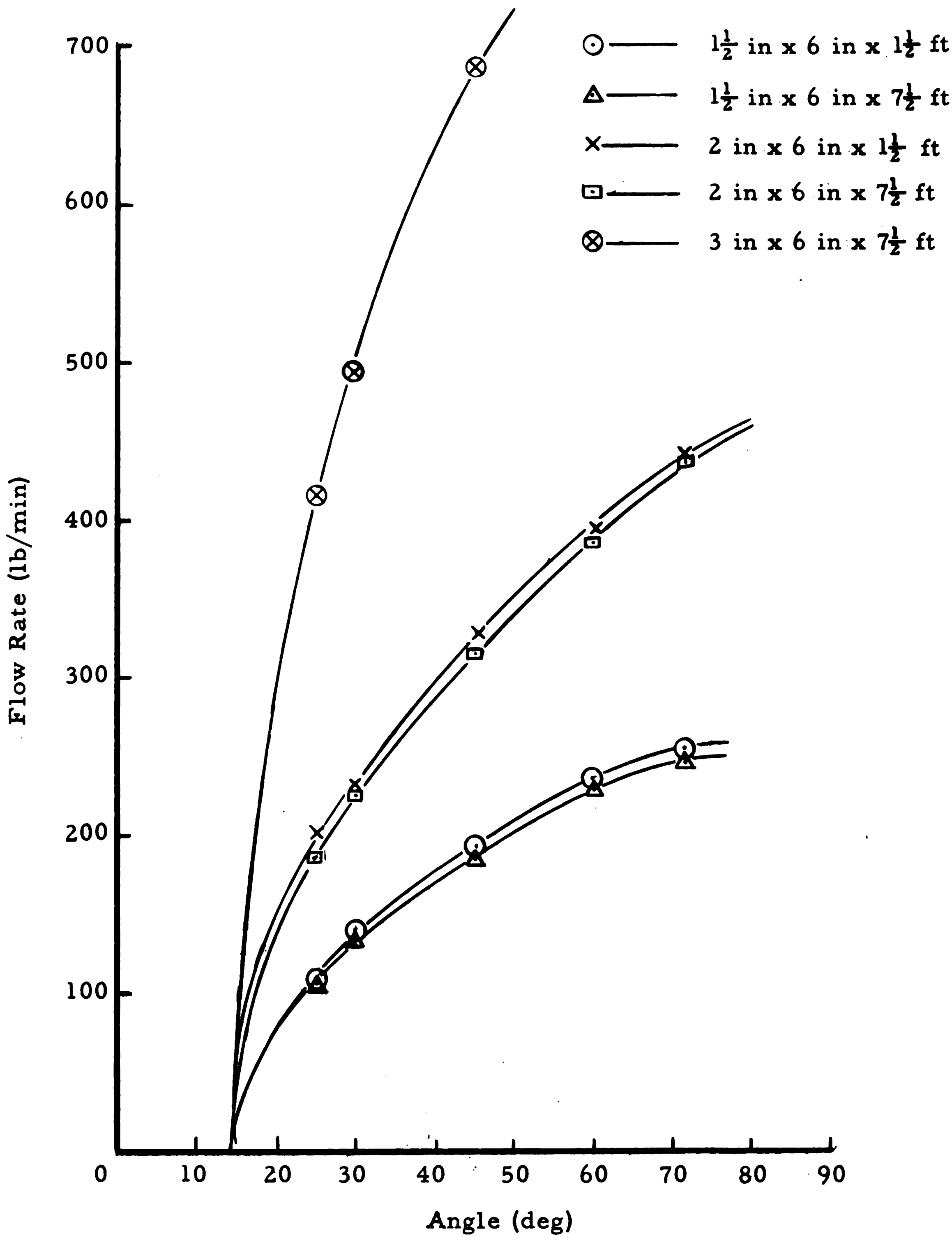

Fig. 8 - Flow rate of shelled corn through steel chutes $1\frac{1}{2}$ ft and $7\frac{1}{2}$ ft long with various orifice sizes and chute angles.

Since discharge from an orifice placed horizontally in the bottom of a bin and discharge from a chute 90 deg from horizontal are both in free fall the flow rates should be comparable. Attempts were made to calculate discharge rates from equations proposed by Ewalt (1962). His equation for a rectangular orifice positioned horizontally is as follows:

$$Q = 0.1531\ W^{1.62}\ L^{1.40} \qquad (14)$$

Where:

Q = flow rate of corn (bu/min)

W = width of the orifice (in)

L = length of the orifice (in)

By this equation a rectangular orifice $1\frac{1}{2}$ x 6 in. should give a flow of 3.64 bu/min or 204.0 lb/min. Since F = Q and F = KA sin θ, then $K = \frac{Q}{A \sin \theta}$ of $K = \frac{204.0}{9 \times 1} = 22.65$, where A (in^2) equals the area of the orifice and θ equals 90 deg. The mean of the K constants from Tables 5 and 6 for this size orifice is 28.95. The difference between the calculated K and measured K is 21.8%.

In analyzing this difference it became apparent that the grain had an approach velocity prior to flowing through the orifice in the chute. Even though care was taken to keep the orifice covered with grain during all the tests, the velocity created by movement from the dome formed in the bin to the orifice in the chute caused the flow rate to increase.

Tests were conducted to evaluate this approach velocity. The chute orifice was placed at the end of the chute and inserted into the bin of shelled corn. Runs were made using $1\frac{1}{2}$ x 6 in. and 2 x 6 in. orifices at 30 and 45 deg. Three replications of each size of orifice and angle were made. Table 8 shows the comparison factor to vary from 1.39 to 1.45 with the average equal to 1.42. This factor accounts for the approach velocity of the grain used in previous tests. The flow through orifices placed 6 in. from the end of the chute discharged at a rate 1.42 times faster than orifices placed in the end of the chute.

TABLE 5

Constant K values as determined by the equation $K = \frac{F}{A \sin \theta}$ for wood chutes at various angles and chute orifice sizes.

Wood Chute sizes (in x in x ft)	Angle (deg)	Flow Rate (lb/min)	K*
$1\frac{1}{2}$ x 6 x $1\frac{1}{2}$	25	108.3	28.50
"	30	128.4	28.40
"	45	181.5	28.45
"	60	222.0	28.45
"	72	245.5	28.60
$1\frac{1}{2}$ x 6 x $7\frac{1}{2}$	25	108.9	28.60
"	30	128.9	28.61
"	45	180.5	28.40
"	60	223.8	28.59
"	72	252.6	29.45
2 x 6 x $1\frac{1}{2}$	25	170.3	33.60
"	30	212.7	35.45
"	45	307.5	36.20
"	60	392.8	37.80
"	72	430.0	37.65
2 x 6 x $7\frac{1}{2}$	25	180.4	35.60
"	30	218.7	36.50
"	45	315.1	37.10
"	60	400.5	38.50
"	72	441.0	38.60

*Average K for wood chutes with $1\frac{1}{2}$ x 6 in. orifice 28.60.
Average K for wood chutes with 2 x 6 in. orifice 36.70.

TABLE 6

Constant K values as determined by the equation $K = \frac{F}{A \sin \theta}$ for steel chutes at various angles and chute orifice sizes

Steel Chute Sizes (in x in x ft)	Angle (deg)	Flow Rate (lbs/min)	K*
1½ x 6 x 1½	25	107.7	28.30
"	30	140.6	31.20
"	45	193.3	30.28
"	60	236.8	30.28
"	72	255.4	29.81
1½ x 6 x 7½	25	106.5	28.00
"	30	132.3	29.40
"	45	181.9	28.58
"	60	223.0	28.62
"	72	244.9	28.62
2 x 6 x 1½	25	205.7	40.40
"	30	233.5	38.85
"	45	330.5	38.95
"	60	390.2	37.50
"	72	442.3	38.70
2 x 6 x 7½	25	184.9	36.45
"	30	225.9	37.65
"	45	312.7	36.90
"	60	386.6	37.20
"	72	440.5	38.60

*Average K for steel chutes with 1½ x 6 in. orifice 29.31.
Average K for steel chutes with 2 x 6 in. orifice 38.12.

TABLE 7

A comparison of the standard deviation and coefficient of variation of the constant K for wood and steel chutes $1\frac{1}{2}$ and $7\frac{1}{2}$ ft long with $1\frac{1}{2}$ x 6 in. and 2 x 6 in. orifices.

Chute		Standard Deviation	Coefficient of Variation (%)
Type	Size (in x in x ft)		
Wood	$1\frac{1}{2}$ x 6 x $1\frac{1}{2}$	0.31	1.08
Wood	2 x 6 x $7\frac{1}{2}$	2.42	4.22
Steel	$1\frac{1}{2}$ x 6 x $1\frac{1}{2}$	1.05	3.58
Steel	2 x 6 x $7\frac{1}{2}$	1.19	3.12

TABLE 8

Comparison of the flow rate in wood chutes with the chute orifices inside and outside the storage bin.

Chute Size (in x in x ft)	Angle (deg)	Discharge Orifice in Chute (lb/min)	Discharge Orifice in Bin (lb/min)	Comparison Factor *
$1\frac{1}{2}$ x 6 x $1\frac{1}{2}$	30	128.4	90.34	1.422
$1\frac{1}{2}$ x 6 x $1\frac{1}{2}$	45	181.5	122.25	1.449
2 x 6 x $1\frac{1}{2}$	30	212.7	153.3	1.387
2 x 6 x $1\frac{1}{2}$	45	307.5	218.5	1.405

*Average Conversion Factor 1.42

Since the tests were conducted with the orifice 6 in. from the end of the chute this comparison factor must be applied to Ewalt's formula for horizontal orifices to correlate results. Ewalt's formula then becomes:

$$Q = 0.1531\ W^{1.62}\ L^{1.40}\ (1.42) \tag{16}$$

With W = 1.5 in., L = 6 in. and $\theta = 90^{\circ}$

Q = 5.15 bu/min or 288.5 lb/min

Since Q = F

Then:

$$Q = KA \sin\theta \text{ or } K = \frac{Q}{A \sin\theta} \tag{17}$$

$$K = \frac{288.5}{9 \times 1} \quad \text{of } 32.06$$

The difference in K's between the average of Tables 5 and 6 and that determined by Ewalt's equation is 10.8%. Ewalt found for the $1\frac{1}{2}$ x 6 in. orifice placed horizontally in the bin the actual measured flow rate was 255.4 lb/min. The constant K for a $1\frac{1}{2}$ x 6 in. orifice now is:

$$K = \frac{255.4}{9 \times 1} = 28.4.$$

The difference between this constant and the average K from Tables 5 and 6 for this size orifice is 0.19%. This indicates that Ewalt's equation is only valid for orifices wider than $1\frac{1}{2}$ in. Also the measured flow Q from an orifice is KA sin θ. The constant K, however, is different for different size orifices.

The flow from a 2 x 6 in. orifice placed horizontally in a bin by Ewalt was 324.8 lb/min by formula and 312.6 lb/min by actual measurement. Corresponding K's are 38.33 and 37.93. These constants differ from the average K in Tables 5 and 6 by 2.4 and 1.4%.

Similarly the flow from a 3 x 6 in. orifice placed horizontally in a bin by Ewalt was 888.0 lb/min by formula and 931.0 lb/min by actual measurement. Corresponding K's are 49.4 and 51.7. These constants differ from the average K computed from Tables 8 and 9 by 7.5 and 3.18%

These results indicate that flow rates determined by the equation $F = KA \sin \theta$ are nearly equal to flow rates as determined by the equation:

$$Q = 0.1531\ W^{1.62}\ L^{1.40} \sin \theta \tag{18}$$

with the chute angle over 25 deg and W greater than $1\frac{1}{2}$ in.

Since the value of K depends on the size of the orifice it would be more convenient to use the equation for Q which applies to any size of orifice. Also the values for the constant K in Tables 5 and 6 are valid only for equipment similar to that used in these tests with chute angles between 25 and 90 deg. The constants were found to differ by a factor of 1.42 from flow rates as determined by Ewalt.

Results of Tests on Depth of Flow in Chutes

Tests were run to determine the depth of corn at various points along the chutes set at different angles and using the different orifice sizes. The measurements were made with a depth gage graduated in 0.01 in. (See page 19 for a more detailed description of the depth gage.)

Readings were taken at the orifice and at 5 points along the long ($7\frac{1}{2}$ ft) wood chutes. Depth of corn versus distance along the chute was plotted for 25, 30, 45 and 60 deg angles, Figure 9. With a chute orifice of $1\frac{1}{2}$ x 6 in. the depth appeared to remain constant beyond about 2 ft from the orifice regardless of the angle over 25 deg. Using a 2 x 6 in. orifice, Figure 10, the corn reached a constant depth at about 5 ft from the orifice.

An additional series of tests was conducted to determine the effect of the chute material on the depth of flow. Readings were taken at the orifice and at the same locations along a ($7\frac{1}{2}$ ft) steel chute using the same chute angles. A plot of depth of corn versus distance along the chute, Figure 11, showed a relationship similar to the wood chute. Using the same size orifices, similar depths occurred at about the same location along the metal chute. The corn depth was slightly less in the metal chute than in the wood chute using a $1\frac{1}{2}$ x 6 in. orifice. See Tables 15 and 16, Appendix A. However, the opposite relationship occurred in comparing the wood and steel chutes using a 2 x 6 in. orifice, Figure 12. See also Tables 17 and 18, Appendix A. It appeared that the chute material had little effect on the depth of flow in the chutes.

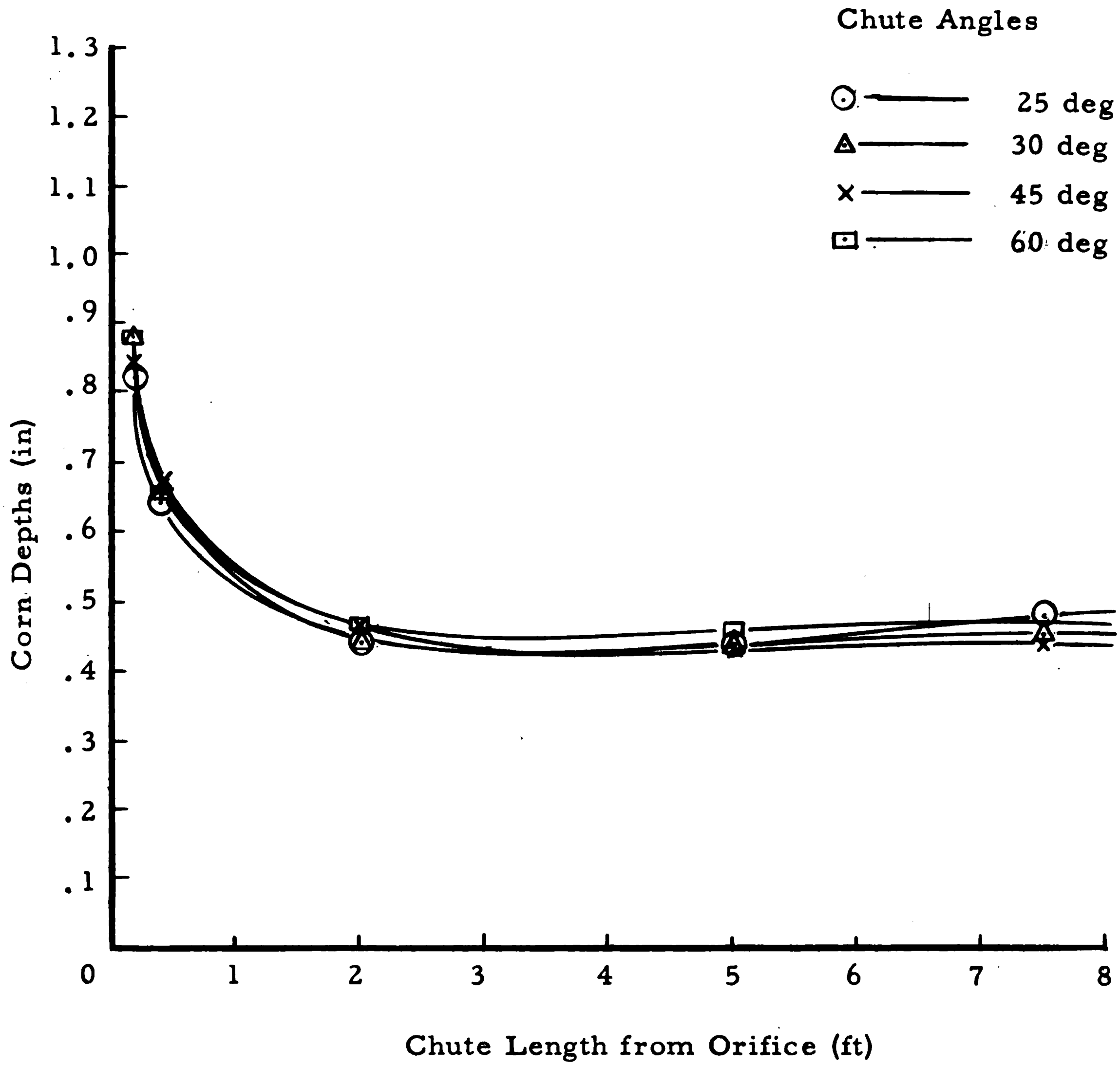

Fig. 9 - Depth of corn flowing in a $7\frac{1}{2}$ ft wood chute at angles of 25, 30, 45 and 60 deg with a $1\frac{1}{2}$ x 6 in. orifice.

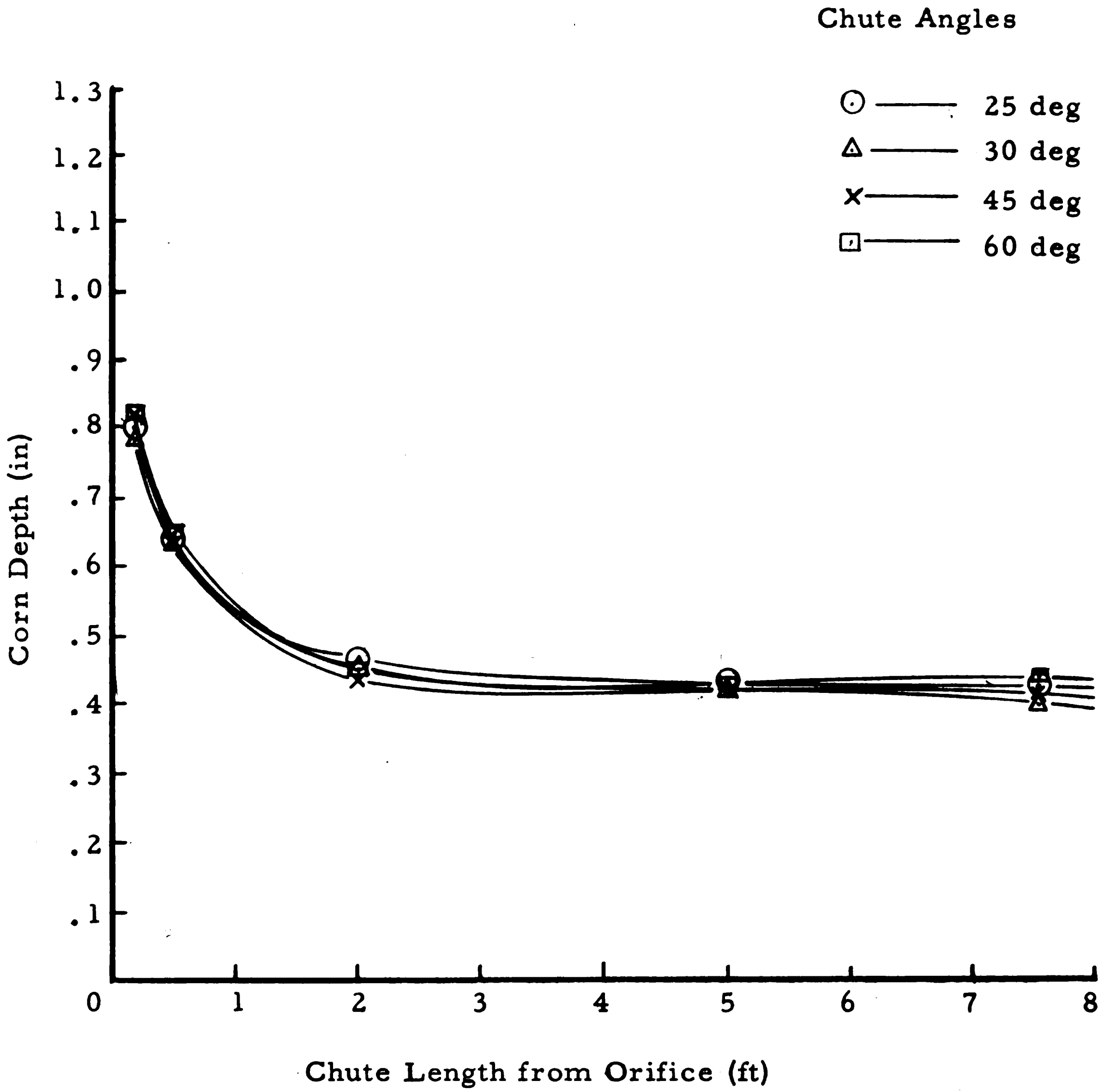

Fig. 10 - Depth of corn flowing in a $7\frac{1}{2}$ ft wood chute at angles of 25, 30, 45 and 60 deg with a 2 x 6 in. orifice.

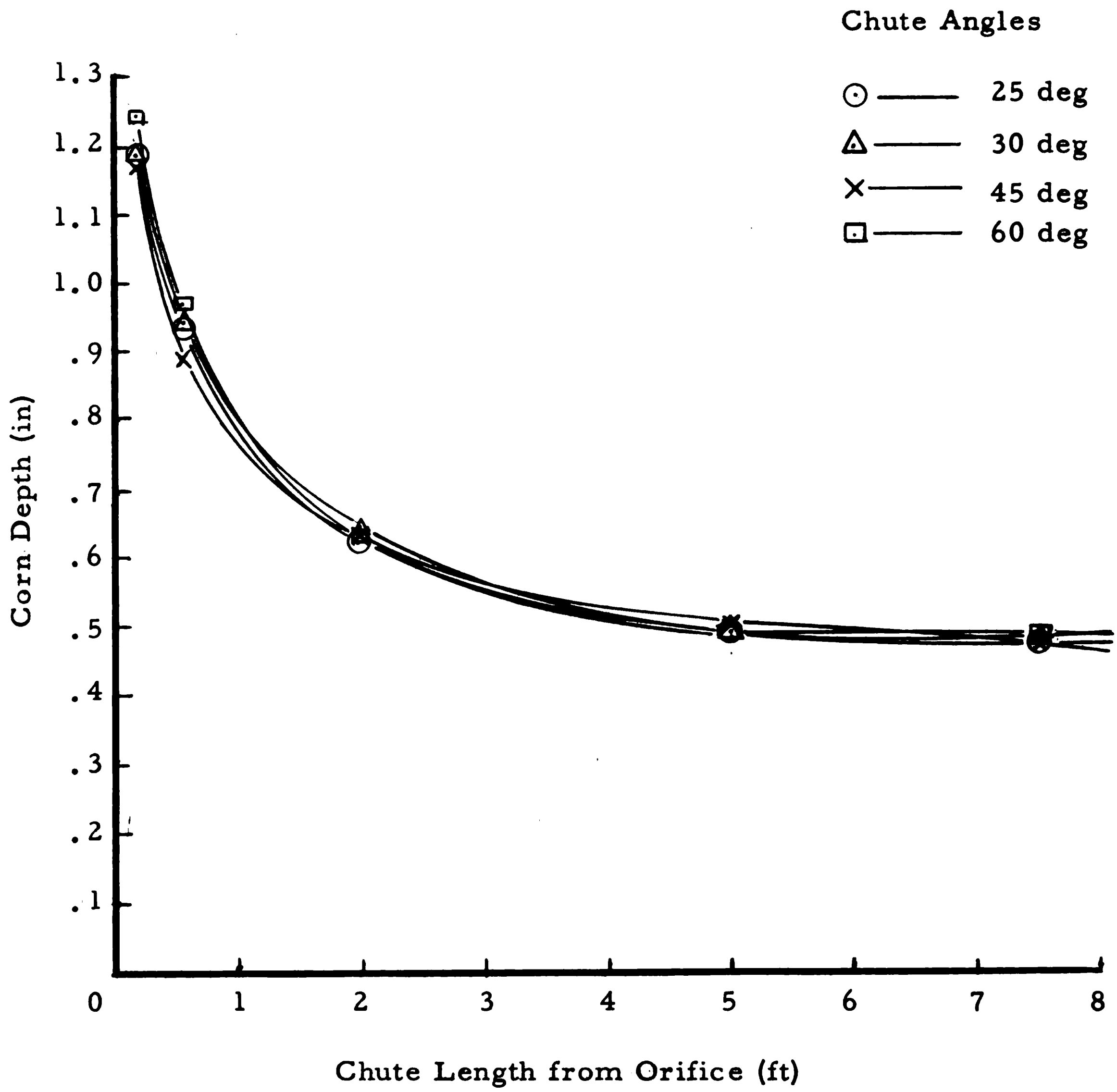

Fig. 11 - Depth of corn flowing in a $7\frac{1}{2}$ ft steel chute at angles of 25, 30, 45 and 60 deg with a $1\frac{1}{2}$ x 6 in. orifice.

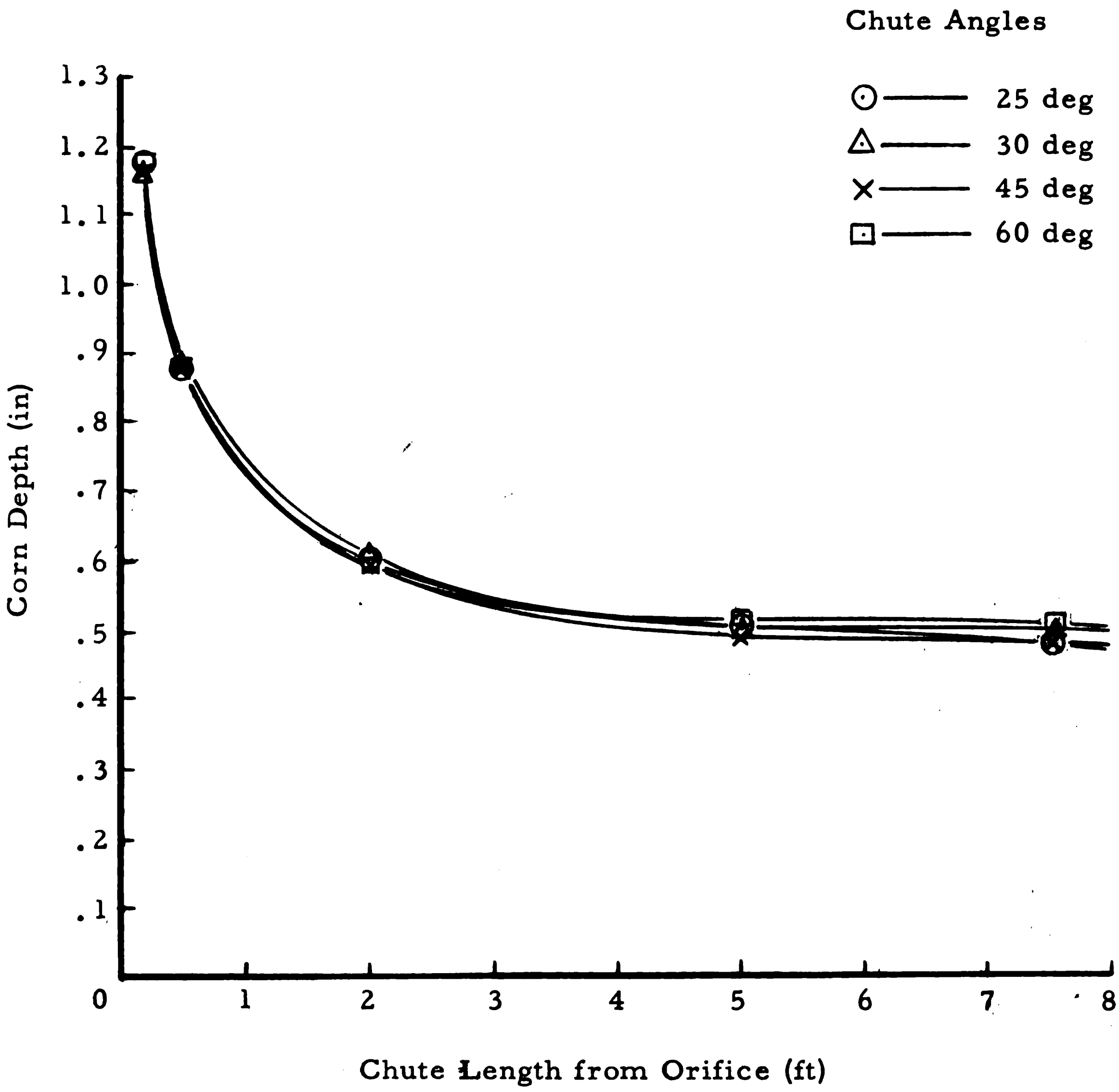

Fig. 12 - Depth of corn flowing in a $7\frac{1}{2}$ ft steel chute at angles of 25, 30, 45 and 60 deg with a 2 x 6 in.orifice.

SUMMARY

It is important that all parts of a grain handling system function smoothly and with a precision that the design engineer can predict. Considerable work has been done on discharge of semi-fluids through orifices in storage bins. Very little information is available on the flow of semi-fluids in chutes. Information has been obtained on the performance of different chute materials, the effect of location and angle of the chute orifice at the bin location and the effect of chute angle on grain velocities and flow depths in the chutes.

Several equations have been proposed describing the relationships involved in grain flow through orifices placed in bins. Lack of knowledge of flow of semi-fluids in transporting devices such as chutes often necessitates a trial and error approach.

The purposes of this work were (1) to attempt to determine the mechanical behavior of shelled corn through chutes, (2) to study the relationship between length of grain chutes and flow characteristics, (3) to study the relationship between size and shape of grain chutes and flow characteristics and (4) to study the relationship between the slope of grain chutes and flow characteristics.

Apparatus was used that had been constructed principally for the study of grain flow. It was selected to accommodate chute lengths as short as 2 ft and as long as 8 ft. The basic equipment consisted of a storage bin suspended about 5 ft off the floor. This made it possible to move a balance beam platform scale under the storage bin for gravity flow. A second portable bin was elevated on pivoted channel iron beams and powered by an electric motor driving a winch. The short (2 ft) chutes were attached to the storage bin and the flow rates were determined

as the grain flowed into the portable bin. The grain was then elevated and dumped into the storage bin. The longer (8 ft) chutes were attached to the elevated storage bin and the flow rates were measured into a third bin placed on the scale. Hand dumping into the portable bin completed the flow pattern. Yellow dent shelled corn that ranged in moisture content from 10.19 to 8.38% w.b. was used throughout the tests.

The flow varied but was essentially unaffected by the chute length. The relationship describing the flow of shelled corn through rectangular orifices was determined. The flow was found to depend on a constant, the area of the orifice and the sine of the chute angle. The constant K was determined by the equation $K = \frac{F}{A \sin \theta}$ and was found to vary with the size of the orifice. The coefficient of variation for the various orifice sizes ranged from 1.08 to 4.22%.

It became apparent during the tests that semi-fluids flowing from a storage bin are influenced by the velocities prior to flowing through the orifice in the chute. With the orifice placed in the chute 6 in. from the storage bin this approach velocity increased the flow 1.42 times the flow with the orifice in the end of the chute.

The depth of corn flowing in a chute varied with the length of the chute and was independent of the chute angle. It could not be determined that chute material effected the depth of corn in comparing the flow in wood and steel chutes with various size orifices.

CONCLUSIONS

1. The rate of flow was found to be independent of the chute length with the chute angle over 25 deg. Some variation was found when comparing the flow rate through $1\frac{1}{2}$ ft and $7\frac{1}{2}$ ft chutes with different size orifices. However, no relationship of flow rate to chute length could be established.

2. The relationship describing the flow of shelled corn through rectangular orifices placed in chutes at different angles was found to be:

$$F = KA \sin \theta$$

Where:

F = flow rate (lb/min)

K = constant for a given orifice size and shape

A = orifice area (in^2)

θ = chute angle (deg)

K was found to increase by 1.42 with the orifice placed 6 in. from the end of the chute as compared to the orifice in the end of the chute.

3. The flow rate equation for rectangular orifices may be written as follows:

$$F = 0.1531\ W^{1.62}\ L^{1.40}\ \sin \theta$$

At angles over 25 deg, the flow rate F was found to be equal to flow rates through horizontal orifices as determined by Ewalt, multiplied by the sine of the angle. His equation for a rectangular orifice positioned horizontally is as follows:

$$Q = 0.153\ W^{1.62}\ L^{1.40}$$

Where:

Q = flow rate of shelled corn (bu/min)

W = width of orifice (in)

L = length of orifice (in)

4. The depth of shelled corn flowing in chutes was found to vary with the distance from the orifice and was found to remain constant beyond 2 ft from the orifice using a $1\frac{1}{2}$ x 6 in. orifice. Depth remained constant beyond 5 ft from the orifice using a 2 x 6 in. orifice.

5. With the same orifice opening, the depth of shelled corn flowing in chutes was found to be independent of the chute angle beyong 25 deg. As the angle was increased the shelled corn appeared to flow faster but at the same depth as other angles.

6. Different chute materials did not appear to influence the depth of shelled corn flowing in the chutes at various chute angles beyond 25 deg.

RECOMMENDATIONS FOR FURTHER STUDY

1. An attempt should be made to relate the hydraulic jump that apparently occurs with grain flowing in a chute to fluid flow equations.

2. Studies should be made to determine the influence of approach velocities to the flow rates through orifices.

3. More direct methods of measuring the velocities of grains in chutes should be studied.

4. The influence of oorrosion of construction materials and films formed by dust and other foreign matter on flow rate in chutes should be studied.

5. Work should be done to determine flow rate equations for grains other than shelled corn.

6. Tests should be conducted to determine the effect of moisture on the flow rate of grains.

7. Further work should be done on the effect of chute materials on the flow rate of grain.

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APPENDIX A

EXPERIMENTAL RESULTS

TABLE 9

Flow of shelled corn through a
$1\frac{1}{2}$ x 6 in. orifice in wood chutes.

Chute Size (in x in x ft)	Angle (deg)	Flow Rates (lb/min)		
$1\frac{1}{2}$ x 6 x $1\frac{1}{2}$	25	108.2	108.5	108.3
	30	125.0	123.9	125.0
	45	181.5	181.5	181.0
	60	221.5	223.0	221.5
	72	250.0	241.0	245.5
$1\frac{1}{2}$ x 6 x $7\frac{1}{2}$	25	108.8	109.0	109.0
	30	127.8	128.5	130.5
	45	179.6	181.9	180.0
	60	224.5	223.3	223.5
	72	250.0	253.9	253.9

TABLE 10

Flow of shelled corn through a
2 x 6 in. orifice in wood chutes.

Chute Size (in x in x ft)	Angle (deg)	Flow Rates (lb/min)		
2 x 6 x $1\frac{1}{2}$	25	170.0	170.8	170.0
	30	215.5	212.0	210.5
	45	304.6	310.9	307.1
	60	401.7	381.7	395.0
	72	437.0	424.0	429.0
2 x 6 x $7\frac{1}{2}$	25	180.8	180.8	179.6
	30	213.1	225.0	218.0
	45	313.8	317.1	314.3
	60	393.3	400.8	407.5
	72	436.0	435.0	452.0

TABLE 11

Flow of shelled corn through a
$1\frac{1}{2}$ x 6 in orifice in steel chutes.

Chute Size (in x in x ft)	Angle (deg)	Flow Rates (lb/min)		
$1\frac{1}{2}$ x 6 x $1\frac{1}{2}$	25	104.1	108.2	110.9
	30	138.9	141.8	141.2
	45	193.1	195.0	191.7
	60	238.0	238.5	234.0
	72	254.3	256.0	257.1
$1\frac{1}{2}$ x 6 x $7\frac{1}{2}$	25	101.8	107.7	110.0
	30	132.2	139.9	132.8
	45	182.9	182.5	180.4
	60	224.0	225.0	223.0
	72	254.4	236.4	243.8

TABLE 12

Flow of shelled corn through a
2 x 6 in. orifice in steel chutes.

Chute Size (in x in x ft)	Angle (deg)	Flow Rates (lb/min)		
2 x 6 x $1\frac{1}{2}$	25	205.0	205.4	206.8
	30	233.0	233.5	234.0
	45	330.0	331.4	330.0
	60	407.0	401.5	405.8
	72	389.8	446.0	387.0
2 x 6 x $7\frac{1}{2}$	25	186.7	183.5	184.6
	30	229.0	222.2	226.4
	45	314.9	312.9	310.4
	60	386.7	385.7	387.5
	72	434.6	437.0	450.0

TABLE 13

Flow of shelled corn through a
3 x 6 in orifice in wood chutes.

Chute Size (in x in x ft)	Angle (deg)		Flow Rates (lb/min)	
3 x 6 x 7½	25	375.8	383.3	373.3
	30	478.0	470.0	478.0
	45	725.0	676.7	681.3
	60	982.5	1035.0	1020.0

TABLE 14

Flow of shelled corn through a
3 x 6 in. orifice in steel chutes.

Chute Size (in x in x ft)	Angle (deg)		Flow Rates (lb/min)	
3 x 6 x 7½	25	400.8	426.7	427.5
	30	497.0	481.0	501.0
	45	692.0	675.0	698.3

TABLE 15

Depths of shelled corn flowing at various distances from the orifice in wood chutes with an orifice 1½ x 6 in.

Chute Size (in x in x ft)	Angle (deg)	Corn Depths (in) Chute Length				
		2 in	6 in	2 ft	5 ft	7½ ft
1½ x 6 x 7½	25	.82	.64	.44	.43	.48
	30	.87	.66	.44	.43	.45
	45	.84	.67	.47	.44	.45
	60	.87	.65	.47	.47	--

TABLE 16

Depths of shelled corn flowing at various distances from the orifice in steel chutes with an orifice 1½ x 6 in.

Chute Size (in x in x ft)	Angle (deg)	Corn Depths (in) Chute Length				
		2 in	6 in	2 ft	5 ft	7½ ft
1½ x 6 x 7½	25	.80	.63	.47	.43	.42
	30	.77	.62	.45	.41	.39
	45	.81	.62	.42	.42	.41
	60	.82	.64	.44	.42	.43

TABLE 17

Depths of shelled corn flowing at various distances from the orifice in wood chutes with an orifice 2 x 6 in.

Chute Size (in x in x ft)	Angle (deg)	Corn Depths (in) Chute Length 2 in	6 in	2 ft	5 ft	7½ ft
2 x 6 x 7½	25	1.19	.93	.62	.49	.47
	30	1.19	.94	.64	.49	.48
	45	1.17	.88	.63	.50	.47
	60	1.25	.96	.63	.49	.49

TABLE 18

Depths of shelled corn flowing at various distances from the orifice in steel chutes with an orifice 2 x 6 in.

Chute Size (in x in x ft)	Angle (deg)	Corn Depths (in) Chute Length 2 in	6 in	2 ft	5 ft	7½ ft
2 x 6 x 7½	25	1.18	.88	.60	.50	.47
	30	1.16	.89	.61	.50	.49
	45	1.17	.88	.59	.49	.48
	60	1.18	.89	.59	.51	.50