74-9104

BERN, Carl Joseph, 1940-
EFFECTS OF AUGER STIRRING ON AIR FLOW
RESISTANCE AND OTHER PHYSICAL PROPERTIES
OF CORN.

Iowa State University, Ph.D., 1973
Engineering, agricultural

University Microfilms, A XEROX Company, Ann Arbor, Michigan

Effects of auger stirring on air flow resistance and other physical properties of corn

by

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A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major: Agricultural Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1973

TABLE OF CONTENTS

DEFINITION OF SYMBOLS

Symbol	Definition	Basic dimension
ANG	Angle between $\partial P/\partial x$ and $\partial P/\partial y$	Radian
A	Grain characteristic coefficient	T^2L^{-2}
A'	Bed cross sectional area	L^2
A_c	Cross sectional area change	L^2
A_D	Cross sectional area disturbed per unit grain depth	L
A_p	Particle area	L^2
a	Empirical coefficient	-
B	Grain characteristic coefficient	TL^{-1}
b	Empirical coefficient	-
BD	Bulk Density	FL^{-3}
C	Grain Characteristic coefficient	-
c	Constant empirical coefficient	-
D	Diameter of column	L
D_{BD}	Percent decrease in bulk density	-
d	Characteristic particle diameter	L
d_e	Diameter of a sphere having specific surface S_v	L
d_p	Diameter of a sphere having volume equivalence with a particle	L
e	Roughness length	L
f	Particle friction factor = $\Delta pd/LU^2\rho$	-
G	Mass velocity	FTL^{-3}

h_x	Horizontal distance between grid points	L
h_y	Vertical distance between grid points	L
I	Vertical coordinate subscript	L
J	Horizontal coordinate subscript	L
K,K_1,K_2	Proportionality coefficients	variable
k,k_1,k_2	Proportionality coefficients	-
L	Depth of column	L
m,m_1	Exponent or constant	-
N	Distance normal to isopressure line	L
n,n_0,n_1,n_2,n_3	Exponent or coefficient	-
P	Pressure, height of water column	L
ΔP	Pressure drop, height of water column	L
Δp	Pressure	FL^{-2}
Q	Volume flow rate	L^3T^{-1}
Q_A	Rate of volume change	L^3T^{-1}
Q_D	Volume rate of grain disturbance per unit grain depth	L^2T^{-1}
R^2	Square of multiple correlation coefficient	-
Re	Particle Reynolds number = $\rho vd/\mu$	-
S	Surface area of particles per unit volume of packed space	L^{-1}
S_A	Auger speed	LT^{-1}
S_C	Surface area of confining column	L^2
S_P	Surface area of solids	L^2
S_V	Specific surface area of solids per unit volume of solids	L^{-1}

U	Superficial fluid velocity based on cross sectional area of column	LT^{-1}
u	Velocity component in horizontal direction	LT^{-1}
V	Particle volume	L^3
v	Velocity component in vertical direction	LT^{-1}
x	Length in horizontal direction	L
y	Length in vertical direction	L
α	Streamline coefficient	-
β	Turbulent coefficient	-
ε	Fractional void volume	-
μ	Fluid absolute viscosity	FTL^{-2}
ρ	Fluid density	FT^2L^{-4}
ϕ_c	Wall correction factor	-
ϕ_s	Shape factor	-
ψ	Sphericity = $\frac{\text{area of sphere having volume of particle}}{\text{area of particle}}$	

INTRODUCTION

Early studies of fluid flow through granular solids involved only non-biological solids. D'Arcy (1856), for example, experimented with water flow through sand beds. The studies of Blake (1922) involved flow of various fluids through beds of glass beads, glass rings and glass cylinders.

Growth of the practice of drying grain and hay artificially made the air flow resistance characteristics of these biological products important because drier design involves a prediction of pressure drop across the bed of product to be dried. According to Hukill (1957), artificial drying of grain was carried on to a very limited extent in the period prior to World War I. Acceptance by farmers of the practice of artificially drying grain came in succeeding years and paralleled the adoption of the combine for harvesting grain. One of the first studies of air flow resistance of grain was that of Stirniman et al. (1931) who worked with rough rice. Most studies on this topic were carried out after 1940.

Studies as early as Henderson (1943) recognized the importance of grain bulk density changes on the air flow resistance of grain. Shedd (1953) listed pressure drop correction factors to account for grain bulk density differences resulting from various filling procedures.

In the period from 1965 through 1967, according to Toms (1968), auger grain stirrers were introduced by several manufacturers. The grain stirrer consists of one or more open augers suspended from the bin roof and sidewall and extending to near the bin floor. The augers are turned and simultaneously moved horizontally through the grain. Grain stirrers are now widely used with bin drying systems.

The literature of various stirrer manufacturers state that auger stirring of corn will: loosen grain, increase airflow, reduce static pressure, reduce final moisture content variation to less than 1 percent, reduce drying time and drying cost by 50 percent, and improve grain quality. Most of these claimed effects have not been reported in research literature.

REVIEW OF LITERATURE

The effects of auger-stirring corn have not been studied extensively. However, a large amount of research has been reported on the resistance of granular solids to fluid flow. Because this research relates to air flow resistance of corn, the pertinent studies have been reported in this section. This section is divided into studies involved with non-biological materials and studies involved with biological materials. Included in the second category is research which involved auger stirring.

Resistance of Non-Biological Granular Solids to Fluid Flow

Fluid flow through granular solids has been the topic of many research studies. Practically all of these studies have been largely empirical. This is true in spite of the fact that the principles of motion of viscous fluids, including those flowing through granular solids, are expressed in the Navier-Stokes equations of classical hydrodynamics. The reason for this is expressed by Muskat (1937):

> Unfortunately...the mathematical difficulties of applying these [Navier-Stokes] equations to porus media are for practical purposes entirely unsurmountable.

Some the earliest work reported on fluid flow through granular solids was by D'Arcy (1856). By experiments with water flowing through a sand filter, he concluded that the rate of flow was proportional to the cross sectional area of the filter and the difference in pressure between the inlet and outlet of the filter, and inversely proportional to the thickness of the filter. In equation form:

$$Q = \frac{K\ A'\Delta P}{L} \tag{1}$$

where K is a coefficient which was characteristic of the sand. Equation 1 is generally referred to as D'Arcy's law.

This equation and subsequent modifications have been used extensively to describe laminar flow of fluids through granular solids. There are two limitations associated with the use of D'Arcy's law: it is applicable only within the velocity range below the onset of turbulence, and the coefficient, K, is valid only for a particular fluid-solid combination because of the many properties it must account for. This velocity range below the onset of turbulence (called the seepage velocity domain) has been commonly defined by a maximum particle Reynolds number, Re. Muskat (1937) gives the maximum as Re=1 with the characteristic length dimension, d, being "any reasonable average diameter of the sand grains".

Scheidegger (1960) reviewed twenty-five studies in which determinations of this maximum Re were made. He found a range of Reynolds numbers from Re=0.1 to Re=75. Scheidegger attributes this wide range to an inconsistency in choosing the characteristic length dimension, d, and the inadequacy of this length dimension, however defined, in accounting for particle geometry.

Blake (1922) used a dimensional analysis approach to study the resistance to fluid flow of tower packings. His work led to this equation of dimensionless groups:

$$\frac{\Delta p \; d}{L \; U^2 \; \rho} = F\left(\frac{\rho \; U \; d}{\mu}\right) \tag{2}$$

The dimensionless groups obtained are seen to be the friction factor, f, and Re. These are analogous to dimensionless groups commonly employed in the study of fluid flow in conduits. Experimenting with different types of column packings and plotting one dimensionless group versus the other, Blake found that results for each type of packing fell on a different line. This suggested that the packing material was not adequately described in the dimensionless groups. Blake then replaced the characteristic particle diameter, d, with ε/S, the ratio of fractional void volume to surface area of packing per unit volume of packed space. He also replaced U by U/ε which in effect gave an actual fluid velocity rather than a superficial one. This eliminated some but not all of the variation among packings when the dimensionless groups were plotted.

Furnas (1929) proposed the equation

$$\frac{\rho \; \Delta P}{L} = KG^m \tag{3}$$

to describe the flow of gases through beds of broken solids. In this equation, K and m are constants for a given system but may vary with particle size, fluid viscosity, fluid molecular weight, fractional voids, column diameter and particle shape. Furnas concluded that the equation was not theoretically exact, but was very convenient and "has been found to apply with sufficient accuracy". Furnas came to the important conclusion that pressure drop per unit column height is independent of the total column height. Another important contribution was his investigation of the wall effect. He formulated graphs which enable correction of K for various D/d (column diameter to particle diameter) ratios.

Brownell and Katz (1947) developed further the dimensional analysis approach of Blake (1922) by modifying the Reynolds number and friction factor to account for other variables. The modified Reynolds number (Re') was defined as

$$Re' = \frac{\rho \; U \; d}{\mu \varepsilon^{m}} \tag{4}$$

and the modified friction factor (f') as

$$f' = \frac{2 \; d \; \Delta p \; \varepsilon^{n}}{L \; U^{2} \; \rho} \tag{5}$$

The exponents m and n are functions of ψ/ε where ψ is the sphericity of the particle defined as

$$\psi = \frac{\text{area of a sphere having volume of particle}}{\text{area of particle}} \qquad (6)$$

The range of these exponents is approximately from n=5.6 and m=2.8 for ψ/ε =4.0 to n=37 and m=18 for ψ/ε =0.3.

A plot of f' versus Re' was developed, by Brownell and Katz with curves for various values of relative roughness, e/d, in which e is a characteristic roughness length. The values of relative roughness are tabulated for various materials. For particles of uneven size, a procedure is given to calculate d by a sieve analysis.

Another study modifying the Reynolds number and friction factor approach was made by Leva (1949). His prediction equation is

$$\Delta p = \frac{2\, fU^2 \rho L\, (1 - \varepsilon)^{3-n}}{d_p\, \Phi_s^{3-n}\, \varepsilon^3} \qquad (7)$$

where Φ_s is a shape factor and n is a constant and d_p is the diameter of a sphere having volume equivalence with a particle. To use the equation, a Reynolds number is calculated using d_p as the characteristic particle length. Using this Reynolds number, values of n and f are read from graphs. The shape factor is defined as

$$\Phi_s = 4.87\, \frac{V^{0.667}}{A_p} \qquad (8)$$

where V is the particle volume and A_p is the particle area. Knowing the fraction of voids, the bed height and the fluid density the equation can then be solved for a pressure drop prediction.

Reynolds (1900), studying heat transfer in the boiler of a steam locomotive, was first to suggest that the resistance offered by friction to the motion of a fluid was the sum of two terms, proportional respectively to the first power of the fluid velocity and to the product of fluid density and fluid velocity squared. Ergun (1952), aware of the earlier observation by Osborne Reynolds, developed a two part equation which considered the pressure drop of a fluid flowing through granular solids to be due to simultaneous viscous and kinetic energy losses.

$$\frac{\Delta p}{L} = k\ U + k_2\ \rho\ U^2 \tag{9}$$

This general form of the pressure drop prediction equation had been suggested but not developed by Furnas (1929), Muskat (1937) and others. Modifications of D'Arcy's law have shown viscous losses to be proportional to μ. This suggested that k be replaced by k_1/μ.

Based on work of Ergun and Orning (1949) and tests with nitrogen flow through coke, Ergun showed that viscous energy losses are proportional to $(1 - \varepsilon)^2/\varepsilon^3$ and kinetic energy losses to $(1 - \varepsilon)/\varepsilon^3$. As a characteristic length dimension for the particles, Ergun used d_e, the diameter of a sphere having specific surface S_v, which is expressed as

$$d_e = \frac{6}{S_v} \tag{10}$$

This gave a prediction equation of this form:

$$\frac{\Delta p}{L} = k_1 \frac{(1 - \varepsilon)^2}{\varepsilon^3} \frac{U}{d_e^2} + k_2 \frac{(1 - \varepsilon)}{\varepsilon^3} \frac{\mu U^2}{d_e} \tag{11}$$

Ergun used the results from 640 experiments to determine k_1 and k_2 by the method of least squares. In these experiments, the solids used were sand, pulverized coke, and various sized spheres of a non-identified material. The fluids used were CO_2, N_2, CH_4 and H_2. The k values obtained were: $k_1 = 150$ and $k_2 = 1.75$.

Yen (1967) studied available methods for predicting pressure drop through packed beds for the purpose of evaluating the accuracy of prediction. He selected the methods of Brownell, Leva, and Ergun for careful evaluation from "a bewildering variety of calculation methods." Data from five studies reported in the literature were used for evaluation. The studies involved a variety of solids and fluids. None of the data had been used by Brownell, Leva, or Ergun. Results of Yen's evaluation are shown in Table 1. For the four experiments which most closely approximate air flow through

Table 1. Pressure drop prediction error (Yen, 1967)

Prediction method	Error range percent	Standard deviation percent
Brownell	-45 to + 11	24
Leva	-57 to + 63	28
Ergun	-67 to + 46	40

grain (air flow through granules), the Ergun equation gave the most accurate prediction in three experiments.

Fan (1959), using data from Crowther (1952) modified the Ergun equation to better represent the characteristics of the packed bed, and to improve the accuracy of predictions. The prediction equation developed by Fan was

$$\frac{\Delta p}{L} = \frac{\alpha \Phi_c (36)(1 - \varepsilon)^2 \rho U}{\varepsilon^3 d_e^2} + \frac{\beta (6)(1 - \varepsilon) \rho U^2}{\varepsilon^3 d_e} \qquad (12)$$

This equation is seen to resemble the Ergun equation, with the constants changed and coefficients α, Φ_c, and β added. The factor α is called a streamline coefficient. Its purpose is to account for particle shape and packing density. The computational procedure for α is based on Fan's theory that the force on a particle is proportional to its projected perimeter, and on experimental correlations. The factor α is a function of the fraction of voids, the surface area of the packing and the mean projected perimeter of the particles.

The factor Φ_c is a wall correction factor. Its computational procedure was developed by empirical means by Sullivan and Hertel (1940). The formula for computing Φ_c is

$$\Phi_c = \left[1 + \frac{(2/\alpha)^{1/2} S_c}{S_p(1 - \varepsilon)}\right]^2 \tag{13}$$

where S_p is the surface area of the packing particles and S_c is the surface area of the walls of the confining column. The factor β is referred to as the turbulent coefficient. It was empirically correlated with particle shape.

On tests with SAE 60 lubricating oil, air and water flowing through five different materials, Fan's predictions for α ranged from 22.5 percent high to 10.2 percent low. Predictions for β ranged from 37.9 percent high to 21.2 percent low.

Robison (1960) studied the laminar flow of helium, nitrogen, hydrogen and n-butane through particles of porous insulating firebrick coated with sibutyl phthalate substrate. He used the laminar flow term of the basic Ergun equation and added an empirical packing factor multiplier. This packing factor was a function of column diameter, particle diameter, bulk density of the packing, the amount of substrate added. A rigorous statistical procedure was used in deriving the packing factor computation equation.

Robison also ran a factorial experiment to determine which bed variables contributed to variations in the packing factor. Variables which proved significant were used in a multiple regression analysis. The polynomial determined by this analysis was used as the prediction equation for the packing factor. In final form, the prediction equation was able to account for 92.7 percent of the variation in the packing factor. This study by Robison was the only study of resistance of non-biological solids to fluid flow reviewed that used a rigorous statistical analysis.

Bunn (1960) developed the following empirical equation to predict pressure drop for air flow through steel shot:

$$\frac{\Delta P}{L} = a(e^{bU^2/\Delta P/L} - 1) \tag{14}$$

In this equation, a and b are empirically determined coefficients. Bunn tested over 40 equation forms and selected this as being the form able to best represent the data. He pointed out that the major disadvantage of this equation form is the inability to determine a and b by standard least squares methods. An iteration procedure was used to compute values of a and b from experimental data.

Some conclusions can be drawn from the studies reviewed in regard to which factors are important to consider when studying the resistance of granular solids to fluid flow. In order to predict fluid pressure drop per unit length of bed depth, there is general agreement that the fluid properties are adequately accounted for by specification of U, μ, and ρ. There is no general agreement as to how to adequately account for characteristics of the bed. Specification of ε and a characteristic particle length has been found important by most studies. Definition of this particle length varies considerably. Other factors which have been considered are D, e, particle shape, and particle orientation.

Resistance of Biological Granular Solids to Air Flow

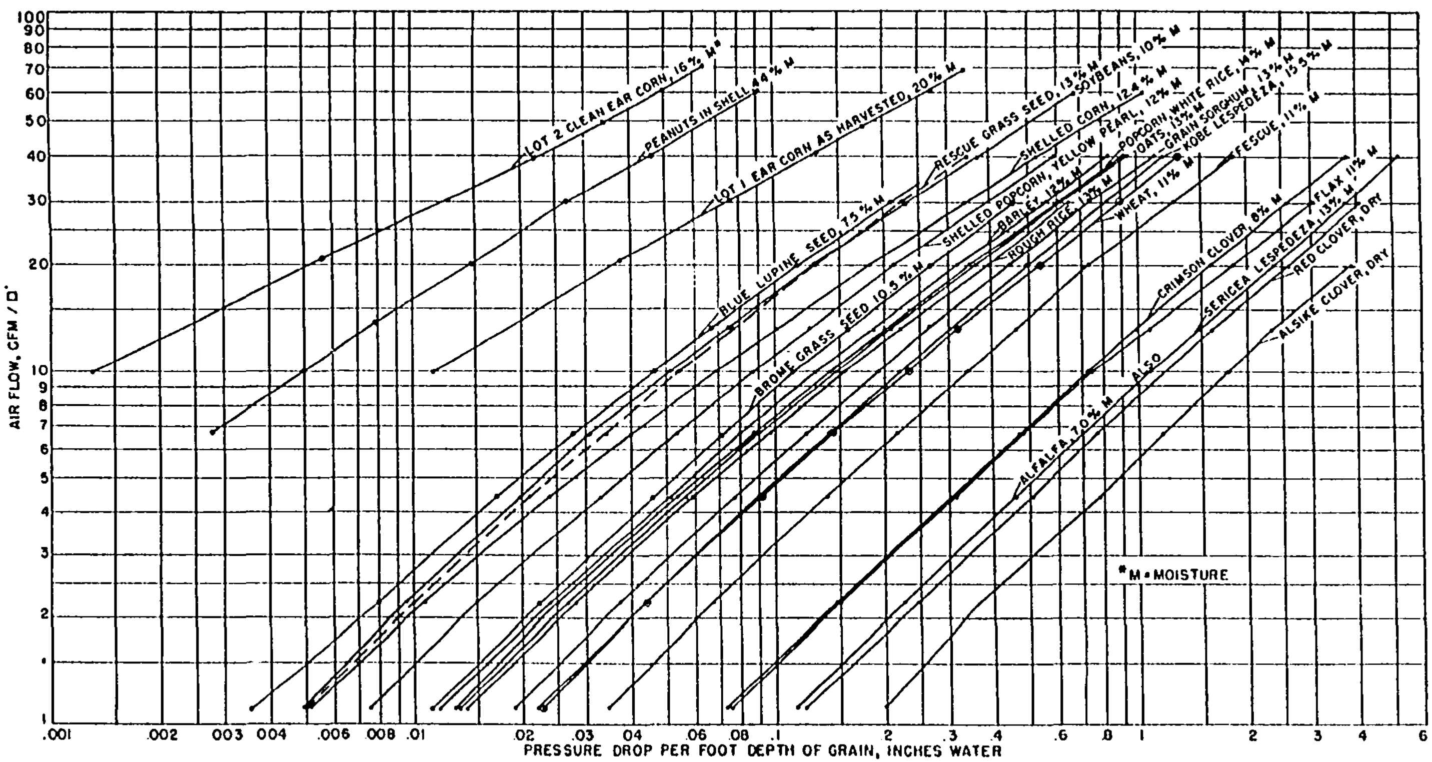
This section is conveniently divided into studies where air flow paths were straight and parallel, studies where air flow paths were non-parallel or divergent, and studies which involved auger stirring.

Parallel air flow

Probably the most common approach used in estimating pressure drop through grain is to use experimental curves relating air flow and pressure drop. Shedd (1953) developed such curves for common seeds and grains (Figure 1). These curves, commonly known as "Shedd's curves," are widely used and were adopted in 1948 as ASAE Technical Data D272 (American Society of Agricultural Engineers (1972), page 367).

Many other studies have involved development of similar experimental curves for various products. Stirniman et al.

Figure 1. Shedd's curves for resistance of loosely filled, clean grain and seed to air flow (Shedd, 1953)


LOT 2 CLEAN EAR CORN, 16% M*
PEANUTS IN SHELL, 4.4% M
LOT 1 EAR CORN AS HARVESTED, 20% M
RESCUE GRASS SEED, 13% M
SOYBEANS, 10% M
SHELLED CORN, 12.4% M
SHELLED POPCORN, YELLOW PEARL, 12% M
POPCORN, WHITE RICE, 14% M
OATS, 13% M
GRAIN SORGHUM, 13% M
KOBE LESPEDEZA, 15.5% M
BLUE LUPINE SEED, 7.5% M
BARLEY, 12% M
ROUGH RICE, 12% M
WHEAT, 11% M
FESCUE, 11% M
BROME GRASS SEED, 10.5% M
CRIMSON CLOVER, 8% M
FLAX 11% M
SERICEA LESPEDEZA, 13% M
RED CLOVER, DRY
ALSIKE CLOVER, DRY
ALSO
ALFALFA, 7.0% M
*M = MOISTURE
AIR FLOW, CFM / □'
PRESSURE DROP PER FOOT DEPTH OF GRAIN, INCHES WATER

(1931) worked with rough rice; Henderson (1943) with corn; Henderson (1944) with oats and soybeans; Shedd (1945) with ear corn; Shedd (1951) with soybeans, corn, oats, rough rice, red clover, and alsike clover; Day (1963) with crushed and non-crushed dry hay; Husain and Ojha (1969) with rough rice, Calderwood (1972) with rough and milled rice.

The use of these experimental curves has a definite advantage in convenience, but the accuracy of the pressure drop prediction may be poor because of insufficient consideration of the effects of variations in some important factors. Most important is variation in ε, a factor responsive to filling method.

Shedd (1951) observed changes in pressure drop of over 60 percent at the same air flow rate when the filling method was changed. Shedd's curves are for a loose fill condition which was obtained by pouring grain into a funnel, the outlet of which was held just above the surface of the grain in the bin. Shedd (1953) listed correction factors to apply to values from Shedd's curves to account for variations in filling method, grain moisture content, and foreign material in the grain.

Several studies have involved attempts to fit equations to experimental curves relating air flow and pressure drop. Henderson (1943) used the equation

$$U = K\left(\frac{\Delta P}{L}\right)^{C} \qquad (15)$$

where K and c are constants. Shedd (1953) also fitted an equation of this form to the data of several of Shedd's curves. He stated that a particular set of constants would give good prediction accuracy over only a narrow range of flow rates. This equation form assumes a straight line relationship between ΔP and U on a log-log plot.

Hukill and Ives (1955) fitted the following equation to Shedd's data:

$$\frac{\Delta P}{L} = \frac{a\ U^2}{\log_e\ (1 + bU)} \tag{16}$$

With suitable values of a and b, it was found to fit Shedd's data very closely.

Agrawal and Chand (1972) studied the air flow characteristics of rough rice. They used the approach of Blake (1922) and plotted particle Reynolds number versus the friction factor. Three varieties of rice gave three separate curves.

Muchiri (1969) determined correction factors to apply to each term of the Ergun equation (Equation 11) to make it applicable for corn. Air flow rates used ranged from 4.6 to 123 cfm/ft^2. Some experimental observations varied considerably from corrected Ergun equation predictions. Muchiri attributed these deviations to errors in measuring the fraction of voids by a mercury displacement method. One conclusion from another part of Muchiri's study was that at an air flow rate of 8.93 cfm/ft^2 pressure drop does not vary with corn moisture content if the fractional void volume is held constant. Tests were conducted with grain moisture content ranging from 8 to 28 percent wet basis.

Bakker-Arkema et al. (1969) reviewed pressure drop prediction methods in order to find a suitable equation for prediction of air pressure drop through beds of cherry pits. They found that the Ergun equation (Equation 11), with a single correction factor multiplier applied to both terms, was convenient to use and gave sufficiently accurate pressure drop predictions. The correction factor for cherry pits was empirically found to be 1.22. The researchers proposed that ASAE Technical Data D272 (Shedd's curves) be replaced by correction factors for the Ergun equation, tabularized for different grains, bed porosities, and foreign material percentages.

In a later paper (Patterson et al., 1971) these same researchers investigated the effect of bed porosity, particle moisture content, air temperature, and percentage of foreign material on pressure drop through beds of corn and navy beans. They found the effect of bed porosity was very pronounced and that its effect can be accounted for in the Ergun equation. Using bulk density as an indication of bed porosity made measurements easier and was shown to be sufficiently accurate.

At a constant bed porosity and air flow, Patterson et al. (1971) found that static pressure will increase with grain moisture content for corn, but will decrease for navy beans. Moisture content was varied from 15 to 25 percent wet basis. This is not in agreement with the conclusion of Muchiri (1969) previously reported. At a constant air flow rate, Patterson et al. (1971) found that pressure drop increased significantly when air temperature was raised from 87 to 120°F. The effect was attributed to the change in bed porosity caused by thermal expansion of the particles.

To determine the effect of foreign material, Patterson et al. (1971) tested corn containing 0, 2, and 5 percent of material which would pass a 12/64 in. round hole sieve. At a constant air flow, pressure drop increased with percent of foreign material. The effect was attributed to resulting changes in bed porosity and equivalent particle diameter. A table of correction factors for the Ergun equation was presented for corn and navy beans. It contained a correction factor for various bed porosities, grain moisture contents, air temperatures, and foreign material percentages.

Non-linear air flow

In many systems involving air flow through grain, flow lines are not parallel. Hukill and Ives (1955) integrated their empirical prediction equation (Equation 16) along a two dimensional radial flow line and determined an equation for predicting pressure at any radial distance. Observed pressures agreed closely with predicted pressures except in the region near the duct surface.

Hukill and Shedd (1955) in a study of aeration developed a graphical method for computing air flow traverse time for any point in a two-dimensional model of a grain mass. The traverse time for a point in the grain mass is the time required for air to pass through the grain to that point. Traverse time is an index for effectiveness of aeration. Before this time could be calculated for a given situation, it was necessary to determine the pressure distribution. The procedure used by Hukill and Shedd consisted of drawing isopressure lines, and then flow lines which crossed isopressure lines at right angles. Hall (1955) and Collins (1953) described similar procedures, but used aeration rate per unit volume of grain as an index for effectiveness of aeration. Brooker (1958a) carried out a similar analysis and compared different types of air ducts for aeration effectiveness.

Brooker (1961) described a method of determining the pressure distribution within a two-dimensional grain mass by numerical methods. He first assumed that in the direction of flow

$$U = K\left(\frac{\partial P}{\partial N}\right)^{c} \tag{17}$$

which is seen to be a differential form of Equation 15. Values of K and c were determined by fitting a curve to experimental data. Other assumptions made were:

1. Air will flow in a direction normal to isopressure lines.
2. Pressure gradients in the x and y directions are related by the equation:

$$\left(\frac{\partial P}{\partial N}\right)^2 = \left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2 \qquad (18)$$

3. Velocity components in the x and y directions are related to the velocity in the direction of flow as follows:

$$\frac{u}{U} = \frac{\partial P/\partial x}{\partial P/\partial N} \qquad (19)$$

$$\frac{v}{U} = \frac{\partial P/\partial y}{\partial P/\partial N} \qquad (20)$$

Combining Equations 19 and 20 with 18 and 17 led to two equations which related u and v respectively to $\partial P/\partial x$, $\partial P/\partial y$, K, and c. These equations were differentiated with respect to x and y, and substituted into the continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (21)$$

The continuity equation was then converted to a finite difference form, based on nine grid points and a 4 in. by 4 in. grid spacing. The pressure at the center point was solved for in terms of K, c, and the pressures at the eight surrounding points. An electronic digital computer was programmed to iterate toward a final pressure distribution, that is, to consider each grid point in turn and compute a "better" pressure value for that point. The process was repeated until no grid point changed by more than a set value from one iteration to the next.

Brooker, using the method he developed, computed the pressure distribution in a bin section 8 ft in height and 4 ft in width, having an 8 in. high by 16 in. wide duct centered at the bottom. Traverse times for the longest air flow path were computed by the method of Hukill and Shedd (1955) for a bin of wheat using a pressure distribution determined by numerical methods and a measured pressure distribution. Results were almost identical for all duct static pressures tested. Values for c and K in Equation 17 were obtained by fitting the data of Shedd's curve for wheat.

Bunn (1960) used the method of Brooker (1961) to predict the pressure distribution in a two dimensional bed of steel shot. He evidently learned of this method through Brooker (1958b), a conference paper presented prior to the publication of Brooker (1961). Bunn found that Equation 14, with a and b determined from experimental data, gave a more accurate pressure distribution prediction than did Equation 17 as used by Brooker. Bunn used a 1-1/2 by 1-1/2 in. grid and a bin cross section 2 ft square with a 3 in. square duct in the lower left corner. Predicted pressures were found to agree with measured pressures within the limits of experimental error.

Brooker (1969) used the same numerical technique to determine the pressure distribution in a bin section of corn 2 ft wide and 8 ft tall, with an 8 in. square closed-top duct in the lower right corner. He fit Equation 17 to Shedd's curve for corn. To provide a close fit, he used five values of K and c to cover the range of air flows from approximately 1 to 40 cfm/ft^2. He ceased iterating when no point in the field had changed more than 0.0001 in. of water between successive iterations. After the pressure distribution had been calculated, the magnitude and direction of the air velocity was determined at each point. Velocity distributions for different duct static pressures were then drawn. Calculated pressures differed somewhat from pressures measured on an actual bin section. The author suggests that this may have been due to pressure drop occurring across the duct screen.

Jindal and Thompson (1972) used the method of Brooker (1961) to determine the pressure distribution in grain sorghum piles of triangular cross section. They also developed a computer method to determine the coordinates of points lying on flow paths. Figures in their paper show isopressure lines and flow lines for angles of repose of 25, 35, and 45 degrees. They reported good agreement between predicted and observed pressures.

Airflow through auger-stirred corn

Grain stirrers were introduced by several manufacturers between 1965 and 1967 according to Toms (1968). A discussion of grain stirrer systems and typical management procedures for them is given in Appendix C.

The effects of auger stirring grain have not been extensively studied. Frus (1968) compared bin batch drying systems with and without stirring augers. He conducted two tests using two 18-ft diameter bins equipped with identical drying floors, 7 1/2 hp fans, heaters, controls and distributors. One bin was equipped with stirring equipment and one was not. Results from this test are shown in Table 2.

Table 2. Comparison of bin batch drying systems with and without stirrers

Grain depth	Bin batch without stirrer	Bin batch with stirrer
2-1/2 to 3 ft		
Lb water removed per hour	277	278
Lb water removed per penny	1.67	2.02
Final moisture content variation	4.3 percent	2.0 percent
4 to 6 ft		
Lb water removed per hour	247	302
Lb water removed per penny	1.84	2.22
Final moisture content variation	11.8 percent	6.2 percent

Complete details of the experiment are not given but the results indicate that a bin batch dryer with a stirrer may dry the grain faster and at a lower fuel cost, and that moisture content variation is reduced. Frus also observed that about 6 to 8 in. of corn along the bin wall had not been stirred and that "this band of corn did not dry."

Toms (1968) carried out an extensive study of the effects of auger stirring corn. In one part of the study, a 6-ft diameter bin 6 ft in depth was equipped with a 2-in. diameter stirring auger, perforated floor and variable-flow fan. A total of 34 stirring tests were run, keeping a constant pressure drop of 3.2 inches of water across the corn mass. Change in air flow rate was used as the criterion of stirring effectiveness. The auger could be moved in concentric circles of chosen radii, in either a clockwise or counter-clockwise direction. The rate of angular rotation was not adjustable. Auger linear speed varied from 1.94 in. per minute at a radius of 1.5 in. to 44.99 in. per minute at a radius of 34.5 in.

In tests with 11.90 percent, wet basis, moisture content corn, varying successive auger paths from 0.5 to 18 in., Toms observed the greatest air flow increase (34.1%) with successive auger paths at 1.5 inches, and with successive paths moving inward. In each case, the spacing was maintained until the bin radius had been traversed. Tests with equal diameter constant-pitch and variable-pitch augers gave the same results.

Initial grain bulk density, which was adjusted using a hand-held concrete vibrator, was found to have little effect on the final air flow for 1.5, 3, and 6-in. spacings between auger paths. With 9-in. spacings, a higher initial bulk density gave a lower air flow increase. Moving the auger clockwise or counter-clockwise around the bin produced the same flow increases.

A test using 25.68 percent moisture corn and 1.5-in. auger spacings resulted in a 56.5 percent increase in air flow, whereas the increase for a comparable test with 11.90 percent moisture corn was 31.5 percent.

Toms observed some other significant effects of stirring. In one test with auger spacings of 1.5 in., stirring was begun at the bin center and progressed to the wall. This produced a typical air flow increase of 18.2 percent. Upon reaching the bin wall, the auger was worked back progressively to the center producing a further increase for a total increase of 30.0 percent. The auger was then worked back progressively to the bin wall, decreasing air flow to almost exactly the 18.2 increase noted after the initial traverse. Toms also observed in almost every test a decrease in air flow as the grain 6 to 12 in. from the bin wall was stirred. Another observation made was that practically no air flow increase was produced by stirring unless the stirring auger was moving horizontally.

Toms, in a second part of the study, constructed a 6 ft square bin cross section 4 in. in thickness. A vertical open auger was mounted in the center. One wall was constructed of Plexiglas. During filling, four horizontal bands of colored corn were inserted to facilitate observations of the mixing action of the auger. Toms made photographs showing the mixing action. The area disturbed was approximately 6 in. wide at the bottom and in different tests varied from 31 to 38 in. wide at the top. The side boundaries were slightly curved outward. After approximately 15 minutes of stirring, the disturbed area became constant. Toms observed that a variable-pitch and a constant-pitch auger produced the same results, and that high moisture corn gave a narrower area of influence throughout the corn depth. No kernel movement was noted outside the boundary of the disturbed area.

This study did not attempt to determine the effects of different auger linear speeds. Toms suggested this as a topic for future study. Several conclusions from this study indicated that auger-stirring a mass of grain will change the air flow resistance. Determination of the air flow resistance of stirred grain and extensive investigation of the effects which cause changes in resistance were beyond the scope of the study.

OBJECTIVES

The effects of stirring corn with a moving open auger have not been studied in detail. An understanding of the effects of auger stirring on the air flow resistance of corn and on related factors could contribute toward improvement of auger-stirring system design and management.

The objectives of this study are:

1. To define the boundaries of the region disturbed by stirring.
2. To determine the effects of stirring on corn bulk density.
3. To investigate the effects of stirring on kernel orientation.
4. To determine the air flow resistance of grain disturbed by stirring.
5. To determine the air pressure and velocity distributions within the stirred grain as air flows through.

PROCEDURE

The approach taken toward realization of the objectives of this study involved three experiments with shelled corn. The first experiment was designed to obtain information on bulk density and kernel orientation changes during auger stirring and to define the shape of the region disturbed by the stirring auger. The second and third experiments involved air flow tests. Experiment two also involved auger-stirred corn. Experiment three involved parallel air flow tests to determine corn-air flow characteristics.

Experiment I: Bulk Density and Disturbance Effects

An experiment was devised which permitted definition of the cross sectional area of the volume disturbed by a stirring auger, measurement of grain bulk density, and observation of disturbed and non-disturbed kernel orientation.

Experimental grain

The grain for this study was hybrid corn obtained from University Farm Service. Grain from the same lot was used for all experiments. The hybrid brand was Pioneer; the hybrid number could not be determined. The corn had been dried in a continuous flow dryer and placed in storage immediately after drying. All of the corn was cleaned with a mechanical grain cleaner before use in this study to provide a uniform product for testing. The corn used was passed through a 28/64 in. round hole sieve and over an 18/64 in. round hole sieve in the mechanical cleaner.

Moisture content of the corn was determined at various times using the air-oven method and maintaining samples at 103°C for 72 hrs. Temperature and time are in accordance with ASAE Standard S352, American Society of Agricultural Engineers (1972). The moisture content of a sample taken before any tests was 11.70 percent, wet basis. Successive determinations during the experiments gave these values: 10.88, 10.96, and 11.55 percent, wet basis. The average of these values is 11.27 percent, wet basis. For purposes of description, the grain was assumed to have a moisture content of 11.3 percent, wet basis throughout this study.

Equipment

The main equipment for Experiment I consisted of a grain bin set on a wheeled cart, a stirring auger, and a winch system to move the grain bin during stirring.

The grain bin was constructed of 3/4 in. plywood with an exterior frame of 2x4-in. lumber. The bin was designed so that one end was held on by six wing nuts and could easily be removed. Approximate inside dimensions were: length, 40 1/16 in.; width, 24 1/16 in. and depth, 30 in. Measurements of length and width at several depths were averaged. From these averages, a horizontal cross sectional area of 6.69 ft^2 was computed. Bin width was measured while the bin was loaded in order to check for wall deflection. These widths did not vary significantly from the previous measurements taken with the bin unloaded.

Bin dimensions were chosen so as not to exceed the volume limitation of the available dump hopper and the stability limitations of the available fork lift, and so that the width dimension would exceed the maximum width of the area disturbed by the auger by at least four in. An estimate of this width was obtained from a review of a study by Toms (1968). As described in the Review of Literature, Toms observed mixing patterns of corn being stirred in a 4-in. thick bin section. He also made a motion picture showing the mixing process.

In order to permit observation of the cross sectional area of the region disturbed by the stirring auger, the bin was designed to enable a 1/4-in. thick Plexiglas sheet to be pushed up through a slot in the bottom of the bin half way between the ends and to permit removal of corn from each bin half separately. Removal of the bin end and half of the corn permitted observation of the stirring pattern.

The top edge of the Plexiglas sheet was tapered toward the face nearest the corn to be left in the bin in order to facilitate insertion and to minimize disturbace to the grain. The sheet was admitted through a slot cut in the floor of the bin. This slot was covered with overlapping flaps of duct tape to prevent corn leakage. The sheet was guided by pairs of 1/2 x 1/2 in. angle irons attached to the side walls of the bin. It was found necessary to insert 1/4 x 1/4 x 30-in. pieces of wood against the wall between these tracks before filling in order to avoid wedging of kernals as the sheet was inserted. These strips were pushed out ahead of the sheet as it was inserted.

The bin was emptied through holes in the floor covered by movable 1/16 in. steel plates. During stirring, the bin was clamped onto a government surplus bomb carrier cart.

The stirring auger and associated equipment are shown in Figure 2. The steel auger was a right hand type of 2 in. diameter, and had a constant pitch of 2 7/8-in. Shaft diameter was one in. and the flight cross section was 1/4 x 1/2 in.

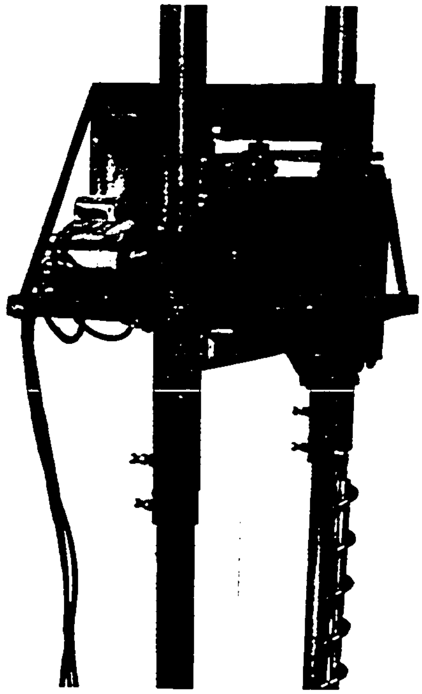
The auger was powered by a 1 hp 1725 rpm (full load) capacitor-start induction-run motor. A roller chain drive and jack-shaft type speed reducer was used to obtain an auger speed of 480 rpm. This drive assembly and auger were mounted on a carriage which could be raised or lowered at approximately 9 in./minute by a 1/4 hp, 86 rpm (full load) capacitor start induction run gearmotor also mounted on the carriage which turned a 3/4 in. diameter NC screw. The complete auger and vertical drive assembly was mounted on a frame at a height sufficient to clear the grain bin as shown in Figure 6.

To move the auger through the grain while stirring, the cart supporting the grain bin was pulled by a winch of the type shown in Figure 3. Two winches were constructed to obtain four cable speeds. The winch shown was driven by a 1/4 hp, 1140 rpm (full load) motor. It pulled the cable at a speed of 8.71 in./ minute. Doubling the cable, attaching a pulley to the cart frame and anchoring the cable end to the winch gave a cart speed of 4.35 in./minute. The other winch was driven by a 1/10 hp (full load) gearmotor. It pulled the cable at a speed of 24.30 in./minute. Doubling the cable gave a cart speed of 12.26 in./minute. These speed values were obtained by timing the cart over a distance of 3 ft. During these tests, a drag weighted with three concrete building blocks was attached behind the cart to approximate the load produced by the auger. Results of these tests are shown in Table 3.

In the study by Toms (1968), auger speed varied from 1.94 in./minute for a 1.5 in. auger path radius to 44.49 in./minute for a 34.5 in. auger path radius. Calculations from the literature of one stirring auger manufacturer gave an average auger speed of 5 in./minute for a single stirring auger operating in a flower-petal pattern in a 24-ft diameter bin. Literature from another manufacturer whose stirrer moves in a circular pattern gave figures to indicate that in a 36-ft diameter bin, an auger at the maximum path radius would be moving at about 8-in./minute, and an auger at a minimum path

Figure 2. Stirring auger and vertical drive assembly

Figure 3. Winch used to pull grain bin cart



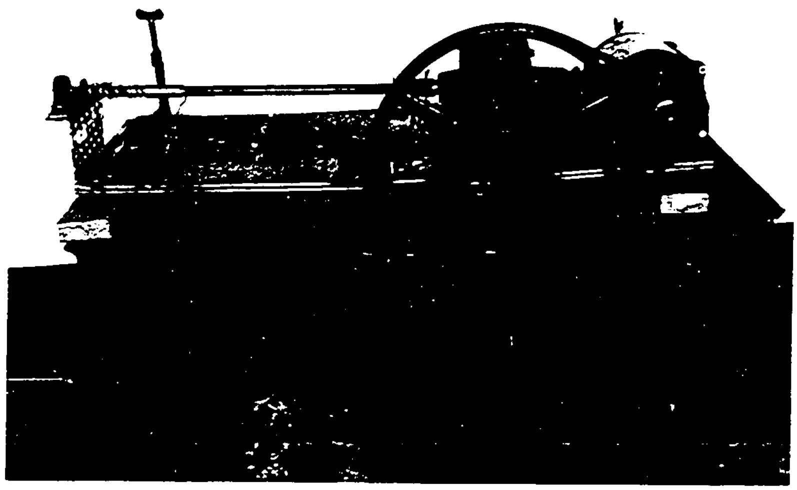


Table 3. Cart speed test results

Winch	Cart speed (in./minute)	Average cart speed (in./minute)
Fast	24.242	
	24.275	
	24.374	24.30
Fast, double cable	12.252	
	12.266	
	12.252	12.26
Slow	8.689	
	8.741	
	8.713	8.71
Slow, double cable	4.348	4.35

radius would be moving at about 1 in./minute.

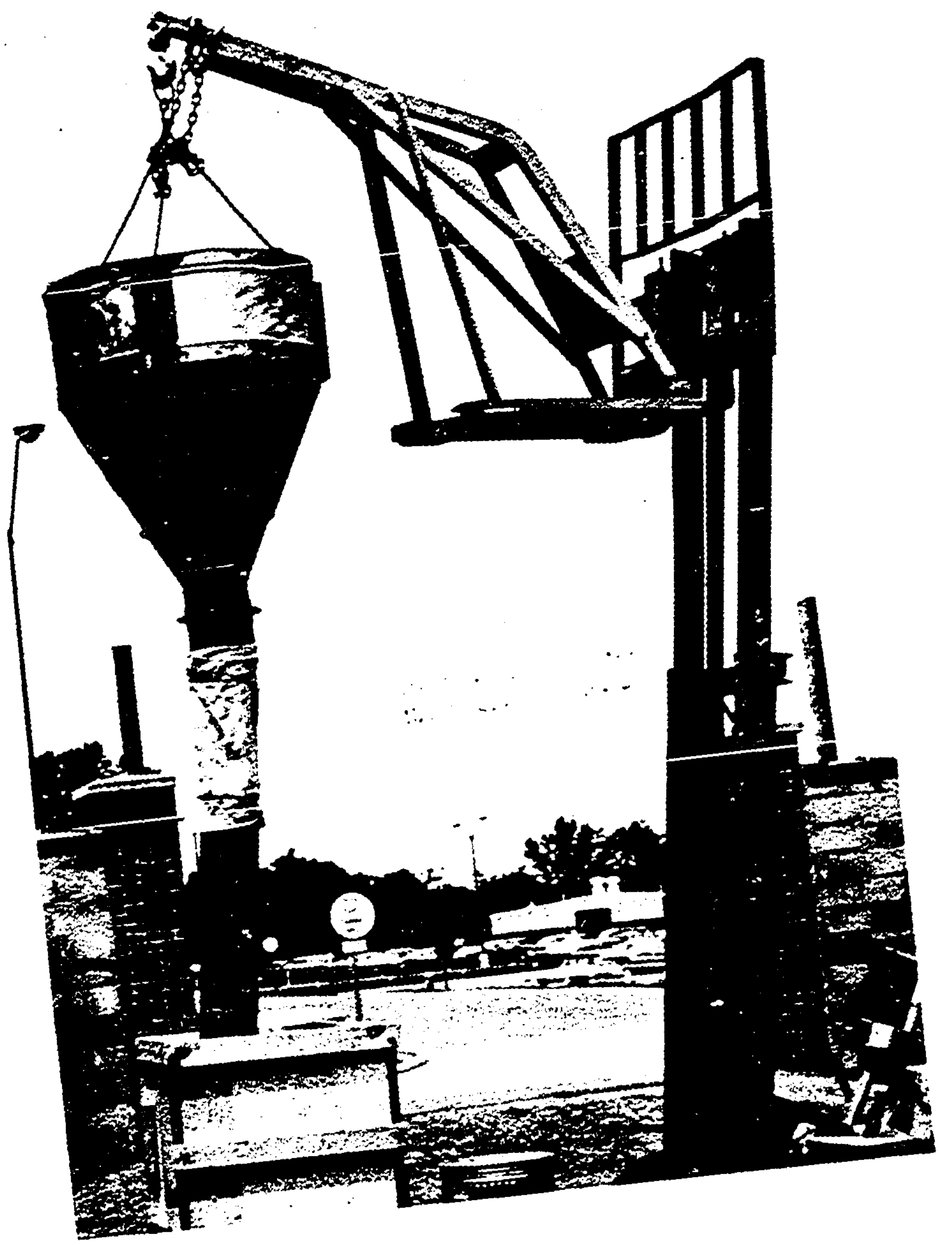
All grain weights were determined with a Fairbanks-Morse model 5942, 310 lb capacity platform scale equipped with a Spinks type A-1 balance indicator. Before use, the scale was reconditioned by Fairbanks-Morse Company. Accuracy was brought to within applicable tolerance limitations of the State of Iowa Department of Agriculture Weights and veasures Law (1971). These tolerance limitations are ±5/8 oz on weights 40 to 50 lb, and ± 1 oz on weights 51 to 99 lb.

Tests

A total of 14 stirring tests were made in Experiment I. These involved three replications at each auger speed for speeds of 4.35, 8.71, 12.26, and 24.30 in./minute, and two replications with zero auger speed. The procedure followed consisted of weighing the test grain from storage, placing it into the dump hopper, dumping the grain into the bin, measuring the grain volume, stirring the grain, again measuring the grain volume, inserting the Plexiglas sheet, removing the grain from one-half of the bin, removing a bin end, recording the shape of disturbed area, and returning all grain to storage.

The 11.3 percent, wet basis, grain was weighed in 5-gallon containers and placed in a dump hopper made from a discarded cyclone separator. This hopper had a capacity of approximately 750 lb of corn, and was equipped with a variable flow valve. After filling, this hopper was raised to a height of 8 ft above the bin floor, giving an average dropping height of 7 ft for a 2 ft grain depth. This height was maintained on all tests. Grain was released from the dump hopper at a rate of approximately 300 lb/minute. No attempt was made to vary this. At depths of 6, 12, 18, and 24 in. filling was stopped for addition of painted kernels. At each of these depths, a band of marked corn approximately one in. deep and 8 in. wide was poured across the full width of the bin in the region where the Plexiglas sheet would be pushed up. For marking, this corn was sprayed with acrylic enamel and allowed to dry. Red, white, black, and green colors were used during tests of Experiment I. The filling equipment is shown in Figure 4.

Figure 4. Dump hopper in position for filling grain bin

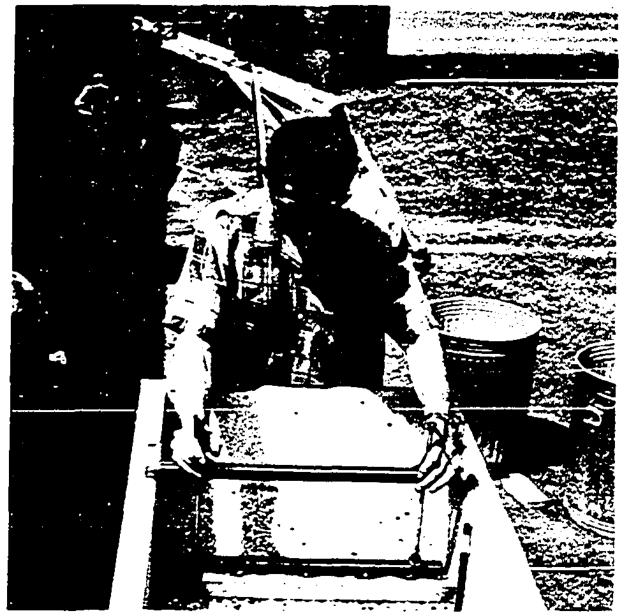


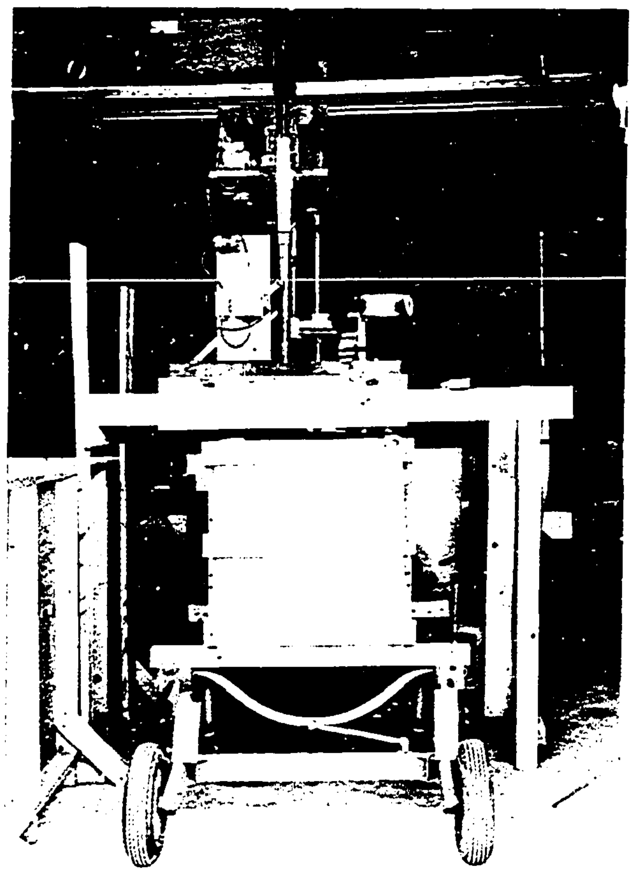
When filling was completed, the grain was smoothed to a constant depth with the device shown in Figure 5. This device consisted of a frame supported on the top of the bin side walls and connected to a smoothing blade by means of two 3/8 in. NC threaded rods which turned through nuts welded to the frame. The smoothing blade was set parallel to the frame initially, and maintained in the parallel position by turning each rod the same number of turns up or down. By adjustment and smoothing, a condition was reached where the smoothing blade touched the grain over the entire bin, but did not push any kernels along. When this condition was reached, the distance was measured from the bottom of the smoothing blade to the top of the bin wall. The accuracy of defining the top of the grain mass is estimated at $\pm$ 1/2 turn, or $\pm$ 1/32 in.

The cart was then wheeled into position under the auger and attached to the winch. Figure 6 shows the cart in position under the auger. The auger was then lowered into the grain at the end of the bin opposite the removable end. Collars on the pipes supporting the auger carriage stopped the downward motion when the bottom of the auger was approximately 1/4 in. above the bin floor. The winch was then turned on, and when the cable became visibly taught, the auger drive motor was started. When the auger contacted the removable end of the bin, the winch and auger drive were stopped and the auger was raised out of the grain. For the tests at zero horizontal auger speed, the auger was lowered into the grain at the center of

Figure 5. Grain being smoothed to a constant depth in bin

Figure 6. Cart and bin in position under stirring auger





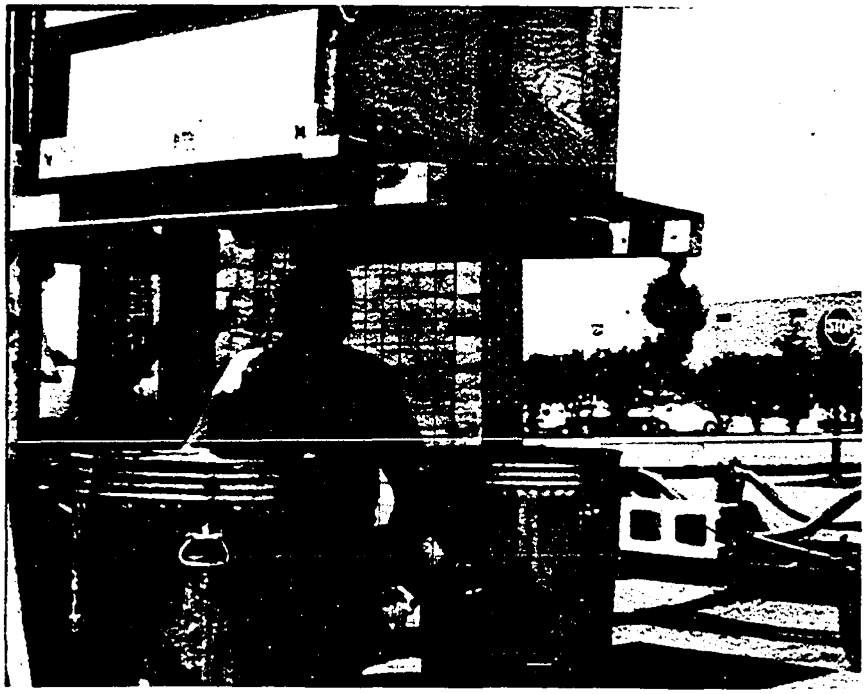
the bin and allowed to run until the disturbed region was judged to be of constant volume. This required a stirring time of 5 minutes.

The cart was then moved into open area and the grain levelled in the bin. A second measurement of distance from the grain surface to the top of the bin wall was made. Next a fork lift was used to raise the bin off the cart to permit insertion of the Plexiglas sheet as shown in Figure 7.

With the sheet inserted, a 2 x 4 -in. board was clamped across the bin against the Plexiglas sheet above corn level to minimize deflection of the sheet and the bin walls. Grain was then removed from the half of the bin stirred last and removal of the bin end permitted viewing of the region disturbed by the auger as shown in Figure 8. In this figure, the marked kernels visible in the non-disturbed area between marking layers are kernels marked with different colors in previous tests. The disturbed area was outlined on the Plexiglas sheet using a grease pencil. Points where slippage of the colored layer began were sometimes difficult to define because portions of the layer hau moved down slightly in the region outside the area where slippage was obvious. These points were placed where, by sight, it appeared that definite slippage had occurred. When the disturbed area had been outlined, the remainder of the grain was removed and returned to storage. The outline was drawn to scale on 8 1/2 x 11 in. graph paper and then the Plexiglas sheet was cleaned.

Figure 7. Insertion of Plexiglas sheet

Figure 8. Bin in position for viewing of disturbed grain



An investigation was made to determine if kernels in the disturbed region had a different orientation than kernels in the non-disturbed region. After the disturbed region had been outlined, every visible kernel was designated as pointing up, down, or horizontal. If the kernel tip was higher than the center of the kernel butt, the kernel was counted as pointing up. If the tip was lower, the kernel was counted as pointing down. Kernels for which a slope could not be discerned were counted as horizontal.

Experiment II: Airflow Resistance Effects of Auger Stirring

This experiment was conducted to determine the airflow resistance of stirred and non-stirred corn.

Equipment

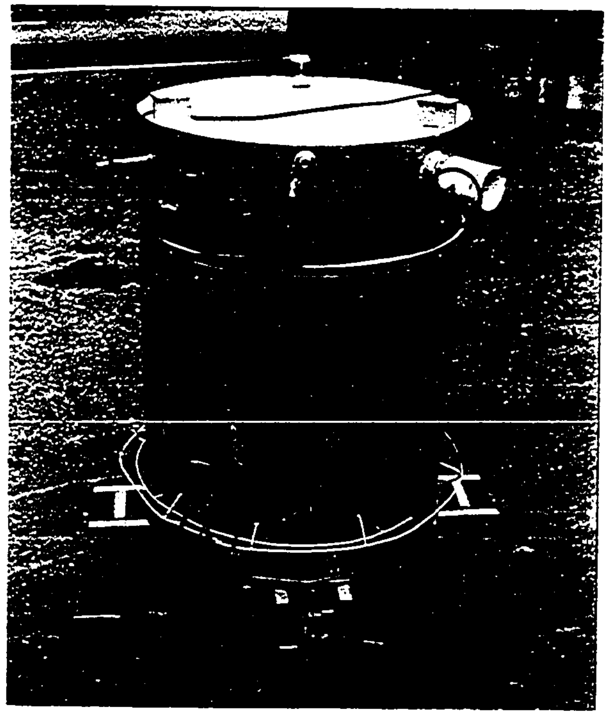
The equipment for this experiment consisted of a grain bin mounted on a wheeled cart, a stirring auger, a winch system to move the grain bin during stirring, a variable air flow blower system, and an airflow measurement system.

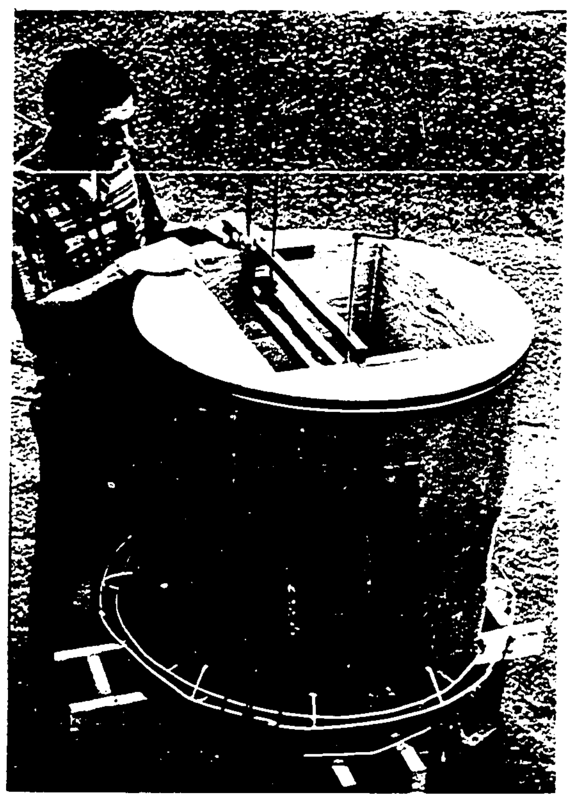
The grain bin for Experiment II is shown in Figures 9 and 10. It was made from a steel brine tank three-ft in diameter and four-ft deep having one open end. The tank was cut at a level one ft from the closed end. This one-foot section then served as the top of the bin as shown in Figure 9.

Figure 9. Steel bin with top section in place

1. Outlet port
2. Top section handles
3. Piezometric orifice
4. Piezometric ring

Figure 10. Steel bin with top section removed





A perforated floor was installed at a level 6 in. from the open end. This floor was 1/16 in. steel with 3/32 in. round holes punched on a pitch length of 0.25 in. This combination of hole size and pitch yields 12.76 percent open area. This floor was welded in place to the wall of the tank. To provide additional support, two 1-1/2 in. angle irons were placed under the floor and also welded to the bin wall. Inside of the outlet port (1 in Figure 9) was an air filter made of a wire netting cylinder covered with cloth. This filter was necessary to keep fine material from the grain mass from moving into the air measurement device.

Steel pipes (item 2 in Figure 9) to serve as handles were welded to the top of the bin. There are no holes through the tank walls at their points of attachment. Two piezometer orifice were made in the top to measure static pressure above the grain. One is shown at 3 in Figure 9; the other, which was connected in parallel, is on the opposite side. These each consisted of a 1/16 in. hole with a short length of 1/4 in. steel brake tube silver soldered over the hole. Orifice construction was in accordance with the Test Code for Air Moving Devices (Air Moving and Conditioning Association, Inc. (1967)). All air pressure measurement tubing was 3/16 in. black latex rubber.

A 3/4 in. plywood bin liner was installed to provide a constant bin cross section and length for the stirring experiment. The interior dimensions of this liner were: 23.99 in.

width, 20.75 in. length and 31.54 in. depth. This depth dimension is the average of 17 measurements over the entire floor of the distance from the bin floor to the top of the wood liner walls. These readings, taken with the bin full of grain to account for floor deflection, varied over a range of 1/4 in. The bin had a cross sectional area of 3.45 ft^2. All wood-to-wood joints were glued, fastened with screws, and then sealed with silicone sealant. Equal bin widths between this bin and the bin of Experiment I permitted use of the same device and procedure for determining grain depth. The bin liner was sealed to the top of the bin wall and the top one-ft section was sealed to the bin liner using 2 in. wide duct tape. The bin liner was taped to the bin and left for the entire experiment; the top was taped to the bin liner before each air flow resistance test.

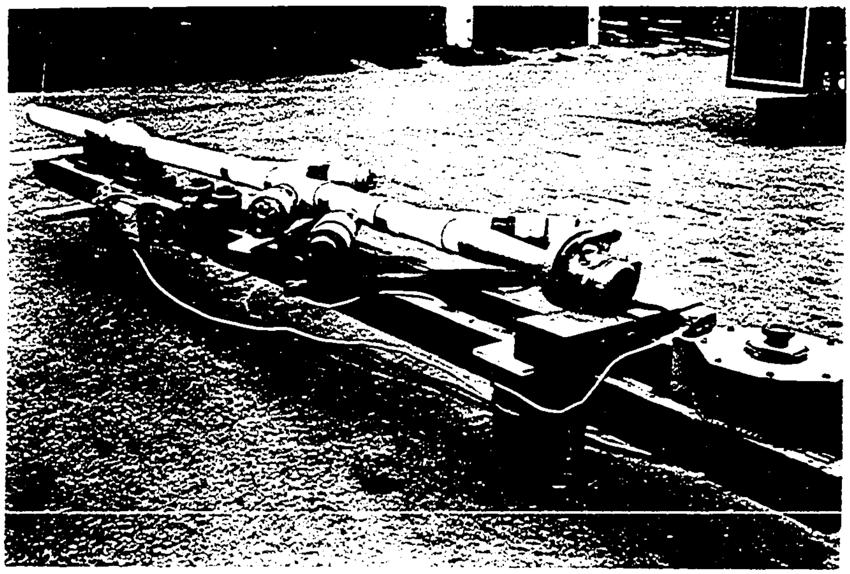
A piezometer ring with orifice of the same design as previously described was installed at the level of the top of the bin floor. It was installed to measure pressure at the bottom of the grain mass, above the perforated floor. The decision to use a bin liner, however, prevented its use. With the liner in place, the region above the bin floor and outside the liner was at atmospheric pressure. The pressure measured in the piezometer ring would have been atmospheric pressure and not the pressure at the bottom of the grain mass. This ring, and a guard ring made of steel rod are shown as item 4 in Figures 9 and 10.

Measurements of pressure drop across the bed of grain were made with the Meriam micromanometer shown in Figure 12 and described in the Experiment III procedure section. The high pressure side of this instrument was left open to the atmosphere; the low pressure side was connected to the two piezometer orifice in the top. Connection in this manner meant that the pressure indicated on the micromanometer included the pressure drop across the bed of grain and the bin floor. An experimental determination of the pressure drop across the bin floor for various flow rates was made and each pressure drop reading taken in this experiment was corrected to reduce the pressure drop to that across the grain only. The method used to determine pressure drop across the bin floor is described in Appendix B.

The entire bin assembly was placed on a steel-wheel dolly equipped with a special frame made of 2 x 4-in. wood. The same winch and auger stirring apparatus used in Experiment I were used with this experiment.

The variable flow blower system and the Meriam laminar flow meter are shown in Figure 11. This laminar flow meter and the inclined and U-tube manometers used in conjunction with it are shown in Figure 12 and are described in the Experiment III equipment section.

Figure 11. Laminar flow meter and variable air flow blower assembly



The variable flow blower system consisted of five centrifugal blowers placed in parallel. Flow was varied by varying the number of blowers in use, and by controlling blower speed using variable transformers. The end unit is an Ace model AlX, 115 V, 9 amp universal motor blower. Its speed was controlled by the nearby variable transformer, which could supply any voltage from 0 to the rated blower voltage. The other four blowers are Singer model MB-12-20, 115 V, 5.2 amp universal motor blowers. Two of these were controlled by the two variable transformers shown. These transformers were also capable of supplying any voltage up to rated voltage. The other two blowers were not used with speed controls. The duct arrangement connecting these blowers was made of 4-in. styrene sewer pipe and fittings. This pipe has an inside diameter of 3 15/16-in. Joints were sealed either with pipe cement or with 2-in. wide duct tape. During a preliminary test this blower system produced a flow of 416 cfm at a pressure of 22.5-in. water. Some blowers received less than rated voltage during this test. Complete pressure-flow characteristics at rated voltage were not determined. The thermometer shown protruding from the pipe was used to measure air temperature.

The blower system was connected to the outlet port on the top of the bin. Connected in this manner it reduced the pressure above the grain causing air to flow up through the grain. This arrangement was used because of significant air temperature rise encountered using this type of blower and a positive pressure system.

Tests

Three replications were made at each auger speed, for speeds of 4.35, 8.71, 12.26, and 24.30 in./minute. For each replication at each auger speed, the procedure followed consisted of weighing the test grain from storage, placing it into the dump hopper, dumping the grain into the bin, measuring the grain volume, measuring the air flow resistance, measuring the grain volume, stirring the grain, measuring the grain volume, measuring the air flow resistance, measuring the grain volume, and returning the grain to storage.

The 11.3 percent, wet basis grain was weighed in 5-gallon containers and placed in the dump hopper which was raised with a fork lift to an average drop height of 7 ft. Grain was dumped into the bin at a rate of approximately 300 lb/minute. No attempt was made to closely regulate the rate of filling the bin. The dump hopper in filling position is shown in Figure 4.

Grain volume was determined using the procedure described in Experiment I. The grain smoothing device used in determining grain volume is shown in Figure 5 and Figure 10.

After grain volume had been determined, the bin was wheeled into position for air flow resistance tests. The bin top was lifted into place and the joints sealed with 2 in. wide duct tape. Pressure drop measurements were taken for air flow rates of approximately 3, 13, 30, 40, 50, 65, 80, 94, 110, and 123 cfm/ft^2. The order in which measurements were taken was completely random. Flow rates were corrected for temperature and pressure as described in the Experiment III Equipment section. The flow rates used cover the range of the air flow measurement system. All common grain drying systems except some low temperature and supplemental heat systems use air flow rates within this range.

The bin top was then removed and a second determination of grain volume was made. The bin was then wheeled into position for stirring. Exactly the same test procedure as described for Experiment I was used during the stirring operation. In this experiment, the auger traversed a distance of 20.75 in.

With stirring complete, a third grain volume measurement was made, and pressure drop measurements were taken at approximately the same air flow rates used before stirring, again in a random order. A last grain volume measurement was made and the grain was removed from the bin and placed in storage.

Experiment III: Air Flow Resistance of Non-Stirred Corn

The analysis procedure used for the determination of air flow resistance of stirred corn required information on the airflow resistance of corn over a range of bulk densities from

45.5 to 50.0 lb/ft^3. The air flow tests before stirring, conducted in Experiment II, provided information at the upper part of this bulk density range. Experiment III was conducted to provide information on the air flow resistance of corn in the lower part of this bulk density range.

Equipment

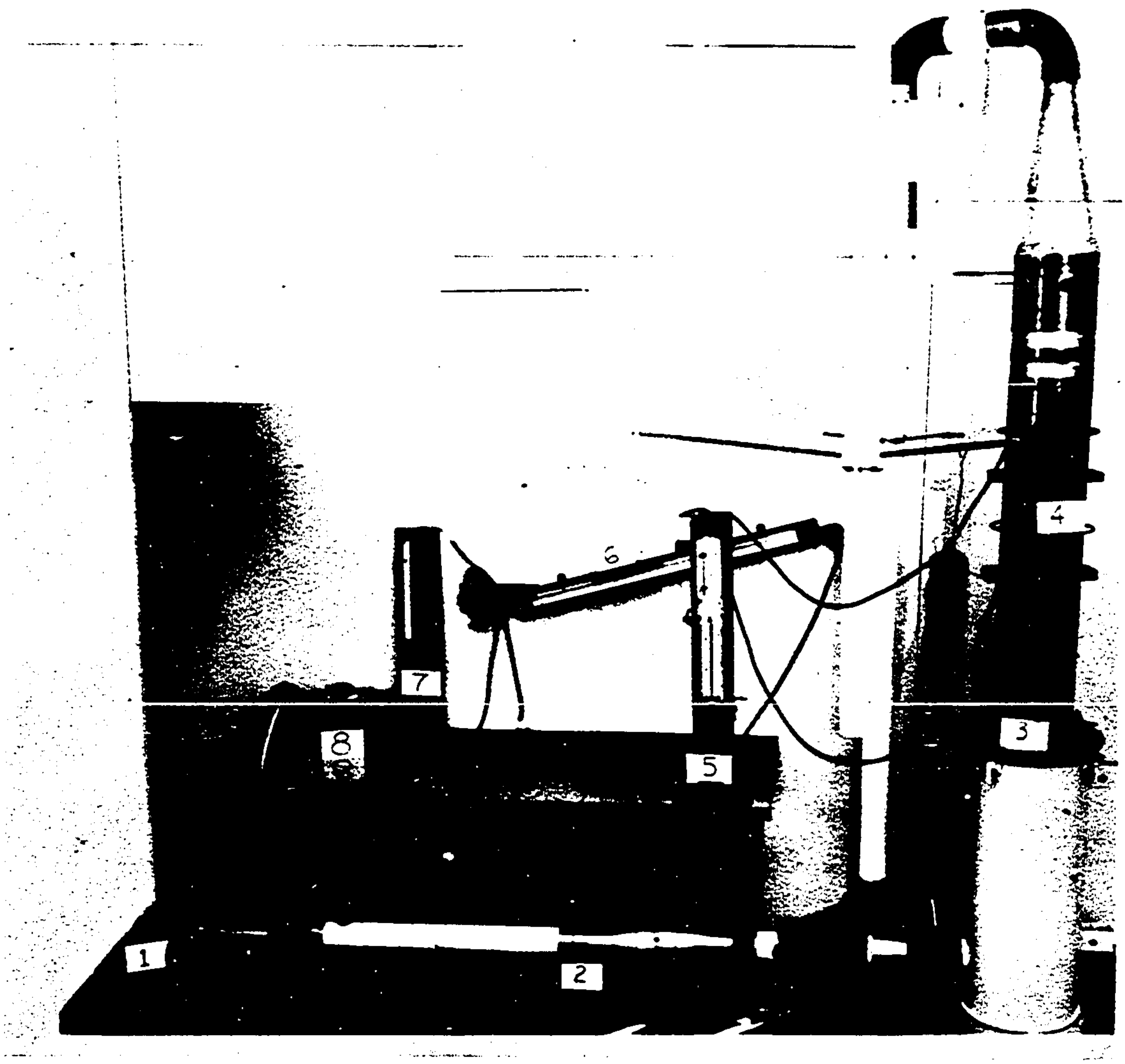
The complete test apparatus for this experiment is shown in Figure 12. It consisted of a variable flow blower system, and the grain column.

The variable flow blower system consisted of the Ace model A1X, 115 V, 9 amp universal motor blower controlled by a variable transformer which was used as a part of the blower system for Experiment II. These are 1 and 8 in Figure 12. The complete characteristics of this blower system were not determined, but it is capable of flows and pressures considerably above the 65 cfm at 10 in. of water which was the maximum for this experiment.

The air flow measurement system consisted of a Meriam model 50 MC 2-4SF laminar flow meter, a Meriam model 34 FB2 micoromanometer and a U-tube manometer. These are items 2, 5, and 7 in Figure 12. (For this experiment, the micromanometer was connected to the air flow meter and the inclined manometer was connected to the grain column. The inclined manometer afforded sufficient accuracy for column measurements and the greater accuracy of the micromanometer was needed with the

Figure 12. Experiment III test apparatus

1. Blower
2. Laminar flow meter
3. Plenum
4. Grain column
5. Micromanometer
6. Indined manometer
7. U-tube manometer
8. Variable transformer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laminar flow element at the low flow rates.)

The Meriam laminar flow meter consists of a stainless steel matrix within a metal enclosure. The flow passages through this matrix are small enough so that flow is laminar over the operating range of the meter. The enclosure has pressure connections at the ends of the matrix section. The maintenance of laminar flow through the matrix results in a relationship between pressure drop across the matrix and flow through the element which is very nearly linear and thus permits use over a wide range of flow. The maximum flow for this unit is 424 cfm, which corresponds to a pressure drop of 8 in. of water. A calibration curve for the range from 0 to 424 cfm was supplied with the meter. This calibration is stated to be within ±0.5 percent of Meriam Instrument Company flow standards. The accuracy of the instrument is not specified, but error is stated to be a constant percent of any flow within its rated range.

Pressure drop across the laminar flow element was measured using a Meriam model 34FB2 micromanometer (5 in Figure 12). This instrument consists of a well type manometer with the well movable in the vertical plane by means of a precision ground lead screw. The smallest scale graduation is 0.001 in. of water. A calibration check by Meriam Instrument Company September 9, 1970 indicated the instrument to read 0.001 in. of water high at pressures of 2.000 and 4.000 in. of water.

This manometer used Meriam 1000 Green indicating fluid, stated to have a specific gravity of 1.000.

Correction factors to account for variations in temperature and pressure are given in the Instruction Manual (Meriam Instrument Company (1968)). All flow rates were corrected to 70°F, 29.92 in. Hg using these charts. Corrections were made to the data using a Fortran Watfiv program on the ISU Computation Center IBM System 360 electronic digital computer.

The U-tube manometer (7 in Figure 12) was used to measure the difference between atmospheric and inlet pressures on the laminar flow element. This information was needed for the pressure correction. This manometer was also charged with Meriam 1000 Green indicating fluid. It has a maximum scale reading of 27 in. of water and a smallest scale division of 0.2 in. of water. Barometric pressures were obtained from WOI Studios and corrected to absolute pressure. Air temperatures were read from a thermometer placed in the airstream between the grain and the laminar flow element. Pressure hoses were 3/16 in. latex rubber.

The grain column was built from a 38.5 in. length of thin wall steel pipe with an inside diameter of 9.789 in. and a wall thickness of approximately 3/32 in. The column is item 4 in Figure 12. This inside column diameter is the average of 21 measurements with a Federal dial indicator having a smallest scale graduation of 0.0005 in. The extremes of these measurements varied by 0.034 in.

The assumption was made that at this column diameter, the pressure drop across the grain mass is independent of column diameter. Bakker-Arkema et al. (1969) determined that wall effect was negligible for a ratio of bed diameter to particle diameter larger than 16. Assuming the diameter of a corn kernel to be the diameter of a sphere of equal volume yields a particle diameter of approximately 0.324 in. and a ratio of bed diameter to particle diameter of 30.21.

A perforated floor was installed 1.5 in. from the bottom of the column. The pipe was sectioned at this level and a floor of 3/64 in. perforated stainless steel was sandwiched and silver soldered in place. This floor had 1/8 in. holes on a 3/16 in. pitch, giving 40.3 percent open area. While soldering was being done, the floor took a permanent upward bow. The volume lost in this dome was calculated to be 10.41 $in.^3$ by measuring dome height at 6 different radii and graphically integrating. Column volume was corrected by this amount. Floor deflection was measured to be 0.0024 in. at the center when the column was filled with corn. Column volume was thus assumed independent of the quantity of grain in the column.

Piezometer orifices were installed at levels of 5, 11, and 23 in. above the bin floor. These consisted of one in. lengths of 1/4 in. steel brake tubing silver soldered over 0.043 in. holes in the column wall. At the 17 and 29 in. levels, four-orifice piezometer rings with the same orifice construction were installed. Orifice construction was in accordance with the Test Code for Air Moving Devices (Air Moving and Conditioning Association, Inc. (1967)). For Experiment III, all pressure drop readings were made across 24 in. of grain between the piezometer orifice at the 5-in. level and the piezometer ring at the 29-in. level. The other orifices were capped with rubber policemen.

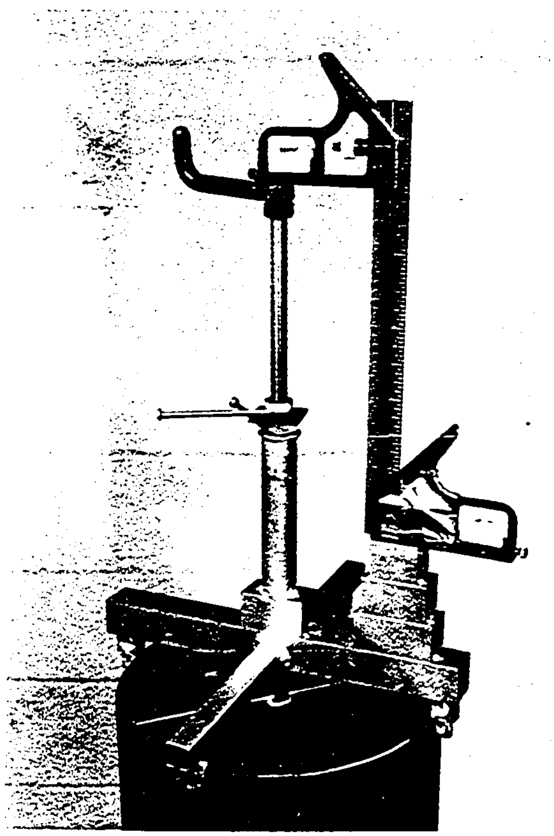
Pressure drop across the grain bed was measured using a Meriam model 40HE35 inclined manometer having a 10 in. of water range, and a smallest scale graduation of 0.01 in. of water (item 6 in Figure 12). The manometer was charged with Meriam 1000 Green indicating fluid, with a stated specific gravity of 1.000. Pressure hoses were 3/16 in. latex rubber.

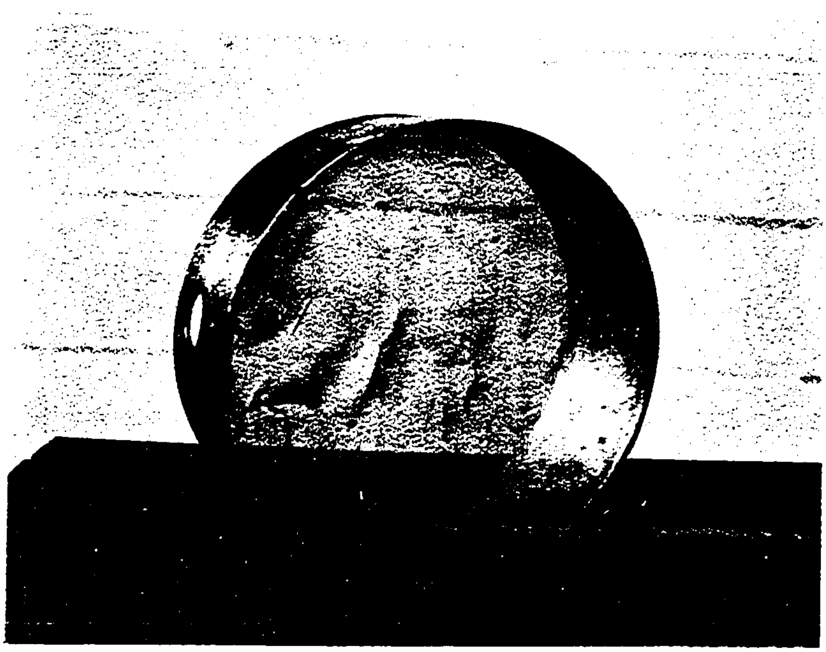
The measurement of grain volume was carried out as shown in Figure 13. The cross blade was lowered to grain level by means of a 1/2 in. NC threaded rod. After initial smoothing, a position was reached where the cross blade contacted many kernels, but did not push along any kernels. The distance from a platform to the top of the threaded rod was then measured as illustrated. The accuracy of defining the top surface of the grain mass is estimated to be $\pm$ 1/2 turn, which corresponds to $\pm$ .0017 ft^3 of column volume.

A filter constructed from 100-mesh copper screen was placed above the grain column to prevent material from the grain mass from clogging the matrix of the laminar flow element. This filter is shown in Figure 14.

Figure 13. Grain volume measurement apparatus

Figure 14. Air filter



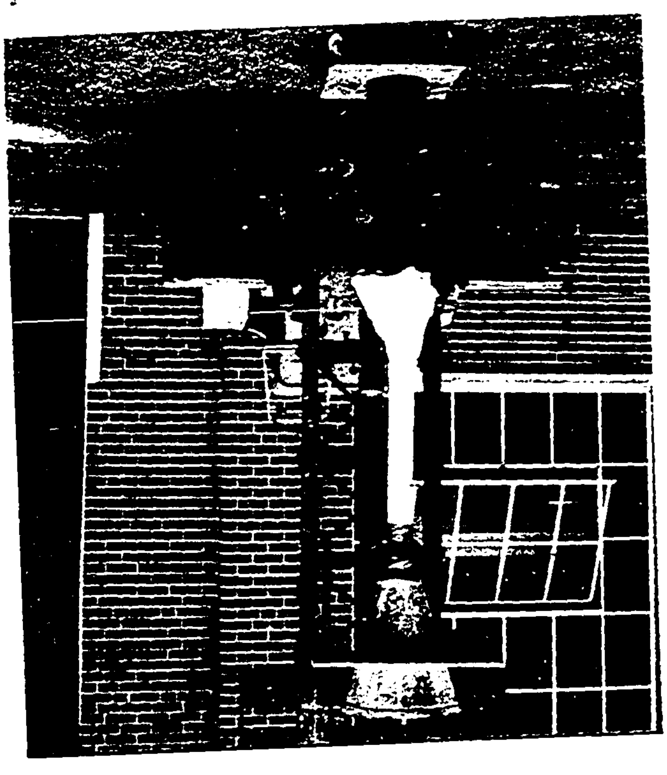


The air flow path through the system components can be traced by reference to Figure 12. Air entered the bottom of the plemum (3), passed up through the grain column, filter, then through a duct system to the air flow element and finally out through the blower discharge. All duct work, except for the two transition pieces, was styrene sewer pipe having an inside diameter of 3 15/16-in. The two transition pieces were fabricated of galvanized steel with soldered seams. All duct joints were sealed using either styrene pipe cement or 2-in. wide duct tape. This system of sealing was tested by blocking the inlet and outlet, and pressurizing the system to 10 in. of water. Pressure decreased to 2 in. of water in 10 minutes, indicating a negligible leakage.

The column filling equipment is shown in Figure 15. The hopper, equipped with a butterfly valve in the bottom, was raised to the desired fill height by means of the fork lift. Grain dropped within a 4-in. styrene sewer pipe which extended to the top of the column. This apparatus was used for average drop heights of 2, 3, 5 and 6 ft. For the fill at no drop condition, grain was allowed to flow from the bottom of a 3-in. inside diameter tube, the bottom of which was kept just above grain level. This equipment is shown in Figure 16. A similar procedure was used by Shedd (1953) for the condition he called "loose fill." Shedd's curves were obtained using a grain column filled by this method.

Figure 15. Dump hopper is position for filling grain column

Figure 16. Filling at zero drop height



Tests

Two replications were made for each fill method for fill at no drop, and average drop heights of 2, 3, 5, and 6 ft. These were taken in a random order. For each of these ten tests, pressure drop was recorded for air flow rates of approximately 5, 15, 25, 35, 50, 54, 80, 95, 110, and 125 cfm/ ft^2. The order in which these measurements were taken was completely random.

The procedure followed for each air flow resistance replication consisted of filling the column with 11.3 percent, wet basis corn, weighing the grain and column, measuring the grain volume, recording pressure drop at each of ten air flow rates, again measuring the grain volume, again weighing the grain and column, and returning the grain to storage.

The fill rate for drop heights of 2, 3, 5, and 6 ft was approximately 350 lb/minute. No attempt was made to vary this fill rate.

RESULTS AND ANALYSIS

Shape of Disturbed Volume Cross Section

The shape of the disturbed volume cross section was determined for corn which had been stirred with a non-enclosed auger. This cross section was determined for a corn depth of approximately 26 in. and for auger speeds of 0, 4.35, 8.71, 12.26, and 24.30 in./minute. Figures 17 and 18 show typical shapes as outlined on the inserted plastic sheet. Figure 17 shows the outline from Test S-8 for which the auger speed was 8.71 in./minute. Figure 18 is from Test S-9 with an auger speed of 24.30 in./minute. The auger moved through the bin in the direction toward the viewer.

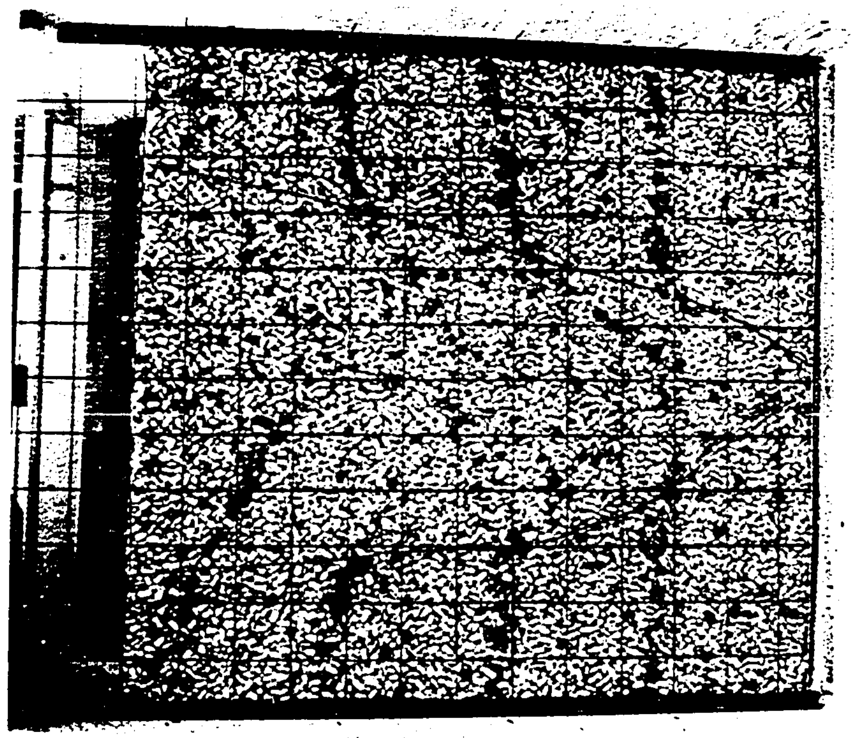
The y-coordinates corresponding to x-coordinates at 1-in. intervals and top and bottom end points were recorded. The origin for this coordinate system was taken to be the center of the bin at floor level. Table A-1 in Appendix A is a complete listing of these coordinates.

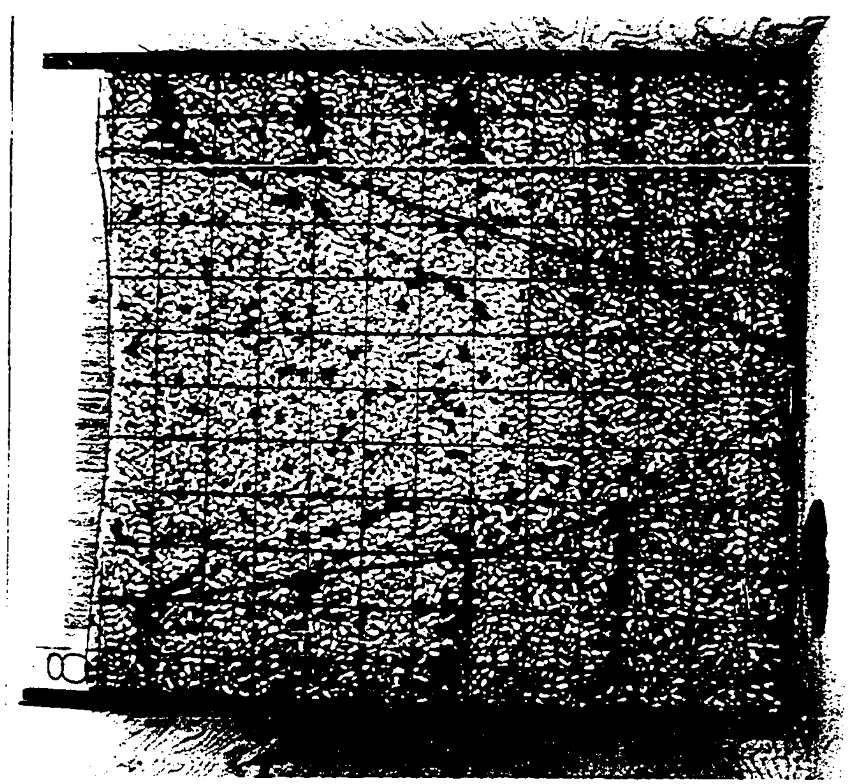
A least squares equations of each boundary of each disturbed area was calculated using an Omnitab program on the ISU Computation Center IBM System 360 electronic digital computer. A cubic equation form was chosen, giving an equation of the form

$$y = n_o + n_1x + n_2x^2 + n_3x^3 \qquad (22)$$

Figure 17. Disturbed volume cross section from Test S-8 with auger speed of 8.71 in./minute

Figure 18. Disturbed volume cross section from Test S-9 with auger speed of 24.30 in./minute





where n_o, n_1, n_2, and n_3 are least squares coefficients. The cubic form was chosen because the sides of almost every disturbed area exhibited two bends.

Tables 4 and 5 show the cubic equations for the left and right sides respectively. Also listed for each equation is R^2, the square of the multiple correlation coefficient. R^2 is equal to or less than unity and states the fraction of the total sum of squares about the mean which is accounted for by the equation. It is, thus, an indication of the goodness of fit. For these equations, values of R^2 ranged from 0.883 to 1.000.

The coefficients of the prediction equations are listed at the bottom of each of the tables. These are least squares equations computed by combining coordinates of all replications at a particular auger speed. Graphs of these equations, along with data points for each test are shown in Figures 19 through 23. The auger in each case has moved through the grain in a direction toward the viewer.

All of the combined fit equations are third degree polynomials except the equation for the right side at a speed of 24.30 in./minute. This is shown in Figure 23. The cubic equation fit to the data was judged as not representing the physical situation. This cubic equation exhibited a maximum at approximately $y = 20.5$ and $x = 9$. A second degree polynomial was used instead.

Table 4. Equations of left boundaries of the cross sectional areas disturbed by the stirring auger

Form: $y = n_o + n_1x + n_2x^2 + n_3x^3$

Test number	Auger speed $\frac{\text{in.}}{\text{minute}}$	n_o	n_1	n_2	n_3	R^2
S-2	24.30	-4.1667E 00	-5.6712E 00	-1.4919E 00	-1.4600E-01	0.979
S-3	24.30	-3.2317E 00	-6.1269E 00	-1.6963E 00	-1.8020E-01	0.995
S-4	12.26	-2.6684E 00	-3.9343E 00	-1.0388E 00	-1.3323E-01	0.997
S-5	12.26	-1.0878E 00	-2.5415E 00	-5.5906E-01	-6.4256E-02	0.994
S-6	12.26	-4.2786E 00	-6.3802E 00	-1.9825E 00	-2.3733E-01	0.994
S-7	8.71	-1.5637E 00	-2.9833E 00	-7.3720E-01	-8.0975E-02	0.997
S-8	8.71	-9.5414E-01	-1.7207E 00	-2.8964E-01	-4.7614E-02	1.000
S-9	24.30	-2.5029E 00	-5.7421E 00	-1.8458E 00	-2.1176E-01	0.993
S-10	4.35	-4.6393E-01	-9.5968E-01	-1.5667E-01	-3.5721E-02	0.995
S-11	4.35	-5.7304E-01	-4.9259E-01	2.0293E-01	-4.4295E-03	0.999
S-12	4.35	-2.3001E 00	-2.6978E 00	-3.9822E-01	-6.3783E-02	0.999
S-13	8.71	-1.8442E 00	-2.8025E 00	-2.6225E-01	-4.1044E-02	0.998
S-14	0	-2.1433E 00	-2.6746E 00	-5.9003E-01	-5.9635E-02	0.997
S-15	0	-3.9733E 00	-4.4321E 00	-8.9959E-01	-7.2863E-02	0.993
S-14,15	0	-3.0583E 00	-3.5533E 00	-7.4481E-01	-6.6249E-02	0.990
S-10,11,12	4.35	2.1248E-01	1.7298E-01	3.4433E-01	3.5062E-03	0.932
S-7,8,13	8.71	-8.5095E-01	-1.6392E 00	-1.7328E-01	-3.6787E-02	0.924
S-4,5,6	12.26	1.1332E 00	1.5106E 00	7.9160E-01	3.7609E-02	0.894
S-2,3,9	24.30	-1.5019E 00	-3.2234E 00	-8.1911E-01	-1.0417E-01	0.916

Table 5. Equations of right boundaries of the cross sectional areas disturbed by the stirring auger

Form: $y = n_o + n_1x + n_2x^2 + n_3x^3$

Test number	Auger speed $\frac{\text{in.}}{\text{minute}}$	n_o	n_1	n_2	n_3	R^2
S-2	24.30	-8.9985E-01	8.3678E-01	3.0846E-01	-1.5181E-02	0.999
S-3	24.30	-3.1447E 00	6.1122E 00	-1.7581E 00	2.0339E-01	0.991
S-4	12.26	-5.0802E-01	1.0322E 00	-2.6238E-02	4.7859E-02	0.991
S-5	12.26	-1.2063E 00	2.8406E 00	-5.3574E-01	9.2019E-02	0.999
S-6	12.26	-4.7832E 00	5.7835E 00	-1.3011E 00	1.3296E-01	0.985
S-7	8.71	-1.9059E 00	3.7831E 00	-8.5186E-01	1.1866E-01	0.997
S-8	8.71	-1.2854E 00	1.7808E 00	-4.5041E-02	2.5794E-02	1.000
S-9	24.30	-1.2097E 00	2.3376E 00	7.4667E-02	1.2532E-02	0.999
S-10	4.35	-2.5766E 00	2.9229E 00	-5.0990E-01	5.0486E-02	0.999
S-11	4.35	-2.3950E 00	2.8584E 00	-5.3102E-01	6.0140E-02	0.999
S-12	4.35	-3.1245E 00	3.6333E 00	-7.8388E-01	8.2204E-02	0.996
S-13	8.71	-9.4446E-01	1.2814E 00	6.2625E-02	1.4562E-02	0.999
S-14	0	-4.5769E 00	5.3719E 00	-1.3491E 00	1.2180E-01	0.992
S-15	0	-5.4900E 00	5.8686E 00	-1.1994E 00	9.2112E-02	0.969
S-14,15	0	-3.4228E 00	3.8957E 00	-8.1692E-01	7.3318E-02	0.945
S-10,11,12	4.35	-9.1130E-01	1.2611E 00	-1.2305E-01	2.9631E-02	0.971
S-7,8,13	8.71	2.4144E-01	-1.0354E-01	5.1053E-01	-1.6480E-02	0.952
S-4,5,6	12.26	-6.1157E-01	1.2922E 00	-1.9354E-02	3.8694E-02	0.958
S-2,3,9	24.30	-2.4721E 00	2.9023E 00	-9.2264E-03	0000E 00	0.883

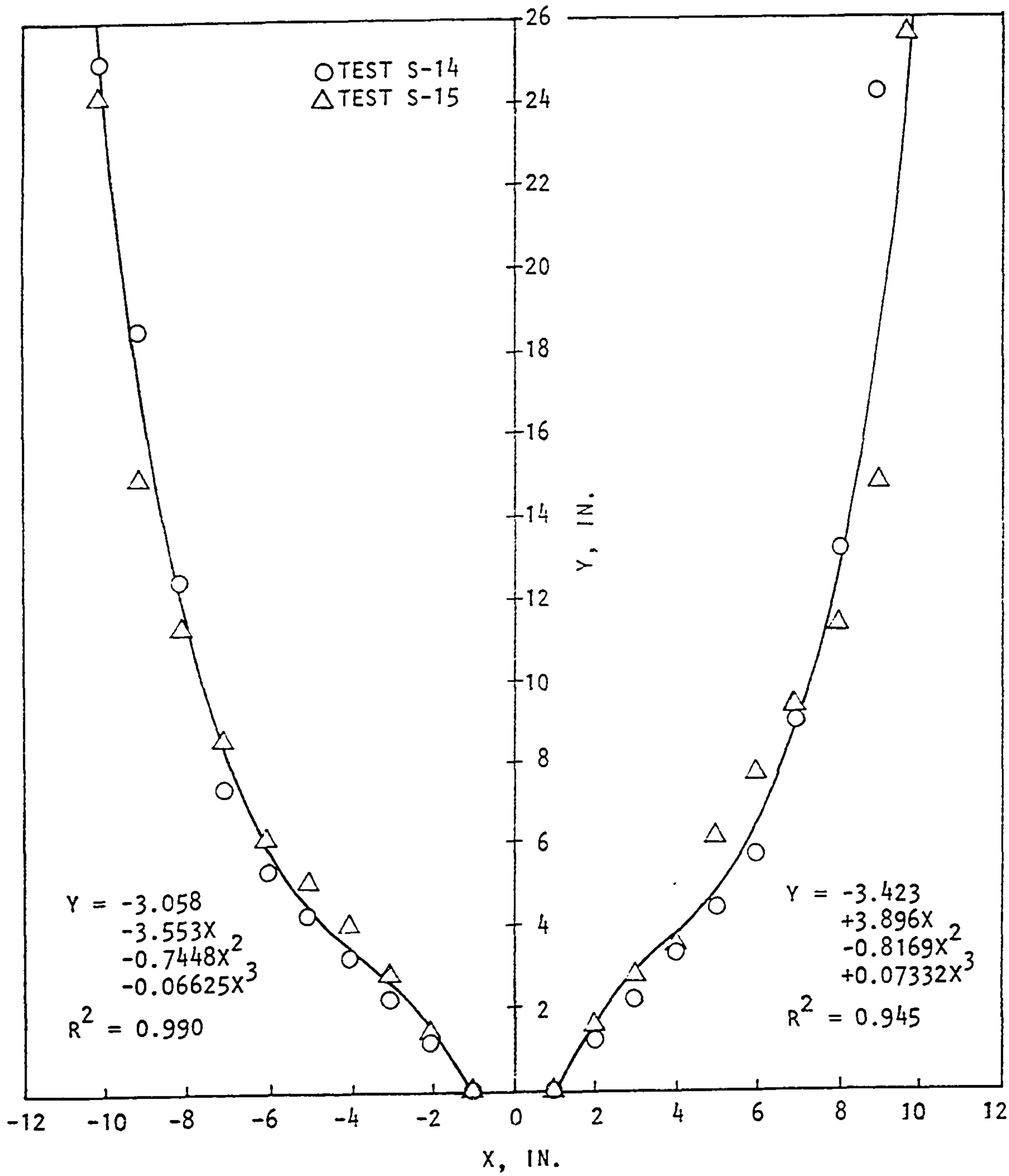


Figure 19. Shape of disturbed volume cross section for an auger speed of 0 in./minute in corn in a test bin

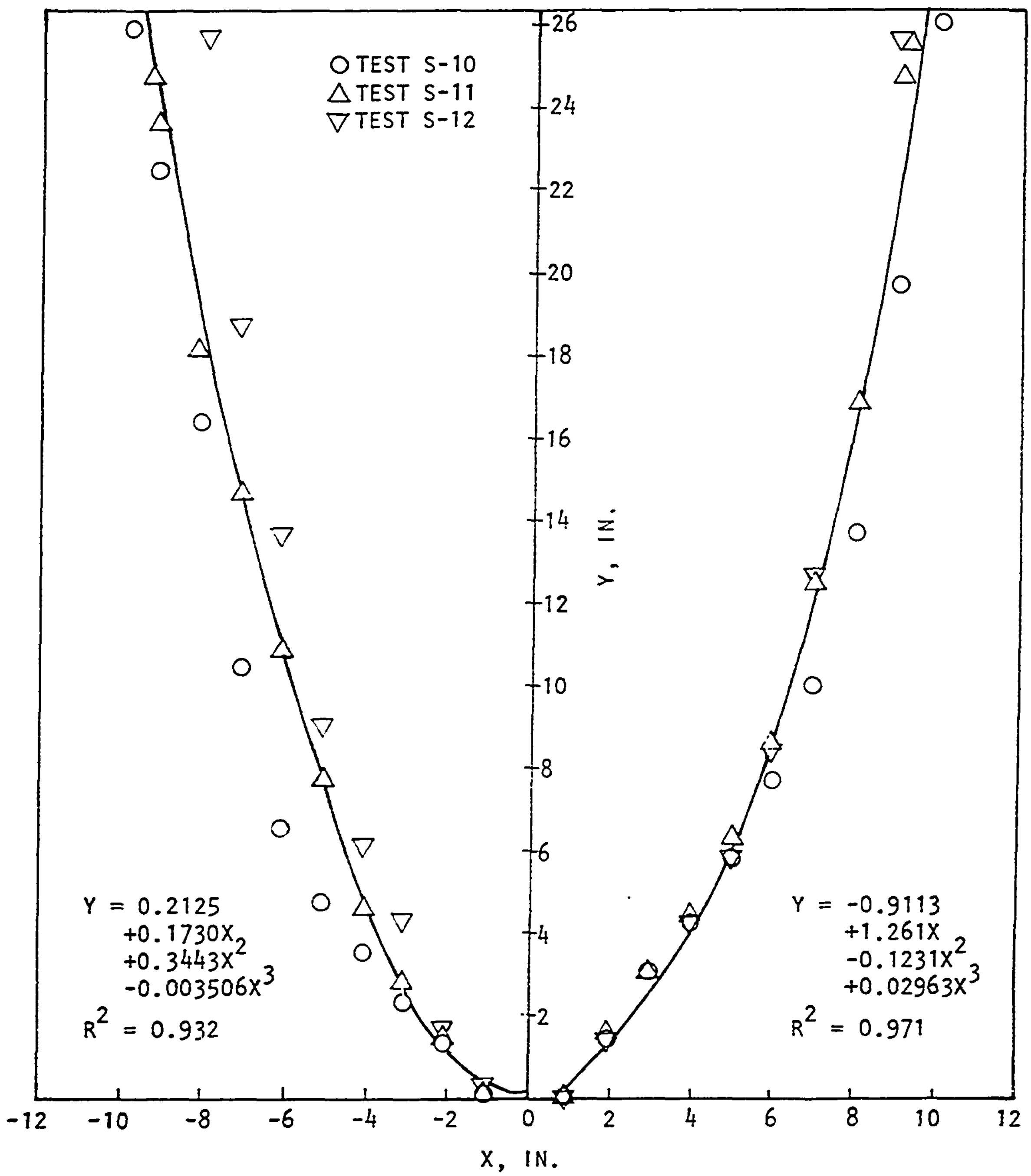


Figure 20. Shape of disturbed volume cross section for an auger speed of 4.35 in./minute in corn in a test bin

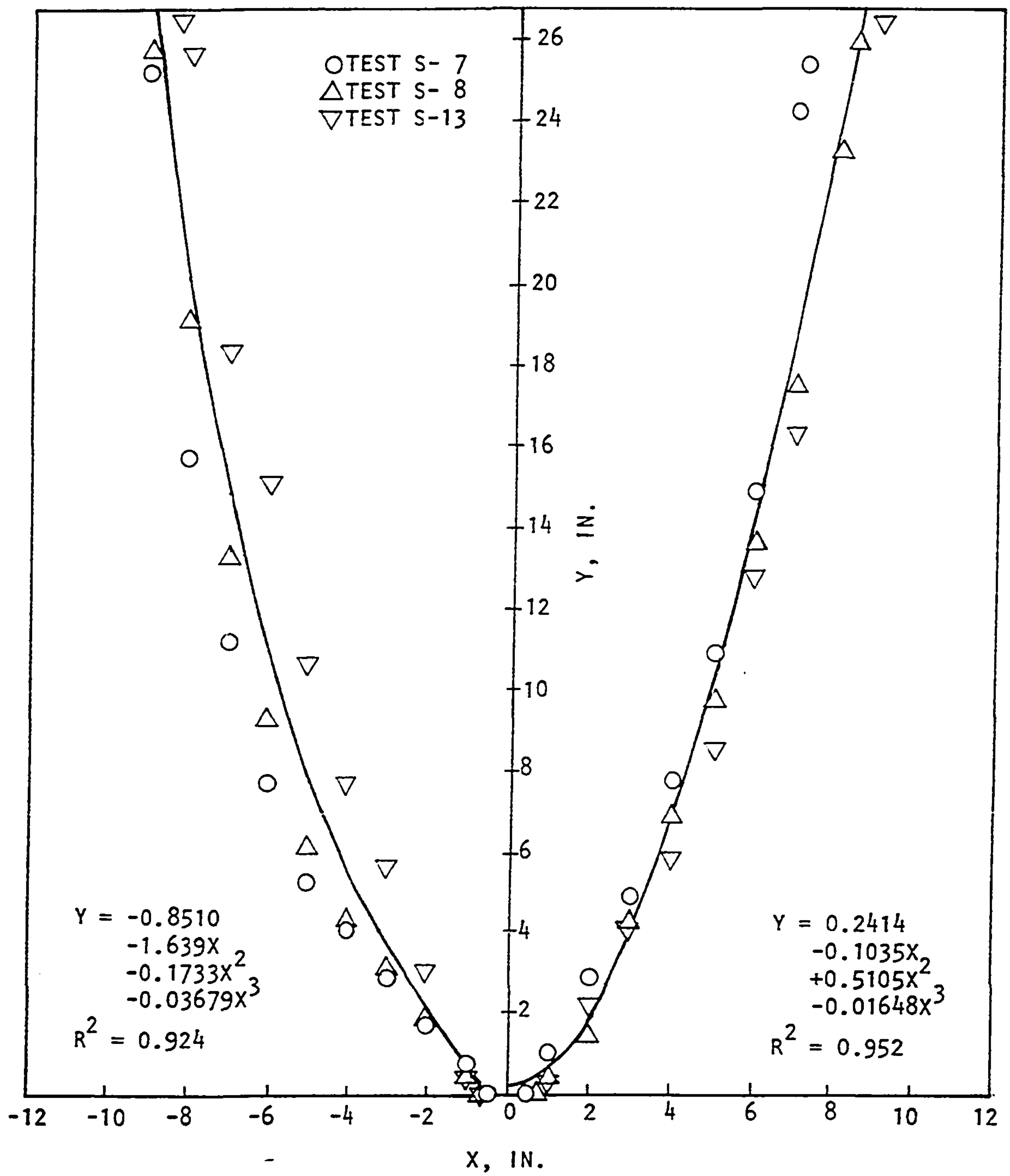


Figure 21. Shape of disturbed volume cross section for an auger speed of 8.71 in./minute in corn in a test bin

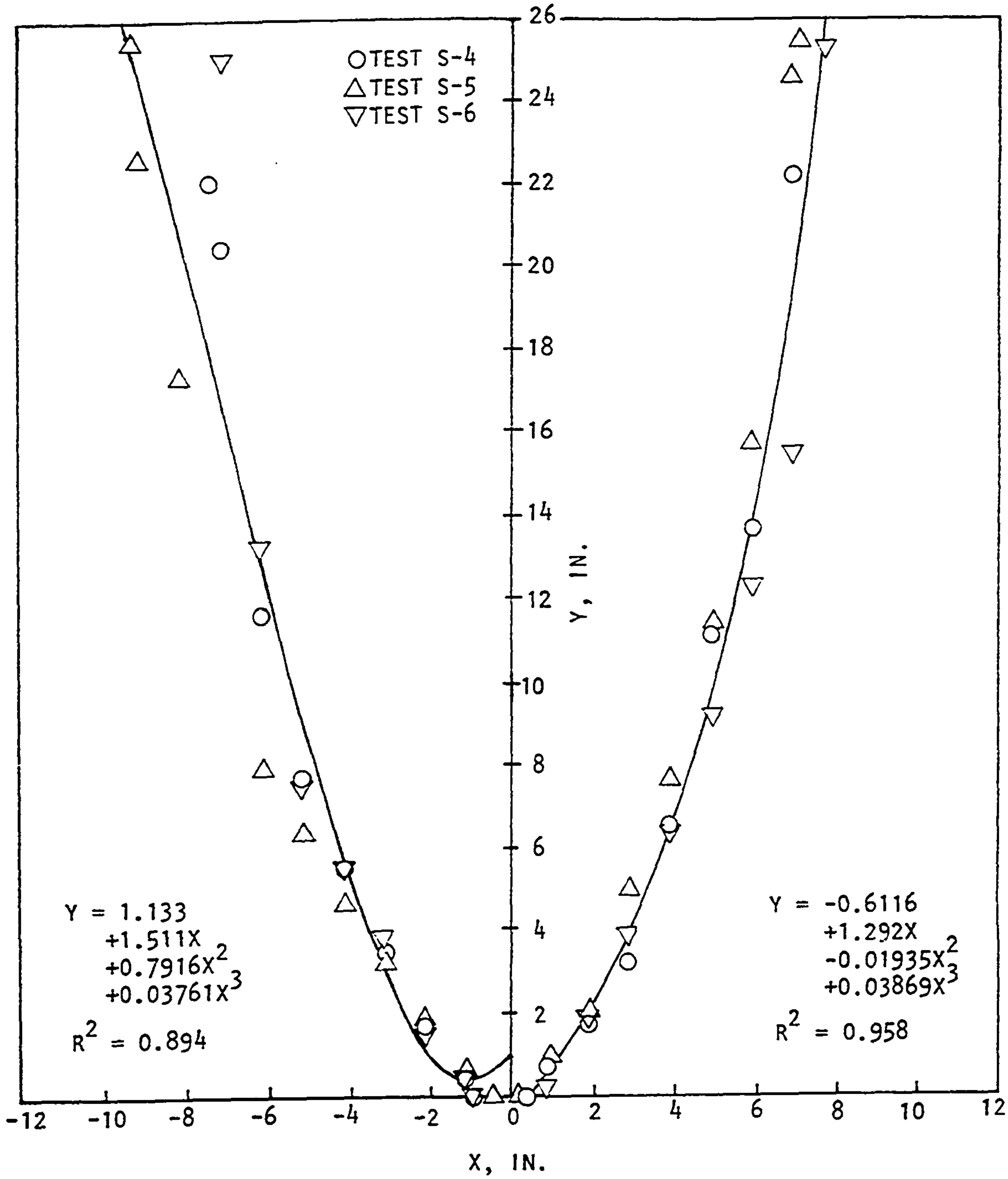


Figure 22. Shape of disturbed volume cross section for an auger speed of 12.26 in./minute in corn in a test bin

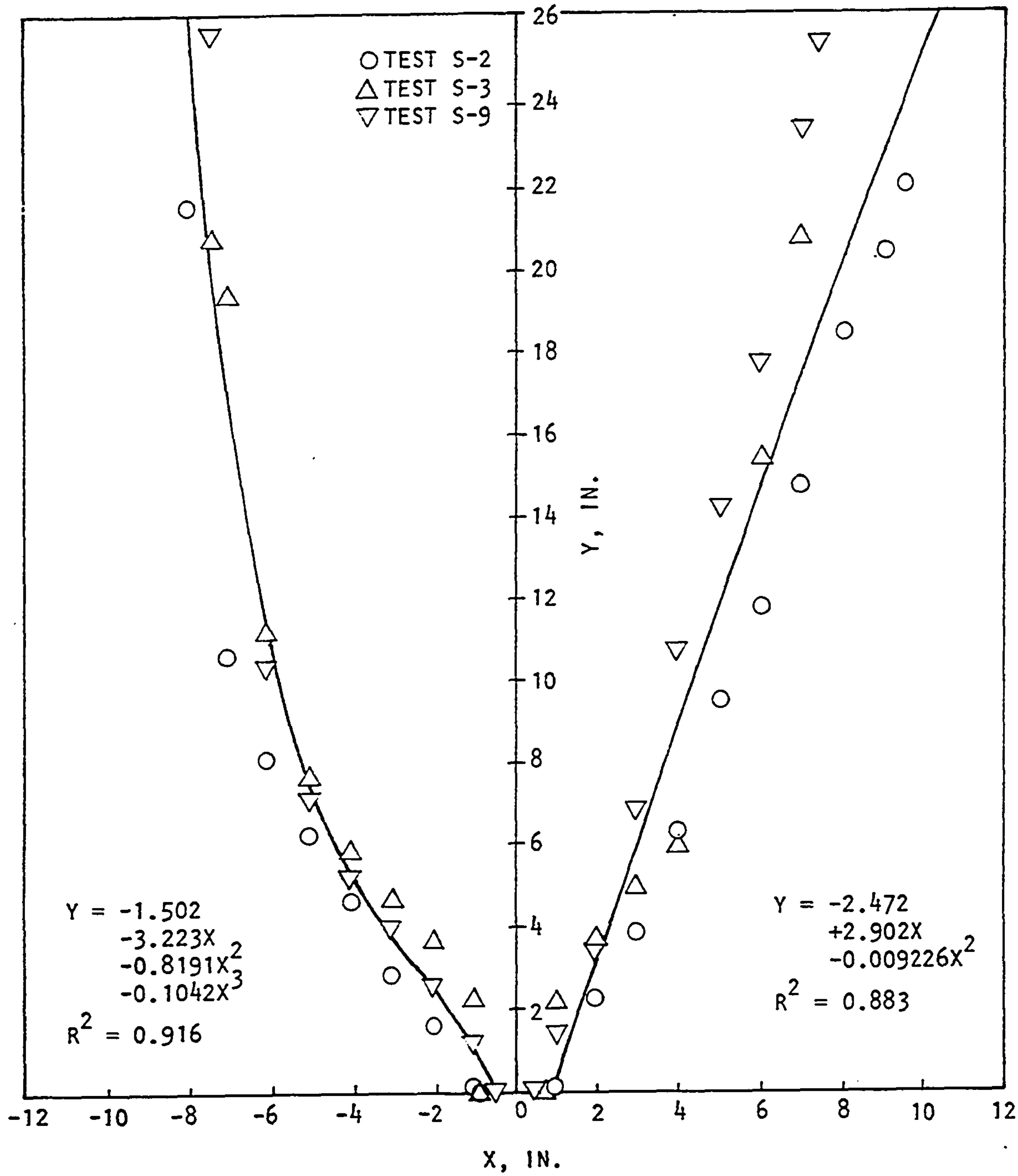


Figure 23. Shape of disturbed volume cross section for an auger speed of 24.30 in./minute in corn in a test bin

An increase in variability among test replications as auger speed increased can be seen in Figures 19-23. Also a trend toward lower values of R^2 at higher auger speeds can be noted. At the higher auger speeds, the dividing line between the disturbed and undisturbed regions was more difficult to define.

The shape equations permitted analysis of the symmetry of the disturbed region about the bin cross section vertical centerline. The disturbed portion of the bin cross-sectional area was computed for each side at each auger speed by integration of the combined fit equations. Results are shown in Table 6.

For four of the five cases, the area on the left was greater. This suggests that more than half the corn lifted by the auger may be loaded on the side of the advancing auger which corresponds to the left side of Figures 19-23.

The relationship between auger speed and area disturbed is shown in Figure 24. For each test, the area disturbed was calculated graphically using the graph paper on which the outline of the disturbed cross sectional area was recorded from the Plexiglas sheet. Results were also computed as area per ft of grain depth because grain depths varied among tests. The data is shown in Table 7.

A second-power curve was fitted to this data using an Omnitab program on the ISU IBM 360 computer. The relation was

Table 6. Disturbed areas of corn on the right and left of centerlines in Figures 19-23 to a depth of 26 in.

Figure	Auger speed, in./minute	Area left of centerline, ft^2	Area right of centerline, ft^2
19	0	1.36	1.31
20	4.35	1.12	1.20
21	8.71	1.09	0.97
22	12.26	1.08	0.94
23	24.30	1.04	0.99

found to be

$$A_D = 1.162 - 0.0300S_A + 0.000655S_A^2 \qquad (23)$$

where A_D = cross sectional area disturbed per ft of grain depth, ft^2/ft

S_A = auger speed, in./minute

The R^2 for this model was 0.756.

Bulk Density Effects

The tests of Experiment I involved measurement of the grain volume before and after stirring. The effect of the stirring was always to increase the grain volume.

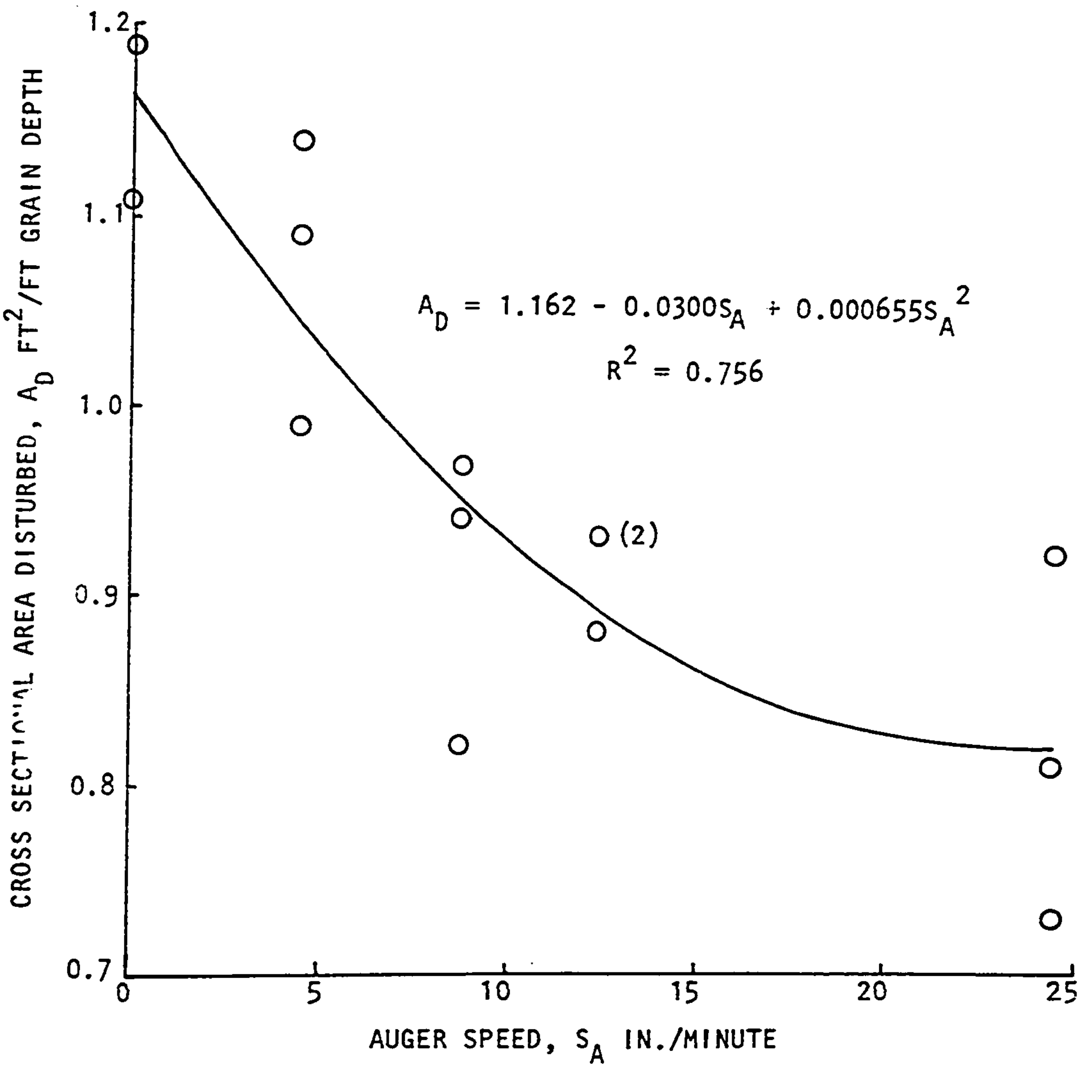


Figure 24. Cross sectional area disturbed as affected by stirring auger speed

Table 7. Bulk density of corn and disturbed cross sectional area data from Experiment I

Test number	Auger speed in./minute	Corn weight, lb	Initial bulk density, lb/ft^3	Disturbed grain bulk density, lb/ft^3	Bulk density decrease of stirred grain, percent
S-2	24.30	582.5	48.45	45.19	6.73
S-3	24.30	553.6	-[a]	-[a]	-[a]
S-4	12.26	617.5	49.20	44.72	9.10
S-5	12.26	676.7	48.91	45.13	7.72
S-6	12.26	686.6	49.63	45.79	7.73
S-7	8.71	683.9	49.44	45.12	8.72
S-8	8.71	716.8	49.71	46.28	6.89
S-9	24.30	683.5	49.40	45.46	7.99
S-10	4.35	686.8	48.75	45.54	6.60
S-11	4.35	686.8	49.74	45.78	7.95
S-12	4.35	686.8	49.54	46.27	6.61
S-13	8.71	686.8	48.95	45.42	7.21
S-14	0	688.1	49.34	44.91	8.99
S-15	0	687.3	48.89	44.01	9.98

[a]Data not taken.

Table 7 (Continued)

Test number	Auger speed	Change in cross sectional area of grain mass	Cross sectional area of volume disturbed		Rate of volume change	Rate of grain disturbance
	in./minute	ft^2	ft^2	ft^2/ft of grain depth	ft^3/minute	ft^3/minute/ft of grain depth
S-2	24.30	0.117	1.70	0.92	0.237	1.86
S-3	24.30	-[a]	1.38	0.73	-[a]	1.48
S-4	12.26	0.167	1.73	0.88	0.171	0.90
S-5	12.26	0.159	2.00	0.93	0.162	0.95
S-6	12.26	0.159	2.00	0.93	0.162	0.95
S-7	8.71	0.158	1.77	0.82	0.115	0.60
S-8	8.71	0.150	2.17	0.97	0.109	0.70
S-9	24.30	0.142	1.73	0.81	0.288	1.64
S-10	4.35	0.166	2.49	1.14	0.060	0.41
S-11	4.35	0.174	2.12	0.99	0.063	0.36
S-12	4.35	0.157	2.33	1.09	0.057	0.34
S-13	8.71	0.150	2.04	0.94	0.109	0.68
S-14	0	-[b]	2.51	1.19	-[b]	-[b]
S-15	0	-[b]	2.37	1.11	-[b]	-[b]

[b]Not applicable.

The assumption was made that grain outside of the outlined disturbed region was undisturbed and that the disturbed cross section remained the same over the entire bin length traversed by the stirring auger. The volume of the disturbed grain was assumed to increase by the amount of the volume change of the entire grain mass. From grain weight, bin dimensions, cross sectional area of the disturbed region, and the initial and final grain volumes, computation was made of the original and final bulk densities of the disturbed grain. This information for each test is listed in Table 7. The relationship between bulk density decrease and auger speed is shown in Figure 25. A least squares linear equation was computed using an Omnitab program on the ISU IBM 360 computer. The equation was

$$D_{BD} = 8.231 - 0.03997S_A \tag{24}$$

where D_{BD} is the percent decrease in bulk density. R^2 for the fit was 0.083. A t-test was run to test the null hypothesis that the slope of this line equals zero. The computed t was 1.00 and $t_{0.05} = 2.20$ for a two-tailed test with 11 degrees of freedom. Therefore we must fail to reject the null hypothesis. This says that at the 5 percent probability level, the data does not show the slope to be different from zero. The magnitude of the bulk density change of the corn disturbed was thus not shown to be dependent on the speed at which the auger

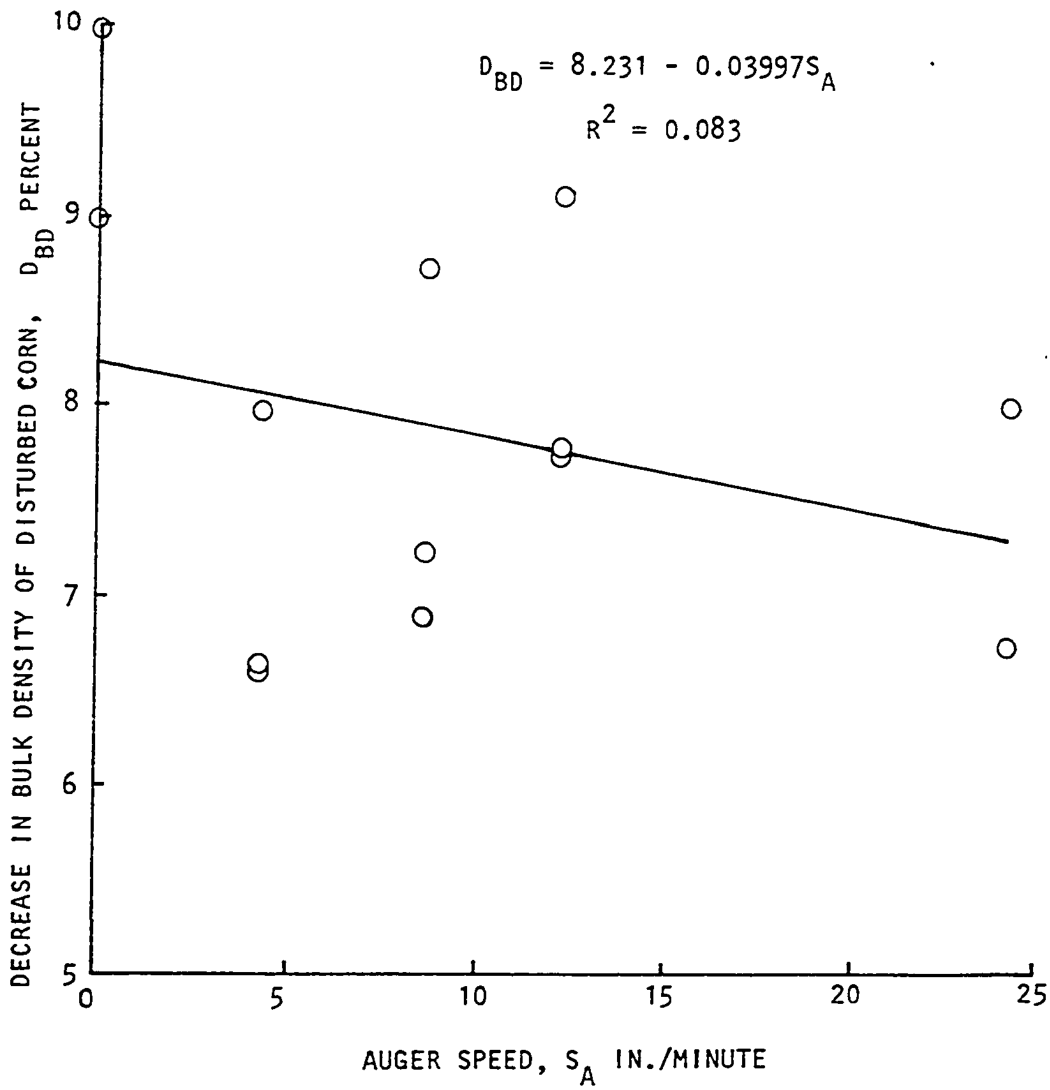


Figure 25. Percent decrease in bulk density of disturbed corn as affected by auger speed

moved through the grain.

The rate of volume change is another meaningful characteristic of a stirring auger. The relationship between auger speed and rate of volume change is shown in Figure 26. A least squares linear equation was fitted to this data using an Omnitab program on the ISU IBM 360 computer. The linear model was chosen because the reduction in sum of squares achieved by fitting a second or third degree equation was found to be not significant at the 5 percent probability level. The equation computed was

$$Q_A = 0.02436 + 0.01015S_A \tag{25}$$

where Q_A is the rate of corn volume change in ft^3/minute. The R^2 for this fit was 0.953. The data for the graph is in Table 7.

Figure 27 shows the relationship between auger speed and the change in cross-sectional area of the grain mass. This change was the cross-sectional area of the continuous mound formed by the stirring auger as it moved through the corn. A least squares linear equation was fitted to this data using an Omnitab program on the ISU IBM 360 computer. The equation was

$$A_C = 0.1734 - 0.001676S_A$$

where A_C is the change in cross-sectional area in ft^2. R^2 for this fit was 0.609. Data for the graph is shown in Table 7.

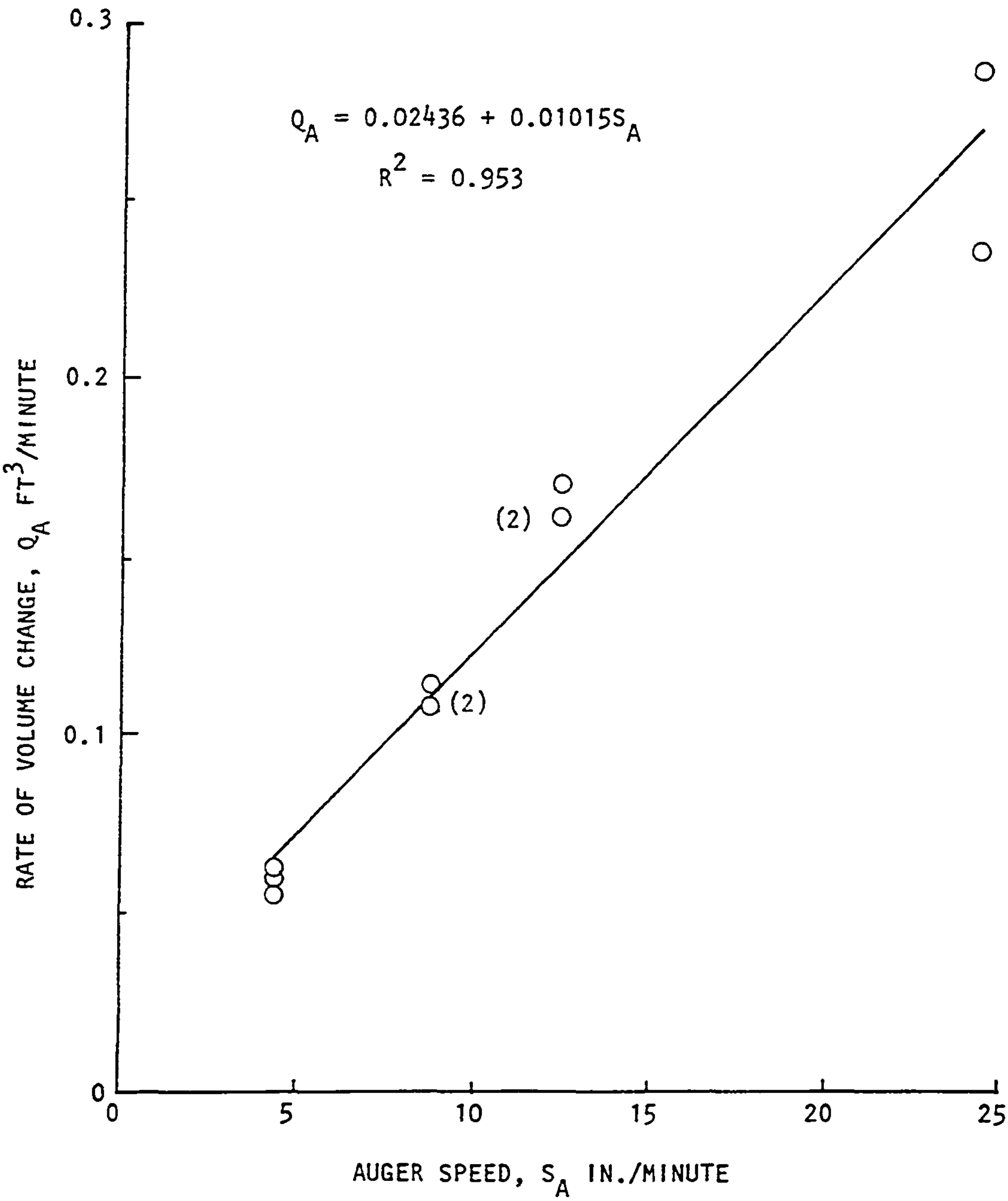


Figure 26. Rate at which corn volume changed as affected by stirring auger speed

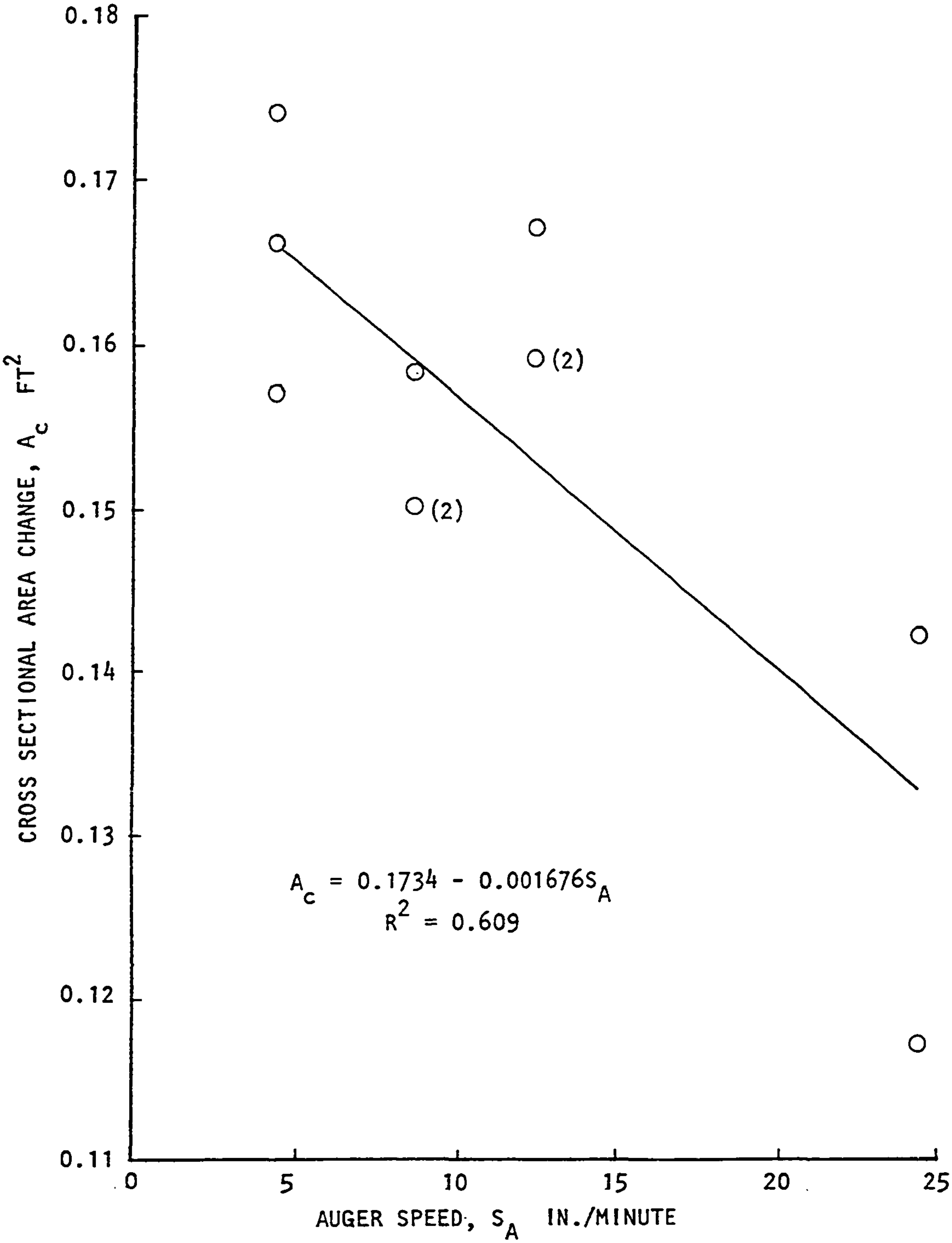


Figure 27. Change in cross sectional area of corn mass due to stirring as affected by auger speed

By multiplying the cross-sectional area per ft of grain depth by the auger speed, the volume rate at which grain was being disturbed can be computed. The relationship between this volume rate of disturbance and auger speed is shown in Figure 28. Data for the graph is shown in Table 7. A second degree least squares curve was fitted to the data using an Omnitab program on the ISU IBM 360 computer. The equation was

$$Q_D = 0.0360 + 0.0775S_A - 0.000436S_A^2 \qquad (26)$$

where Q_D has units of ft^3/minute/ft of grain depth. R^2 for this fit was 0.969.

Corn Kernel Orientation

The experiment to investigate if corn kernels in the disturbed region have a different orientation than kernels in the non-disturbed region was conducted during test S-12 of Experiment I. In this test the auger speed was 4.35 in./minute.

All kernels visible through the inserted plastic sheet were designated as pointing up, pointing down, or horizontal. If the kernel tip was higher than the center of the butt, the kernel was counted as pointing up. If the tip was lower, the kernel was counted as pointing down. Kernels for which a slope could not be discerned were counted as horizontal. The results are shown in Table 8.

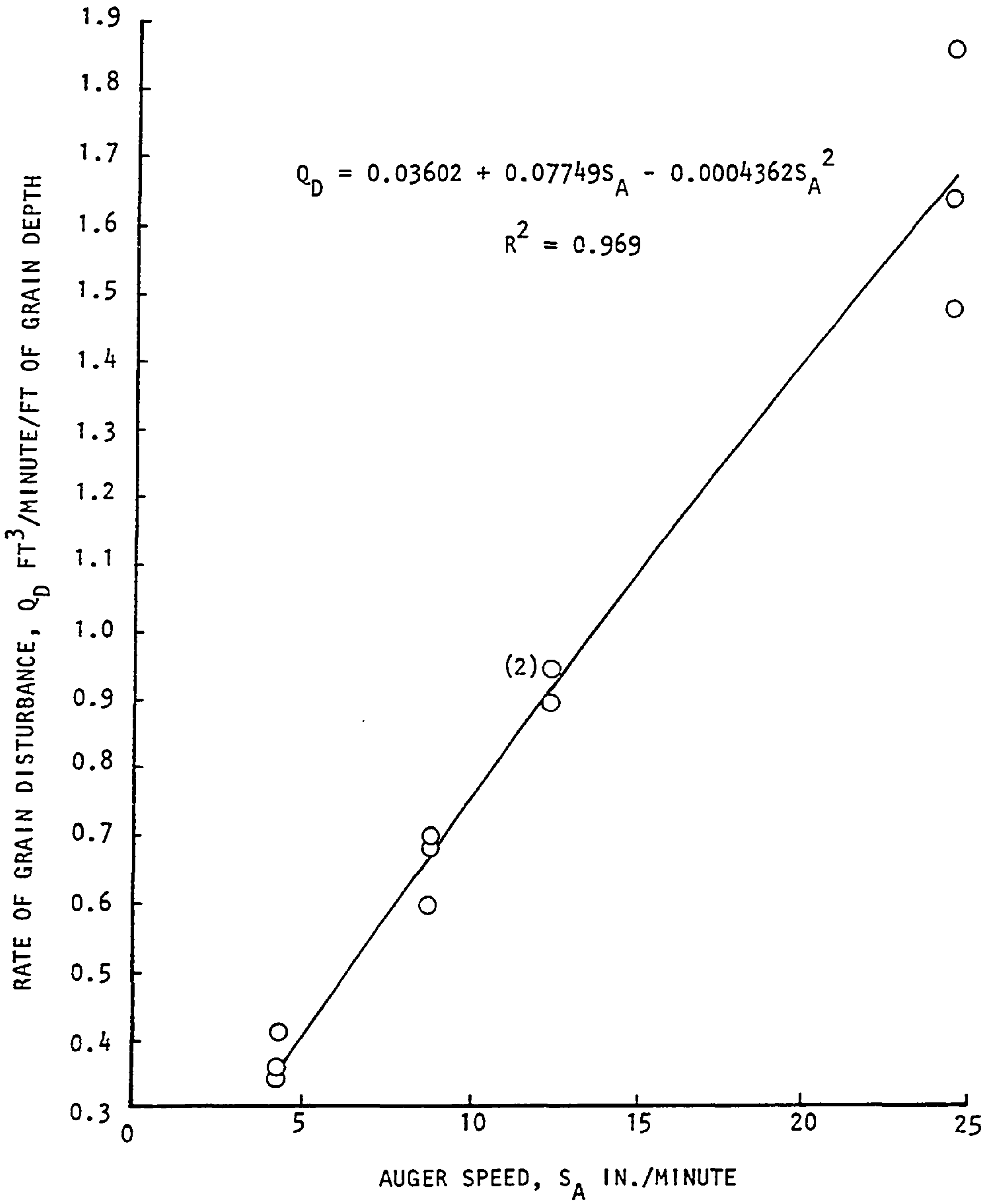


Figure 28. Volume rate at which corn was disturbed as affected by stirring auger speed

Table 8. Corn kernel orientation test results from Experiment I

Kernel orientation	Inside disturbed area				Outside disturbed area				Total observed number
	Observed Percent	Observed Number	Expected number	$\frac{(O-E)^2}{E}$	Observed Percent	Observed Number	Expected number	$\frac{(O-E)^2}{E}$	
Up	51.7	1584	1587.2	0.0065	51.9	1347	1343.8	0.0076	2931
Down	40.8	1251	1256.8	0.0268	41.2	1070	1064.2	0.0316	2321
Horizontal	7.5	231	222.0	0.3649	6.9	179	188.0	0.4309	410
Total		3066	3066.0			2596	2596.0		5662

$$\chi^2 = \sum_i \frac{(O_i - E_i)^2}{E_i} = 0.8683 \qquad (27)$$

$$\chi^2_{0.05} \text{ (5 degrees of freedom)} = 11.1$$

A statistical analysis was carried out to test the null hypothesis that kernel orientation is the same within and outside the region disturbed by the stirring auger. The test statistic used was chi square, χ^2, with 5 degrees of freedom. A value for the test statistic was calculated using Equation 27 shown in Table 8. The expected values were computed by multiplying the product of the orientation and location probabilities by the total number of kernels. For example, the expected number of kernels up and within the boundary of the disturbed grain was computed as follows:

$$\frac{2931}{5662} \cdot \frac{3066}{5662} \cdot 5662 = 1587.2$$

The computed value of χ^2 (0.8683) was less than $\chi^2_{0.05}$ with 5 degrees of freedom (11.1). This means the null hypothesis must be accepted, and we must conclude that kernel orientation is the same within and outside the boundary of the area disturbed by the stirring auger. With a true null hypothesis, χ^2 will, by chance, exceed 11.1 five percent of the time.

Air Flow Resistance of Corn

Measurements of the air flow resistance of corn which had not been disturbed by a stirring auger were made in Experiments II and III. Determination of a prediction equation for pressure drop across the test corn was not a primary objective, but such an equation was required for accomplishment of two other objectives.

The variable factors to be considered in predicting the pressure drop per unit depth of bed for air flow through corn of constant moisture content are air velocity, fraction of voids, and kernel orientation. As was earlier reported, bulk density has been shown to be an adequate index of bed porosity. Expressed in equation form,

$$\frac{\Delta P}{L} = F(U, BD, \text{kernel orientation}) \qquad (28)$$

where ΔP is the pressure drop in in. of water, L is the bed depth in ft, U is the superficial fluid velocity in cfm/ft^2 and BD is the bulk density in lb/ft^3.

The approach taken in this study consisted of fitting a second degree polynomial of the following form to each air flow test:

$$\frac{\Delta P}{L} = AU^2 + BU + C \qquad (29)$$

A, B, and C in Equation 29 will be referred to as grain characteristics coefficients.

A least squares fit was made for each test using an Omnitab program on the ISU IBM 360 computer. The equations and test data for each test are listed with the data for Experiments II and III in Appendix A. The odd numbered tests in Experiment II, which were air flow resistance tests conducted before stirring, and all tests in Experiment III were used to supply air flow resistance data. With bulk density (BD) data available for each test, equations were determined relating the grain characteristics coefficients A, B, and C of Equation 29 to BD. Substituting these functions of BD for A, B, and C gave a pressure drop prediction equation in terms of U and BD. No attempt was made to include kernel orientation as a variable.

A second degree polynomial form was chosen for several reasons. This equation form is suggested by the physical situation in the bed. Pressure losses have been shown to be the sum of the viscous and turbulent losses, proportional respectively to the first and second powers of the fluid velocity. The previously reviewed work of Ergun (1952) and Patterson et al. (1971) also suggested this equation form. To obtain the best possible fit, the fitted equation was not forced through the origin. Because of this, one term of each equation is a constant.

This equation form is very convenient to fit repeatedly using the Omnitab programming language. It is also readily solvable for air flow rate, which was an advantage in later analysis work.

The second degree polynomial was found to fit the data very closely. Except for the lowest flow rate for each run, the equation was within approximately 1 percent of the pressure at any data point. The R^2 value for each fit equation is listed with the equation in Appendix A, Tables A-2 and A-3.

Figures 29, 30, and 31 show the relationship between BD and A, B, and C respectively. In each figure, circled points are for resistance determinations made in Experiment II. The filling method for each of these determinations was the same, and consisted of dropping the grain from an average height of 7 ft at a rate of approximately 300 lb/minute. The bulk density ranged from 48.23 to 49.60 lb/ft^3 for these tests. In order to extend this range of bulk densities, Experiment III was conducted. Points within triangles are for resistance determinations made in Experiment III. As earlier reported, in Experiment III, the grain column was filled at zero drop height, and at average heights of 2, 3, 5, and 6 ft. The bulk densities obtained ranged from 45.71 to 46.13 lb/ft^3. These dropping heights were selected in an attempt to attain bulk density values ranging from a minimum attainable by dropping up to the lowest value obtained for Experiment II. As is evident in Figures 29, 30, and 31, the highest bulk density attained here was considerably less than the lowest of Experiment II.

The points within down-pointing triangles are the two replications for filling at zero drop height. These points were not used in computation of the least squares line because values of A and B for both replications ranged from approximately 6 to 24 percent above the least squares line through the remainder of the points.

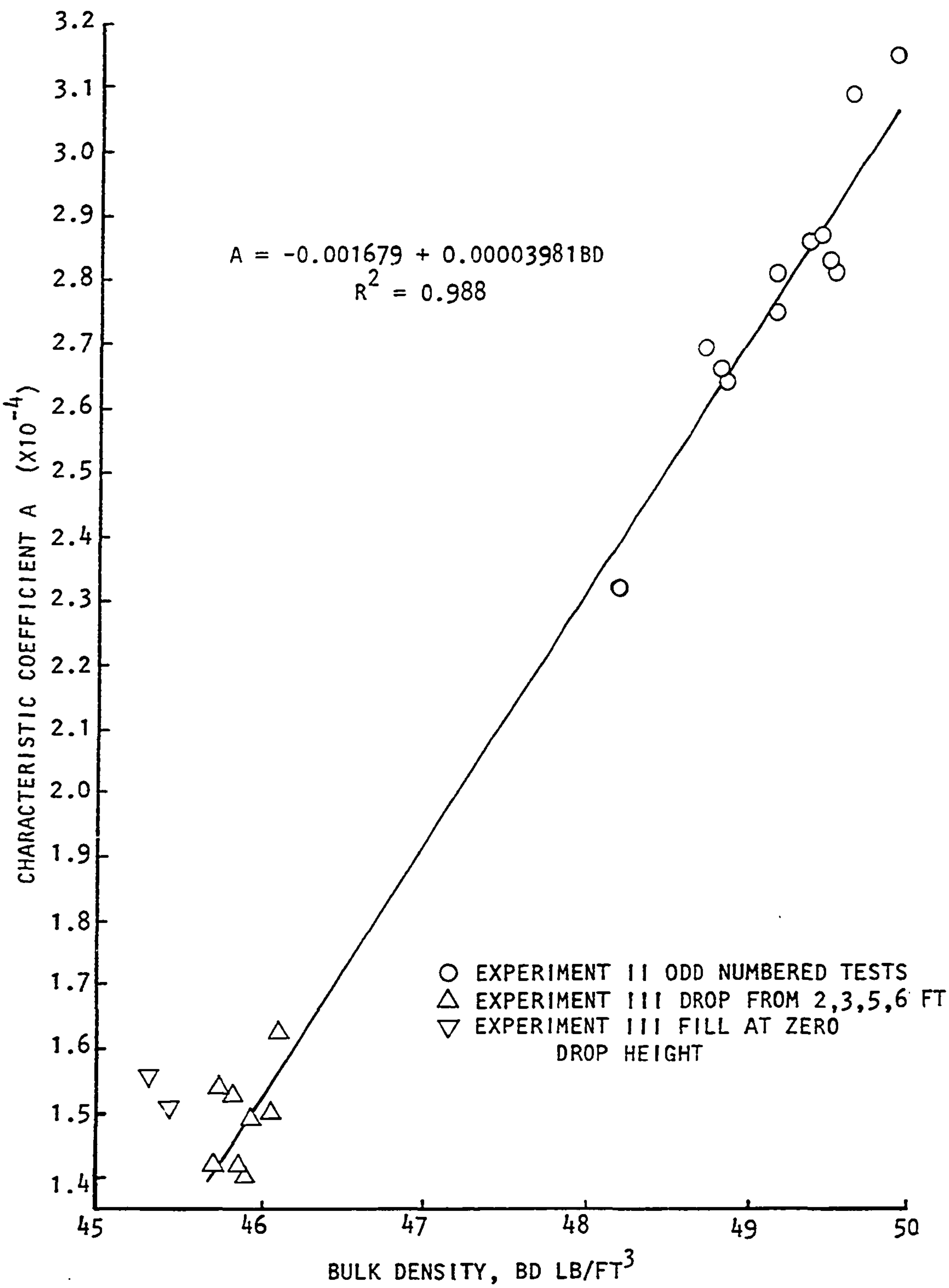


Figure 29. Corn characteristic coefficient A as related to bulk density

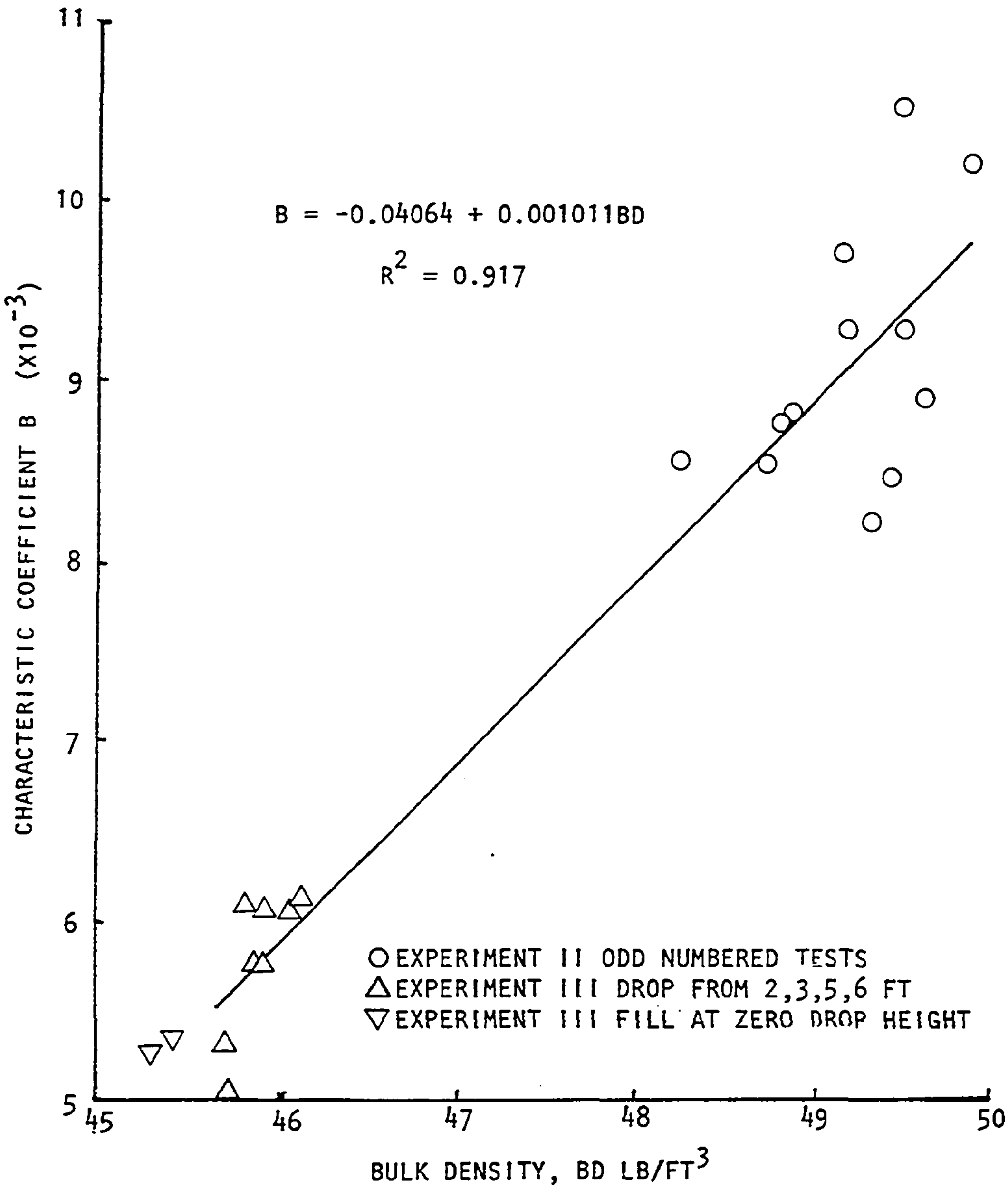


Figure 30. Corn characteristic coefficient B as related to bulk density

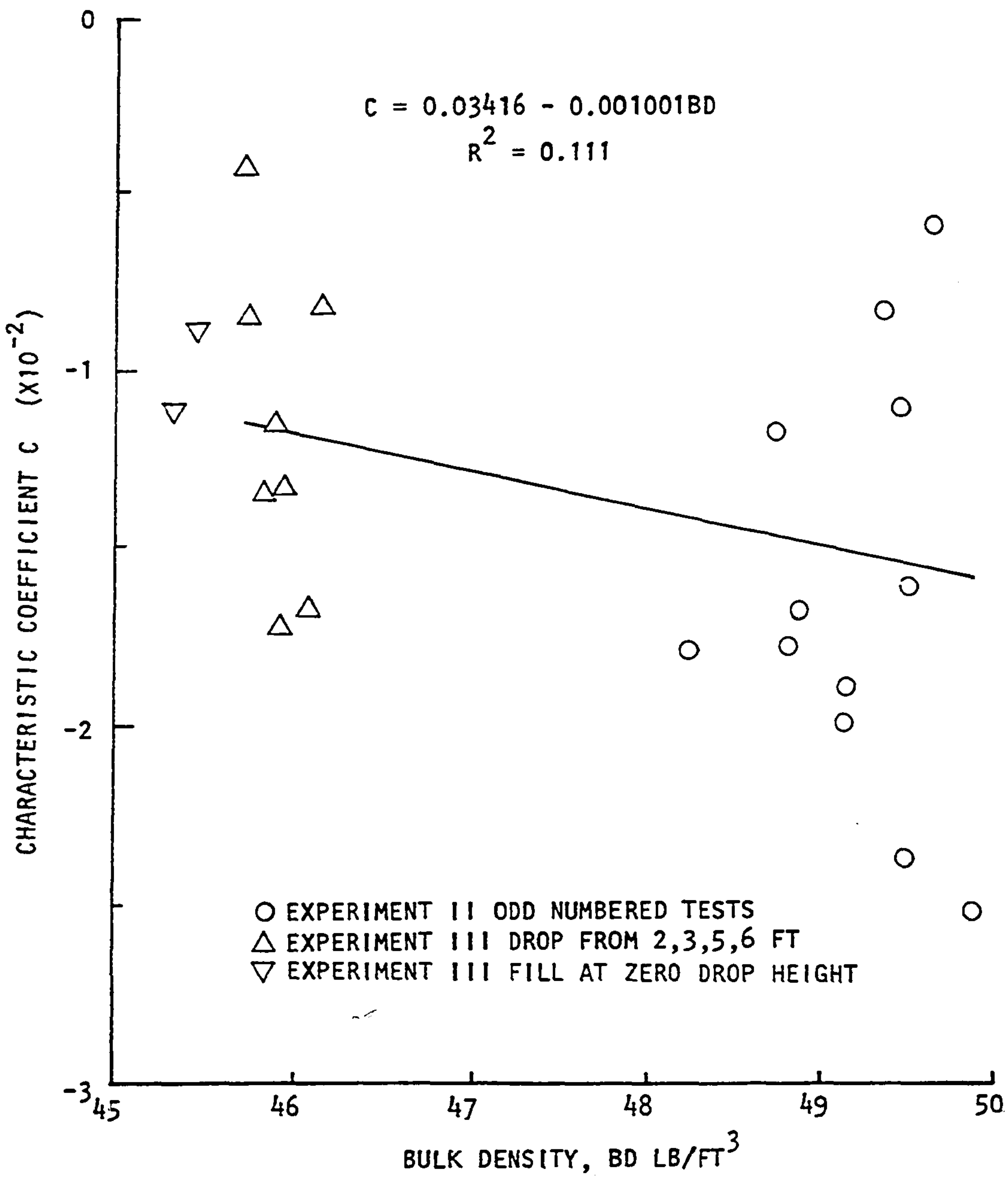


Figure 31. Corn characteristic coefficient C as related to bulk density

The least squares equations for the lines of Figures 29, 30, and 31 were determined using an Omnitab program on the ISU IBM 360 computer. The equations and their R^2 values are listed below.

$$A = -0.001679 + 0.00003981\ (BD) \qquad (30)$$
$$R^2 = 0.988$$

$$B = -0.04064 + 0.001011\ (BD) \qquad (31)$$
$$R^2 = 0.917$$

$$C = 0.03416 - 0.001001\ (BD) \qquad (32)$$
$$R^2 = 0.111$$

Substitution of Equations 30, 31, and 32 into Equation 29 gives

$$\frac{\Delta P}{L} = (-0.001679 + 0.00003981\ BD)U^2 + (-0.04064 + 0.001011\ BD)U$$
$$+ 0.03416 - 0.001001\ BD \qquad (33)$$

Equation 33 can be used to predict pressure drop through drop-filled beds of clean, 11.3 percent, wet basis, moisture content corn for air flows in the range of approximately 5 to 120 cfm/ft^2 and for bulk densities in the range of approximately 45.7 to 49.6 lb/ft^3.

Pressure and Velocity Distribution Within Stirred Corn Mass

A numerical analysis approach was used to arrive at the pressure and velocity distributions existing within a mass of stirred grain. Using an extension of a method described by Brooker (1961), an electronic digital computer was programmed to compute the pressure and velocity at points on the bin cross section.

Numerical analysis approach

The basic analysis procedure consisted of deriving an equation which permitted solution for the pressure at a point in the grain mass in terms of the pressure at surrounding points, and the grain characteristics. As was noted in the Review of Literature, the basic procedure is from Brooker (1961). It has been used and modified by Bunn (1960), Brooker (1969), and Jindal and Thompson (1972).

Brooker method The Brooker method involves definition of the continuity equation in finite difference form, and solution for the pressure at the center of a 9-point grid.

For two-dimensional steady flow of an incompressible fluid, it can be shown that

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{34}$$

This relationship is known as the continuity equation. The derivation is shown in Brooker (1961), and Murphy (1950), p. 262.

Air flowing through a mass of grain is assumed to flow in a direction normal to the isopressure lines. For a particular mass of grain, the velocity is considered to be a function of the pressure gradient. For this study, the relation used was Equation 29 expressed in a differential form:

$$\frac{\partial P}{\partial N} = AU^2 + BU + C \tag{35}$$

where N is the distance normal to isopressure lines. Solution of Equation 35 for velocity yields

$$U = \frac{-B + \left(B^2 - 4A\left(C - \frac{\partial P}{\partial N}\right)\right)^{\frac{1}{2}}}{2A} \tag{36}$$

None of the previous studies used a second degree polynomial for this relationship. As explained earlier, this form offers several advantages.

The pressure gradients in the x and y directions are related to the pressure gradient in the direction of flow by the equation

$$\left(\frac{\partial P}{\partial N}\right)^2 = \left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2 \tag{37}$$

The velocity components in the x and y directions are related to the velocity in the direction of flow by these equations:

$$\frac{u}{U} = \frac{\partial P/\partial x}{\partial P/\partial N} \tag{38}$$

$$\frac{v}{U} = \frac{\partial P/\partial y}{\partial P/\partial N} \tag{39}$$

Combining Equations 36, 37, 38, and 39 permits solving for u or v in terms of A, B, C, ∂P/∂x, and ∂P/∂y:

$$u = \frac{-B + \left(B^2 - 4AC + 4A\left(\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2\right)^{\frac{1}{2}}\right)^{\frac{1}{2}} \frac{\partial P}{\partial x}}{2A\left(\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2\right)^{\frac{1}{2}}} \tag{40}$$

$$v = \frac{-B + \left(B^2 - 4AC + 4A\left(\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2\right)^{\frac{1}{2}}\right)^{\frac{1}{2}} \frac{\partial P}{\partial y}}{2A\left(\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2\right)^{\frac{1}{2}}} \tag{41}$$

Taking the partial derivative of Equation 40 with respect to x and Equation 41 with respect to y yields relationships which may be substituted into Equation 34. Carrying out this operation and simplifying yields this equation:

$$0 = B\left(\frac{\partial P}{\partial y}\frac{\partial^2 P}{\partial y^2} + \frac{\partial P}{\partial x}\frac{\partial^2 P}{\partial x^2}\right) + \left(\frac{1}{2}\right)\left(\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2\right)$$

$$\left(B^2 - 4AC + 4A\left(\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2\right)^{\frac{1}{2}}\right)^{-\frac{1}{2}}$$

$$\left[\frac{\partial^2 P}{\partial y^2}\left(2B^2 - 8AC + 4A\left[\left(\frac{\partial P}{\partial y}\right)^2\left(\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2\right)^{-\frac{1}{2}} +\right.\right.\right.$$

$$\left.2\left(\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2\right)^{\frac{1}{2}}\right] - \left(B^2 - 4AC + 4A\left(\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2\right)^{\frac{1}{2}}\right)$$

$$\left.\left(\frac{\partial P}{\partial y}\right)^2\right) + \frac{\partial^2 P}{\partial x^2}\left(2B - 8AC + 4A\left[\left(\frac{\partial P}{\partial x}\right)^2\left(\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2\right)^{-\frac{1}{2}}\right.\right.$$

$$\left. + 2\left(\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2\right)^{\frac{1}{2}}\right] - \left(B^2 - 4AC + 4A\left(\left(\frac{\partial P}{\partial x}\right)^2 + \left(\frac{\partial P}{\partial y}\right)^2\right)^{\frac{1}{2}}\right)$$

$$\left.\left.\left(\frac{\partial P}{\partial x}\right)^2\right)\right] \tag{42}$$

To obtain a numerical solution of Equation 42, a grid was set up over the grain bin cross section, with points designated as shown in Figure 32.

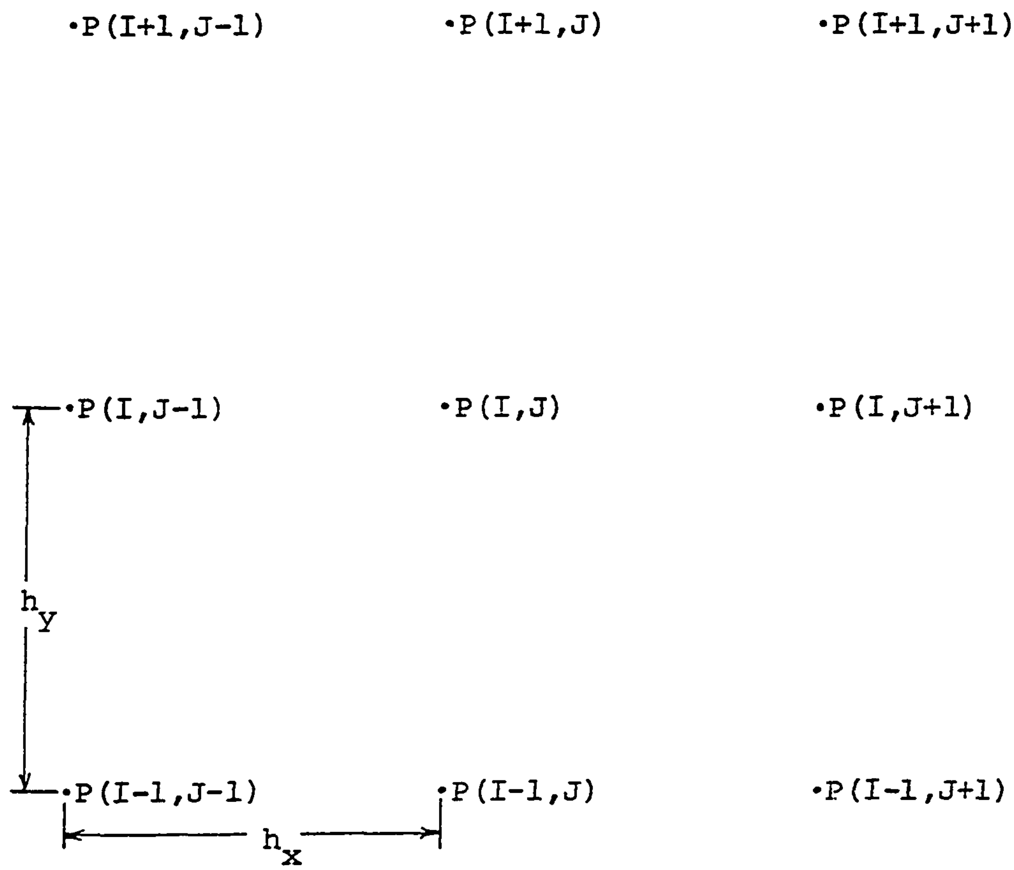


Figure 32. Grid layout on grain bin cross section

Quantities in Equation 42 may be then defined in finite difference form as follows:

$$\frac{\partial P}{\partial x} = \frac{P(I,J+1) - P(I,J-1)}{2h_x} \tag{43}$$

$$\frac{\partial P}{\partial y} = \frac{P(I+1,J) - P(I-1,J)}{2h_y} \tag{44}$$

$$\frac{\partial^2 P}{\partial x^2} = \frac{P(I,J+1) + P(I,J-1) - 2P(I,J)}{(h_x)^2} \tag{45}$$

$$\frac{\partial^2 P}{\partial y^2} = \frac{P(I+1,J) + P(I-1,J) - 2P(I,J)}{(h_y)^2} \tag{46}$$

Then, Equation 42 may be expressed in finite difference form as

$$0 = B\left(\frac{P(I+1,J)-P(I-1,J)}{2h_y}\;\frac{P(I+1,J)+P(I-1,J)-2P(I,J)}{(h_y)^2} + \right.$$

$$\left.\frac{P(I,J+1)-P(I,J-1)}{2h_x}\;\frac{P(I,J+1)+P(I,J-1)-2P(I,J)}{(h_x)^2}\right) +$$

$$\left(\frac{1}{2}\right)(GRAD)^{-\frac{1}{2}}(FAC1)^{-\frac{1}{2}}\left[\frac{P(I+1,J)+P(I-1,J)-2P(I,J)}{(h_y)^2}\right.$$

$$\left(2B^2 - 8AC + 4A\left[\left(\frac{P(I+1,J)-P(I-1,J)}{2h_y}\right)^2(GRAD)^{-\frac{1}{2}}\right.\right.$$

$$\left.\left. + 2(GRAD)^{\frac{1}{2}}\right] - (FAC1)\left(\frac{P(I+1,J)-P(I-1,J)}{2h_y}\right)^2\right) +$$

$$\frac{P(I,J+1)+P(I,J-1)-2P(I,J)}{(h_x)^2}\left(2B^2 - 8AC + 4A\right.$$

$$\left[\left(\frac{P(I,J+1)-P(I,J-1)}{2h_x}\right)^2 (GRAD)^{-\frac{1}{2}} + 2(GRAD)^{\frac{1}{2}}\right]$$

$$\left.\left. - (FAC1)\left(\frac{P(I,J+1)-P(I,J-1)}{2h_x}\right)^2\right)\right] \tag{47}$$

where

$$GRAD = \left[\frac{P(I,J+1)-P(I,J-1)}{2h_x}\right]^2 + \left[\frac{P(I+1,J)-P(I-1,J)}{2h_y}\right]^2$$

and

$$FAC1 = B^2 - 4AC + 4A(GRAD)^{\frac{1}{2}}$$

Equation 47 is seen to include the term P(I,J) four times. Solving this equation for P(I,J) results in an equation expressing the pressure at point I, J in terms of the pressure at eight surrounding points, and the grain characteristic coefficients A, B, and C.

Because of the complexity of the equation, P(I, J) cannot be readily solved for directly. Instead of direct solution, the Scientific Subroutines subprogram RTMI was used to solve for P(I, J). Using this subprogram on the ISU IBM 360 computer permitted Equation 47 to be written as shown and solved for P(I, J) by an iterative procedure when values for all other terms were specified.

A Fortran program was written which considered each point on the grid in turn and iterated toward a final pressure distribution. The details of the programming procedure will be considered in a later section. The iterative solution procedure for P(I, J) proved to be unstable and gave, under some conditions, erroneous values for P(I, J). The instability problem was not solved and the approach was ultimately abandoned. Brooker (1961), Bunn (1960), Brooker (1969) and Jindal and Thompson (1972) all used the method described, but with different equation forms relating U and $\partial P/\partial N$. In each case they obtained a finite difference equation which was much simpler than Equation 47 and which could be solved directly for P(I, J).

Amos method Brooker (1969) described a slightly different analytical approach which he called the "Amos Method". This method avoids the complex finite difference equation encountered previously. In his study, Brooker (1969) abandoned the Amos Methods because it required more computation time per iteration and converged toward a constant pressure distribution more slowly. Part of his problem was the fact that the equation he used to relate U and $\partial P/\partial N$ could not be solved directly for U, and thus necessitated the use of an iterative procedure for solution. As may be seen in Equation 36, the relationship used in this study is readily solvable for U. The Amos Method showed promise for use in this study, and a second analysis procedure was undertaken using it.

The Amos Method utilizes a modified grid layout which is shown in Figure 33. Points a, b, c and d are midway between P(I, J) and P(I, J + 1), P(I + 1, J), P(I, J - 1), and P(I - 1, J), respectively.

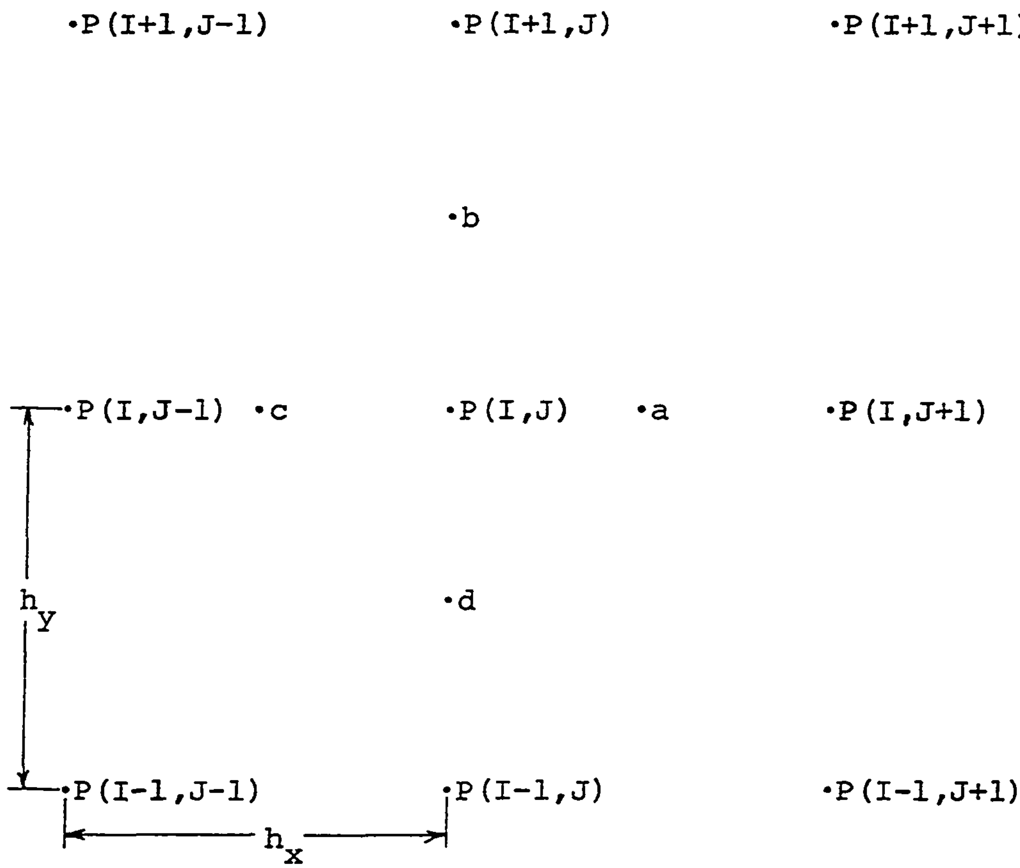


Figure 33. Grid layout on grain bin cross section for Amos Method

At point a, f_a is defined as

$$f_a = \frac{U}{\frac{\partial P}{\partial N}} \qquad (48)$$

and the finite difference pressure gradients as

$$\frac{\partial P}{\partial x} = \frac{P(I,J+1)-P(I,J)}{h_x} \qquad (49)$$

$$\frac{\partial P}{\partial y} = \frac{1}{2}\left(\frac{P(I+1,J+1)-P(I-1,J+1)+P(I+1,J)-P(I-1,J)}{2h_y}\right) \quad (50)$$

and at point c, f_c is defined as

$$f_c = \frac{U}{\frac{\partial P}{\partial N}} \quad (51)$$

and the finite difference pressure gradients as

$$\frac{\partial P}{\partial x} = \frac{P(I,J)-P(I,J-1)}{h_x} \quad (52)$$

$$\frac{\partial P}{\partial y} = \frac{1}{2}\left(\frac{P(I+1,J)-P(I-1,J)+P(I+1,J-1)-P(I-1,J-1)}{2h_y}\right) \quad (53)$$

At each point $\partial P/\partial N$ can be computed using Equation 37. Substituting into Equation 38, and then converting to a finite difference form, these relationships are obtained:

at a $$u = f_a \frac{\partial P}{\partial x} = f_a\left(\frac{P(I,J+1)-P(I,J)}{h_x}\right) \quad (54)$$

at c $$u = f_c \frac{\partial P}{\partial x} = f_c\left(\frac{P(I,J)-P(I,J-1)}{h_x}\right) \quad (55)$$

Now a finite difference relationship for $\partial u/\partial x$ at P(I, J) can be written:

$$\frac{\partial u}{\partial x} = \frac{f_a(P(I,J+1)-P(I,J))-f_c(P(I,J)-P(I,J-1))}{h_x^{\,2}} \tag{56}$$

In like manner, considering points b and d, a finite difference relationship can be written for $\partial v/\partial y$ at P(I, J):

$$\frac{\partial v}{\partial y} = \frac{f_b(P(I+1,J)-P(I,J))-f_d(P(I,J)-P(I-1,J))}{h_y^{\,2}} \tag{57}$$

Substituting into Equation 34 and solving for P(I, J), this relationship is obtained:

$$P(I,J) = \frac{f_a P(I,J+1)+f_b P(I+1,J)+f_c P(I,J-1)+f_d P(I-1,J)}{f_a + f_b + f_c + f_d} \tag{58}$$

This equation permits determination of P(I, J) in terms of the pressures at eight surrounding points, and the grain characteristic coefficients A, B, and C.

<u>Computer program</u> A grid was set up over the 24 in. wide by 26 in. deep bin cross section and a Fortran language computer program was written which directed the computer to consider each grid point in turn and compute a "better" pressure for that point. The ISU IBM 360 computer was used for this purpose. The computer swept over the bin cross section again and again iterating toward a constant pressure distribution. When pressure at no grid point changed more than a preset amount from the previous sweep, the iteration process was stopped.

The grid spacing used was $h_x = 1$ in. and $h_y = 1$ in. This is a compromise between the added computer time required for a smaller spacing and the reduced precision of a larger spacing. Brooker (1961) used a 4 in. by 4 in. grid spacing over a bin cross section 4 ft wide by 8 ft high. Bunn (1961) used a 1½ in. by 1½ in. grid spacing over his 2 ft. square cross section. Brooker (1969) used a 1 in. by 1 in. grid spacing in the region of the air entry point, and a 4 in. by 4 in. grid spacing over the remainder of the bin cross section. In this study, by Brooker, the bin cross section was 2 ft wide by 8 ft high. Jindal and Thompson (1972) did not specify the grid spacing used over their triangular grain pile cross section.

The computer program used in this study was written so that the horizontal and vertical grid spacing could be varied independently. Different combinations of horizontal and vertical grid spacings were tried in an effort to speed the convergence toward a constant pressure distribution. None of the combinations tried significantly altered the speed of convergence, and the 1 in. by 1 in. spacing was retained.

The bin walls were considered to be airtight boundaries. Mirror images were used to obtain a complete set of grid points when the point under consideration was located on a side boundary.

Pressures at the top and bottom boundaries were set initially, and remained constant. Airflow tests in Experiment

II and Experiment III were run with zero pressure at the bottom boundary, and a negative pressure at the top boundary. For computer simulation of these tests, a zero pressure was set at the top boundary, and a positive pressure set at the bottom boundary. The initial pressure distribution from which iteration began was a linear distribution across the bin cross section from bottom to top. Successive computer runs used the final distribution of the previous run as a starting point. This reduced the number of sweeps necessary to obtain a final pressure distribution. Trial runs verified that the final pressure distribution was independent of the distribution used as a starting point.

In order to simulate the effect of the stirring auger, the computer was programmed to decide if each midway point for each selected grid point was inside or outside of the cross sectional area of grain disturbed by the stirring auger. The disturbed cross sectional area was defined by the appropriate boundary equations from Figure 19. If the midway point under consideration was found to be outside the disturbed region, grain characteristic coefficients A, B, and C corresponding to the bulk density of the non-disturbed grain was used in computing the "better" pressure. If the midway point under consideration was found to be within the disturbed region, a different set of grain characteristic coefficients were used corresponding to the different bulk density.

The iteration procedure was stopped when no pressure on the grid had changed more than 0.0001 in. water from the previous sweep. This corresponds to the cut-off point used by Brooker (1969). Bunn (1960) continued iteration "until the values for two consecutive approximations were equal." He does not state to what accuracy they were equal. Brooker (1961) and Jindal and Thompson (1972) did not specify their cutoff points.

When the final pressure distribution had been computed and printed by the computer, the velocity distribution and the average flow rate of air leaving the grain were determined. The magnitude of the velocity at each midway point on the Amos grid pattern (Figure 33) was computed as part of the pressure iteration procedure, using Equation 36. It was convenient to print the velocity magnitude at each midway point b, which was midway between the grid point being considered and the grid point above. For the row of grid points 1 in. above the bin floor, the magnitude of the velocity at midway points b and d were printed. Midpoint d being the point half way between the grid point being considered and the grid point below.

To compute the average flow rate, the values for v were computed at each b midway point over the entire cross section. Making use of the relationships expressed in Equations 37, 38, and 39, the angle between the velocity vector and the vertical axis was computed at each point using the relationship

$$ANG = \text{Arctan}\left(\frac{\partial P/\partial x}{\partial P/\partial y}\right) \qquad (59)$$

Then v at each b midway point was computed using the equation

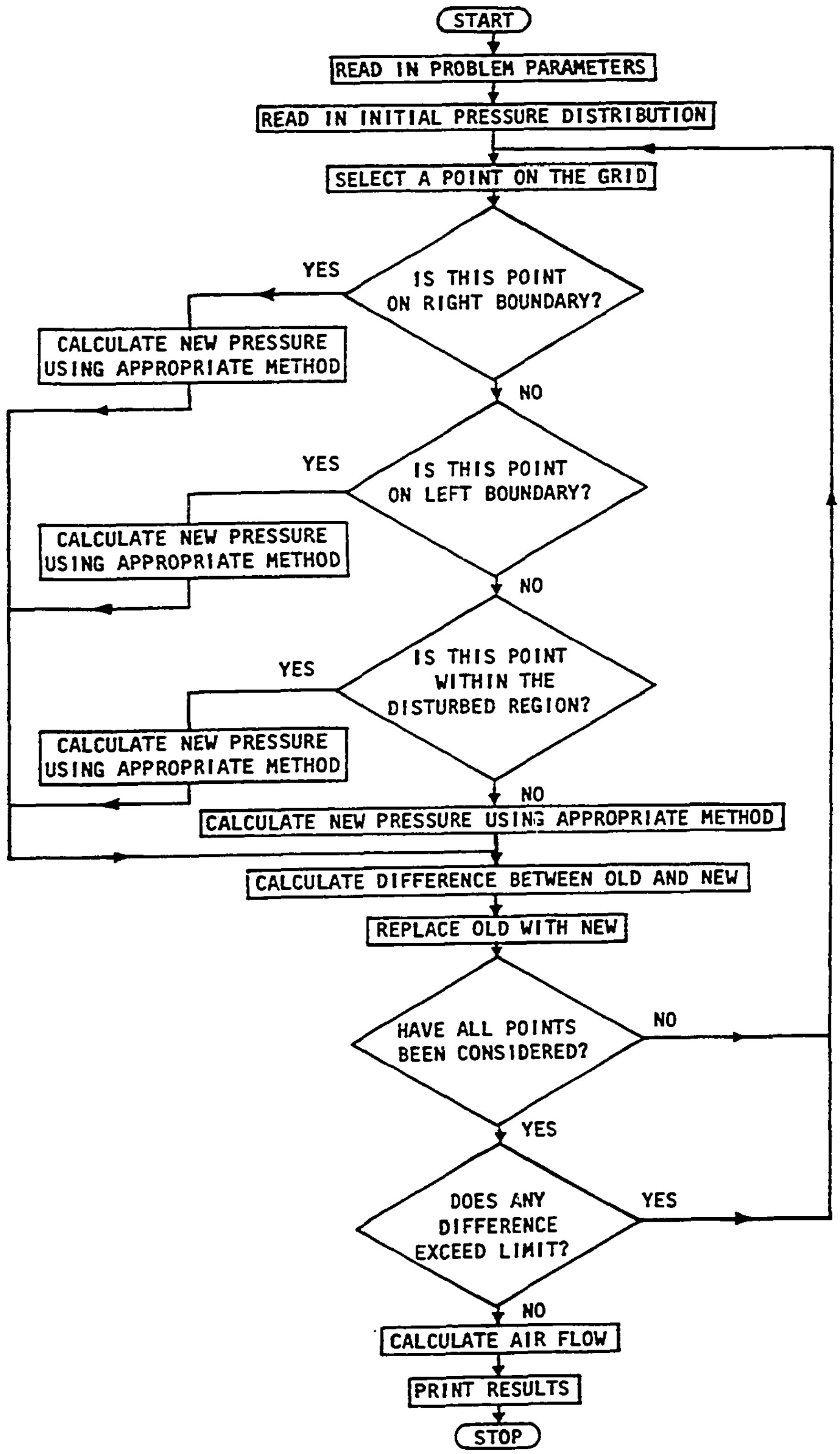
$$v = U\cos(ANG) \qquad (60)$$

The vertical velocities were integrated across the bin cross section at a particular level. Then this value was divided by the bin width to give the average flow rate at that level in cfm/ft^2. The mean of these flow rates at one-in. levels from top to bottom of the bin cross section was used as the average flow rate through the bin cross section. This mean was taken as the average flow rate through the bin cross section because the computed average flow rate at different levels in the bin were not exactly equal.

A flow chart of the complete computer program is shown in Figure 34. The program was written and brought to an operational state using Fortran Watfiv. Actual simulation runs were made using a Fortran H object deck. Using Fortran H, the program required a total storage of 56,136 bytes. Approximately 170 sweeps were required to reach the cut-off point beginning with a linear pressure distribution. A central processing unit time of approximately 1.6 seconds was required for each sweep.

To check the accuracy of the computer program at predicting pressures, a test was conducted to predict pressures

Figure 34. Flow chart of computer program for computation of pressure and velocity distributions within a mass of auger-stirred corn


START
READ IN PROBLEM PARAMETERS
READ IN INITIAL PRESSURE DISTRIBUTION
SELECT A POINT ON THE GRID
IS THIS POINT ON RIGHT BOUNDARY?
YES
CALCULATE NEW PRESSURE USING APPROPRIATE METHOD
NO
IS THIS POINT ON LEFT BOUNDARY?
YES
CALCULATE NEW PRESSURE USING APPROPRIATE METHOD
NO
IS THIS POINT WITHIN THE DISTURBED REGION?
YES
CALCULATE NEW PRESSURE USING APPROPRIATE METHOD
NO
CALCULATE NEW PRESSURE USING APPROPRIATE METHOD
CALCULATE DIFFERENCE BETWEEN OLD AND NEW
REPLACE OLD WITH NEW
HAVE ALL POINTS BEEN CONSIDERED?
NO
YES
DOES ANY DIFFERENCE EXCEED LIMIT?
YES
NO
CALCULATE AIR FLOW
PRINT RESULTS
STOP

within a bed of steel shot. Bunn (1960) presented measurements and predictions of the pressures in this bed. Pressure predictions using the computer method developed in this present study agreed very closely with predictions and measurements by Bunn (1960). Details of the test are presented in Appendix D.

Computer simulations

Computer simulations of eight Experiment III tests were carried out. Two tests were selected at random from the three replications at each of the four auger speeds.

For each simulation, it was necessary to specify the pressure at the upper and lower boundaries, the equations of the left and right boundaries of the cross sectional area disturbed by the stirring auger, and the grain characteristic factors A, B, and C for the disturbed corn and for the undisturbed corn. The depth and width of the grain bin cross section were held constant at 26 and 24 in., respectively. Simulations were carried out for an average airflow rate of 35.0 cfm/ft^2. This flow rate is within the range of flow rates commonly employed in drying systems using stirring augers.

The pressure specified at the lower boundaries was calculated by solving for ΔP the empirical equation relating $\Delta P/L$ and U for the test being simulated. Values for L and U were specified as 2.167 ft (26 in.) and 35 cfm/ft^2, respectively. A pressure of zero was specified at the upper boundary.

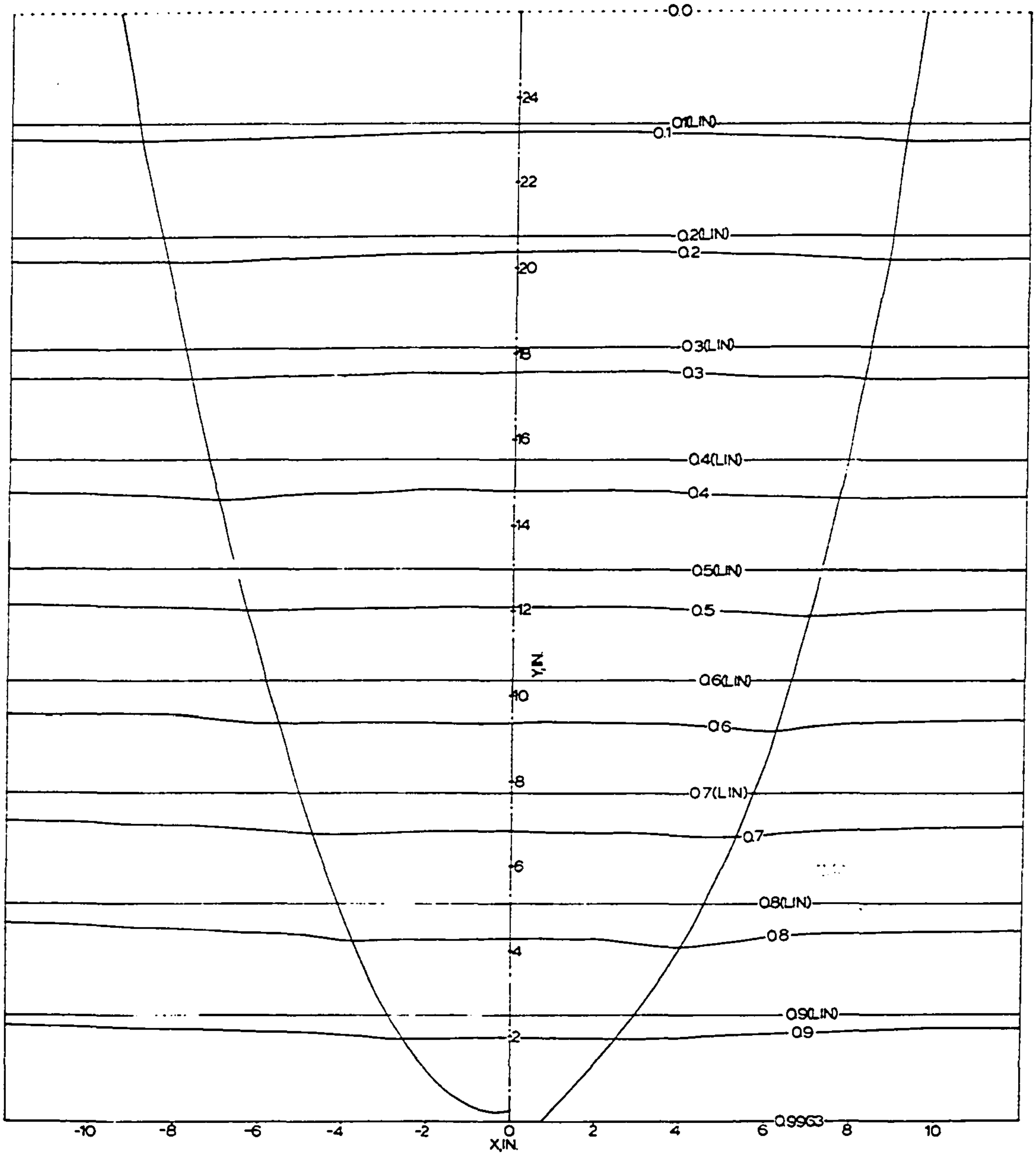
The equations used to specify the left and right boundaries of the cross sectional area disturbed by the stirring auger were the equations determined for each auger speed in Experiment I. These are shown in Figures 20, 21, 22, and 23.

Grain characteristics factors A, B, and C were computed as functions of bulk density using Equations 30, 31, and 32. For the undisturbed corn, the bulk density was assumed to be equal to that of the grain in the bin before stirring. This is the bulk density specified for the Experiment II test preceeding the test being simulated. The bulk density of the disturbed grain was initially assumed to be approximately 7 percent less than that of the undisturbed grain. This bulk density was adjusted on succeeding computer runs to give an average flow rate of 35.0 cfm/ft^2.

Numerical analysis results

Computer simulations were carried out for Experiment II Tests R-4, R-6, R-10, R-12, R-16, R-18, R-22, and R-24. The final pressure and velocity distributions for these simulations are shown in Appendix F. One of the two simulations carried out at each auger speed was selected at random and figures were prepared showing lines of constant pressure and lines of constant air velocity magnitude over the bin cross section.

Figures 35, 36, 37, and 38 show lines of constant pressure at 0.1 in. of water intervals over the bin cross section after



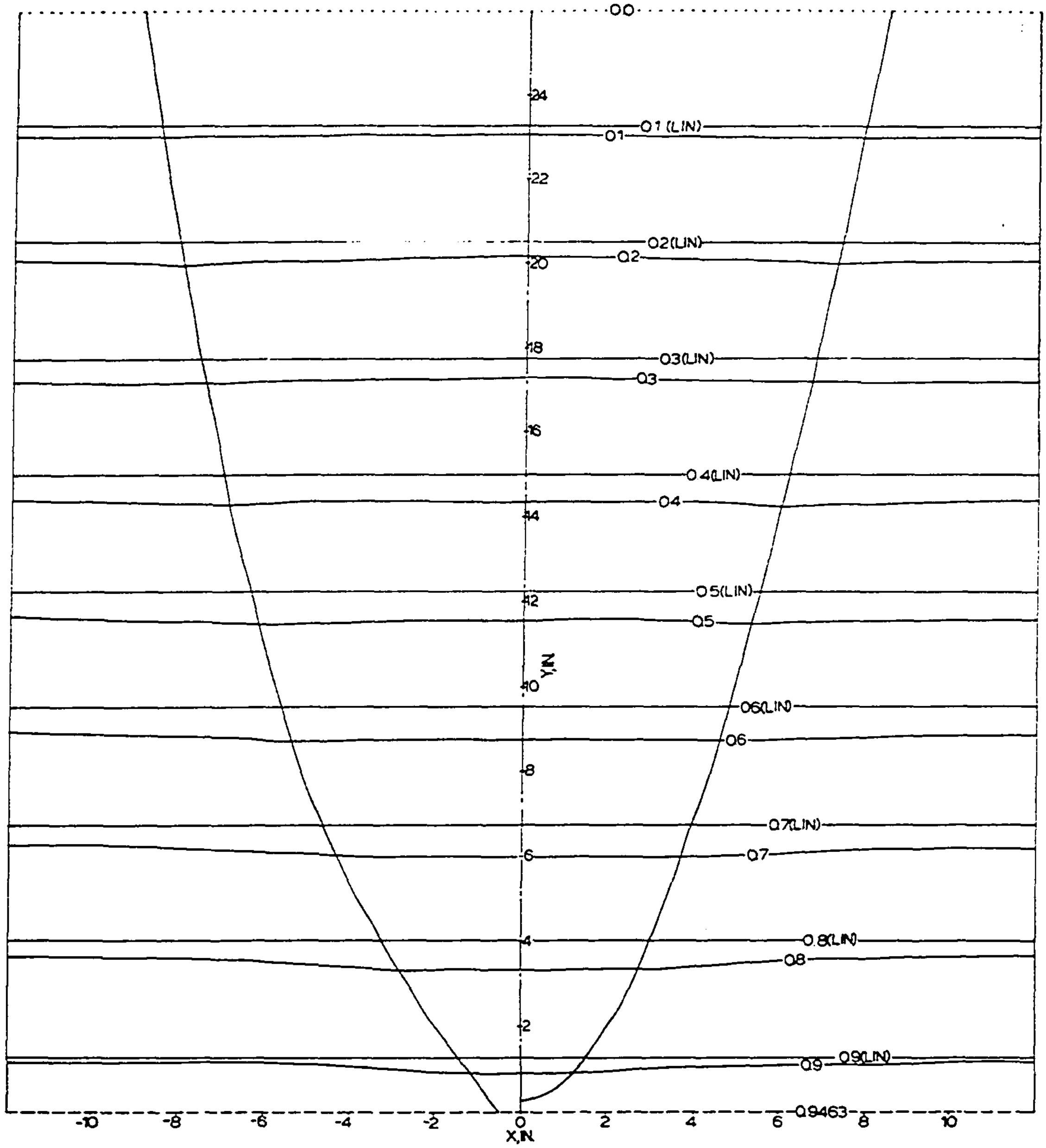
PRESSURES IN IN. OF WATER

AUGER SPEED: 4.35 IN./MINUTE

AVERAGE FLOW RATE: 35.0 CFM/FT^2

BULK DENSITY: 45.61 LB/FT^3 (DISTURBED), 49.49 LB/FT^3 (UNDISTURBED)

Figure 35. Computed air pressure distribution over cross section of auger-stirred corn mass for Test R-12



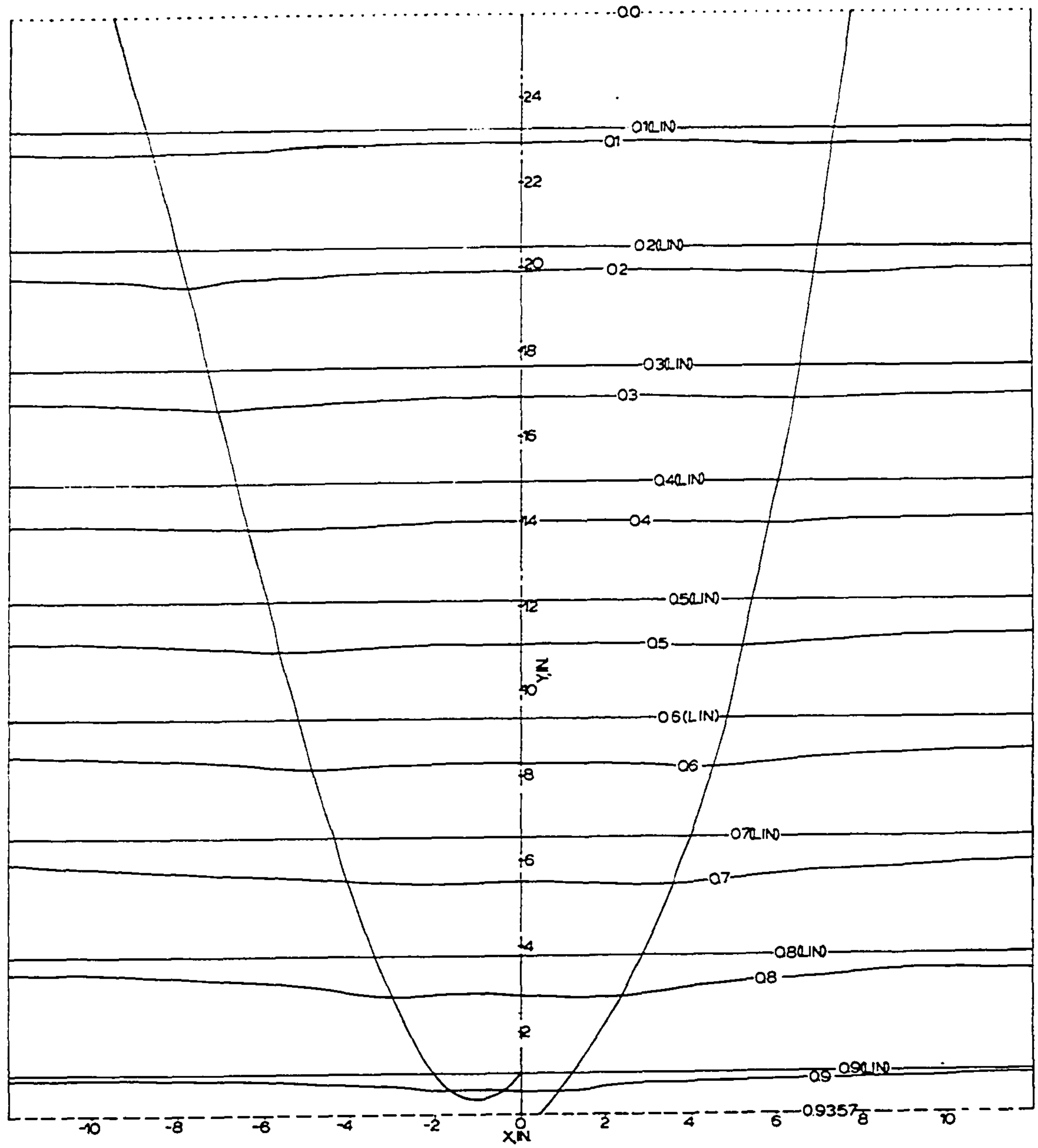
PRESSURES IN IN. OF WATER

AUGER SPEED: 8.71 IN./MINUTE

AVERAGE FLOW RATE: 35.0 CFM/FT^2

BULK DENSITY: 45.53 LB/FT^3 (DISTURBED), 49.17 LB/FT^3 (UNDISTURBED)

Figure 36. Computed air pressure distribution over cross section of auger-stirred corn mass for Test R-6



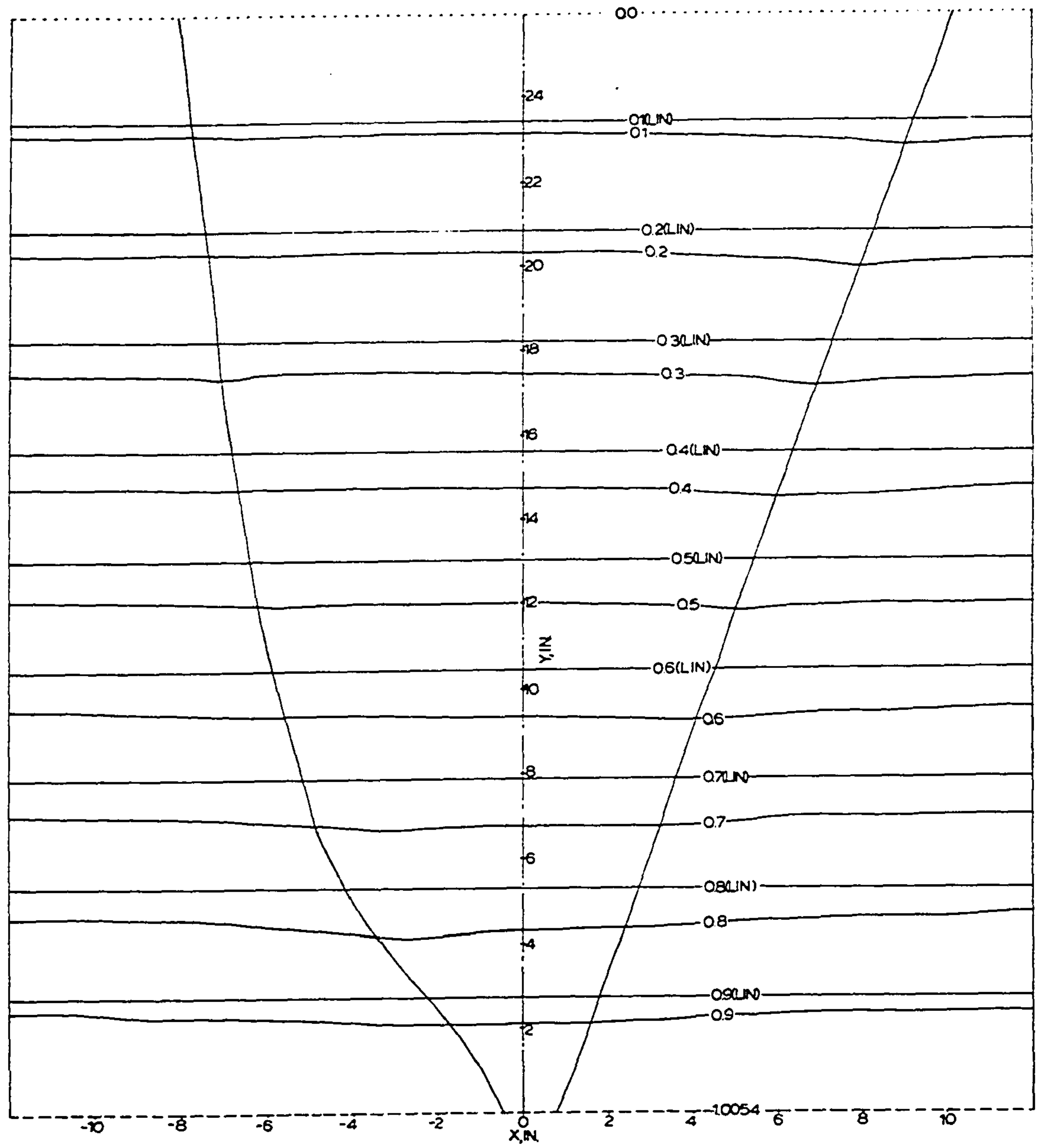
PRESSURES IN IN. OF WATER

AUGER SPEED: 12.26 IN./MINUTE

AVERAGE FLOW RATE: 35.0 CFM/FT^2

BULK DENSITY: 44.93 LB/FT^3 (DISTURBED), 49.34 LB/FT^3 (UNDISTURBED)

Figure 37. Computed air pressure distribution over cross section of auger-stirred corn mass for Test R-24



PRESSURES IN IN. OF WATER

AUGER SPEED: 24.30 IN./MINUTE

AVERAGE FLOW RATE: 35.0 CFM/FT^2

BULK DENSITY: 45.58 LB/FT^3 (DISTURBED), 48.86 LB/FT^3 (UNDISTURBED)

Figure 38. Computed air pressure distribution over cross section of auger-stirred corn mass for Test R-16

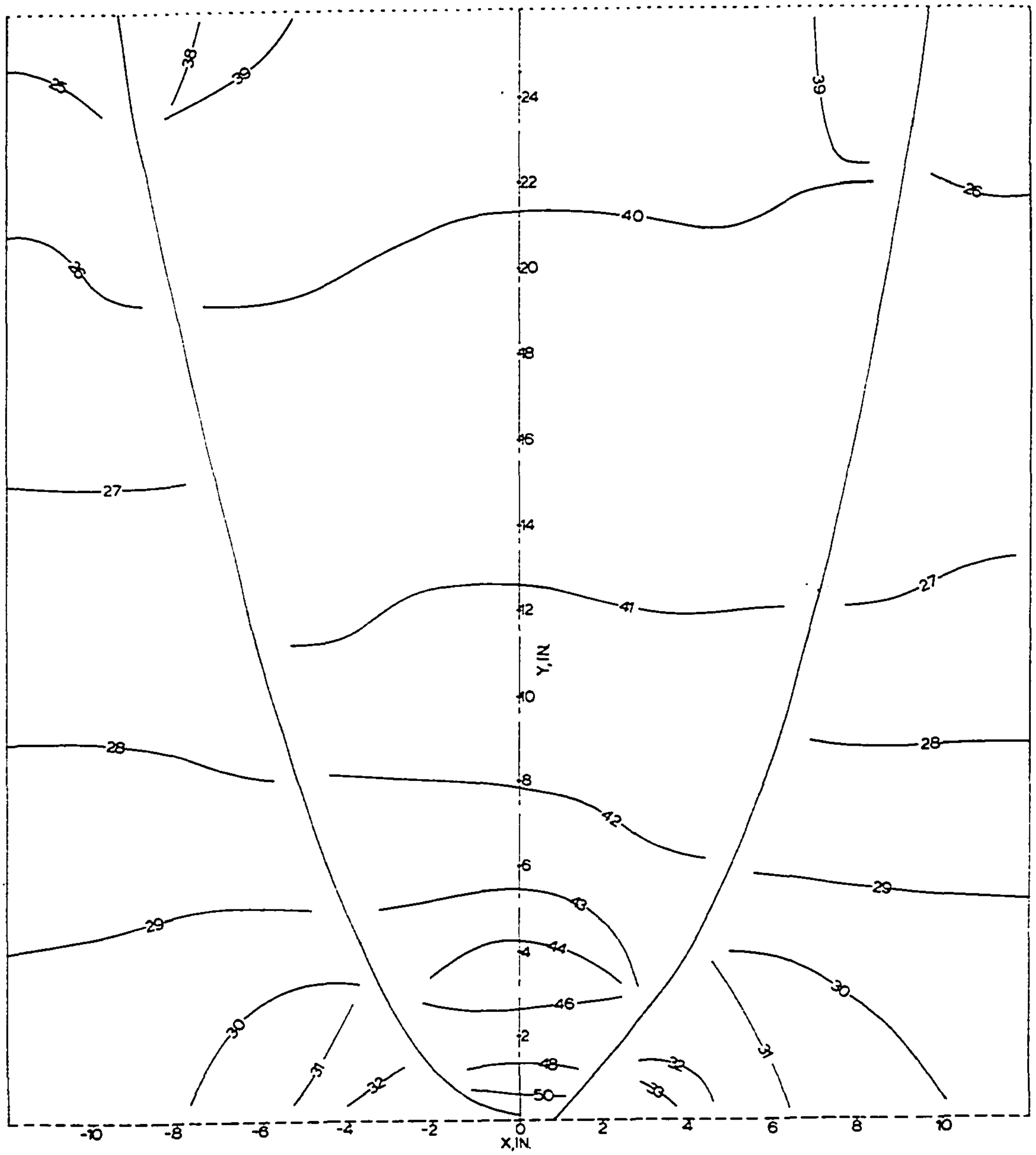
stirring at speeds of 4.35, 8.71, 12.26, and 24.30 in./minute, respectively. Also shown on the figures for comparison are lines of constant pressure at the same intervals assuming a linear decrease in pressure from bottom to top.

This linear distribution would exist if all of the grain had the same airflow resistance. At all auger speeds all pressures were lower than pressures which would have existed if distribution were linear from bottom to top.

At every auger speed, the pressures at the wall are in most cases higher than the pressures at the disturbed grain boundary for the same depth of corn in the bin. Higher wall pressures are more pronounced in the lower portion of the bin cross section. This gradient indicates that there is a flow of air across the boundary into the disturbed area.

A horizontal pressure gradient also exists within the disturbed area. In most cases, the pressures near the vertical center line are higher than the pressures at the boundaries of the disturbed area for the same grain depth. This gradient indicates that the air velocity has a horizontal component toward the nearest disturbed area boundary due to the widening of the low resistance channel from bottom to top.

Figures 39, 40, 41, and 42 show lines of constant air velocity magnitude over the bin cross section after stirring at speeds of 4.35, 8.71, 12.26, and 24.30 in./minute, respectively. In the nondisturbed areas, air velocity is seen



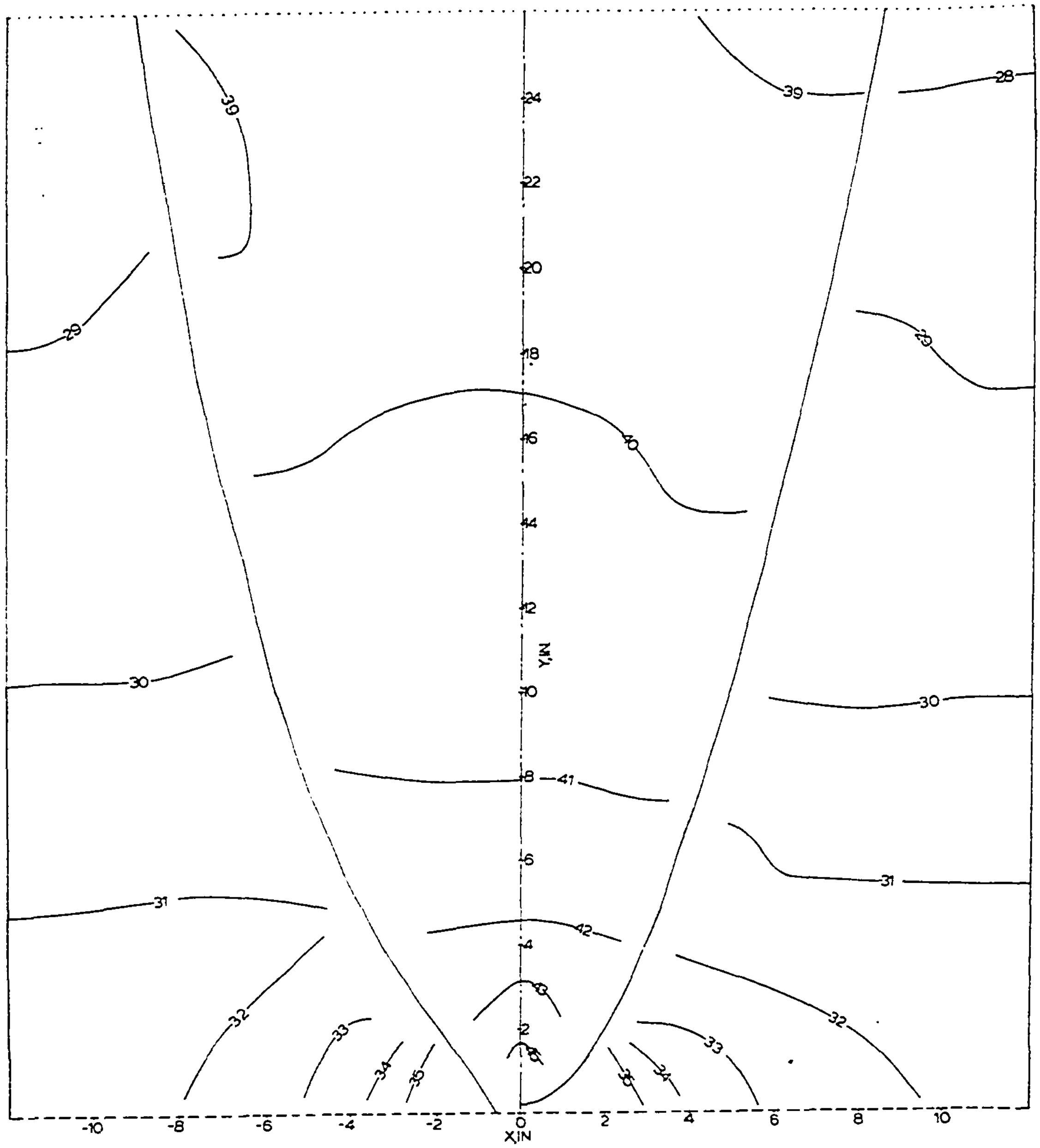
VELOCITIES IN FT/MINUTE

AUGER SPEED: 4.35 IN./MINUTE

AVERAGE FLOW RATE: 35.0 CFM/FT^2

BULK DENSITY: 45.61 LB/FT^3 (DISTURBED), 49.49 LB/FT^3 (UNDISTURBED)

Figure 39. Computed air velocity distribution over cross section of auger-stirred corn mass for Test R-12



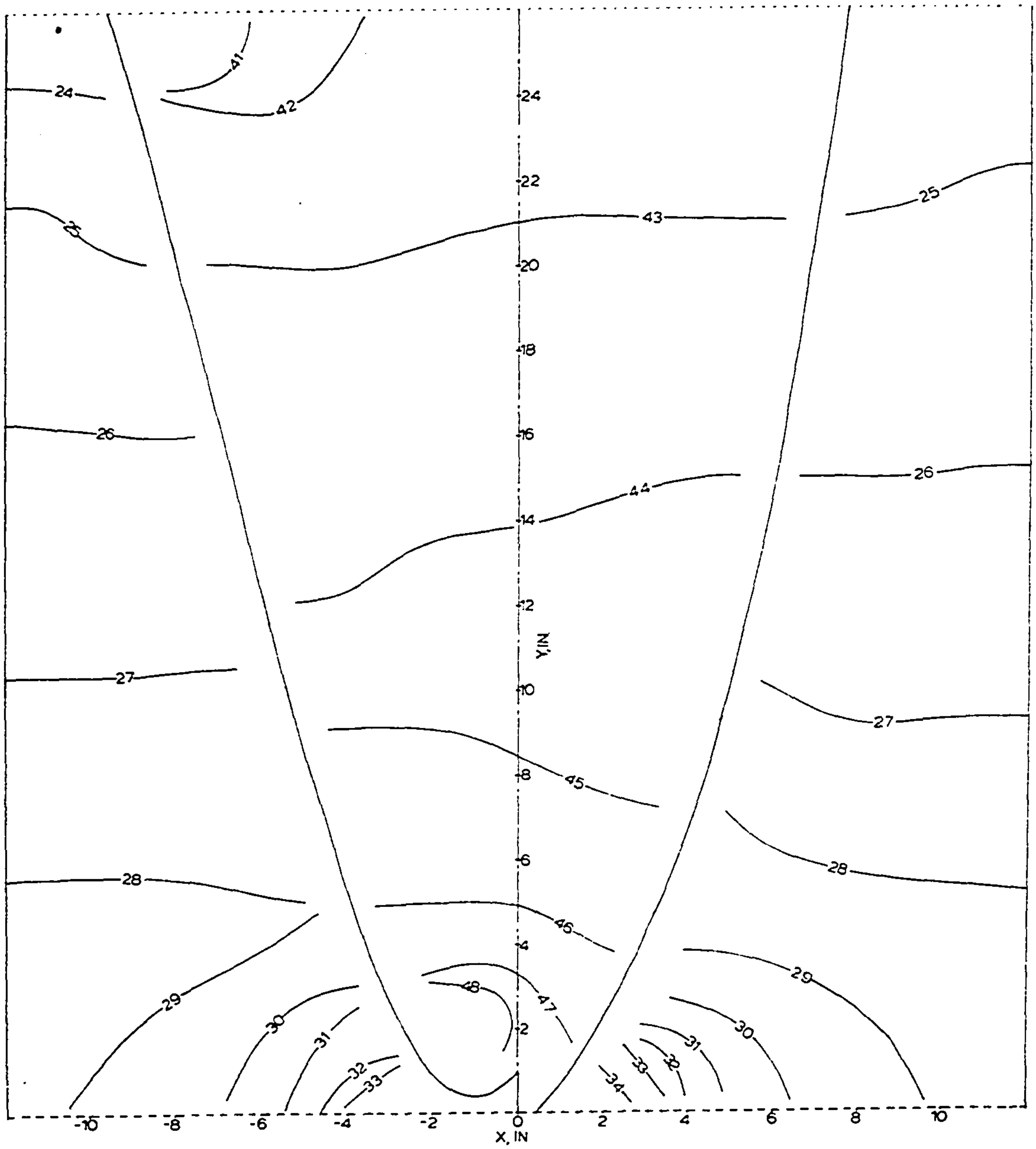
VELOCITIES IN FT/MINUTE

AUGER SPEED: 8.71 IN./MINUTE

AVERAGE FLOW RATE: 35.0 CFM/FT^2

BULK DENSITY: 45.53 LB/FT^3 (DISTURBED), 49.17 LB/FT^3 (UNDISTURBED)

Figure 40. Computed air velocity distribution over cross section of auger-stirred corn mass for Test R-6



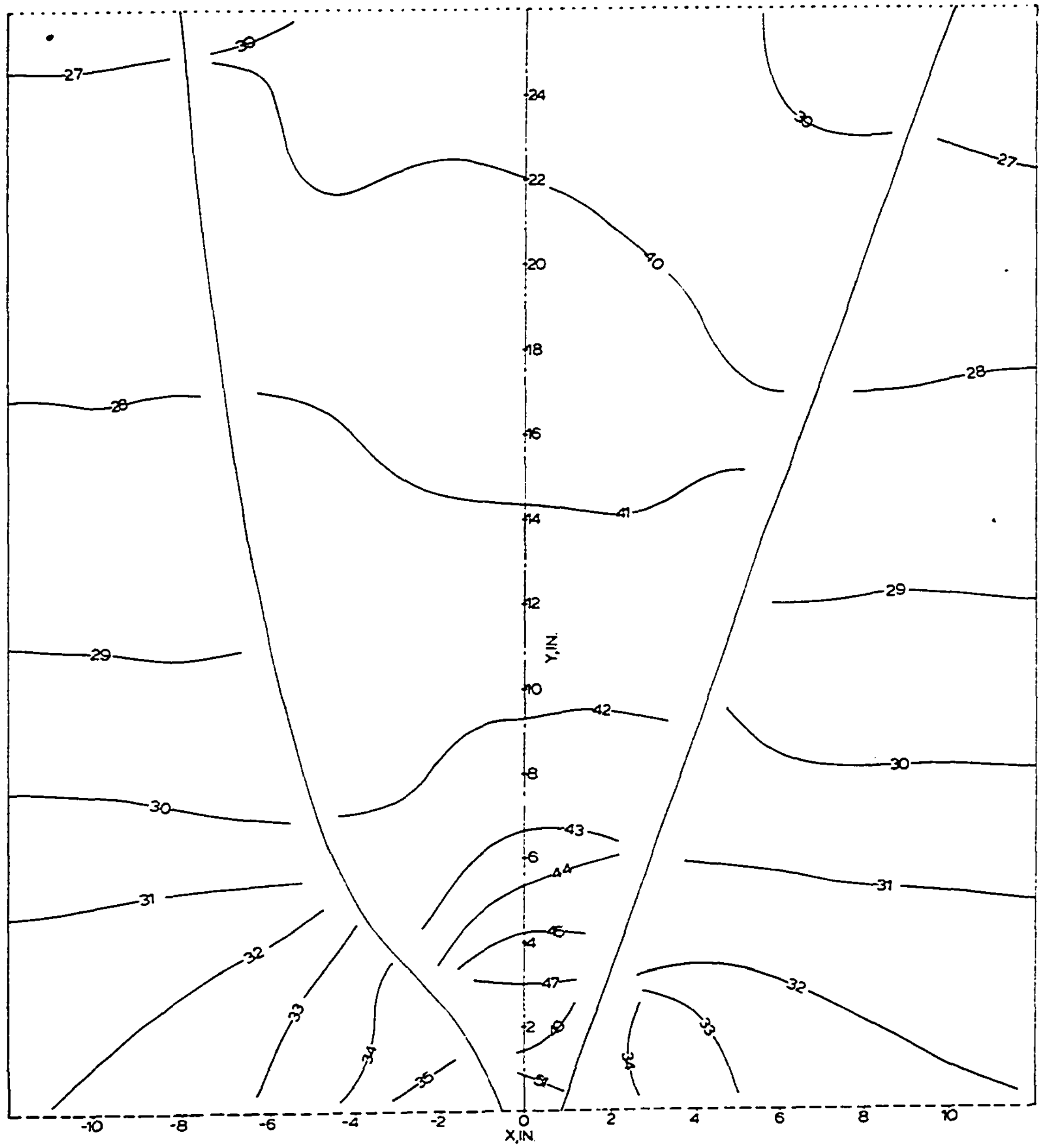
VELOCITIES IN FT/MINUTE

AUGER SPEED: 12.26 IN./MINUTE

AVERAGE FLOW RATE: 35.0 CFM/FT^2

BULK DENSITY: 44.93 LB/FT^3 (DISTURBED), 49.34 LB/FT^3 (UNDISTURBED)

Figure 41. Computed air velocity distribution over cross section of auger-stirred corn mass for Test R-24



VELOCITIES IN FT/MINUTE

AUGER SPEED: 24.30 IN./MINUTE

AVERAGE FLOW RATE: 35.0 CFM/FT^2

BULK DENSITY: 45.58 LB/FT^3 (DISTURBED), 48.86 LB/FT^3 (UNDISTURBED)

Figure 42. Computed air velocity distribution over cross section of auger-stirred corn mass for Test R-16

to decrease from bottom to top as more and more air crosses the boundary into the disturbed area. In the disturbed area, air velocity also decreases from bottom to top as the stream spreads to fill the widening low resistance channel. The highest velocities in every simulation occurred at the bottom of the disturbed area and the lowest at the top of the non-disturbed area.

Air Flow Resistance of Corn Disturbed by a Stirring Auger

The pressure drop through 11.3 percent moisture content, wet basis, corn can be calculated as a function of flow rate and bulk density using Equation 33. This equation was formulated using corn which was brought to its test bulk density by dropping from some height. An analysis was carried out to determine if this equation is applicable to corn which has been brought to its bulk density by the disturbing action of a stirring auger. In other words, the answer was sought for this question: Is the air flow resistance of corn which has been brought to its bulk density by being dropped the same as the air flow resistance of corn which has been brought to the same bulk density by being disturbed by a stirring auger?

For each of the eight tests simulated on the computer, the bulk density was computed for the disturbed grain. This computed bulk density was compared with the computer simulation bulk density, which was the value for bulk density of the disturbed grain that gave an average flow rate of 35.0 cfm/ft^2 when the test was simulated on the computer. These figures are shown in Table 9.

To compute the bulk density of the disturbed grain, the volume of the disturbed region was first computed by integrating the appropriate disturbed area shape equations to a depth equal to the grain depth before stirring and multiplying this area by the length of the grain bin used for the test. The grain depth before stirring is the grain depth recorded in the Appendix Table A-2 for the test previous to the test being considered. This volume was multiplied by the bulk density of the entire bin before stirring, which is the bulk density recorded for the previous test. The resulting product was the weight of the grain disturbed.

The final volume of the disturbed grain was computed by adding the previously computed volume to the volume change which occurred during stirring. This change is the difference between the volume recorded for the test being simulated and the volume recorded for the previous test. Bulk density was computed from the volume and the weight.

Table 9 shows that the simulation bulk density minus computed bulk density difference ranged from -0.34 to +0.55 lb/ft^3 and averaged -0.16 lb/ft^3.

A t-test was run to test the null hypothesis that the mean difference in bulk density is not different from zero.

Table 9. Computed and simulation bulk densities of corn disturbed by a stirring auger

Test number	Auger speed, in./minute	Computed final bulk density lb/ft^3	Simulation bulk density lb/ft^3	Difference simulation-computed lb/ft^3
R-10	4.35	45.33	45.53	0.20
R-12	4.35	45.50	45.61	0.11
R-4	8.71	45.14	45.03	-0.11
R-6	8.71	44.98	45.53	0.55
R-22	12.26	45.31	45.02	-0.29
R-24	12.26	45.27	44.93	-0.34
R-18	24.30	45.63	45.42	-0.21
R-16	24.30	45.65	45.58	-0.07
			Mean difference =	-0.16

$$t = \frac{|\text{mean difference} - 0|}{\sqrt{\frac{s^2}{n}}} = 1.365$$

$t_{0.05} = 2.365$ (two tailed for 7 degrees of freedom)

For this test, t = 1.365 and $t_{0.05}$ = 2.365 for a two-tailed test and 7 degrees of freedom. Thus the null hypothesis is accepted.

Because the mean difference in bulk density was found not significantly different from zero, this experiment has not shown the air flow resistance of corn which has been brought to its bulk density by being dropped to be different from the air flow resistance of corn which has been brought to the same bulk density with a stirring auger.

DISCUSSION

Shape of Disturbed Volume Cross Section

The equations describing the shape of the disturbed volume cross section for different auger speeds (Figures 19-23) were determined for a corn depth of approximately 26 in. These equations are probably not applicable for greater grain depths. The cubic equations used to describe the shape will in many cases exhibit a maximum for a y-coordinate value not too much greater than 26 in.

The disturbed area on the left in Figures 19-23 was found larger than the area on the right in four out of five cases. A possible explanation for this is the difference in relative speeds between the outer edge of the flighting and the corn on opposite sides of the auger. As the right-hand auger advances, the maximum flighting-to-corn speed is greater on the left side of the advancing auger (which corresponds to the right side of Figures 19-23) by an amount approximately twice the speed of advance. For a 2-in. diameter auger turning at 480 rpm, the peripheral speed is 3015.9 in./minute. At a speed of 24.30 in./minute, the faster auger speed used, relative speeds on the left and right sides are 3040.2 and 2991.6 in./minute, respectively. These two speeds differ by 1.6 percent of the greater speed. It is possible that more than half of the corn lifted by the auger may be loaded on the side with the lower flight-to-corn speed.

The area on the left was also greater at zero linear auger speed. With no auger movement, the flight-to-corn speeds were the same on all sides, which suggests that the previous explanation is not plausible. No explanation for this occurrence is known.

Bulk Density Effects

The assumption was made that the cross sections of the disturbed volumes were the same over the entire bin length traversed by the stirring auger. The procedure followed during the experiment consisted of lowering the stirring auger into the grain along the end wall of the bin. Rotational and horizontal movement was begun with the auger lowered and in contact with the end wall. The auger probably moved through the grain for some distance before the cross section of the disturbed volume became constant. There is also the possibility that this cross section changed as the stirring auger approached the opposite wall.

These two effects probably make the volume computed by multiplying the disturbed volume cross section at the center of the bin by the bin length larger than the actual disturbed volume. This difference would affect the results shown in Figures 25, 26, 27, and 28. The magnitude of any error introduced as a result of this volume estimation was thought to be small.

From consideration of Figures 25 and 28, a recommendation can be made concerning stirring auger operation. Figure 25 and the associated statistical analysis show that the bulk density change in the disturbed corn is not dependent on the rate at which the auger moves through the grain. Figure 28 shows that the volume rate of grain disturbance increases with increasing auger speed. Thus, in order to achieve the maximum disturbance effect per unit time on a mass of grain, the auger should be moved through as rapidly as possible. This, of course, does not take into consideration other factors which may be important such as power requirement and equipment stresses.

Corn Kernel Orientation

The kernel orientation investigation conducted as a part of Test S-12 of Experiment I failed to show a difference in kernel orientation between the disturbed and non-disturbed portions of the bin cross section. In this investigation, there is a possibility that the disturbance of inserting the plastic sheet destroyed existing differences in kernel orientation. The majority of the kernels observed were in contact with the plastic sheet and could possibly have been reoriented during insertion.

Air Flow Resistance of Corn

A second degree polynomial was used to relate pressure drop to flow rate (Equation 29). In order to obtain the best possible fit, the fitted equation was not forced through the origin. The resulting equations, if extrapolated to zero air flow, indicate a negative pressure drop exists. Indication of a negative pressure drop cannot be descriptive of the physical situation. This fact is not considered to be a disadvantage of the equation when used above the minimum air flow rate specified (5 cfm/ft^2).

A limitation of the second degree polynomial equation form is that the accuracy of pressure drop predictions are likely to be poor at the low flow rates if, in the data fitted, the highest air flow rate is greater than approximately 10 times the lowest rate. For example, second degree polynomial will not provide an accurate fit over the entire range of Shedd's curves. This is probably the reason this equation form has not been used by researchers seeking a fit over a wide range of air flow rates.

For comparison, a second degree polynomial was fitted to the data of Shedd's curve for 12.4 percent moisture content, wet basis, corn using an Omnitab program on the ISU IBM 360 computer. Only data points for flow rates within the range of flow rates used in this study were fitted. Flow rates fitted ranged from 6.6 to 60 cfm/ft^2. The equation computed was:

$$\frac{\Delta P}{L} = 0.0002554U^2 + 0.001454U + 0.03330 \qquad (61)$$

Shedd (1953) wrote that the corn used for testing was free of cracked grain and foreign material, and had a bulk density of 45.6 lb/ft^3.

The grain characteristic coefficients A, B, and C in Equation 61 vary considerably from coefficients computed solving Equations 30, 31, and 32 using a bulk density of 45.6 lb/ft^3. Computed values for A, B, and C are 0.000137, 0.00545, and -0.0145, respectively. Even though computed values of A, B, and C vary considerably from values in Equation 61, the pressure drop predictions at a particular flow rate will be quite close because the variations in A and C tend to cancel the effect of the variation in B.

Equation 33 fits the data of Shedd for dry corn for the range of flows from 6.6 to 60 cfm/ft^2 very closely when a bulk density of 46.6 lb/ft^3 is assumed.

In computing the least square lines for Figures 29, 30, and 31, the data for corn which had been placed by filling at zero drop height were not used because of their deviations from the least squares line. The deviations indicate that the air flow resistance of corn placed by filling at zero drop height is considerably higher than the air flow resistance of corn at the same bulk density which was placed by dropping. A possible explanation for this deviation is that filling at zero drop height produces a kernel orientation which gives the corn a higher resistance. As was noted in the Review of Literature, Shedd's curves were determined using grain which was placed in the grain column by a procedure similar to the fill at zero drop height procedure used in this study.

Equation 33, the derived pressure drop prediction equation for 11.3 percent moisture content wet basis corn, was determined for airflows in the range of approximately 5 to 120 cfm/ft^2 and for bulk densities in the range of approximately 45.7 to 49.6 lb/ft^3. The accuracy of this equation will probably be maintained for higher and lower bulk densities and for higher airflow. Judging from the previously reviewed results for Muchiri (1969) and Patterson et al. (1971), the prediction accuracy also should be maintained for higher and lower moisture contents.

The availability of equations of this form, along with information on bulk densities normally obtained for various filling methods, could be an improvement over Shedd's curves as a means of predicting pressure drop through various grains. Improved accuracy would result because bulk density would be more completely accounted for. Two equations would be required for each kind of grain in order to cover the range of airflow rates normally encountered in grain conditioning.

Pressure and Velocity Distribution Within Stirred Grain Mass

The grid spacing used for the computer simulation tests done in this study $h_x = 1$ in. and $h_y = 1$ in. Earlier tests were conducted using a grid spacing of $h_x = 2$ in. and $h_y = 2$ in. This larger spacing involved one-fourth as many points, and much less computer time per sweep. However, distortions in the pattern of constant velocity lines were evident. Lines of constant velocity tended to converge toward points on the disturbed grain boundary where this boundary had passed very close to a grid point. The distortions were evident at distances up to 6 in. from this grid point.

Changing to a grid spacing of $h_x = 1$ in. and $h_y = 1$ in. greatly reduced this distortion. It is, however, still evident in certain locations. Notice, for example, the region around the right disturbed region boundary in Figure 39 at a grain depth of 4 in.

This distortion had little effect on the computed average airflow rate. It was found to decrease approximately 1 cfm/ft^2 when grid spacing was reduced from 2- to 1 in. and all other parameters were held constant.

The mean of the average flow rates at 1-in. levels from top to bottom of the grain bin cross section was taken to be the average flow rate through the grain bin cross section. This mean was used, rather than the average flow rate at one particular level because the flow rates varied slightly from one level to another.

The range of variations was highest at 3.6 cfm/ft^2 for the simulation of Test R-24, and lowest at 1.1 cfm/ft^2 for the simulation of Test R-18. These variations, which constitute violations of the continuity equation, occur because at the point when iteration is stopped, the computed pressures and velocities are still changing with each sweep over the grain bin cross section. To show the effect of the changing pressures and velocities, the simulation of Test R-22 was continued for 100 sweeps beyond the normal cutoff value of 0.0001 in. of water change per sweep.

At the end of these 100 extra sweeps, the maximum pressure change per sweep was between 0.00005 and 0.0001 in. of water. The range of flow rates at the different levels in the bin cross section had dropped from 3.4 to 2.3 cfm/ft^2, and the standard deviation about the mean from 1.2 to 0.80 cfm/ft^2. The mean of the flows at all levels dropped by 0.076 cfm/ft^2.

Air Flow Resistance of Corn Disturbed by a Stirring Auger

Results shown in Table 9 indicate that the air flow resistance of auger-stirred corn is the same as the air flow resistance of corn dropped to the same bulk density. Equation 33 should, therefore, be applicable to auger-stirred corn.

Prediction of the effects of stirring

As reported in the Review of Literature, Toms (1968) conducted stirring tests on corn in a 6-ft diameter bin. Predictions of the air flow he measured in Test 1 and Test 2 were made using Equation 33.

The predictions and measured values are shown in Table 10. In these tests, Toms used 7542 lb. of 11.90 percent moisture content, wet basis, corn. The airflow increase predicted using Equation 33 is lower than the observed increase for 1.5 in. auger path spacing and inward auger movement, and higher than observed for 3.0 in. auger path spacing and outward auger movement.

The predictions for the initial airflow of Test 1 and the final airflow of Test 2 agree very closely. Differences are 2.8 and 1.4 percent of the observed values, respectively.

Suggestions for Future Study

Stirring tests carried out in this study involved grain depths of approximately 26 in. Additional research using the techniques developed here with greater grain depths would be of value in further defining the stirring process. Investigation of the effects of varying initial bulk density, grain moisture content, and auger rotational speed would also be of value.

Table 10. Comparing predicted air flow rates with air flow rates measured by Toms (1968)

Toms test number	Auger path spacing in.	Auger path direction in relation to bin center	Corn bulk density, lb/ft^3	Pressure drop across corn mass, in. water	Toms		Equation 33	
					Air flow through corn cfm	Increase in air flow, percent	Air flow through corn cfm	Increase in air flow, percent
1	1.5	in	50.6(I)[a]	3.164	872		847.9	
			47.5(F)[b]	3.142	1169	34.1	1024	20.8
2	3.0	out	51.0(I)	3.180	896		831.8	
			47.5(F)	3.110	1035	15.8	1050	26.2

[a]Initial.

[b]Final.

The effects of auger stirring on the drying process need to be studied. Tests to determine the effects of various stirring techniques on drying rate and drying cost would provide valuable information for users and manufacturers of stirring equipment.

The technique developed in this study for calculating the air pressure and velocity within a grain mass of varying airflow resistance could be used in other ways. Air pressure and velocity could be calculated for regions of a grain mass containing differing amounts of fines. Effects of leaving an outside ring of grain unstirred in a bin equipped with a stirring system could be determined.

The investigations of airflow resistance of corn completed in this study left many questions unanswered. How do various filling methods affect airflow resistance of different grains? Is the airflow resistance of corn different in different directions? Are there grain disturbance techniques which can significantly change airflow resistance? Research studies could be made to find answers to these questions.

SUMMARY AND CONCLUSIONS

Investigations were carried out studying effects of auger-stirring 11.3 percent moisture content, wet basis, corn. A computer simulation technique was developed to study air flow effects of auger stirring.

The boundaries of the region disturbed by a stirring auger were defined for auger speeds of 0, 4.35, 8.71, 12.26, and 24.30 in./minute with a constant rotational speed of 480 rpm. Effects of stirring on corn bulk density and kernel orientation were investigated. A computer technique was developed to compute the air pressure and velocity distributions within a mass of grain previously stirred with a stirring auger. The air flow resistance of corn disturbed by a stirring auger and of corn placed by dropping from a height was determined.

The study led to the following conclusions:

1. The boundaries of the cross-sectional area disturbed by a stirring auger can be described by third degree polynomial equations. This cross-sectional area decreases with increasing auger speed.
2. Data from this experiment did not show the decrease in bulk density of corn disturbed by a stirring auger to be dependent on auger speed.
3. Kernel orientation within the region disturbed by a stirring auger is not significantly different from kernel orientation outside the disturbed region for

the kernels visible through an inserted plastic sheet.

4. The air pressure drop per unit bed depth across beds of corn can be expressed as a function of air flow rate and grain bulk density by the equation

$$\frac{\Delta P}{L} = (-0.001679 + 0.00003981\ BD)U^2$$
$$+ (-0.04064 + 0.001011\ BD)U + 0.03416 - 0.001001\ BD$$

for air flows in the range of approximately 5 to 120 cfm/ft^2 and for bulk densities in the range of approximately 45.7 to 49.6 lb/ft^3.

5. A modification of the Amos numerical analysis method described by Brooker (1969) was shown to accurately predict pressures measured by Bunn (1960) within a bed of steel shot. This method can be used to compute air pressure and velocity distributions within masses of auger-stirred corn.

6. Air velocity in corn disturbed by a stirring auger was found to be considerably higher than air velocity in undisturbed parts. The lowest air velocity occurred near the bottom of the disturbed region.

7. The air flow resistance of corn brought to its bulk density by auger stirring was not different from the air flow resistance of corn brought to the same bulk density by dropping from a height.

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ACKNOWLEDGMENTS

The author expresses sincere appreciation to Dr. Leon F. Charity, Department of Agricultural Engineering for serving as major professor and for assistance in all phases of this study.

Appreciation is also expressed to:

The other members of the Graduate Committee, Dr. George H. Junkhan, Department of Mechanical Engineering; Dr. Clarence W. Bockhop, Department of Agricultural Engineering; Professor William V. Hukill, United States Department of Agriculture (retired); Dr. David F. Cox, Department of Statistics; and Professor Gerald L. Kline, United States Department of Agriculture; for their guidance and help.

Other staff members of the Agricultural Engineering Department for use of facilities and many helpful suggestions.

The Investor-Owned Electric Utility Companies of Iowa for their financial contributions supporting the study.

The Iowa State University Agriculture and Home Economics Experiment Station and College of Engineering for unsponsored computer use funds.

Mr. Regis Boily for assistance with computer programming.

The author wishes to express special thanks to his wife, Nancy, for her help and consideration during this study.

APPENDIX A: EXPERIMENTAL DATA

Table A-1. Boundary coordinates of disturbed volume cross sectional area (Experiment I)

x-coordinate,* in.	y-coordinate, in. Test number						
	S-2	S-3	S-4	S-5	S-6	S-7	S-8
-10				25.5(-9.2)			
-9				22.6		25.1	25.6
-8	21.4	20.6(-7.3)	22.1(-7.3)	17.4		15.6	19.0
-7	10.5	19.2	20.5	10.0	25.0	11.1	13.2
-6	8.0	11.1	11.6	7.9	13.2	7.6	9.2
-5	6.2	7.5	7.7	6.3	7.5	5.2	6.1
-4	4.6	5.8	5.5	4.6	5.6	4.0	4.3
-3	2.8	4.6	3.4	3.2	3.8	2.8	3.1
-2	1.6	3.6	1.7	1.9	1.4	1.7	1.8
-1	0.1	2.2	0.4	0.6	0.4	0.7	0.4
0	0.0(-0.8)	0.0(-0.8)	0.0(-0.8)	0.0(-0.3)	0.0(-0.8)	0.0(-0.5)	0.0(-0.6)
0		0.0(0.8)	0.0(0.5)	0.0(0.4)		0.0(0.5)	0.0(0.7)
1	0.1	2.2	0.7	1.0	0.2	1.0	0.4
2	2.2	3.7	1.7	3.0	2.2	2.9	2.4
3	3.8	5.0	3.2	5.0	3.8	4.9	4.2
4	6.3	6.0	6.5	7.6	6.4	7.7	6.8
5	9.4	8.2	11.1	11.4	9.2	10.9	9.7
6	11.7	15.3	13.7	15.8	12.2	14.8	13.6
7	14.6	20.6(6.8)	22.3	24.6	15.5	24.1	17.6
8	18.3			25.5(7.2)	25.3(7.8)	25.3(7.2)	23.2
9	20.3						25.9(8.4)
10	21.9(9.5)						

* unless listed beside y-coordinate

Table A-1 (Continued)

x-coordinate* in.	y-coordinate, in. Test number S-9	S-10	S-11	S-12	S-13	S-14	S-15
-10		25.9(-9.7)	24.7(-9.2)			24.8	24.0
-9		22.4	23.6		26.4(-8.3)	18.4	14.8
-8	25.6	16.3	18.1	25.7(-7.9)	25.6	12.3	11.2
-7	19.1	10.4	14.6	18.7	18.2	7.3	8.5
-6	10.3	6.5	10.8	13.6	15.0	5.3	6.2
-5	7.1	4.7	7.7	9.0	10.6	4.2	5.1
-4	5.2	3.5	4.6	6.2	7.6	3.2	4.0
-3	4.0	2.3	2.8	4.3	5.6	2.2	2.8
-2	2.6	1.3	1.4	1.6	3.0	1.2	1.5
-1	1.2	0.1	0.1	0.2	0.4	0.0	0.0
0	0.0(-0.4)				0.0(-0.6)		
0	0.0(0.5)						
1	1.4	0.0	0.1	0.0	0.3	0.0	0.0
2	3.4	1.4	1.5	1.4	2.2	1.2	1.6
3	6.8	3.0	3.0	2.8	4.0	2.2	2.8
4	10.6	4.2	4.4	4.2	5.8	3.3	4.4
5	14.1	5.8	6.3	5.8	8.5	4.4	6.1
6	17.6	7.6	8.6	8.4	12.7	5.7	7.6
7	23.3	10.0	12.4	12.6	16.2	8.9	9.2
8	25.3(7.4)	13.7	16.8	16.7	20.4	13.0	11.2
9		19.7	24.7	25.6(8.9)	26.4	24.0	14.6
10		26.0	25.5(9.2)				25.4(9.8)

* unless listed beside y-coordinate

Table A-2. Experiment II data

Test no.: R-1 Condition: Grain dropped from 7 ft height

Grain volume: 7.557 ft^3 Temperature: 74°F

Grain weight: 364.5 lb Absolute barometric pressure:

Bulk density: 48.23 lb/ft^3 28.86 in. Hg

Grain depth: 2.186 ft R^2 = 1.000

Least squares equation:

$$\frac{\Delta P}{L} = (2.3255E-04)U^2 + (8.5554E-03)U - (1.7827E-02)$$

Air flow, U cfm/ft^2	Pressure drop, $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
3.02	0.022	0.1
12.37	0.120	0.5
28.52	0.409	1.5
37.97	0.633	2.5
47.50	0.905	3.5
61.47	1.385	5.2
75.48	1.967	7.2
89.12	2.615	9.4
103.07	3.319	11.8
114.49	4.006	14.2

Table A-2 (Continued)

Test no.: R-2 Condition: R-1 stirred at 8.71 in./minute

Grain volume: 7.798 ft^3

Temperature: 74 °F

Absolute barometric pressure: 28.86 in Hg

$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (1.6896E-04)U^2 + (6.1023E-03)U - (1.1158E-02)$$

Air flow, U cfm/ft^2	Pressure drop, ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
3.02	0.015	0.1
12.37	0.089	0.4
28.52	0.291	1.4
37.99	0.462	2.1
47.53	0.658	3.0
61.53	1.010	4.4
75.59	1.427	6.1
89.30	1.880	7.9
103.31	2.412	10.0
114.82	2.921	12.0

Table A-2 (Continued)

Test no.: R-3 Condition: Grain dropped from 7 ft height

Grain volume: 7.363 ft^3 Temperature: 72°F

Grain weight: 364.5 lb Absolute barometric pressure:

Bulk density: 49.50 lb/ft^3 29.14 in. Hg

Grain depth: 2.130 ft $R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (2.8115E-04)U^2 + (9.2412E-03)U - (1.6031E-02)$$

Air flow, U cfm/ft^2	Pressure drop, $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
3.08	0.027	0.0
12.58	0.140	0.5
29.00	0.468	1.7
38.60	0.760	2.7
48.29	1.089	3.8
62.47	1.674	5.7
76.70	2.334	7.9
90.53	3.144	10.4
104.64	4.015	13.2
112.22	4.563	15.0

Table A-2 (Continued)

Test no.: R-4   Condition: R-3 stirred at 8.71 in./minute

Grain volume: 7.699 ft^3

Temperature: 72 °F

Absolute barometric pressure: 29.14 in Hg

$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (1.8174E\text{-}04)U^2 + (6.5118E\text{-}03)U - (1.3718E\text{-}02)$$

Air flow, U cfm/ft^2	Pressure drop, $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
3.08	0.016	0.0
12.58	0.096	0.4
29.01	0.320	1.4
38.63	0.501	2.2
48.33	0.721	3.1
62.56	1.112	4.6
76.84	1.570	6.4
90.76	2.081	8.4
104.99	2.663	10.6
116.68	3.220	12.7

Table A-2 (Continued)

Test no.: R-5 Condition: Grain dropped from 7 ft height

Grain volume: 7.413 ft^3 Temperature: 79°F

Grain weight: 364.5 lb Absolute barometric pressure:

Bulk density: 49.17 lb/ft^3 28.94 in. Hg

Grain depth: 2.144 ft R^2 = 1.000

Least squares equation:

$$\frac{\Delta P}{L} = (2.7500E-04)U^2 + (9.2337E-03)U - (1.9907E-02)$$

Air flow, U cfm/ft^2	Pressure drop, $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
2.98	0.022	0.0
12.18	0.135	0.4
28.09	0.434	1.6
37.40	0.710	2.5
46.78	1.016	3.6
60.53	1.526	5.4
74.30	2.215	7.6
87.72	2.903	9.9
101.42	3.767	12.5
112.66	4.489	14.9

Table A-2 (Continued)

Test no.: R-6 Condition: R-5 stirred at 8.71 in./minute

Grain volume: 7.739 ft^3

Temperature: 81 °F

Absolute barometric pressure: 28.94 in Hg

R^2 = 1.000

Least squares equation:

$$\frac{\Delta P}{L} = (1.8579E-04)U^2 + (6.4515E-03)U - (1.1292E-02)$$

Air flow, U cfm/ft^2	Pressure drop, ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
2.96	0.018	0.0
12.10	0.092	0.4
27.89	0.306	1.4
37.14	0.478	2.1
46.48	0.687	2.9
60.16	1.050	4.4
73.90	1.489	6.2
87.30	1.971	8.0
100.98	2.543	10.2
112.25	3.043	12.1

Table A-2 (Continued)

Test no.: R-7 Condition: Grain dropped from 7 ft height

Grain volume: 7.415 ft^3 Temperature: 82 °F

Grain weight: 364.4 lb Absolute barometric pressure:

Bulk density: 49.15 lb/ft^3 28.94 in. Hg

Grain depth: 2.145 ft R^2 = 1.000

Least squares equation:

$$\frac{\Delta P}{L} = (2.8073E\text{-}04)U^2 + (9.7085E\text{-}03)U - (1.8919E\text{-}02)$$

Air flow, U cfm/ft^2	Pressure drop, $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
2.95	0.028	0.0
12.05	0.134	0.5
27.78	0.459	1.7
36.99	0.711	2.5
46.27	1.029	3.6
59.87	1.556	5.4
73.49	2.224	7.6
86.77	2.961	9.9
100.32	3.792	12.5
111.44	4.525	14.9

Table A-2 (Continued)

Test no.: R-8 Condition: R-7 stirred at 4.35 in./minute

Grain volume: 7.739 ft^3

Temperature: 84 °F

Absolute barometric pressure: 28.94 in Hg

R^2 = 1.000

Least squares equation:

$$\frac{\Delta P}{L} = (1.9315E-04)U^2 + (6.6146E-03)U - (1.3393E-02)$$

Air flow, U cfm/ft^2	Pressure drop, ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
2.93	0.016	0.0
27.58	0.092	0.4
11.96	0.308	1.4
36.73	0.486	2.1
45.97	0.695	2.9
59.50	1.060	4.4
73.08	1.514	6.2
86.33	2.002	8.1
99.86	2.581	10.3
111.02	3.090	12.1

Table A-2 (Continued)

Test no.: R-9 Condition: Grain dropped from 7 ft height

Grain volume: 7.478 ft^3 Temperature: 87°F

Grain weight: 364.4 lb Absolute barometric pressure:

Bulk density: 48.73 lb/ft^3 29.00 in. Hg

Grain depth: 2.163 ft $R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (2.6958E-04)U^2 + (8.5293E-03)U - (1.1746E-02)$$

Air flow, U cfm/ft^2	Pressure drop, $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
2.90	0.023	0.1
11.85	0.124	0.6
27.32	0.419	1.7
36.38	0.653	2.6
45.52	0.921	3.5
58.90	1.433	5.3
72.32	2.026	7.3
85.39	2.687	9.5
98.73	3.454	12.1
109.69	4.164	14.4

Table A-2 (Continued)

Test no.: R-10 Condition: R-9 stirred at 4.35 in./minute

Grain volume: 7.780 ft^3

Temperature: 87°F

Absolute barometric pressure: 29.00 in Hg

$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (1.8448E-04)U^2 + (6.2726E-03)U - (9.4861E-03)$$

Air flow, U cfm/ft^2	Pressure drop, $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
2.90	0.016	0.1
11.85	0.092	0.5
27.33	0.292	1.5
36.40	0.459	2.2
45.55	0.655	3.0
58.96	1.001	4.4
72.43	1.423	6.1
85.56	1.879	8.0
98.99	2.427	10.1
110.05	2.905	11.9

Table A-2 (Continued)

Test no.: R-11 Condition: Grain dropped from 7 ft height

Grain volume: 7.363 ft^3 Temperature: 88 °F

Grain weight: 364.4 lb Absolute barometric pressure:

Bulk density: 49.49 lb/ft^3 29.00 in. Hg

Grain depth: 2.130 ft $R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (2.8335E\text{-}04)U^2 + (1.0500E\text{-}02)U - (2.3606E\text{-}02)$$

Air flow, U cfm/ft^2	Pressure drop, $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
2.89	0.027	0.1
11.81	0.136	0.5
27.22	0.461	1.7
36.24	0.719	2.7
45.34	1.019	3.6
58.66	1.566	5.5
72.02	2.211	7.6
85.02	2.948	10.0
98.31	3.761	12.5
109.21	4.474	14.9

Table A-2 (Continued)

Test no.: R-12 Condition: R-11 stirred 4.35 in./minute

Grain volume: 7.708 ft^3

Temperature: 88°F

Absolute barometric pressure: 29.00 in Hg

R^2 = 1.000

Least squares equation:

$$\frac{\Delta P}{L} = (1.9251E\text{-}04)U^2 + (6.7771E\text{-}03)U - (1.3152E\text{-}02)$$

Air flow, U cfm/ft^2	Pressure drop, ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
2.89	0.020	0.1
11.81	0.092	0.5
27.23	0.301	1.5
36.22	0.480	3.2
45.37	0.685	3.1
58.74	1.050	4.5
72.15	1.483	6.2
85.23	1.973	8.1
98.59	2.544	10.3
109.59	3.021	12.2

Table A-2 (Continued)

Test no.: R-13 Condition: Grain dropped from 7 ft height

Grain volume: 7.307 ft^3

Grain weight: 364.5 lb

Bulk density: 49.88 lb/ft^3

Grain depth: 2.113 ft

Temperature: 92 °F

Absolute barometric pressure: 29.00 in. Hg

$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (3.1580E-04)U^2 + (1.0194E-02)U - (1.5120E-02)$$

Air flow, U cfm/ft^2	Pressure drop, ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
2.84	0.027	0.1
11.63	0.144	0.5
26.81	0.475	1.8
35.69	0.747	2.7
44.65	1.070	3.8
57.77	1.623	5.6
70.92	2.284	7.8
83.71	3.077	10.3
96.77	3.952	13.0
107.50	4.703	15.4

Table A-2 (Continued)

Test no.: R-14 Condition: R-13 stirred at 24.30 in./minute

Grain volume: 7.609 ft^3

Temperature: 88°F

Absolute barometric pressure: 29.00 in Hg

R^2 = 1.000

Least squares equation:

$$\frac{\Delta P}{L} = (2.1024E-04)U^2 + (7.0927E-03)U - (1.0563E-02)$$

Air flow, U cfm/ft^2	Pressure drop, ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
2.89	0.020	0.1
11.81	0.102	0.5
27.23	0.330	1.5
36.26	0.518	2.3
45.37	0.741	3.2
58.72	1.124	4.7
72.12	1.606	6.5
85.20	2.131	8.4
98.54	2.734	10.7
109.54	3.277	12.6

Table A-2 (Continued)

Test no.: R-15 Condition: Grain dropped from 7 ft height

Grain volume: 7.460 ft^3 Temperature: 89°F

Grain weight: 364.5 lb Absolute barometric pressure:

Bulk density: 48.86 lb/ft^3 29.00 in. Hg

Grain depth: 2.158 ft $R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (2.6403E-04)U^2 + (8.8025E-03)U - (1.6646E-02)$$

Air flow, U cfm/ft^2	Pressure drop, $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
2.88	0.024	0.1
11.76	0.122	0.5
27.12	0.406	1.7
36.11	0.637	2.5
45.18	0.917	3.5
58.46	1.383	5.2
71.78	1.990	7.3
84.75	2.650	9.5
98.00	3.396	12.0
108.87	4.046	14.4

Table A-2 (Continued)

Test no.: R-16 Condition: R-15 stirred at 24.30 in./minute

Grain volume: 7.706 ft^3

Temperature: 94°F

Absolute barometric pressure: 29.00 in Hg

$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (2.0453E-04)U^2 + (6.2718E-03)U - (6.0076E-03)$$

Air flow, U cfm/ft^2	Pressure drop, ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
2.82	0.019	0.1
11.54	0.093	0.4
26.61	0.300	1.5
35.44	0.471	2.2
44.36	0.665	3.0
57.41	1.035	4.5
70.53	1.464	6.2
83.31	1.936	8.1
96.37	2.495	10.3
107.11	3.010	12.3

Table A-2 (Continued)

Test no.: R-17 Condition: Grain dropped from 7 ft height

Grain volume: 7.348 ft^3 Temperature: 94 °F

Grain weight: 364.5 lb Absolute barometric pressure: 29.00 in. Hg

Bulk density: 49.60 lb/ft^3

Grain depth: 2.125 ft $R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (3.0911E\text{-}04)U^2 + (8.8926E\text{-}03)U - (5.9380E\text{-}03)$$

Air flow, U cfm/ft^2	Pressure drop, ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
2.82	0.028	0.1
11.54	0.138	0.5
26.61	0.448	1.7
35.43	0.689	2.6
44.32	0.981	3.6
57.34	1.522	5.5
70.40	2.181	7.6
83.20	2.859	9.1
96.08	3.715	12.6
104.30	4.272	14.5

Table A-2 (Continued)

Test no.: R-18   Condition: R-17 stirred at 24.30 in./minute

Grain volume: 7.645 ft^3

Temperature: 92°F

Absolute barometric pressure: 29.00 in Hg

$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (1.9992E{-}04)U^2 + (6.9976E{-}03)U - (1.2029E{-}02)$$

Air flow, U cfm/ft^2	Pressure drop, $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
2.84	0.020	0.1
11.63	0.097	0.5
26.82	0.308	1.5
35.72	0.485	2.2
44.69	0.695	3.1
57.85	1.060	4.5
71.06	1.502	6.3
83.94	1.998	8.2
97.10	2.565	10.4
107.93	3.053	12.3

Table A-2 (Continued)

Test no.: R-19 Condition: Grain dropped from 7 ft height

Grain volume: 7.469 ft^3 Temperature: 92 °F

Grain weight: 364.5 lb Absolute barometric pressure:

Bulk density: 48.80 lb/ft^3 29.00 in. Hg

Grain depth: 2.160 ft R^2 = 1.000

Least squares equation:

$$\frac{\Delta P}{L} = (2.6568E{-}04)U^2 + (8.7560E{-}03)U - (1.7731E{-}02)$$

Air flow, U cfm/ft^2	Pressure drop, $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
2.84	0.021	0.1
11.63	0.119	0.5
26.81	0.401	1.7
35.70	0.620	2.5
44.67	0.897	3.5
57.80	1.377	5.2
70.98	1.948	7.2
83.84	2.604	9.1
96.89	3.332	12.0
107.67	3.987	14.2

Table A-2 (Continued)

Test no.: R-20 Condition: R-19 stirred at 12.26 in./minute

Grain volume: 7.726 ft^3

Temperature: 75°F

Absolute barometric pressure: 28.89 in Hg

$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (1.8373E{-}04)U^2 + (5.8305E{-}03)U - (1.0016E{-}02)$$

Air flow, U cfm/ft^2	Pressure drop, $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
3.02	0.018	0.0
12.34	0.086	0.4
28.45	0.299	1.4
37.89	0.467	2.2
47.41	0.680	3.0
61.36	1.042	4.6
75.38	1.477	6.3
89.03	1.969	8.3
102.97	2.546	10.6
114.44	3.054	12.6

Table A-2 (Continued)

Test no.: R-21 Condition: Grain dropped from 7 ft height

Grain volume: 7.377 ft^3 Temperature: 75 °F

Grain weight: 364.5 lb Absolute barometric pressure: 28.89 in. Hg

Bulk density: 49.41 lb/ft^3

Grain depth: 2.134 ft $R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (2.8711E\text{-}04)U^2 + (8.4665E\text{-}03)U - (1.1054E\text{-}02)$$

Air flow, U cfm/ft^2	Pressure drop, $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
3.02	0.025	0.0
12.34	0.139	0.4
28.44	0.454	1.7
37.87	0.712	2.6
47.37	1.030	3.8
61.28	1.580	5.6
75.22	2.267	7.9
88.79	3.011	10.4
102.61	3.892	13.3
112.01	4.522	15.4

Table A-2 (Continued)

Test no.: R-22 Condition: R-21 stirred at 12.26 in./minute

Grain volume: 7.685 ft^3

Temperature: 76 °F

Absolute barometric pressure: 28.89 in Hg

$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (1.9565E-04)U^2 + (6.0258E-03)U - (1.0428E-02)$$

Air flow, U cfm/ft^2	Pressure drop, ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
3.01	0.018	0.0
12.29	0.091	0.4
28.35	0.311	1.4
37.75	0.489	2.2
47.24	0.707	3.1
61.13	1.093	4.7
75.08	1.549	6.6
88.67	2.073	8.6
102.56	2.665	10.9
113.96	3.210	13.1

Table A-2 (Continued)

Test no.: R-23 Condition: Grain dropped from 7 ft height

Grain volume: 7.388 ft^3 Temperature: 76°F

Grain weight: 364.5 lb Absolute barometric pressure:

Bulk density: 49.34 lb/ft^3 28.89 in. Hg

Grain depth: 2.137 ft $R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (2.8631E-04)U^2 + (8.2079E-03)U - (8.2397E-03)$$

Air flow, U cfm/ft^2	Pressure drop, ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
3.01	0.024	0.0
12.29	0.132	0.4
28.34	0.446	1.6
37.73	0.714	2.6
47.20	1.018	3.7
61.06	1.562	5.6
74.96	2.223	7.8
88.49	2.950	10.2
102.27	3.829	13.1
111.62	4.475	15.3

Table A-2 (Continued)

Test no.: R-24 Condition: R-23 stirred at 12.26 in./minute

Grain volume: 7.694 ft^3

Temperature: 77°F

Absolute barometric pressure: 28.89 in Hg

R^2 = 1.000

Least squares equation:

$$\frac{\Delta P}{L} = (1.9350E-04)U^2 + (5.7453E-03)U - (6.2566E-03)$$

Air flow, U cfm/ft^2	Pressure drop, ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
3.00	0.018	0.0
12.25	0.092	0.3
28.25	0.309	1.4
37.62	0.472	2.2
47.07	0.698	3.1
60.92	1.060	4.6
74.83	1.506	6.4
88.37	2.028	8.5
102.21	2.598	10.8
113.58	3.138	12.9

Table A-3. Experiment III data

Test no.: SC-01
Drop height: Fill at zero drop height
Temperature: 75°F
Grain volume: 1.532 ft^3
Barometric pressure (absolute): 29.13 in. Hg
Grain weight: 69.42 lb
Bulk density: 45.32 lb/ft^3
$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (1.5603E-04)U^2 + (5.2821E-03)U - (1.1093E-02)$$

Air flow, U cfm/ft^2	Pressure drop $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
118.22	2.800	8.8
104.27	2.235	7.0
90.24	1.713	5.4
76.11	1.320	4.2
61.94	0.908	2.9
47.71	0.593	1.9
33.43	0.348	1.1
23.89	0.208	0.6
14.34	0.088	0.1
4.78	0.020	0.0

Table A-3 (Continued)

Test no.: SC-02
Drop height: Fill at zero drop height
Temperature: 77°F
Grain volume: 1.510 ft^3
Barometric pressure (absolute): 29.13 in. Hg
Grain weight: 68.59 lb
Bulk density: 45.44 lb/ft^3
$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (1.5139E\text{-}04)U^2 + (5.3736E\text{-}03)U - (8.8543E\text{-}03)$$

Air flow, U cfm/ft^2	Pressure drop $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
117.40	2.728	8.6
103.55	2.158	6.8
89.60	1.663	5.3
75.58	1.270	4.0
61.50	0.893	2.8
47.36	0.605	1.9
33.19	0.348	1.1
23.72	0.190	0.6
14.24	0.098	0.2
4.75	0.018	0.0

Table A-3 (Continued)

Test no.: SC-21

Drop height: 2 ft

Grain volume: 1.505 ft^3

Grain weight: 68.95 lb

Bulk density: 45.83 lb/ft^3

Temperature: 80°F

Barometric pressure (absolute): 29.03 in. Hg

$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (1.5369E-04)U^2 + (6.1060E-03)U - (1.3321E-02)$$

Air flow, U cfm/ft^2	Pressure drop $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
115.73	2.765	8.6
102.06	2.190	6.9
88.31	1.708	5.4
74.48	1.328	4.2
60.61	0.922	3.0
46.68	0.603	2.0
32.71	0.345	1.2
23.38	0.213	0.7
14.04	0.098	0.3
4.68	0.025	0.0

Table A-3 (Continued)

Test no.: SC-22

Drop height: 2 ft

Grain volume: 1.470 ft^3

Grain weight: 67.52 lb

Bulk density: 45.93 lb/ft^3

Temperature: 78 °F

Barometric pressure (absolute): 29.13 in. Hg

R^2 = 1.000

Least squares equation:

$$\frac{\Delta P}{L} = (1.4098E\text{-}04)U^2 + (6.0886E\text{-}03)U - (1.3382E\text{-}02)$$

Air flow, U cfm/ft^2	Pressure drop ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
117.02	2.745	8.3
103.20	2.180	6.6
89.28	1.743	5.3
75.31	1.300	4.0
61.29	0.900	2.7
47.19	0.613	1.9
33.07	0.353	1.1
23.64	0.218	0.6
14.19	0.083	0.2
4.73	0.033	0.0

Table A-3 (Continued)

Test no.: SC-31

Drop height: 3 ft

Grain volume: 1.473 ft^3

Grain weight: 67.97 lb

Bulk density: 46.13 lb/ft^3

Temperature: 78°F

Barometric pressure (absolute): 29.03 in. Hg

R^2 = 1.000

Least squares equation:

$$\frac{\Delta P}{L} = (1.6329E\text{-}04)U^2 + (5.9437E\text{-}03)U - (8.0802E\text{-}03)$$

Air flow, U cfm/ft^2	Pressure drop ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
116.50	2.903	9.1
102.77	2.328	7.2
88.94	1.810	5.6
75.03	1.348	4.2
61.05	0.970	3.0
47.02	0.643	2.0
32.95	0.358	1.1
23.55	0.228	0.8
14.14	0.100	0.3
4.71	0.028	0.0

Table A-3 (Continued)

Test no.: SC-32

Drop height: 3 ft

Grain volume: 1.506 ft^3

Grain weight: 69.38 lb

Bulk density: 46.06 lb/ft^3

Temperature: 77°F

Barometric pressure (absolute): 29.13 in. Hg

$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (1.5009E-04)U^2 + (6.0492E-03)U - (1.6701E-02)$$

Air flow, U cfm/ft^2	Pressure drop $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
117.40	2.788	8.6
103.56	2.175	6.7
89.59	1.745	5.4
75.58	1.283	4.0
61.49	0.950	2.9
47.36	0.605	1.9
33.19	0.348	1.1
23.72	0.218	0.6
14.24	0.083	0.1
4.75	0.023	0.0

Table A-3 (Continued)

Test no.: SC-51

Drop height: 5 ft

Grain volume: 1.510 ft^3

Grain weight: 69.34 lb

Bulk density: 45.94 lb/ft^3

Temperature: 78°F

Barometric pressure (absolute): 29.13 in. Hg

$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (1.4036E-04)U^2 + (5.7830E-03)U - (1.7177E-02)$$

Air flow, U cfm/ft^2	Pressure drop $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
117.07	2.580	8.0
103.23	2.083	6.4
89.31	1.610	5.0
75.33	1.223	3.8
61.29	0.865	2.7
47.20	0.573	1.8
33.07	0.315	1.0
23.64	0.203	0.6
14.19	0.090	0.2
4.73	0.018	0.0

Table A-3 (Continued)

Test no.: SC-52

Drop height: 5 ft
Grain volume: 1.509 ft^3
Grain weight: 68.97 lb
Bulk density: 45.71 lb/ft^3

Temperature: 80°F
Barometric pressure (absolute): 29.03 in. Hg
$R^2 = 1.000$

Least squares equation:

$$\frac{\Delta P}{L} = (1.4283E-04)U^2 + (5.3213E-03)U - (4.1104E-03)$$

Air flow, U cfm/ft^2	Pressure drop $\Delta P/L$ in. water/ft grain	Meter inlet pressure in. water (negative)
115.82	2.530	8.0
102.13	2.028	6.4
88.36	1.578	5.0
74.52	1.190	3.8
60.63	0.840	2.7
46.70	0.560	1.8
32.72	0.325	1.1
23.38	0.198	0.7
14.04	0.093	0.3
4.68	0.028	0.0

Table A-3 (Continued)

Test no.: SC-61

Drop height: 6 ft

Grain volume: 1.520 ft^3

Grain weight: 69.56 lb

Bulk density: 45.77 lb/ft^3

Temperature: 80°F

Barometric pressure (absolute): 29.03 in. Hg

R^2 = 1.000

Least squares equation:

$$\frac{\Delta P}{L} = (1.5399E-04)U^2 + (5.0111E-03)U - (8.4080E-03)$$

Air flow, U cfm/ft^2	Pressure drop ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
115.77	2.653	8.3
102.11	2.088	6.5
88.35	1.618	5.1
74.50	1.248	4.0
60.63	0.858	2.7
46.70	0.563	1.8
32.72	0.325	1.1
23.38	0.193	0.7
14.04	0.083	0.3
4.68	0.023	0.0

Table A-3 (Continued)

Test no.: SC-62

Drop height: 6 ft
Grain volume: 1.516 ft^3
Grain weight: 69.53 lb
Bulk density: 45.88 lb/ft^3

Temperature: 81°F
Barometric pressure (absolute): 29.03 in. Hg
R^2 = 1.000

Least squares equation:

$$\frac{\Delta P}{L} = (1.4147E\text{-}04)U^2 + (5.7550E\text{-}03)U - (1.1326E\text{-}02)$$

Air flow, U cfm/ft^2	Pressure drop ΔP/L in. water/ft grain	Meter inlet pressure in. water (negative)
115.38	2.548	8.1
101.76	2.018	6.4
88.03	1.600	5.1
74.24	1.190	3.9
60.41	0.858	2.8
46.46	0.570	1.9
32.60	0.328	1.1
23.30	0.198	0.7
13.98	0.083	0.3
4.6	0.028	0.0

APPENDIX B: AIR FLOW RESISTANCE OF BIN FLOOR FROM EXPERIMENT II

The pressure drop measurements taken in Experiment II across the grain mass included the pressure drop across the bin floor. It was therefore necessary to subtract from these pressure drop readings the pressure drop across the bin floor.

To determine the pressure drop across the perforated metal floor, an experiment was conducted using the apparatus of Experiment III. For a grain column, a section of 9.789-in. inside diameter steel pipe was fitted with a floor of the same perforated steel material used for the floor in Experiment II. This flooring was made of 1/16-in. steel with 3/32-in. holes and a pitch of 0.25 in., and an open area of 12.76 percent. Pressure tap holes were drilled at heights of 1, 3, 5, 7, 12, and 15 in. above the bin floor. The column was filled to a level exceeding 15 in. with corn by dropping from a height of 7 ft. Air was moved up through the grain by decreasing the pressure over the grain. Air flow rates were corrected for temperature and pressure to standard cfm. Pressure readings are differences between atmospheric pressure and interior column pressures.

A graphical method described by Lampman (1961), pp. 38, 39 was used to determine the pressure drop across the floor. The assumption was made that the pressure drop through the grain was linear to the interface of the grain and floor.

Extrapolating the line relating pressure and height above the bin floor to a zero height yielded the apparent pressure drop across the perforated sheet. Pressure drops for various flow rates determined in this way are shown in Table B-1. Figure B-1 shows the floor pressure drops plotted against the air flow. This graph was used to correct the pressures observed in Experiment II.

Table B-1. Bin floor resistance data

Air flow cfm/ft^2	Meter inlet pressure in. water	Height above bin floor, in. 1	3	5	7	12	15	Drop across floor in. water
		Pressure within column, in. water						
5.21	0.5	0.004	0.012	0.025	0.034	0.052	0.065	0.0005
19.57	0.5	0.031	0.079	0.133	0.187	0.313	0.396	0.005
28.89	0.9	0.057	0.141	0.242	0.325	0.555	0.688	0.015
39.14	1.4	0.082	0.209	0.376	0.517	0.869	1.072	0.015
49.02	1.9	0.123	0.315	0.518	0.713	1.216	1.502	0.026
63.38	2.8	0.186	0.477	0.778	1.082	1.841	2.284	0.035
78.29	4.0	0.273	0.682	1.116	1.544	2.628	3.257	0.050
92.27	5.2	0.350	0.875	1.435	1.974	3.408	4.254	0.070
107.18	6.7	0.464	1.143	1.867	2.556	4.364	5.450	0.100
122.09	8.4	0.582	1.432	2.359	3.233	5.513	6.881	0.150

Temperature: 69°F
Barometric pressure: 29.05 in. Hg (absolute)

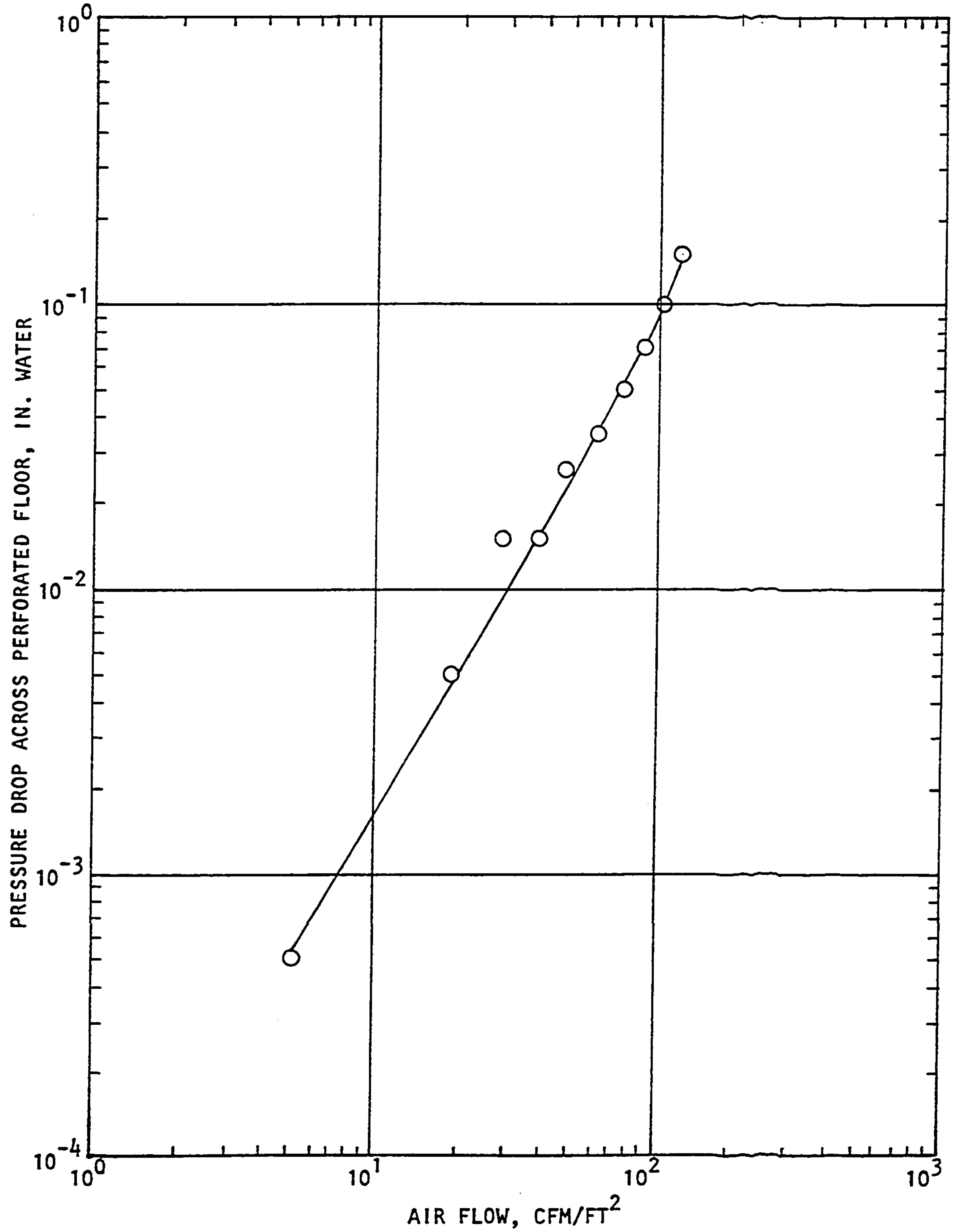


Figure B-1. Pressure drop across bin floor as affected by air flow rate

APPENDIX C: TYPICAL MANAGEMENT PROCEDURES FOR DRYING SYSTEMS EQUIPPED WITH STIRRING AUGERS

Grain stirrer systems on the market now consist of one to seven 2-in. diameter open augers suspended from the roof and sidewall of the bin and extending to near the bin floor. The augers are turned at speeds of 400 to 500 rpm and simultaneously moved horizontally through the grain at speeds in the approximate range of 1 to 8 in./minute. The path traced within the bin varies with manufacturer. One brand traces multi-revolution spirals; another brand alternates tracing fractional revolution spirals and radii. A third brand traces circles. During operation, there is a movement of grain from the bottom region of the bin to the top of the grain mass and a continuous mound of grain can be seen behind the auger.

Grain stirrers are used with two kinds of bin drying systems: the in-storage layer fill drying system in which corn is dried and stored in the same bin to a depth of 16 to 20 ft, and the bin batch drying system in which corn is placed for drying and cooling, and is then removed to storage. In each of these systems, the stirrer offers significant management advantages.

With the in-storage layer system not equipped with stirring equipment, air temperature rise is limited to about 20°F above ambient. Temperatures higher than this will overdry grain near the bottom of the bin because it is subjected to drying air during the entire drying period. The filling rate cannot greatly exceed the drying rate which will be approximately 10 in. per 24 hr. Van Fossen (1967) recommends a limit of 4 feet of wet grain in the bin at any time. If this system is equipped with a stirrer, the air temperature may be increased to as high as 140°F according to the FS Grain Drying Guide [Farm Automation Department Staff of FS (1971)]. A high temperature can be used because the bottom layer of grain is removed by the stirrer periodically. Increasing air temperature results in much faster drying and permits faster filling of the bin.

With the bin batch system not equipped with a stirrer, grain is dried in batches 2½ to 4 feet deep using air temperatures up to 140°F. Grain depth is limited by the maximum permissible grain moisture content variation from bottom to top. The FS Grain Drying Guide states that a variation of 3 to 5 percent, wet basis, from top to bottom in a 4-foot batch may be expected with an air temperature of approximately 140°F. Frus (1968) observed a variation of 11.8 percent, wet basis, with a batch depth varying from 4 to 6 feet.

When a bin batch system is equipped with a stirrer, grain depth may be increased up to twice the previous maximum according to the FS Grain Drying Guide. Moisture content variation is reduced because of the mixing action of the stirring auger. The increased batch size results in decreased labor requirement by decreasing the number of batches.

APPENDIX D: COMPUTER PROGRAM ACCURACY TEST

To check the accuracy of the computer program developed in this study, a test was run to predict pressures observed by Bunn (1960) within a bed of steel shot. Predicted pressures were compared with observations and predictions by Bunn.

The bed constructed by Bunn was 24 in. wide, 24 in. high and 1.5 in. thick, with a 3-in. square air supply duct in the lower left corner. The top was open and the sides and bottom were closed. The top and right side of the air supply duct were perforated to admit air. The computer program to be checked was modified to satisfy these boundary conditions. The grid spacing used in the computer program was h_y = 1.5 in. and h_x = 1.5 in., which was the same spacing as used by Bunn.

In Bunn's study, the bed was filled with copper-coated steel B-B shot with a calculated mean diameter of 0.0144 ft, and a fraction of voids of 0.437. To determine characteristic coefficients A, B, and C for this material, second degree polynomials were fitted to the experimentally obtained air flow and pressure drop data. Two equations were required for a sufficiently accurate fit over the air flow range of the data. One equation was used for air flow rates from 0.88 to 20 cfm/ft^2; the other for air flow rates from 20 to 173.34 cfm/ft^2. The computer was programmed to choose between the two sets of coefficients, according to the air flow rate being considered.

Pressures along the top and right side of the air supply duct were held constant at 5.393 in. of water. Pressures along the top were held constant at values computed by Bunn. All other pressures were changeable. Pressures predicted by Bunn were used as the starting point. The computational procedure was stopped when no pressure had changed more than 0.0001 in. of water during the previous sweep. This required 160 sweeps.

Predicted and observed pressures along a vertical line 3 in. from the left wall are compared in Table D-1. t was used as a test statistic to compare predicted and observed pressures.

The null hypothesis tested was that the mean of the differences between the predicted and observed pressures is not different from zero. The t value for predictions by Bunn and predictons by the program developed in this study were 0.0022 and 0.0026 respectively. The two-tailed $t_{0.05}$ for 12 degrees of freedom is 2.179. Thus the null hypothesis was accepted in both cases.

The null hypothesis that the predictions by Bunn and the predictions by the method of this study are not different was tested by calculating F as the ratio of the larger χ^2 to the smaller χ^2. The computed F was 1.20, while $F_{0.05} = 3.50$ for a two-tailed test with 11 and 11 degrees of freedom. The null hypothesis in this case was also accepted.

The conclusion from these tests was that, judging from the values compared, the pressures predicted by Bunn and by the

Table D-1. A comparison of observed and predicted pressures along the line X = 3

y in.	(1) Pressure observed by Bunn, in. water	(2) Pressure predicted by program from this study, in. water	(3) Pressure predicted by Bunn, in. water	(1)-(2) in. water	(1)-(3) in. water	$\frac{(1-2)^2}{(1)}$ X 10^{-3} in. water	$\frac{(1-3)^2}{(1)}$ X 10^{-3} in. water
4.5	4.03	4.060	4.086	-0.030	-0.056	0.22	0.78
6	3.23	3.314	3.337	-0.084	-0.107	2.19	3.54
7.5	2.81	2.792	2.809	0.018	0.001	0.11	0.00
8	2.38	2.386	2.396	-0.006	-0.016	0.02	0.11
10.5	2.07	2.052	2.057	0.018	0.013	0.15	0.08
12	1.729	1.764	1.765	-0.035	-0.036	0.71	0.75
13.5	1.462	1.509	1.507	-0.047	-0.045	1.51	1.38
15	1.234	1.275	1.272	-0.041	-0.038	1.36	1.17
16.5	1.062	1.057	1.053	0.005	-0.009	0.02	0.08
18	0.836	0.851	0.847	-0.015	-0.011	0.26	0.14
19.5	0.657	0.652	0.648	0.005	0.009	0.03	0.12
21	0.446	0.458	0.456	-0.012	-0.010	0.31	0.22
22.5	0.260	0.268	0.267	-0.008	-0.007	0.23	0.19
				-0.018 (Mean)	-0.023 (Mean)	7.12 (Total)	8.56 (Total)

$$F = \frac{8.56 \times 10^{-3}}{7.12 \times 10^{-3}} = 1.20$$

$F_{0.05} = 3.50$ (two tail for 11 and 11 degrees of freedom)

$$t = \frac{|\text{Mean} - 0|}{\sqrt{\frac{S^2}{n}}}$$

$t_{(2)} = 0.0022$

$t_{(3)} = 0.0026$

$t_{0.05} = 2.179$ (two-tailed for 12 degrees of freedom) program developed in this study are not significantly different at the 5-percent level from each other nor from the pressure values measured by Bunn.

APPENDIX E: COMPUTER PROGRAM TO PREDICT PRESSURE AND VELOCITY DISTRIBUTIONS WITHIN A CORN MASS

```
C
C
C     DETERMINING PRESSURE AND VELOCITY DISTRIBUTION WITHIN A STIRRED
C     GRAIN MASS USING MODIFIED AMOS METHOD
C
      DIMENSION P(27,25),DIFF(27,25),DPXB(27,25),DPYB(27,25),
     6DPNB(27,25),VY(27,25),VNB(27,25),ANG(27,25),VND(27,25)
      REAL LZER, L1, L2, L3,K4
      READ(5,90)PL,PU,MAXIT,ZIMIT,A,B,C
   90 FORMAT(F7.4,F4.1,I4,F8.5,F11.8,F10.7,F10.6)
C     FORM OF DATA CARD: 6.0 2.0 100 0.001 0.0002 .009369 -.029006
      READ(5,91) AA,BB,CC
   91 FORMAT(F10.7,F9.6,F9.5)
C     FORM OF DATA CARD: 0.000153 0.00695 -0.0266
      READ(5,92) LZER,L1,L2,L3,RZER,R1,R2,R3
   92 FORMAT(F9.5,F9.5,F8.5,F11.7,F8.4,F7.4,F8.4,F9.6)
C     FORM OF DATA CARD: -3.9733 -4.4321 -0.8996 -0.07286 -0.8667 0.8008 0.3182
C     -0.01591
      READ(5,93) IMAX,JMAX
   93 FORMAT(2I3)
C     FORM OF DATA CARD:  14  13
      K1=IMAX-1
      K3=JMAX-1
      K4=K3/2.
      K5=IMAX-2
      HX=24./K3
      HY=26./K1
      KK1=4.*HY
      KK2=4.*HX
      KK3=((26./K1)/(24./K3))**2
      KK4=JMAX+1
      TEST=1.
C
C     READ IN AN INITIAL PRESSURE DISTRIBUTION AND DIFFERENCE
C
      READ(5,94) ((P(I,J),J=1,JMAX),I=1,IMAX)
   94 FORMAT(7F8.4)
```

```
      DO 4 I=1,IMAX,1
      DO 3 J=1,JMAX,1
      K2=I
      DIFF(I,J)=P(I,J)
    3 CONTINUE
    4 CONTINUE
      NCIT=0
      NOIP=0
      GO TO 36
    5 NCIT = NOIT + 1
      NOIP=NOIP+1
      DC26 J=1,JMAX,1
      DO 26 I=2,K1,1
      IF (J.EQ.1) GO TO 17
      IF(J.EQ.JMAX) GO TO 18
C
C     WITHIN GRAIN MASS
C
      DPXA=(P(I,J+1)-P(I,J))/HX
      DPYA = (P(I+1,J) - P(I-1,J) + P(I+1,J+1) - P(I-1,J+1))/KK1
      DPNA=(( ABS(DPXA))**2 +( ABS(DPYA))**2 )**0.5
      DPXB(I,J)=(P(I+1,J+1)-P(I+1,J-1)+P(I,J+1)-P(I,J-1))/KK2
      DPYB(I,J)=(P(I+1,J)-P(I,J))/HY
      DPNB(I,J)=(( ABS(DPXB(I,J)))**2 +( ABS(DPYB(I,J)))**2 )**0.5
      DPXC=(P(I,J)-P(I,J-1))/HX
      DPYC=(P(I+1,J-1)-P(I-1,J-1)+P(I+1,J)-P(I-1,J))/KK1
      DPNC=(( ABS(DPXC))**2 +( ABS(DPYC))**2 )**0.5
      DPXD     =(P(I,J+1)-P(I,J-1)+P(I-1,J+1)-P(I-1,J-1))/KK2
      DPYD     =(P(I,J)-P(I-1,J))/HY
      DPND     =(( ABS(DPXD     ))**2 +( ABS(DPYD     ))**2 )**0.5
      IF(J.GT.13) GO TO 6
C
C     LEFT OF CENTER
C
      YA=(I-1.)*HY
      XA=(J-K4-0.5)*HX
      YB=(I-0.5)*HY
```

```
      XB=(J-K4-1)*HX
      YC=(I-1.)*HY
      XC=(J-K4-1.5)*HX
      YD=(I-1.5)*HY
      XD=(J-K4-1)*HX
      YAT=LZER+L1*XA+L2*(XA**2 )+L3*(XA**3 )
      IF(YAT.LT.YA) GO TO 8
      VNA=(-B+(B**2 +4.*A*(DPNA*12.-C))**0.5)/(2.*A)
      GO TO 9
    8 VNA=(-BB+(BB**2 +4.*AA*(DPNA*12.-CC))**0.5)/(2.*AA)
    9 IF( ABS(DPNA).LT.0.0001) DPNA=-0.0001
      FA=VNA/DPNA
      YBT=LZER+L1*XB+L2*(XB**2 )+L3*(XB**3 )
      IF(YBT.LT.YB) GO TO 10
      VNB(I,J)=(-B+(B**2 +4.*A*(DPNB(I,J)*12.-C))**0.5)/(2.*A)
      GC TO 11
   10 VNB(I,J)=(-BB+(BB**2 +4.*AA*(DPNB(I,J)*12.-CC))**0.5)/(2.*AA)
   11 IF( ABS(DPNB(I,J)).LT.0.0001) DPNB(I,J)=-0.0001
      FB=VNB(I,J)/DPNB(I,J)
      YCT=LZER+L1*XC+L2*(XC**2 )+L3*(XC**3 )
      IF(YCT.LT.YC) GO TO 12
      VNC=(-B+(B**2 +4.*A*(DPNC*12.-C))**0.5)/(2.*A)
      GC TO 13
   12 VNC=(-BB+(BB**2 +4.*AA*(DPNC*12.-CC))**0.5)/(2.*AA)
   13 IF( ABS(DPNC).LT.0.0001) DPNC=-0.0001
      FC=VNC/DPNC
      YDT=LZER+L1*XD+L2*(XD**2 )+L3*(XD**3 )
      IF(YDT.LT.YD) GO TO 14
      VND(I,J)=(-B+(B**2 +4.*A*(DPND     *12.-C))**0.5)/(2.*A)
      GO TO 15
   14 VND(I,J)=(-BB+(BB**2 +4.*AA*(DPND     *12.-CC))**0.5)/(2.*AA)
   15 IF( ABS(DPND     ).LT.0.0001) DPND     =-0.0001
      FD=VND(I,J)/DPND
      GO TO 19
C
C     RIGHT OF CENTER
C
```

```
 6 CONTINUE
   YA=(I-1.)*HY
   XA=(J-K4-0.5)*HX
   YB=(I-0.5)*HY
   XB=(J-K4-1)*HX
   YC=(I-1.)*HY
   XC=(J-K4-1.5)*HX
   YD=(I-1.5)*HY
   XD=(J-K4-1)*HX
   YAT=RZER+R1*XA+R2*(XA**2 )+R3*(XA**3 )
   IF(YAT.LT.YA) GO TO 60
   VNA=(-B+(B**2 +4.*A*(DPNA*12.-C))**0.5)/(2.*A)
   GO TO 61
60 VNA=(-BB+(BB**2 +4.*AA*(DPNA*12.-CC))**0.5)/(2.*AA)
61 IF( ABS(DPNA).LT.0.0001) DPNA=-0.0001
   FA=VNA/DPNA
   YBT=RZER+R1*XB+R2*(XB**2 )+R3*(XB**3 )
   IF(YBT.LT.YB) GO TO 62
   VNB(I,J)=(-B+(B**2 +4.*A*(DPNB(I,J)*12.-C))**0.5)/(2.*A)
   GO TO 63
62 VNB(I,J)=(-BB+(BB**2 +4.*AA*(DPNB(I,J)*12.-CC))**0.5)/(2.*AA)
63 IF( ABS(DPNB(I,J)).LT.0.0001) DPNB(I,J)=-0.0001
   FB=VNB(I,J)/DPNB(I,J)
   YCT=RZER+R1*XC+R2*(XC**2 )+R3*(XC**3 )
   IF(YCT.LT.YC) GO TO 64
   VNC=(-B+(B**2 +4.*A*(DPNC*12.-C))**0.5)/(2.*A)
   GO TO 65
64 VNC=(-BB+(BB**2 +4.*AA*(DPNC*12.-CC))**0.5)/(2.*AA)
65 IF( ABS(DPNC).LT.0.0001) DPNC=-0.0001
   FC=VNC/DPNC
   YCT=RZER+R1*XD+R2*(XD**2 )+R3*(XD**3 )
   IF(YDT.LT.YD) GO TO 66
   VND(I,J)=(-B+(B**2 +4.*A*(DPND     *12.-C))**0.5)/(2.*A)
   GO TO 67
66 VND(I,J)=(-BB+(BB**2 +4.*AA*(DPND     *12.-CC))**0.5)/(2.*AA)
67 IF( ABS(DPND     ).LT.0.0001) DPND     =-0.0001
   FD=VND(I,J)/DPND
```

```
   19 PT=(FB*P(I+1,J)+FD*P(I-1,J)+FC*P(I,J-1)*KK3
     6 +FA*P(I,J+1)*KK3)/(FA*KK3+FB+FC*KK3+FD)
      GO TO 20
C
C     LEFT BOUNDARY
C
   17 DPXA=(P(I,J+1)-P(I,J))/HX
      DPYA=(P(I+1,J)-P(I-1,J)+P(I+1,J+1)-P(I-1,J+1))/KK1
      DPNA=(( ABS(DPXA))**2 +( ABS(DPYA))**2 )**0.5
      VNA=(-B+(B**2 +4.*A*(DPNA*12.-C))**0.5)/(2.*A)
      IF( ABS(DPNA).LT.0.0001) DPNA=-0.0001
      FA=VNA/DPNA
      DPXB(I,J)=0.
      DPYB(I,J)=(P(I+1,J)-P(I,J))/HY
      DPNB(I,J)= ABS(DPYB(I,J))
      VNB(I,J)=(-B+(B**2 +4.*A*(DPNB(I,J)*12.-C))**0.5)/(2.*A)
      IF( ABS(DPNB(I,J)).LT.0.0001) DPNB(I,J)=-0.0001
      FB=VNB(I,J)/DPNB(I,J)
      DPXC=(P(I,J)-P(I,J+1))/HX
      DPYC=(P(I+1,J+1)-P(I-1,J+1)+P(I+1,J)-P(I-1,J))/KK1
      DPNC=(( ABS(DPXC))**2 +( ABS(DPYC))**2 )**0.5
      VNC=(-B+(B**2 +4.*A*(DPNC*12.-C))**0.5)/(2.*A)
      IF( ABS(DPNC).LT.0.0001) DPNC=-0.0001
      FC=VNC/DPNC
      DPXD      =0.
      DPYD      =(P(I,J)-P(I-1,J))/HY
      DPND      = ABS(DPYD      )
      VND(I,J)=(-B+(B**2 +4.*A*(DPND      *12.-C))**0.5)/(2.*A)
      IF( ABS(DPND      ).LT.0.0001) DPND      =-0.0001
      FC=VND(I,J)/DPND
      PT=(FB*P(I+1,J)+FD*P(I-1,J)+FC*P(I,J+1)*KK3
     6 +FA*P(I,J+1)*KK3)/(FA*KK3+FB+FC*KK3+FD)
      GO TO 20
C
C     RIGHT BOUNDARY
C
   18 DPXA=(P(I,J)-P(I,J-1))/HX
```

```
      DPYA=(P(I+1,J)-P(I-1,J)+P(I+1,J-1)-P(I-1,J-1))/KK1
      DPNA=(( ABS(DPXA))**2 +( ABS(DPYA))**2 )**0.5
      VNA=(-B+(B**2 +4.*A*(DPNA*12.-C))**0.5)/(2.*A)
      IF( ABS(DPNA).LT.0.0001) DPNA=-0.0001
      FA=VNA/DPNA
      DPXB(I,J)=0.
      DPYB(I,J)=(P(I+1,J)-P(I,J))/HY
      DPNB(I,J)= ABS(DPYB(I,J))
      VNB(I,J)=(-B+(B**2 +4.*A*(DPNB(I,J)*12.-C))**0.5)/(2.*A)
      IF( ABS(DPNB(I,J)).LT.0.0001) DPNB(I,J)=-0.0001
      FB=VNB(I,J)/DPNB(I,J)
      DPXC=(P(I,J)-P(I,J-1))/HX
      DPYC=(P(I+1,J-1)-P(I-1,J-1)+P(I+1,J)-P(I-1,J))/KK1
      DPNC=(( ABS(DPXC))**2 +( ABS(DPYC))**2 )**0.5
      VNC=(-B+(B**2 +4.*A*(DPNC*12.-C))**0.5)/(2.*A)
      IF( ABS(DPNC).LT.0.0001) DPNC=-0.0001
      FC=VNC/DPNC
      DPXD     =0.
      DPYD     =(P(I,J)-P(I-1,J))/HY
      DPND     = ABS(DPYD     )
      VND(I,J)=(-B+(B**2 +4.*A*(DPND     *12.-C))**0.5)/(2.*A)
      IF( ABS(DPND     ).LT.0.0001) DPND     =-0.0001
      FD=VND(I,J)/DPND
      PT=(FB*P(I+1,J)+FD*P(I-1,J)+FC*P(I,J-1)*KK3
     6 +FA*P(I,J-1)*KK3)/(FA*KK3+FB+FC*KK3+FD)
   20 DIFF(I,J)=PT-P(I,J)
      P(I,J)=PT
   26 CONTINUE
      IF(NOIP.EQ.10) GO TO 51
      IF(NOIT.EQ.MAXIT)GO TO 36
      DO 31 J=1,JMAX,1
      DO 30 I=2,IMAX,1
      TEST= ABS(DIFF(I,J))
      IF(TEST.GT.ZIMIT)GO TO 5
   30 CONTINUE
   31 CONTINUE
C
```

```
C     PRINTOUT OF INFORMATION
C
   36 WRITE(6,37)PU
   37 FORMAT('1',//,10X,'UPPER PRESSURE = 'F8.4)
      WRITE(6,38)PL
   38 FORMAT(//,10X,'LOWER PRESSURE = 'F8.4)
      WRITE(6,39)MAXIT
   39 FORMAT(//,10X,'MAXIMUM ITERATIONS = 'I3)
      WRITE(6,40)ZIMIT
   40 FORMAT(//,10X,'MAXIMUM PRESSURE CHANGE = 'F8.6)
      WRITE(6,70)
   70 FORMAT(//,10X,'LEFT BOUNDARY OF DISTURBED GRAIN:')
      WRITE(6,71) LZER,L1, L2, L3
   71 FORMAT(/,10X,'Y = ',F8.4,' + ',F8.4,' X + ',F8.4,' X**2 + ',F8.
     6 4,' X**3')
      WRITE(6,72)
   72 FORMAT(//,10X,'RIGHT BOUNDARY OF DISTURBED GRAIN :')
      WRITE(6,73) RZER, R1, R2, R3
   73 FORMAT(/,10X,'Y = ',F8.4,' + ',F8.4,' X + ',F8.4,' X**2 + ',F8.
     6 4,' X**3')
      WRITE(6,74)
   74 FORMAT(//,10X,'UNDISTURBED GRAIN :')
      WRITE(6,75)A, B, C
   75 FORMAT(/,10X,'DP/DN = ',F10.8,'  V**2 + ',F10.8,' V + ',F10.7)
      WRITE(6,76)
   76 FORMAT(//,10X,'DISTURBED GRAIN :')
      WRITE(6,77) AA, BB, CC
   77 FORMAT(/,10X,'DP/DN = ',F10.8,'  V**2 + ',F10.8,' V + ',F10.7)
      WRITE(6,79)HX,HY
   79 FORMAT(//,10X,'HX = ',F8.4,' HY = ',F8.4)
   51 CONTINUE
      WRITE(6,53)
   53 FORMAT('1',10X,'      PRESSURE DISTRIBUTION')
      WRITE(6,49)NOIT
   49 FORMAT(//,10X,'NUMBER OF ITERATIONS',I4)
      DO 52 L=1,IMAX,1
      I=IMAX+1-L
```

```
      WRITE(6,50) (P(I,J),J=1,12)
   50 FORMAT(/////,1X,12F10.4)
   52 CONTINUE
      WRITE(6,43)
   43 FORMAT('1')
      DO 45 L=1,IMAX,1
      I=IMAX+1-L
      WRITE(6,46) (P(I,J),J=13,JMAX)
   46 FORMAT(/////,1X,13F10.4)
   45 CONTINUE
      IF(NOIT.EQ.MAXIT) GO TO 54
      IF(TEST.LE.ZIMIT)GO TO 54
      NOIP=0
      GO TO 5
   54 CONTINUE
      WRITE(7,81) ((P(I,J),J=1,JMAX),I=1,IMAX)
   81 FORMAT(07F8.4)
C
C     CALCULATION OF FLOW RATE
C
   82 CONTINUE
      WRITE(6,21)
   21 FORMAT('1','  FLOW RATE AT 1 IN INTERVALS STARTING 1/2 IN
     6 FROM TOP')
      AVG=0.
      DC 59 L=1,K5,1
      I=K1+1-L
      TOT=0.
      DO 41 J=2,K3,1
      ANG(I,J)=ATAN(DPXB(I,J)/DPYB(I,J))
      VY(I,J)=VNB(I,J)*COS(ANG(I,J))
   41 TOT=TOT+VY(I,J)
      VY(I,1)=VNB(I,1)*0.5
      TCT=TOT+VY(I,1)
      VY(I,JMAX)=VNB(I,JMAX)*0.5
      TOT=TOT+VY(I,JMAX)
      FLOW=TOT/K3
```

```
      WRITE(6,55) FLOW
   55 FORMAT( /,10X,'FLOW =    ',F8.4,'  CFM/SQ FT'//)
      AVG=AVG+FLOW
   59 CONTINUE
      AVG=AVG/25.
      WRITE(6,58) AVG
   58 FORMAT(1X,'  AVERAGE FLOW RATE =  ',F10.4,'CFM/ SQ FT')
      WRITE(6,85)
   85 FORMAT('1',10X,'VELOCITY DISTRIBUTION')
      DO 88 L=2,K1,1
      I=IMAX+1-L
      WRITE(6,87) (VNB(I,J),J=1,12)
   87 FORMAT(/////,1X,12F10.3)
   88 CONTINUE
      WRITE(6,98) (VND(2,J),J=1,12)
   98 FORMAT(/////,1X,12F10.3)
      WRITE(6,44)
   44 FORMAT('1')
      DO 47 L=2,K1,1
      I=IMAX+1-L
      WRITE(6,48) (VNB(I,J),J=13,25)
   48 FORMAT(/////,1X,13F10.3)
   47 CONTINUE
      WRITE(6,42) (VND(2,J),J=13,JMAX)
   42 FORMAT(/////,1X,13F10.3)
      WRITE (6,86)
   86 FORMAT('1')
      STOP
      END
```

APPENDIX F: COMPUTED PRESSURE AND VELOCITY DISTRIBUTIONS

GRID SPACING: 1 IN. X 1 IN.; AUGER SPEED: 4.35 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2 BULK DENSITY: 45.53 LB/FT^3 (DISTURBED), 48.73 LB/FT^3 (UNDISTURBED)

Figure F-1. Computed air pressures over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-10

26.031	25.937	25.673	37.058	37.699	38.281	38.651	38.964	39.148	39.278	39.370	39.423	39.443	39.448	39.423	39.366	39.274	39.149	39.003	38.842	38.693	38.519	26.372	26.375	26.381
26.268	26.183	25.791	35.587	37.813	38.534	38.883	39.076	39.212	39.314	39.392	39.445	39.463	39.463	39.438	39.381	39.311	39.201	39.039	38.834	38.594	38.412	26.318	26.380	26.403
26.801	26.892	27.325	28.783	35.953	39.370	39.242	39.269	39.351	39.423	39.473	39.522	39.554	39.526	39.489	39.444	39.378	39.271	39.105	38.851	38.439	37.915	26.218	26.413	26.476
27.011	27.067	27.227	27.438	35.714	39.460	39.400	39.400	39.436	39.483	39.527	39.562	39.559	39.609	39.595	39.557	39.483	39.432	39.320	39.072	39.447	36.227	26.239	26.626	26.706
27.065	27.074	27.062	27.007	35.267	39.282	39.358	39.450	39.524	39.568	39.616	39.645	39.664	39.670	39.653	39.633	39.635	39.627	39.691	39.884	40.520	29.210	27.741	27.287	27.182
27.135	27.110	26.996	26.753	31.569	38.980	39.253	39.478	39.596	39.679	39.717	39.740	39.745	39.746	39.747	39.732	39.724	39.733	39.773	39.946	40.257	27.843	27.616	27.431	27.369
27.295	27.256	27.161	26.646	36.705	38.855	39.437	39.625	39.723	39.786	39.817	39.824	39.824	39.823	39.822	39.800	39.772	39.755	39.754	39.791	39.902	27.382	27.403	27.383	27.373
27.524	27.555	27.655	28.369	29.475	40.825	40.120	39.935	39.885	39.856	39.916	39.920	39.906	39.900	39.894	39.871	39.811	39.748	39.650	39.537	39.478	27.154	27.256	27.312	27.329
27.670	27.684	27.744	27.855	27.467	40.294	40.049	39.974	39.971	39.976	39.977	40.005	39.956	39.979	39.952	39.925	39.862	39.756	39.568	39.232	38.751	26.906	27.161	27.290	27.327
27.767	27.751	27.724	27.634	27.407	39.406	39.651	39.915	40.017	40.063	40.071	40.058	40.066	40.054	40.030	39.978	39.933	39.836	39.655	39.070	36.905	26.194	27.252	27.402	27.438
27.901	27.882	27.816	27.661	27.187	37.375	39.479	39.991	40.125	40.141	40.168	40.156	40.153	40.142	40.121	40.102	40.086	40.110	40.285	40.981	29.595	28.196	27.776	27.682	27.662
28.008	28.021	28.055	28.162	28.555	29.541	41.358	40.635	40.391	40.305	40.264	40.261	40.228	40.158	40.160	40.144	40.130	40.125	40.181	40.441	28.062	27.954	27.868	27.814	27.805
28.114	28.125	28.143	28.188	28.279	28.352	40.791	40.503	40.383	40.356	40.325	40.304	40.256	40.279	40.241	40.193	40.121	39.992	39.778	39.487	27.502	27.750	27.854	27.898	27.901
28.221	28.221	28.189	28.119	28.021	27.754	39.799	40.042	40.243	40.249	40.357	40.400	40.333	40.364	40.341	40.288	40.216	40.036	39.481	37.399	27.265	27.780	27.950	28.006	28.020
28.128	28.325	28.311	28.222	28.027	27.506	37.679	39.741	40.262	40.409	40.468	40.493	40.456	40.481	40.476	40.441	40.437	40.612	41.286	29.929	28.630	28.292	28.218	28.206	28.203
28.465	28.404	28.453	28.463	28.527	28.862	30.143	41.540	40.845	40.665	40.624	40.612	40.554	40.569	40.545	40.518	40.446	40.338	40.303	28.320	28.417	28.406	28.388	28.386	28.388
28.618	28.606	28.666	28.607	28.620	28.635	28.547	40.555	40.605	40.688	40.727	40.757	40.749	40.730	40.652	40.659	40.570	40.052	38.072	27.857	28.345	28.493	28.544	28.545	28.551
28.770	28.771	28.753	28.740	28.700	28.560	28.084	38.350	40.309	40.787	40.910	40.927	40.939	40.907	40.876	40.897	41.105	41.837	30.417	29.177	28.843	28.760	28.736	28.748	28.746
28.922	28.923	28.926	28.937	28.965	29.058	29.410	30.675	42.187	41.428	41.223	41.155	41.122	41.089	41.018	40.910	40.819	40.821	28.796	28.932	28.943	28.953	28.956	28.944	28.947
29.073	29.071	29.081	29.092	29.133	29.162	29.183	29.085	41.216	41.233	41.326	41.384	41.374	41.325	41.192	40.937	40.404	38.552	28.351	28.921	29.092	29.133	29.145	29.158	29.157
29.225	29.228	29.250	29.247	29.297	29.305	29.175	28.658	39.022	40.572	41.529	41.738	41.769	41.661	41.500	41.394	41.875	30.772	29.775	29.513	29.435	29.404	29.385	29.373	29.376
29.378	29.395	29.425	29.490	29.554	29.628	29.782	30.142	31.271	42.650	42.301	42.322	42.329	42.169	41.743	40.713	39.455	29.509	29.845	29.820	29.749	29.679	29.636	29.603	29.590
29.546	29.565	29.605	29.668	29.761	29.899	30.049	30.177	29.939	40.495	42.449	42.972	43.119	43.052	42.687	41.203	31.800	30.919	30.492	30.230	30.055	29.942	29.853	29.802	29.785
29.658	29.679	29.739	29.837	29.964	30.146	30.396	30.737	31.317	32.613	44.623	44.265	44.306	44.433	44.937	33.074	32.082	31.353	30.867	30.546	30.318	30.150	30.040	29.975	29.957
29.726	29.755	29.825	29.946	30.125	30.340	30.619	30.980	31.338	31.380	42.778	44.977	45.380	45.116	43.087	31.737	31.810	31.451	31.060	30.727	30.474	30.294	30.161	30.090	30.074
29.750	29.810	29.886	30.307	30.181	30.433	30.771	31.230	31.890	32.965	35.042	48.220	47.577	46.369	35.254	33.283	32.296	31.667	31.201	30.842	30.566	30.362	30.233	30.156	30.129

GRID SPACING: 1 IN. X 1 IN.; AUGER SPEED: 4.35 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2; BULK DENSITY: 45.53 LB/FT^3 (DISTURBED), 48.73 LB/FT^3 (UNDISTURBED)

Figure F-2. Computed air velocities over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-10

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0331	0.0325	0.0323	0.0316	0.0325	0.0334	0.0340	0.0344	0.0347	0.0349	0.0351	0.0352	0.0392	0.0352	0.0351	0.0350	0.0349	0.0347	0.0345	0.0342	0.0340	0.0338	0.0338	0.0338	0.0338
0.0667	0.0661	0.0649	0.0610	0.0652	0.0672	0.0683	0.0691	0.0596	0.0699	0.0702	0.0704	0.0704	0.0704	0.0703	0.0701	0.0699	0.0695	0.0690	0.0684	0.0678	0.0674	0.0674	0.0675	0.0676
0.1014	0.1012	0.1006	0.1002	0.1011	0.1022	0.1032	0.1040	0.1046	0.1051	0.1054	0.1057	0.1058	0.1057	0.1056	0.1053	0.1049	0.1044	0.1036	0.1026	0.1014	0.1002	0.1008	0.1011	0.1015
[illegible]	0.1365	0.1363	0.1363	0.1367	0.1375	0.1383	0.1391	0.1398	0.1404	0.1408	0.1411	0.1412	0.1412	0.1410	0.1407	0.1402	0.1395	0.1386	0.1372	0.1350	0.1305	0.1342	0.1357	0.1360
0.1715	0.1715	0.1717	0.1715	0.1717	0.1724	0.1734	0.1743	0.1751	0.1758	0.1763	0.1766	0.1768	0.1767	0.1766	0.1762	0.1757	0.1750	0.1741	0.1731	0.1718	0.1707	0.1710	0.1715	0.1716
0.2075	0.2071	0.2069	0.2062	0.2056	0.2069	0.2084	0.2096	0.2136	0.2114	0.2119	0.2123	0.2124	0.2124	0.2122	0.2119	0.2113	0.2107	0.2099	0.2090	0.2083	0.2077	0.2075	0.2076	0.2076
0.2434	0.2431	0.2423	0.2400	0.2367	0.2412	0.2436	0.2451	0.2463	0.2471	0.2477	0.2481	0.2483	0.2483	0.2480	0.2476	0.2471	0.2464	0.2456	0.2448	0.2442	0.2438	0.2436	0.2436	0.2436
0.2798	0.2796	0.2791	0.2783	0.2776	0.2786	0.2799	0.2811	0.2822	0.2831	0.2837	0.2841	0.2843	0.2842	0.2840	0.2835	0.2829	0.2820	0.2811	0.2802	0.2795	0.2793	0.2794	0.2795	0.2795
0.3165	0.3164	0.3160	0.3154	0.3150	0.3152	0.3161	0.3172	0.3183	0.3192	0.3198	0.3202	0.3204	0.3203	0.3200	0.3195	0.3188	0.3178	0.3165	0.3151	0.3137	0.3147	0.3150	0.3154	0.3155
0.3537	0.3535	0.3530	0.3522	0.3512	0.3504	0.3518	0.3533	0.3545	0.3554	0.3561	0.3565	0.3567	0.3566	0.3563	0.3557	0.3548	0.3537	0.3521	0.3497	0.3451	0.3491	0.3508	0.3516	0.3518
0.3910	0.3908	0.3902	0.3890	0.3869	0.3826	0.3871	0.3894	0.3909	0.3919	0.3926	0.3930	0.3931	0.3930	0.3926	0.3920	0.3911	0.3900	0.3887	0.3874	0.3864	0.3871	0.3879	0.3884	0.3846
0.4244	0.4235	0.4283	0.4270	0.4259	0.4248	0.4256	0.4267	0.4278	0.4286	0.4293	0.4297	0.4298	0.4255	0.4292	0.4285	0.4275	0.4264	0.4252	0.4243	0.4241	0.4246	0.4252	0.4256	0.4257
0.4668	0.4666	0.4660	0.4652	0.4641	0.4633	0.4631	0.4638	0.4647	0.4655	0.4661	0.4665	0.4666	0.4664	0.4659	0.4651	0.4640	0.4627	0.4612	0.4598	0.4606	0.4617	0.4625	0.4630	0.4632
0.5051	0.5048	0.5042	0.5033	0.5019	0.5004	0.4991	0.5002	0.5014	0.5024	0.5031	0.5035	0.5035	0.5033	0.5028	0.5019	0.5007	0.4991	0.4966	0.4921	0.4966	0.4995	0.5001	0.5009	0.5010
0.5437	0.5435	0.5428	0.5416	0.5398	0.5370	0.5320	0.5362	0.5382	0.5395	0.5403	0.5407	0.5407	0.5405	0.5399	0.5390	0.5378	0.5364	0.5351	0.5345	0.5359	0.5374	0.5385	0.5391	0.5393
0.5827	0.5825	0.5817	0.5806	0.5789	0.5769	0.5749	0.5751	0.5761	0.5770	0.5778	0.5782	0.5782	0.5779	0.5773	0.5763	0.5750	0.5734	0.5720	0.5730	0.5747	0.5761	0.5773	0.5763	0.5782
0.6222	0.6219	0.6212	0.6199	0.6183	0.6163	0.6141	0.6125	0.6136	0.6147	0.6155	0.6159	0.6160	0.6157	0.6150	0.6139	0.6124	0.6103	0.6055	0.6106	0.6134	0.6153	0.6165	0.6172	0.6175
0.6621	0.6618	0.6610	0.6598	0.6580	0.6556	0.6522	0.6466	0.6507	0.6526	0.6536	0.6541	0.6541	0.6537	0.6530	0.6520	0.6507	0.6496	0.6493	0.6513	0.6534	0.6551	0.6564	0.6571	0.6573
0.7024	0.7021	0.7013	0.7001	0.6984	0.6962	0.6936	0.6911	0.6909	0.6916	0.6923	0.6927	0.6926	0.6922	0.6913	0.6901	0.6887	0.6876	0.6893	0.6916	0.6938	0.6955	0.6959	0.6975	0.6973
0.7432	0.7425	0.7422	0.7410	0.7393	0.7371	0.7345	0.7318	0.7297	0.7304	0.7312	0.7317	0.7317	0.7311	0.7300	0.7284	0.7261	0.7221	0.7282	0.7320	0.7346	0.7365	0.7378	0.7386	0.7388
0.7844	0.7842	0.7835	0.7823	0.7807	0.7785	0.7756	0.7715	0.7650	0.7688	0.7706	0.7714	0.7714	0.7707	0.7693	0.7675	0.7661	0.7671	0.7706	0.7738	0.7764	0.7782	0.7795	0.7802	0.7804
0.8261	0.8259	0.8253	0.8242	0.8227	0.8207	0.8181	0.9149	0.8113	0.8102	0.8113	0.8122	0.8122	0.8112	0.8051	0.8059	0.8022	0.8090	0.8134	0.8166	0.8193	0.8207	0.8219	0.8225	0.8227
0.8682	0.8681	0.8676	0.8667	0.8654	0.8637	0.8615	0.8585	0.8544	0.8480	0.8524	0.8543	0.8545	0.8534	0.8506	0.8449	0.8500	0.8545	0.8579	0.8605	0.8625	0.8639	0.8649	0.9654	0.8656
0.9107	0.9106	0.9102	0.9056	0.9087	0.9075	0.9059	0.9037	0.9010	0.9981	0.8974	0.8937	0.8990	0.8981	0.8962	0.8963	0.8987	0.9013	0.9035	0.9053	0.9067	0.9077	0.9043	0.9087	0.9099
0.9535	0.9534	0.9532	0.9529	0.9524	0.9517	0.9509	0.9497	0.9479	0.9450	0.9392	0.9444	0.9456	0.9441	0.9386	0.9441	0.9468	0.9485	0.9497	0.9506	0.9514	0.9519	0.9522	0.9524	0.9525
0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963	0.9963

GRID SPACING: 1 IN. X 1 IN.; AUGER SPEED: 4.35 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2; BULK DENSITY: 45.61 LB/FT^3 (DISTURBED), 49.49 LB/FT^3 (UNDISTURBED)

Figure F-3. Computed air pressures over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-12

24.797	24.693	24.403	36.999	37.719	38.378	38.851	39.161	39.362	39.517	39.631	39.694	39.716	39.699	39.653	39.590	39.491	39.358	39.184	38.994	38.813	38.687	25.141	25.147	25.151
25.058	24.959	24.510	35.148	37.883	38.704	39.070	39.308	39.480	39.587	39.665	39.732	39.750	39.741	39.721	39.660	39.555	39.404	39.217	38.973	38.718	38.506	25.067	25.129	25.155
25.604	25.715	26.185	27.759	40.323	39.627	39.485	39.524	39.604	39.693	39.751	39.783	39.822	39.817	39.780	39.732	39.640	39.515	39.328	39.036	38.544	37.951	24.968	25.168	25.231
25.845	25.908	26.095	26.318	40.011	39.738	39.652	39.669	39.729	39.786	39.845	39.881	39.887	39.905	39.876	39.827	39.783	39.682	39.549	39.276	38.577	36.049	25.004	25.433	25.517
25.943	25.934	25.921	25.843	39.543	39.552	39.633	39.710	39.819	39.891	39.947	39.962	39.983	39.973	39.985	39.958	39.935	39.940	39.973	40.208	40.954	28.238	26.643	26.145	26.043
26.019	25.993	25.862	25.599	38.757	39.226	39.587	39.795	39.901	39.977	40.030	40.073	40.075	40.085	40.070	40.059	40.029	40.038	40.122	40.286	40.626	26.735	26.487	26.287	26.225
26.179	26.137	25.980	25.493	36.647	39.119	39.761	39.958	40.068	40.121	40.145	40.181	40.201	40.188	40.151	40.139	40.113	40.098	40.103	40.156	40.258	26.256	26.287	26.272	26.252
26.458	26.483	26.603	27.042	28.569	41.343	40.560	40.330	40.279	40.288	40.252	40.252	40.285	40.286	40.265	40.209	40.166	40.074	39.980	39.861	39.798	26.019	26.132	26.193	26.214
26.626	26.636	26.690	26.806	26.919	40.744	40.480	40.401	40.395	40.389	40.409	40.407	40.408	40.389	40.362	40.305	40.239	40.112	39.875	39.490	38.993	25.751	26.044	26.190	26.229
26.768	26.753	26.718	26.609	26.338	39.758	40.082	40.336	40.453	40.516	40.526	40.526	40.498	40.485	40.465	40.409	40.338	40.255	40.016	39.347	36.860	25.661	26.159	26.331	26.373
26.895	26.882	26.832	26.673	26.138	37.462	39.888	40.457	40.597	40.623	40.632	40.635	40.643	40.612	40.571	40.546	40.513	40.566	40.799	41.579	28.741	27.217	26.761	26.642	26.621
27.082	27.078	27.098	27.215	27.651	29.139	42.079	41.223	40.948	40.841	40.797	40.765	40.725	40.710	40.686	40.662	40.628	40.600	40.681	40.960	27.063	26.911	26.869	26.807	26.793
27.202	27.210	27.221	27.261	27.357	27.435	41.430	41.084	40.954	40.927	40.911	40.897	40.881	40.846	40.800	40.748	40.675	40.516	40.254	39.921	26.489	26.769	26.883	26.934	26.943
27.354	27.347	27.317	27.253	27.121	26.809	40.327	40.642	40.858	40.942	40.999	41.016	41.018	40.958	40.950	40.878	40.793	40.602	39.993	37.609	26.292	26.946	27.038	27.101	27.122
27.501	27.487	27.453	27.369	27.160	26.585	37.934	40.313	40.919	41.101	41.150	41.171	41.156	41.136	41.117	41.097	41.099	41.284	42.063	29.212	27.818	27.438	27.372	27.371	27.366
27.679	27.679	27.673	27.671	27.751	28.122	29.510	42.429	41.625	41.428	41.385	41.375	41.356	41.326	41.298	41.254	41.191	41.057	40.981	27.478	27.589	27.588	27.578	27.584	27.589
27.895	27.884	27.876	27.864	27.857	27.875	27.771	41.328	41.379	41.488	41.552	41.567	41.531	41.554	41.521	41.465	41.317	40.807	38.486	27.024	27.574	27.737	27.782	27.801	27.810
28.066	28.082	28.079	28.065	28.022	27.863	27.317	38.841	41.145	41.670	41.795	41.823	41.793	41.776	41.767	41.805	42.014	42.876	29.877	28.522	28.157	28.085	28.080	28.067	28.068
28.298	28.292	28.297	28.311	28.339	28.439	28.827	30.201	43.338	42.467	42.230	42.149	42.099	42.035	41.949	41.837	41.731	41.717	28.124	28.303	28.336	28.334	28.339	28.349	28.347
28.485	28.502	28.524	28.548	28.573	28.601	28.615	28.488	42.254	42.285	42.396	42.461	42.456	42.382	42.230	41.966	41.370	39.192	27.702	28.340	28.548	28.606	28.613	28.610	28.616
28.724	28.724	28.741	28.777	28.812	28.801	28.667	28.095	39.792	42.066	42.702	42.929	42.970	42.867	42.672	42.539	43.130	30.424	29.347	29.051	28.971	28.546	28.928	28.906	28.897
28.916	28.937	28.974	29.021	29.096	29.198	29.367	29.772	30.996	44.102	43.643	43.678	43.706	43.524	43.040	42.076	40.362	29.101	29.482	29.455	29.354	29.272	29.223	29.200	29.185
29.107	29.122	29.185	29.275	29.387	29.531	29.705	29.859	29.656	41.610	43.924	44.539	44.708	44.633	44.221	42.470	31.671	30.720	30.230	29.945	29.753	29.608	29.503	29.447	29.434
29.255	29.310	29.357	29.467	29.631	29.858	30.144	30.534	31.177	32.580	46.498	46.122	46.179	46.324	46.965	33.131	32.050	31.226	30.695	30.323	30.066	29.875	29.751	29.673	29.647
29.373	29.407	29.498	29.630	29.817	30.077	30.419	30.822	31.247	31.316	44.404	47.012	47.508	47.219	44.806	31.683	31.790	31.391	30.936	30.566	30.274	30.051	29.894	29.816	29.793
29.439	29.469	29.555	29.708	29.929	30.214	30.594	31.127	31.887	33.113	35.459	50.917	50.165	51.097	35.696	33.482	32.361	31.640	31.115	30.699	30.377	30.152	29.999	29.905	29.874

GRID SPACING: 1IN. X 1IN.; AUGER SPEED: 4.35 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2; BULK DENSITY: 45.61 LB/FT^3 (DISTURBED), 49.49 LB/FT^3 (UNDISTURBED)

Figure F-4. Computed air velocities over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-12

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0326	0.0326	0.0326	0.0326	0.0326	0.0327	0.0328	0.0329	0.0330	0.0331	0.0331	0.0331	0.0331	0.0330	0.0329	0.0327	0.0324	0.0320	0.0313	0.0303	0.0293	0.0302	0.0310	0.0315	0.0317
0.0652	0.0652	0.0651	0.0651	0.0652	0.0653	0.0655	0.0657	0.0660	0.0661	0.0663	0.0663	0.0663	0.0662	0.0659	0.0656	0.0650	0.0643	0.0630	0.0608	0.0561	0.0607	0.0626	0.0635	0.0637
0.0978	0.0977	0.0976	0.0975	0.0976	0.0978	0.0982	0.0986	0.0990	0.0992	0.0995	0.0996	0.0995	0.0994	0.0991	0.0986	0.0980	0.0972	0.0962	0.0951	0.0942	0.0949	0.0958	0.0963	0.0965
0.1304	0.1303	0.1300	0.1297	0.1295	0.1300	0.1307	0.1314	0.1320	0.1324	0.1327	0.1329	0.1329	0.1327	0.1324	0.1319	0.1312	0.1304	0.1296	0.1289	0.1286	0.1289	0.1293	0.1297	0.1298
0.1632	0.1630	0.1624	0.1614	0.1605	0.1618	0.1632	0.1643	0.1652	0.1658	0.1662	0.1664	0.1664	0.1662	0.1658	0.1652	0.1645	0.1635	0.1626	0.1619	0.1620	0.1624	0.1629	0.1632	0.1634
0.1965	0.1962	0.1952	0.1932	0.1885	0.1935	0.1961	0.1976	0.1986	0.1993	0.1998	0.2000	0.2000	0.1998	0.1994	0.1988	0.1978	0.1966	0.1951	0.1936	0.1946	0.1957	0.1966	0.1970	0.1972
0.2304	0.2302	0.2296	0.2287	0.2280	0.2290	0.2303	0.2314	0.2323	0.2331	0.2336	0.2338	0.2339	0.2337	0.2332	0.2325	0.2315	0.2299	0.2273	0.2222	0.2271	0.2294	0.2305	0.2311	0.2313
0.2648	0.2646	0.2642	0.2637	0.2635	0.2638	0.2645	0.2654	0.2663	0.2670	0.2675	0.2678	0.2678	0.2677	0.2672	0.2666	0.2657	0.2646	0.2633	0.2623	0.2632	0.2644	0.2652	0.2657	0.2659
0.2994	0.2992	0.2989	0.2982	0.2977	0.2976	0.2983	0.2993	0.3002	0.3010	0.3016	0.3019	0.3020	0.3018	0.3014	0.3008	0.3000	0.2992	0.2985	0.2984	0.2988	0.2995	0.3002	0.3006	0.3007
0.3342	0.3340	0.3334	0.3324	0.3312	0.3301	0.3315	0.3330	0.3342	0.3352	0.3358	0.3362	0.3363	0.3361	0.3357	0.3350	0.3342	0.3333	0.3327	0.3330	0.3338	0.3346	0.3353	0.3357	0.3358
0.3693	0.3690	0.3683	0.3669	0.3644	0.3592	0.3643	0.3669	0.3684	0.3695	0.3702	0.3706	0.3707	0.3705	0.3700	0.3692	0.3681	0.3663	0.3655	0.3669	0.3684	0.3697	0.3705	0.3711	0.3712
0.4049	0.4046	0.4035	0.4027	0.4013	0.4000	0.4003	0.4020	0.4031	0.4041	0.4048	0.4052	0.4053	0.4051	0.4046	0.4037	0.4023	0.3999	0.3949	0.4004	0.4033	0.4050	0.4061	0.4067	0.4069
0.4408	0.4406	0.4399	0.4388	0.4375	0.4364	0.4362	0.4369	0.4379	0.4388	0.4395	0.4400	0.4401	0.4399	0.4394	0.4387	0.4377	0.4366	0.4350	0.4377	0.4395	0.4410	0.4421	0.4427	0.4429
0.4772	0.4769	0.4762	0.4749	0.4733	0.4714	0.4658	0.4710	0.4725	0.4736	0.4744	0.4749	0.4751	0.4749	0.4744	0.4737	0.4728	0.4723	0.4723	0.4743	0.4760	0.4774	0.4785	0.4791	0.4793
0.5140	0.5137	0.5129	0.5114	0.5092	0.5059	0.4993	0.5047	0.5071	0.5086	0.5095	0.5101	0.5103	0.5101	0.5095	0.5085	0.5073	0.5062	0.5093	0.5105	0.5125	0.5141	0.5152	0.5159	0.5161
0.5514	0.5510	0.5501	0.5486	0.5466	0.5441	0.5416	0.5419	0.5429	0.5440	0.5449	0.5455	0.5457	0.5455	0.5448	0.5435	0.5413	0.5366	0.5431	0.5468	0.5494	0.5512	0.5525	0.5532	0.5535
0.5893	0.5889	0.5880	0.5864	0.5843	0.5818	0.5790	0.5770	0.5782	0.5795	0.5806	0.5812	0.5814	0.5812	0.5806	0.5797	0.5789	0.5789	0.5813	0.5847	0.5871	0.5890	0.5903	0.5911	0.5913
0.6277	0.6274	0.6264	0.6248	0.6225	0.6195	0.6152	0.6082	0.6129	0.6152	0.6165	0.6172	0.6175	0.6173	0.6166	0.6156	0.6146	0.6170	0.6201	0.6230	0.6255	0.6274	0.6287	0.6295	0.6297
0.6668	0.6665	0.6655	0.6639	0.6616	0.6587	0.6552	0.6517	0.6512	0.6519	0.6528	0.6536	0.6539	0.6538	0.6529	0.6510	0.6464	0.6538	0.6594	0.6618	0.6644	0.6664	0.6677	0.6685	0.6688
0.7066	0.7063	0.7053	0.7037	0.7014	0.6984	0.6947	0.6907	0.6874	0.6879	0.6892	0.6903	0.6909	0.6910	0.6906	0.6903	0.6909	0.6947	0.6984	0.7016	0.7041	0.7060	0.7074	0.7082	0.7084
0.7471	0.7468	0.7458	0.7443	0.7420	0.7388	0.7346	0.7287	0.7194	0.7227	0.7255	0.7274	0.7284	0.7286	0.7281	0.7277	0.7311	0.7352	0.7390	0.7421	0.7446	0.7464	0.7477	0.7485	0.7487
0.7882	0.7880	0.7871	0.7857	0.7836	0.7807	0.7768	0.7717	0.7651	0.7577	0.7632	0.7657	0.7669	0.7668	0.7654	0.7614	0.7704	0.7762	0.7803	0.7834	0.7858	0.7875	0.7887	0.7894	0.7896
0.8300	0.8298	0.8291	0.8279	0.8261	0.8237	0.8206	0.8165	0.8117	0.8067	0.8050	0.8061	0.8069	0.8068	0.8065	0.8098	0.8146	0.8193	0.8230	0.8258	0.8278	0.8293	0.8303	0.8307	0.8310
0.8723	0.8721	0.8716	0.8707	0.8695	0.8678	0.8654	0.8624	0.8582	0.8523	0.8426	0.8465	0.8484	0.8470	0.8435	0.8536	0.8598	0.8640	0.8670	0.8691	0.8706	0.8717	0.8724	0.8728	0.8730
0.9149	0.9148	0.9145	0.9141	0.9134	0.9125	0.9113	0.9096	0.9072	0.9037	0.8981	0.8899	0.8951	0.8901	0.8986	0.9043	0.9079	0.9103	0.9120	0.9132	0.9140	0.9146	0.9150	0.9152	0.9152
0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577	0.9577

GRID SPACING: 1 IN. X 1 IN.; AUGER SPEED: 8.71 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2 BULK DENSITY: 45.03 LB/FT^3 (DISTURBED), 49.50 LB/FT^3 (UNDISTURBED)

Figure F-5. Computed air pressures over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-4

24.534	24.532	24.529	24.534	41.762	41.818	41.893	41.978	42.059	42.126	42.172	42.188	42.171	42.110	42.000	41.834	41.587	41.211	40.640	39.812	38.893	23.317	23.745	23.986	24.059
24.532	24.527	24.517	24.510	41.712	41.773	41.864	41.965	42.064	42.142	42.198	42.221	42.215	42.176	42.092	41.960	41.774	41.510	41.053	40.039	36.731	23.473	24.028	24.224	24.274
24.528	24.512	24.475	24.431	41.555	41.643	41.788	41.939	42.068	42.168	42.237	42.281	42.288	42.267	42.215	42.142	42.068	42.057	42.275	43.189	27.220	25.399	24.833	24.669	24.633
24.542	24.513	24.426	24.303	41.207	41.423	41.703	41.942	42.116	42.238	42.318	42.361	42.373	42.361	42.331	42.281	42.238	42.238	42.369	42.742	25.471	25.221	25.015	24.911	24.880
24.648	24.596	24.434	24.122	40.371	41.097	41.669	42.021	42.232	42.359	42.436	42.477	42.484	42.469	42.441	42.389	42.304	42.195	42.091	42.083	24.911	25.009	25.029	25.029	25.024
24.878	24.834	24.666	24.137	37.803	41.097	41.977	42.286	42.430	42.520	42.578	42.610	42.624	42.612	42.575	42.508	42.378	42.126	41.662	41.037	24.584	24.912	25.068	25.132	25.147
25.211	25.249	25.425	26.007	27.864	44.134	43.115	42.798	42.712	42.706	42.723	42.741	42.751	42.758	42.743	42.708	42.624	42.376	41.558	38.300	24.507	25.061	25.240	25.259	25.312
25.429	25.459	25.558	25.759	25.991	43.545	43.109	42.913	42.853	42.850	42.861	42.877	42.851	42.900	42.923	42.966	43.094	43.465	44.545	28.169	26.330	25.755	25.579	25.526	25.513
25.535	25.538	25.531	25.492	25.362	42.786	42.749	42.802	42.870	42.929	42.970	42.996	43.015	43.025	43.036	43.080	43.179	43.415	43.892	26.228	26.020	25.830	25.725	25.679	25.668
25.640	25.615	25.533	25.349	24.986	41.636	42.229	42.668	42.898	43.015	43.077	43.115	43.131	43.132	43.115	43.080	43.041	43.009	43.064	25.582	25.717	25.767	25.784	25.788	25.787
25.794	25.772	25.691	25.475	24.869	38.784	42.025	42.833	43.084	43.175	43.219	43.246	43.261	43.250	43.206	43.104	42.886	42.465	41.891	25.174	25.558	25.760	25.854	25.895	25.905
25.999	26.005	26.038	26.173	26.693	28.467	44.933	43.841	43.499	43.407	43.397	43.402	43.401	43.387	43.354	43.273	43.038	42.238	39.018	25.059	25.675	25.901	25.999	26.039	26.050
26.208	26.208	26.224	26.270	26.365	26.433	44.047	43.649	43.529	43.506	43.517	43.538	43.552	43.562	43.589	43.691	44.041	45.155	28.643	26.884	26.366	26.239	26.218	26.224	26.228
26.405	26.395	26.362	26.293	26.129	25.755	42.612	43.049	43.378	43.553	43.633	43.672	43.650	43.655	43.701	43.734	43.861	44.244	26.641	26.561	26.464	26.424	26.415	26.416	26.418
26.617	26.605	26.559	26.453	26.205	25.532	39.572	42.702	43.468	43.708	43.801	43.836	43.840	43.821	43.760	43.610	43.303	42.884	25.922	26.317	26.491	26.567	26.602	26.618	26.624
26.858	26.854	26.840	26.835	26.913	27.342	28.940	45.399	44.338	44.077	44.042	44.053	44.054	44.031	43.558	43.731	42.962	35.850	25.746	26.422	26.672	26.776	26.827	26.850	26.857
27.122	27.121	27.114	27.103	27.094	27.075	26.901	43.870	43.965	44.114	44.206	44.268	44.305	44.339	44.404	44.683	45.760	29.198	27.608	27.169	27.083	27.082	27.095	27.106	27.110
27.404	27.404	27.397	27.374	27.305	27.096	26.415	40.633	43.607	44.258	44.441	44.518	44.564	44.572	44.519	44.382	44.282	27.213	27.369	27.374	27.369	27.370	27.374	27.376	27.377
27.700	27.703	27.704	27.708	27.724	27.808	28.214	29.702	46.338	45.126	44.832	44.820	44.871	44.853	44.771	44.121	41.122	26.758	27.421	27.610	27.656	27.663	27.661	27.658	27.658
28.014	28.017	28.029	28.042	28.051	28.043	27.979	27.698	44.632	44.543	44.794	45.055	45.258	45.463	45.867	47.090	30.172	28.643	28.188	28.062	28.015	27.984	27.963	27.951	27.949
28.337	28.344	28.368	28.401	28.424	28.394	28.178	27.372	41.339	43.535	44.806	45.422	45.689	45.748	45.687	45.668	28.272	28.457	28.445	28.404	28.355	28.310	28.274	28.253	28.246
28.641	28.659	28.703	28.780	28.887	29.031	29.248	29.712	30.771	43.736	45.932	46.366	46.458	46.266	45.528	42.647	27.962	28.654	28.796	28.769	28.699	28.631	28.575	28.542	28.531
28.918	28.946	29.019	29.141	29.319	29.566	29.919	30.443	31.252	32.125	49.059	47.900	47.650	47.652	48.471	31.495	30.198	29.679	29.416	29.225	29.067	28.944	28.853	28.799	28.784
29.151	29.182	29.275	29.434	29.666	29.973	30.363	30.813	31.163	30.758	45.769	48.005	48.746	47.771	45.364	30.475	30.630	30.302	29.944	29.639	29.399	29.221	29.098	29.024	29.001
29.305	29.350	29.459	29.643	29.913	30.281	30.761	31.380	32.172	33.258	34.904	50.155	52.520	49.983	34.728	32.987	31.804	31.002	30.416	29.982	29.661	29.430	29.277	29.190	29.161
29.404	29.441	29.558	29.755	30.045	30.454	31.003	31.742	32.759	34.228	36.456	39.548	63.146	29.465	36.285	33.973	32.446	31.412	30.692	30.175	29.806	29.544	29.368	29.270	29.240

GRID SPACING: 1 IN. X 1 IN.; AUGER SPEED: 8.71 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2; BULK DENSITY: 45.03 LB/FT^3 (DISTURBED), 49.50 LB/FT^3 (UNDISTURBED)

Figure F-6. Computed air velocities over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-4

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0334	0.0334	0.0334	0.0334	0.0335	0.0336	0.0337	0.0338	0.0339	0.0339	0.0340	0.0341	0.0341	0.0340	0.0339	0.0338	0.0336	0.0333	0.0329	0.0322	0.0315	0.0321	0.0326	0.0329	0.0330
0.0668	0.0668	0.0668	0.0669	0.0670	0.0671	0.0673	0.0675	0.0677	0.0679	0.0681	0.0681	0.0681	0.0681	0.0680	0.0677	0.0674	0.0668	0.0660	0.0645	0.0614	0.0643	0.0655	0.0661	0.0662
0.1002	0.1002	0.1002	0.1002	0.1004	0.1006	0.1010	0.1013	0.1017	0.1019	0.1021	0.1023	0.1023	0.1022	0.1021	0.1018	0.1013	0.1008	0.1001	0.0993	0.0985	0.0990	0.0995	0.0998	0.0999
0.1338	0.1337	0.1337	0.1336	0.1336	0.1340	0.1346	0.1352	0.1356	0.1360	0.1363	0.1365	0.1365	0.1365	0.1362	0.1359	0.1354	0.1349	0.1342	0.1337	0.1334	0.1334	0.1336	0.1338	0.1339
0.1678	0.1675	0.1672	0.1667	0.1663	0.1672	0.1682	0.1691	0.1698	0.1702	0.1706	0.1708	0.1709	0.1708	0.1705	0.1701	0.1696	0.1689	0.1682	0.1677	0.1675	0.1676	0.1678	0.1680	0.1680
0.2017	0.2016	0.2011	0.1999	0.1970	0.2004	0.2021	0.2033	0.2040	0.2046	0.2050	0.2052	0.2053	0.2052	0.2049	0.2045	0.2038	0.2029	0.2018	0.2008	0.2012	0.2017	0.2021	0.2023	0.2024
0.2364	0.2363	0.2360	0.2355	0.2352	0.2360	0.2370	0.2378	0.2386	0.2392	0.2396	0.2398	0.2399	0.2398	0.2395	0.2390	0.2382	0.2371	0.2353	0.2319	0.2347	0.2360	0.2366	0.2369	0.2369
0.2714	0.2711	0.2712	0.2710	0.2710	0.2713	0.2719	0.2726	0.2733	0.2738	0.2742	0.2745	0.2746	0.2745	0.2742	0.2737	0.2730	0.2721	0.2711	0.2702	0.2706	0.2711	0.2715	0.2717	0.2718
0.3068	0.3066	0.3064	0.3061	0.3060	0.3060	0.3066	0.3073	0.3080	0.3086	0.3090	0.3093	0.3094	0.3092	0.3089	0.3084	0.3078	0.3071	0.3064	0.3061	0.3061	0.3063	0.3066	0.3067	0.3068
0.3420	0.3419	0.3416	0.3411	0.3405	0.3399	0.3409	0.3419	0.3428	0.3434	0.3439	0.3442	0.3442	0.3441	0.3437	0.3432	0.3425	0.3418	0.3412	0.3411	0.3413	0.3415	0.3417	0.3419	0.3419
0.3778	0.3775	0.3771	0.3763	0.3748	0.3717	0.3750	0.3767	0.3777	0.3784	0.3789	0.3792	0.3792	0.3790	0.3786	0.3780	0.3771	0.3761	0.3751	0.3756	0.3762	0.3767	0.3770	0.3772	0.3773
0.4135	0.4133	0.4130	0.4123	0.4115	0.4108	0.4114	0.4122	0.4130	0.4136	0.4141	0.4143	0.4143	0.4141	0.4136	0.4129	0.4118	0.4101	0.4067	0.4098	0.4112	0.4120	0.4125	0.4127	0.4128
0.4498	0.4495	0.4491	0.4485	0.4478	0.4472	0.4472	0.4476	0.4483	0.4489	0.4493	0.4495	0.4495	0.4493	0.4488	0.4481	0.4473	0.4464	0.4457	0.4463	0.4471	0.4478	0.4482	0.4485	0.4486
0.4860	0.4859	0.4854	0.4847	0.4838	0.4828	0.4819	0.4826	0.4835	0.4842	0.4846	0.4849	0.4848	0.4846	0.4841	0.4834	0.4827	0.4821	0.4821	0.4826	0.4832	0.4838	0.4842	0.4845	0.4846
0.5228	0.5225	0.5220	0.5211	0.5198	0.5179	0.5142	0.5172	0.5187	0.5196	0.5201	0.5203	0.5203	0.5200	0.5195	0.5187	0.5177	0.5168	0.5175	0.5185	0.5194	0.5200	0.5205	0.5209	0.5209
0.5595	0.5593	0.5588	0.5580	0.5568	0.5553	0.5539	0.5540	0.5546	0.5553	0.5557	0.5560	0.5559	0.5556	0.5550	0.5540	0.5523	0.5491	0.5526	0.5545	0.5557	0.5566	0.5571	0.5575	0.5576
0.5967	0.5965	0.5960	0.5951	0.5939	0.5924	0.5908	0.5896	0.5903	0.5910	0.5915	0.5918	0.5917	0.5914	0.5908	0.5900	0.5852	0.5889	0.5902	0.5915	0.5927	0.5935	0.5941	0.5945	0.5946
0.6342	0.6340	0.6334	0.6325	0.6312	0.6294	0.6269	0.6227	0.6256	0.6269	0.6275	0.6278	0.6277	0.6274	0.6268	0.6259	0.6251	0.6260	0.6275	0.6288	0.6300	0.6309	0.6315	0.6319	0.6320
0.6720	0.6718	0.6712	0.6703	0.6690	0.6674	0.6654	0.6634	0.6631	0.6634	0.6638	0.6641	0.6640	0.6637	0.6630	0.6616	0.6585	0.6625	0.6648	0.6665	0.6677	0.6687	0.6693	0.6697	0.6699
0.7102	0.7100	0.7095	0.7085	0.7072	0.7055	0.7035	0.7012	0.6993	0.6995	0.7001	0.7006	0.7007	0.7005	0.7001	0.6996	0.6997	0.7014	0.7032	0.7047	0.7060	0.7069	0.7076	0.7080	0.7081
0.7488	0.7486	0.7480	0.7471	0.7459	0.7441	0.7418	0.7384	0.7330	0.7348	0.7364	0.7374	0.7377	0.7376	0.7372	0.7368	0.7383	0.7402	0.7420	0.7435	0.7448	0.7457	0.7463	0.7467	0.7469
0.7877	0.7875	0.7871	0.7862	0.7851	0.7835	0.7813	0.7784	0.7747	0.7704	0.7736	0.7749	0.7754	0.7752	0.7741	0.7715	0.7763	0.7793	0.7813	0.7829	0.7841	0.7850	0.7856	0.7859	0.7860
0.8270	0.8265	0.8265	0.8258	0.8248	0.8235	0.8218	0.8196	0.8169	0.8142	0.8132	0.8137	0.8141	0.8138	0.8135	0.8146	0.8173	0.8197	0.8218	0.8229	0.8240	0.8247	0.8252	0.8255	0.8257
0.8668	0.8665	0.8662	0.8657	0.8650	0.8641	0.8628	0.8612	0.8589	0.8557	0.8504	0.8526	0.8535	0.8526	0.8504	0.8558	0.8589	0.8610	0.8625	0.8636	0.8644	0.8649	0.8653	0.8656	0.8656
0.9064	0.9063	0.9062	0.9060	0.9056	0.9051	0.9044	0.9035	0.9022	0.9003	0.8974	0.8931	0.8858	0.8931	0.8974	0.9003	0.9021	0.9034	0.9042	0.9048	0.9052	0.9055	0.9057	0.9058	0.9059
0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463	0.9463

GRID SPACING: 1 IN. X 1 IN.; AUGER SPEED: 8.71 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2 BULK DENSITY: 45.53 LB/FT^3 (DISTURBED), 49.17 LB/FT^3 (UNDISTURBED)

Figure F-7. Computed air pressures over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-6

Figure F-8. Computed air velocities over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-6

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0307	0.0304	0.0298	0.0289	0.0300	0.0310	0.0318	0.0323	0.0326	0.0329	0.0331	0.0332	0.0332	0.0332	0.0332	0.0331	0.0330	0.0329	0.0328	0.0327	0.0327	0.0328	0.0329	0.0329	0.0329
0.0620	0.0615	0.0598	0.0555	0.0607	0.0625	0.0639	0.0648	0.0654	0.0659	0.0662	0.0664	0.0665	0.0665	0.0664	0.0663	0.0660	0.0657	0.0654	0.0652	0.0653	0.0655	0.0657	0.0659	0.0659
0.0946	0.0943	0.0936	0.0930	0.0941	0.0954	0.0966	0.0976	0.0984	0.0991	0.0995	0.0998	0.0999	0.0999	0.0998	0.0995	0.0990	0.0984	0.0978	0.0974	0.0977	0.0982	0.0986	0.0989	0.0990
0.1278	0.1276	0.1272	0.1261	0.1272	0.1282	0.1295	0.1306	0.1316	0.1324	0.1329	0.1333	0.1335	0.1335	0.1332	0.1328	0.1321	0.1312	0.1299	0.1287	0.1298	0.1309	0.1317	0.1321	0.1323
0.1614	0.1611	0.1605	0.1597	0.1590	0.1606	0.1624	0.1638	0.1650	0.1659	0.1666	0.1670	0.1672	0.1672	0.1669	0.1664	0.1656	0.1642	0.1619	0.1570	0.1618	0.1640	0.1657	0.1659	0.1659
0.1953	0.1950	0.1940	0.1920	0.1875	0.1927	0.1955	0.1971	0.1986	0.1996	0.2003	0.2009	0.2010	0.2010	0.2008	0.2004	0.1997	0.1987	0.1976	0.1967	0.1976	0.1986	0.1994	0.1999	0.2003
0.2298	0.2296	0.2289	0.2280	0.2272	0.2283	0.2299	0.2313	0.2326	0.2336	0.2343	0.2348	0.2351	0.2351	0.2349	0.2345	0.2340	0.2334	0.2328	0.2326	0.2329	0.2335	0.2340	0.2343	0.2344
0.2647	0.2645	0.2639	0.2633	0.2628	0.2630	0.2641	0.2654	0.2666	0.2677	0.2685	0.2690	0.2693	0.2693	0.2691	0.2687	0.2682	0.2677	0.2674	0.2674	0.2677	0.2682	0.2687	0.2690	0.2691
0.2998	0.2995	0.2989	0.2980	0.2969	0.2960	0.2976	0.2993	0.3008	0.3019	0.3028	0.3033	0.3036	0.3036	0.3034	0.3029	0.3023	0.3016	0.3011	0.3015	0.3022	0.3029	0.3034	0.3037	0.3038
0.3351	0.3349	0.3341	0.3328	0.3304	0.3255	0.3307	0.3334	0.3351	0.3363	0.3372	0.3378	0.3381	0.3380	0.3377	0.3371	0.3361	0.3349	0.3337	0.3350	0.3364	0.3375	0.3383	0.3387	0.3389
0.3709	0.3706	0.3699	0.3689	0.3675	0.3664	0.3673	0.3686	0.3699	0.3710	0.3719	0.3724	0.3727	0.3727	0.3723	0.3716	0.3703	0.3679	0.3630	0.3693	0.3709	0.3725	0.3734	0.3739	0.3741
0.4069	0.4066	0.4059	0.4050	0.4039	0.4029	0.4028	0.4035	0.4049	0.4058	0.4067	0.4072	0.4075	0.4075	0.4072	0.4066	0.4058	0.4047	0.4040	0.4054	0.4069	0.4081	0.4090	0.4095	0.4096
0.4431	0.4428	0.4421	0.4410	0.4396	0.4379	0.4365	0.4379	0.4394	0.4407	0.4416	0.4422	0.4425	0.4425	0.4422	0.4417	0.4412	0.4409	0.4409	0.4419	0.4430	0.4441	0.4449	0.4454	0.4455
0.4797	0.4794	0.4786	0.4773	0.4754	0.4723	0.4666	0.4716	0.4741	0.4756	0.4767	0.4773	0.4776	0.4776	0.4772	0.4767	0.4761	0.4758	0.4766	0.4778	0.4791	0.4802	0.4811	0.4816	0.4817
0.5166	0.5163	0.5156	0.5143	0.5125	0.5103	0.5083	0.5086	0.5099	0.5111	0.5121	0.5127	0.5129	0.5128	0.5123	0.5115	0.5104	0.5094	0.5113	0.5134	0.5152	0.5165	0.5175	0.5181	0.5183
0.5540	0.5537	0.5529	0.5517	0.5499	0.5478	0.5455	0.5439	0.5453	0.5467	0.5479	0.5484	0.5485	0.5483	0.5476	0.5463	0.5442	0.5395	0.5458	0.5493	0.5516	0.5533	0.5544	0.5550	0.5552
0.5919	0.5915	0.5907	0.5894	0.5876	0.5851	0.5815	0.5753	0.5803	0.5826	0.5838	0.5843	0.5844	0.5841	0.5834	0.5824	0.5914	0.5814	0.5840	0.5867	0.5889	0.5906	0.5918	0.5925	0.5927
0.6301	0.6299	0.6290	0.6277	0.6260	0.6238	0.6212	0.6189	0.6191	0.6198	0.6204	0.6207	0.6207	0.6202	0.6193	0.6181	0.6170	0.6191	0.6219	0.6246	0.6269	0.6285	0.6297	0.6304	0.6306
0.6688	0.6685	0.6678	0.6665	0.6649	0.6626	0.6602	0.6578	0.6568	0.6568	0.6572	0.6574	0.6572	0.6567	0.6555	0.6534	0.6487	0.6556	0.6598	0.6629	0.6652	0.6670	0.6682	0.6689	0.6692
0.7080	0.7078	0.7070	0.7057	0.7039	0.7016	0.6987	0.6955	0.6926	0.6931	0.6939	0.6942	0.6941	0.6937	0.6930	0.6923	0.6926	0.6959	0.6993	0.7021	0.7044	0.7051	0.7073	0.7080	0.7083
0.7478	0.7475	0.7468	0.7455	0.7436	0.7411	0.7376	0.7327	0.7247	0.7288	0.7306	0.7314	0.7314	0.7309	0.7300	0.7293	0.7322	0.7359	0.7392	0.7420	0.7443	0.7459	0.7471	0.7477	0.7480
0.7881	0.7878	0.7871	0.7857	0.7842	0.7817	0.7785	0.7743	0.7695	0.7678	0.7687	0.7694	0.7693	0.7684	0.7666	0.7625	0.7708	0.7761	0.7799	0.7827	0.7848	0.7863	0.7874	0.7880	0.7882
0.8289	0.8287	0.8281	0.8271	0.8255	0.8234	0.8205	0.8166	0.8111	0.8027	0.8071	0.8094	0.8081	0.8071	0.8063	0.8090	0.8140	0.8184	0.8217	0.8242	0.8261	0.8274	0.8283	0.8288	0.8290
0.8701	0.8699	0.8695	0.8688	0.8677	0.8661	0.8639	0.8609	0.8569	0.8521	0.8500	0.8497	0.8477	0.8455	0.8422	0.8521	0.8580	0.8620	0.8647	0.8666	0.8681	0.8690	0.8697	0.8701	0.8702
0.9117	0.9116	0.9114	0.9110	0.9104	0.9095	0.9083	0.9065	0.9039	0.8993	0.8901	0.8934	0.8863	0.8852	0.8950	0.9011	0.9048	0.9072	0.9087	0.9098	0.9106	0.9111	0.9114	0.9116	0.9117
0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534	0.9534

GRID SPACING: 1 IN. X 1 IN.; AUGER SPEED: 12.26 IN./ MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2 BULK DENSITY: 45.02 LB/FT^3 (DISTURBED), 49.41 LB/FT^3 (UNDISTURBED)

Figure F-9. Computed air pressures over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-22

23.730	23.611	23.263	38.668	39.618	40.483	41.107	41.533	41.834	42.044	42.189	42.279	42.324	42.326	42.290	42.219	42.123	42.013	41.916	41.862	24.774	24.810	24.850	24.880	24.889
24.062	23.941	23.429	36.538	39.828	40.872	41.381	41.710	41.949	42.126	42.251	42.331	42.369	42.366	42.324	42.242	42.122	41.978	41.836	41.748	24.731	24.794	24.957	24.999	24.912
24.729	24.839	25.369	27.156	42.867	42.029	41.905	41.993	42.129	42.258	42.359	42.424	42.454	42.445	42.392	42.291	42.131	41.908	41.643	41.440	24.620	24.766	24.893	24.946	24.967
25.041	25.085	25.222	25.365	42.287	42.033	42.052	42.165	42.271	42.401	42.497	42.543	42.566	42.558	42.510	42.408	42.272	41.894	41.343	40.636	24.449	24.777	24.961	25.049	25.074
25.202	25.178	25.081	24.808	41.093	41.629	42.039	42.287	42.444	42.552	42.628	42.677	42.702	42.703	42.690	42.627	42.510	42.219	41.351	38.093	24.471	25.001	25.174	25.236	25.251
25.399	25.360	25.194	24.638	38.296	41.486	42.279	42.539	42.655	42.726	42.780	42.919	42.843	42.862	42.882	42.923	43.043	43.391	44.427	29.213	26.349	25.743	25.547	25.483	25.467
25.683	25.715	25.867	26.405	28.202	44.339	43.292	42.978	42.907	42.911	42.931	42.954	42.975	42.993	43.023	43.091	43.296	43.469	43.941	26.377	26.099	25.855	25.717	25.553	25.634
25.859	25.879	25.946	26.074	26.177	43.496	43.133	43.027	43.019	43.041	43.067	43.095	43.057	43.102	43.101	43.107	43.137	43.219	43.377	25.807	25.831	25.931	25.769	25.749	25.741
25.969	25.961	25.925	25.807	25.490	42.108	42.577	42.913	43.078	43.154	43.192	43.209	43.209	43.192	43.153	43.084	42.975	42.837	42.749	25.487	25.645	25.741	25.791	25.913	25.819
26.094	26.091	26.021	25.832	25.236	39.130	42.307	43.055	43.257	43.315	43.333	43.339	43.328	43.300	43.239	43.111	42.853	42.377	41.739	25.185	25.550	25.749	25.848	25.494	25.907
26.263	26.269	26.307	26.451	26.977	28.756	45.116	44.004	43.641	43.524	43.497	43.478	43.470	43.453	43.420	43.334	43.079	42.244	39.001	25.126	25.704	25.939	25.992	26.027	26.037
26.411	26.415	26.433	26.487	26.596	26.673	44.167	43.766	43.630	43.600	43.601	43.606	43.611	43.624	43.667	43.796	44.166	45.254	28.800	26.974	26.408	26.249	26.209	26.202	26.201
26.546	26.538	26.514	26.451	26.297	25.933	42.721	43.146	43.461	43.622	43.695	43.776	43.736	43.745	43.776	43.874	44.118	44.609	26.856	26.665	26.491	26.406	26.372	26.362	26.361
26.701	26.699	26.652	26.563	26.330	25.677	39.652	42.773	43.539	43.773	43.952	43.873	43.864	43.932	43.784	43.730	43.697	43.752	26.238	26.397	26.452	26.495	26.504	26.513	26.517
26.879	26.830	26.877	26.891	26.993	27.451	29.099	45.456	44.421	44.156	44.092	44.062	44.019	43.942	43.837	43.564	43.139	42.595	25.914	26.238	26.469	26.587	26.647	26.676	26.685
27.079	27.090	27.094	27.095	27.117	27.140	27.022	43.979	44.131	44.239	44.292	44.270	44.221	44.136	43.999	43.695	42.842	39.696	25.729	26.395	26.657	26.783	26.941	26.971	26.991
27.283	27.287	27.290	27.281	27.255	27.102	26.501	40.779	43.849	44.479	44.575	44.545	44.486	44.427	44.416	44.671	45.619	29.219	27.632	27.151	27.065	27.059	27.093	27.102	27.123
27.499	27.504	27.516	27.537	27.594	27.732	28.250	29.962	46.912	45.549	45.074	44.969	44.754	44.651	44.518	44.324	44.176	27.238	27.363	27.353	27.344	27.345	27.349	27.354	27.357
27.726	27.728	27.737	27.752	27.774	27.811	27.970	27.947	45.311	45.384	45.161	45.062	44.999	44.923	44.728	44.036	41.024	26.767	27.403	27.576	27.619	27.627	27.625	27.623	27.624
27.959	27.962	27.966	27.967	27.948	27.876	27.687	27.263	44.391	44.767	45.062	45.213	45.287	45.385	45.714	46.874	30.153	28.594	28.131	29.002	27.956	27.931	27.915	27.905	27.902
28.203	28.209	28.219	28.227	28.215	28.137	27.892	27.133	41.435	44.369	45.213	45.435	45.557	45.506	45.398	45.379	28.183	28.365	28.358	28.316	28.272	28.233	28.202	28.184	28.179
28.452	28.464	28.495	28.540	28.579	28.677	28.815	29.232	33.537	46.933	46.253	46.153	46.021	45.745	45.020	42.261	27.917	28.513	29.669	28.654	28.594	28.531	28.490	28.450	28.440
28.690	28.709	29.762	28.950	28.975	29.135	29.325	29.477	29.199	43.634	46.427	46.897	46.758	46.714	47.489	31.329	29.965	29.474	29.243	29.074	28.935	28.824	28.744	28.695	28.680
28.893	28.921	28.997	29.125	29.314	29.572	29.918	30.391	31.134	32.542	49.959	49.543	47.407	46.445	44.538	29.925	30.261	30.030	29.729	29.460	29.244	29.092	28.969	28.902	28.892
29.045	29.077	29.171	29.332	29.572	29.904	30.349	30.911	31.519	31.712	47.796	50.479	46.689	47.454	34.082	32.536	31.461	30.724	30.183	29.783	29.488	29.278	29.136	29.054	29.029
29.129	29.163	29.264	29.442	29.712	30.100	30.645	31.423	32.588	34.524	39.141	61.546	39.579	39.994	36.259	33.749	32.179	31.154	30.457	29.970	29.624	29.392	29.224	29.136	29.108

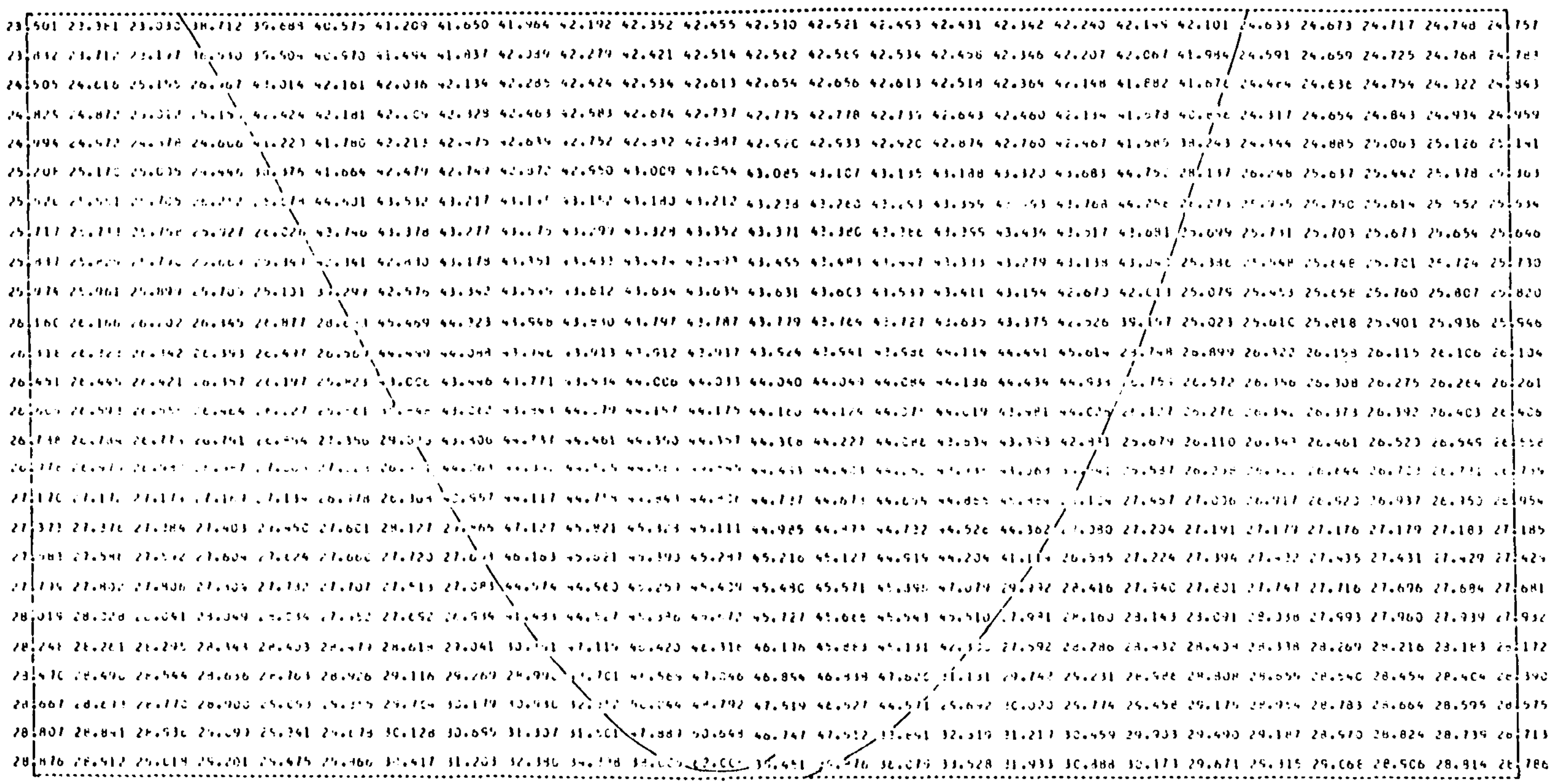
GRID SPACING: 1 IN. X 1 IN.; AUGER SPEED: 12.26 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2 BULK DENSITY: 45.02 LB/FT^3 (DISTURBED), 49.41 LB/FT^3 (UNDISTURBED)

Figure F-10. Computed air velocities over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-22

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0330	0.0297	0.0291	0.0282	0.0293	0.0303	0.0311	0.0316	0.0319	0.0322	0.0324	0.0325	0.0326	0.0326	0.0326	0.0325	0.0324	0.0323	0.0322	0.0321	0.0321	0.0322	0.0323	0.0323	0.0324
0.0605	0.0601	0.0584	0.0541	0.0588	0.0611	0.0624	0.0634	0.0640	0.0645	0.0649	0.0651	0.0652	0.0652	0.0652	0.0650	0.0648	0.0645	0.0642	0.0641	0.0642	0.0644	0.0646	0.0647	0.0648
0.0924	0.0921	0.0915	0.0903	0.0919	0.0932	0.0945	0.0955	0.0963	0.0970	0.0975	0.0978	0.0980	0.0980	0.0975	0.0976	0.0972	0.0966	0.0961	0.0957	0.0960	0.0965	0.0969	0.0972	0.0973
[illegible]	[illegible]	0.1243	0.1243	0.1244	0.1254	0.1267	0.1278	0.1289	0.1297	0.1303	0.1307	0.1309	0.1309	0.1307	0.1303	0.1297	0.1288	0.1275	0.1263	0.1275	0.1287	0.1295	0.1299	0.1301
0.1577	0.1575	0.1565	0.1561	0.1554	0.1571	0.1589	0.1604	0.1616	0.1625	0.1632	0.1637	0.1639	0.1640	0.1638	0.1633	0.1626	0.1613	0.1590	0.1541	0.1590	0.1612	0.1624	0.1630	0.1632
0.1910	0.1907	0.1894	0.1873	0.1833	0.1880	0.1913	0.1932	0.1946	0.1956	0.1964	0.1969	0.1972	0.1973	0.1971	0.1967	0.1961	0.1952	0.1942	0.1933	0.1942	0.1953	0.1961	0.1966	0.1967
[illegible]	0.2246	0.2243	0.2231	0.2224	0.2235	0.2251	0.2266	0.2279	0.2289	0.2297	0.2303	0.2306	0.2307	0.2306	0.2303	0.2294	0.2293	0.2282	0.2297	0.2290	[illegible]	0.2302	0.2305	0.2306
0.2591	0.2589	0.2584	0.2577	0.2573	0.2576	0.2587	0.2600	0.2613	0.2624	0.2633	0.2639	0.2642	0.2644	0.2642	0.2639	0.2635	0.2631	0.2620	0.2625	0.2633	0.2638	0.2643	0.2647	0.2647
[illegible]	0.2934	0.2924	0.2919	0.2908	0.2900	0.2916	0.2934	0.2949	0.2961	0.2973	0.2976	0.2980	0.2981	0.2979	0.2975	0.2970	0.2964	0.2960	0.2965	0.2972	0.2980	0.2986	0.2989	0.2990
0.3284	0.3281	0.3274	0.3261	0.3234	0.3188	0.3241	0.3269	0.3297	0.3300	0.3309	0.3316	0.3319	0.3320	0.3317	0.3312	0.3303	0.3292	0.3283	0.3294	0.3309	0.3321	0.3329	0.3334	0.3335
0.3635	0.3633	0.3626	0.3616	0.3603	0.3552	0.3602	0.3616	0.3629	0.3641	0.3650	0.3657	0.3660	0.3661	0.3656	0.3651	0.3639	0.3617	0.3562	0.3622	0.3649	0.3665	0.3675	0.3681	0.3682
0.3990	0.3987	0.3981	0.3972	0.3961	0.3952	0.3951	0.3960	0.3972	0.3983	0.3993	0.3999	0.4003	0.4003	0.4001	0.3996	0.3983	0.3979	0.3973	0.3988	0.4004	0.4017	0.4026	0.4031	0.4032
0.4347	0.4345	0.4338	0.4327	0.4313	0.4297	0.4283	0.4297	0.4313	0.4326	0.4336	0.4343	0.4347	0.4346	0.4346	0.4342	0.4337	0.4334	0.4337	0.4347	0.4360	0.4371	0.4379	0.4385	0.4386
0.4708	0.4705	0.4697	0.4685	0.4665	0.4635	0.4574	0.4628	0.4654	0.4670	0.4682	0.4689	0.4692	0.4693	0.4690	0.4686	0.4681	0.4678	0.4687	0.4701	0.4714	0.4727	0.4735	0.4741	0.4742
0.5072	0.5069	0.5061	0.5049	0.5031	0.5010	0.4989	0.4991	0.5036	0.5019	0.5030	0.5037	0.5040	0.5039	0.5035	0.5027	0.5017	0.5008	0.5029	0.5051	0.5069	0.5084	0.5094	0.5100	0.5102
0.5440	0.5437	0.5425	0.5417	0.5396	0.5378	0.5336	0.5343	0.5354	0.5369	0.5383	0.5397	0.5389	0.5389	0.5382	0.5372	0.5347	0.5333	0.5357	0.5403	0.5428	0.5445	0.5457	0.5463	0.5465
0.5812	0.5805	0.5801	0.5789	0.5770	0.5745	0.5710	0.5648	0.5698	0.5722	0.5734	0.5740	0.5742	0.5739	0.5733	0.5724	0.5715	0.5716	0.5743	0.5771	0.5794	0.5812	0.5824	0.5831	0.5833
0.6189	0.6186	0.6178	0.6165	0.6148	0.6126	0.6100	0.6077	0.6090	0.6087	0.6094	0.6097	0.6098	0.6094	0.6086	0.6074	0.6063	0.6086	0.6115	0.6143	0.6166	0.6184	0.6196	0.6203	0.6205
0.6565	0.6566	0.6559	0.6546	0.6529	0.6507	0.6483	0.6460	0.6450	0.6451	0.6454	0.6457	0.6456	0.6451	0.6440	0.6419	0.6373	0.6443	0.6487	0.6518	0.6543	0.6561	0.6573	0.6581	0.6583
0.6955	0.6952	0.6944	0.6931	0.6913	0.6890	0.6862	0.6830	0.6801	0.6806	0.6813	0.6818	0.6818	0.6814	0.6807	0.6801	0.6805	0.6839	0.6873	0.6903	0.6926	0.6944	0.6956	0.6964	0.6966
0.7344	0.7342	0.7334	0.7321	0.7303	0.7277	0.7243	0.7194	0.7114	0.7156	0.7174	0.7192	0.7182	0.7178	0.7169	0.7163	0.7193	0.7230	0.7264	0.7293	0.7316	0.7333	0.7345	0.7352	0.7354
0.7739	0.7737	0.7730	0.7718	0.7700	0.7676	0.7644	0.7602	0.7554	0.7538	0.7547	0.7554	0.7551	0.7544	0.7526	0.7486	0.7573	0.7623	0.7652	0.7690	0.7712	0.7728	0.7739	0.7745	0.7747
0.8139	0.8137	0.8131	0.8121	0.8105	0.8084	0.8055	0.8016	0.7961	0.7878	0.7922	0.7935	0.7932	0.7923	0.7915	0.7942	0.7993	0.8037	0.8071	0.8096	0.8115	0.8129	0.8138	0.8143	0.8145
0.8542	0.8541	0.8536	0.8529	0.8513	0.8502	0.8480	0.8451	0.8411	0.8362	0.8342	0.8335	0.8319	0.8257	0.8265	0.8364	0.8423	0.8463	0.8491	0.8510	0.8525	0.8535	0.8541	0.8545	0.8546
0.8945	0.8948	0.8946	0.8942	0.8936	0.8927	0.8915	0.8898	0.8871	0.8826	0.8733	0.8766	0.8656	0.8684	0.8783	0.8844	0.8881	0.8905	0.8921	0.8932	0.8939	0.8945	0.8949	0.8950	0.8951
0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357	0.9357

GRID SPACING: 1 IN. X 1 IN.; AUGER SPEED: 12.26 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2; BULK DENSITY: 44.93 LB/FT^3 (DISTURBED), 49.34 LB/FT^3 (UNDISTURBED)

Figure F-11. Computed air pressures over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-24



GRID SPACING: 1 IN. × 1 IN.; AUGER SPEED: 12.26 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2. BULK DENSITY: 44.93 LB/FT^3 (DISTURBED), 49.34 LB/FT^3 (UNDISTURBED)

Figure F-12. Computed air velocities over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-24

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0342	0.0341	0.0337	0.0325	0.0291	0.0325	0.0339	0.0345	0.0348	0.0349	0.0353	0.0350	0.0350	0.0349	0.0348	0.0346	0.0344	0.0341	0.0338	0.0334	0.0329	0.0326	0.0327	0.0328	0.0329
0.0689	0.0688	0.0685	0.0681	0.0675	0.0692	0.0689	0.0694	0.0697	0.0699	0.0703	0.0701	0.0700	0.0698	0.0696	0.0693	0.0688	0.0683	0.0676	0.0667	0.0656	0.0646	0.0652	0.0657	0.0659
0.1039	0.1038	0.1037	0.1036	0.1036	0.1038	0.1042	0.1046	0.1049	0.1051	0.1052	0.1052	0.1051	0.1048	0.1045	0.1041	0.1034	0.1026	0.1016	0.1002	0.0982	0.0943	0.0977	0.0990	0.0994
0.1390	0.1390	0.1390	0.1390	0.1391	0.1392	0.1395	0.1398	0.1401	0.1403	0.1404	0.1404	0.1403	0.1400	0.1395	0.1389	0.1391	0.1371	0.1359	0.1346	0.1332	0.1324	0.1330	0.1337	0.1339
0.1743	0.1744	0.1744	0.1744	0.1745	0.1746	0.1749	0.1751	0.1754	0.1756	0.1758	0.1757	0.1756	0.1752	0.1747	0.1739	0.1730	0.1718	0.1704	0.1697	0.1672	0.1675	0.1692	0.1697	0.1689
0.2098	0.2098	0.2099	0.2097	0.2097	0.2098	0.2100	0.2104	0.2108	0.2111	0.2112	0.2112	0.2110	0.2106	0.2099	0.2091	0.2080	0.2066	0.2049	0.2025	0.1984	0.2018	0.2034	0.2041	0.2043
0.2455	0.2454	0.2452	0.2450	0.2449	0.2447	0.2451	0.2457	0.2462	0.2466	0.2468	0.2468	0.2465	0.2460	0.2454	0.2444	0.2432	0.2418	0.2403	0.2389	0.2379	0.2397	0.2395	0.2401	0.2402
0.2813	0.2812	0.2809	0.2804	0.2797	0.2789	0.2793	0.2810	0.2818	0.2823	0.2825	0.2825	0.2823	0.2817	0.2809	0.2799	0.2785	0.2769	0.2752	0.2736	0.2741	0.2750	0.2758	0.2763	0.2765
0.3175	0.3174	0.3170	0.3162	0.3146	0.3108	0.3147	0.3166	0.3177	0.3182	0.3185	0.3185	0.3181	0.3175	0.3167	0.3155	0.3139	0.3120	0.3095	0.3054	0.3092	0.3112	0.3123	0.3129	0.3131
0.3543	0.3542	0.3538	0.3532	0.3525	0.3518	0.3526	0.3534	0.3541	0.3546	0.3547	0.3547	0.3543	0.3536	0.3527	0.3514	0.3497	0.3477	0.3457	0.3454	0.3469	0.3483	0.3493	0.3499	0.3501
0.3914	0.3913	0.3910	0.3906	0.3902	0.3899	0.3901	0.3905	0.3908	0.3911	0.3912	0.3910	0.3906	0.3899	0.3889	0.3876	0.3858	0.3832	0.3787	0.3823	0.3844	0.3858	0.3867	0.3873	0.3874
0.4289	[illegible]	0.4285	0.4281	0.4276	0.4273	0.4272	0.4273	0.4276	0.4278	0.4279	0.4277	0.4272	0.4265	0.4255	0.4242	0.4227	0.4212	0.4204	0.4214	0.4226	0.4237	0.4245	0.4250	0.4252
0.4665	0.4664	0.4661	0.4656	0.4649	0.4642	0.4638	0.4639	0.4643	0.4645	0.4646	0.4644	0.4640	0.4633	0.4622	0.4609	0.4593	0.4578	0.4585	0.4596	0.4609	0.4619	0.4626	0.4631	0.4633
0.5045	0.5044	0.5039	0.5032	0.5021	0.5008	0.4995	0.5002	0.5009	0.5014	0.5015	0.5014	0.5010	0.5003	0.4992	0.4977	0.4955	0.4913	0.4955	0.4977	0.4993	0.5003	0.5011	0.5015	0.5017
0.5429	0.5427	0.5422	0.5412	0.5397	0.5373	0.5327	0.5362	0.5378	0.5385	0.5389	0.5387	0.5383	0.5376	0.5367	0.5355	0.5343	0.5338	0.5352	0.5368	0.5382	0.5392	0.5399	0.5404	0.5405
0.5818	0.5816	0.5810	0.5800	0.5786	0.5769	0.5752	0.5753	0.5759	0.5762	0.5764	0.5763	0.5759	0.5753	0.5743	0.5730	0.5718	0.5729	0.5745	0.5761	0.5774	0.5785	0.5792	0.5797	0.5798
0.6212	0.6210	0.6204	0.6193	0.6179	0.6162	0.6146	0.6138	0.6139	0.6141	0.6142	0.6142	0.6139	0.6133	0.6122	0.6102	0.6063	0.6111	0.6138	0.6157	0.6172	0.6183	0.6191	0.6195	0.6197
0.6612	0.6610	0.6603	0.6591	0.6575	0.6554	0.6531	0.6510	0.6513	0.6519	0.6523	0.6524	0.6523	0.6519	0.6512	0.6504	0.6503	0.6523	0.6544	0.6561	0.6575	0.6587	0.6595	0.6599	0.6601
0.7019	0.7017	0.7009	0.6996	0.6978	0.6951	0.6914	0.6853	0.6884	0.6898	0.6906	0.6911	0.6912	0.6909	0.6902	0.6895	0.6912	0.6934	0.6954	0.6972	0.6986	0.6997	0.7005	0.7009	0.7011
0.7433	0.7431	0.7423	0.7413	0.7399	0.7364	0.7331	0.7293	0.7278	0.7284	0.7295	0.7303	0.7309	0.7306	0.7293	0.7257	0.7314	0.7347	0.7371	0.7389	0.7403	0.7414	0.7422	0.7426	0.7428
0.7855	0.7852	0.7845	0.7832	0.7813	0.7788	0.7751	0.7707	0.7638	0.7664	0.7698	[illegible]	0.7714	0.7719	0.7720	0.7725	0.7751	0.7777	0.7798	0.7815	0.7829	0.7839	0.7846	0.7850	0.7852
0.8283	0.8281	0.8275	0.8263	0.8247	0.8224	0.8194	0.8156	0.8105	0.8047	0.8085	0.8114	0.8132	0.8139	0.8139	0.8163	0.8191	0.8214	0.8234	0.8250	0.8262	0.8271	0.8277	0.8281	0.8282
0.8719	0.8717	0.8712	0.8703	0.8690	0.8672	0.8648	0.8619	0.8584	0.8542	0.8495	0.8546	0.8568	0.8568	0.8535	0.8600	0.8636	0.8660	0.8678	0.8692	0.8702	0.8709	0.8714	0.8718	0.8719
0.9161	0.9159	0.9156	0.9149	0.9140	0.9128	0.9112	0.9092	0.9070	0.9045	0.9023	0.9022	0.9039	0.9051	0.9057	0.9081	0.9102	0.9119	0.9131	0.9141	0.9148	0.9154	0.9157	0.9160	0.9160
0.9606	0.9606	0.9604	0.9600	0.9596	0.9590	0.9581	0.9568	0.9558	0.9543	0.9519	0.9469	0.9521	0.9542	0.9555	0.9566	0.9576	0.9584	0.9591	0.9596	0.9600	0.9602	0.9604	0.9606	0.9606
1.0054	1.0054	1.0054	1.0054	1.0054	1.0054	1.0054	1.0040	1.0054	1.0054	1.0054	1.0054	1.0054	1.0054	1.0054	1.0054	1.0054	1.0054	1.0054	1.0054	1.0054	1.0054	1.0054	1.0054	1.0054

GRID SPACING: 1 IN. X 1 IN.; AUGER SPEED: 24.30 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2 BULK DENSITY: 45.58 LB/FT^3 (DISTURBED), 48.86 LB/FT^3 (UNDISTURBED)

Figure F-13. Computed air pressures over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-16

26.757	26.705	26.497	25.873	35.272	37.943	38.987	39.432	39.654	39.728	39.802	39.802	39.802	39.728	39.654	39.506	39.357	39.134	38.909	38.609	38.306	38.002	25.968	26.021	26.074
27.017	27.017	27.071	27.495	28.894	40.341	39.809	39.730	39.729	39.802	39.802	39.976	39.802	39.728	39.655	39.581	39.433	39.210	38.913	38.538	38.084	37.544	25.863	26.075	26.127
27.172	27.172	27.276	27.433	27.737	40.246	40.026	39.951	39.950	39.950	39.950	39.876	39.876	39.877	39.729	39.656	39.510	39.289	39.070	38.703	37.971	35.830	25.890	26.141	26.391
27.224	27.275	27.327	27.378	27.430	40.097	40.024	39.951	39.950	39.950	40.023	39.950	39.950	39.977	39.878	39.732	39.587	39.517	39.374	39.391	39.916	29.744	27.395	26.969	26.913
27.327	27.327	27.379	27.378	27.379	40.097	40.024	40.024	40.024	40.097	40.023	40.097	40.024	40.025	39.879	39.808	39.664	39.595	39.378	39.230	39.366	27.224	27.278	27.225	27.224
27.430	27.430	27.327	27.327	27.275	39.950	39.951	40.025	40.098	40.097	40.097	40.097	40.097	40.026	40.028	39.884	39.889	39.675	39.539	38.971	36.929	26.827	27.230	27.180	27.378
27.532	27.481	27.430	27.327	27.224	39.728	39.879	40.026	40.039	40.171	40.244	40.244	40.245	40.173	40.103	40.107	39.965	39.973	40.055	40.802	35.437	28.161	27.794	27.636	27.634
27.583	27.594	27.533	27.380	27.122	39.208	39.661	40.029	40.247	40.318	40.317	40.330	40.319	40.321	40.251	40.139	40.042	39.901	39.827	39.661	27.789	27.844	27.942	27.939	27.838
27.797	27.788	27.738	27.589	27.143	37.467	39.696	40.259	40.469	40.538	40.537	40.463	40.485	40.395	40.326	40.333	40.122	39.914	39.347	37.391	27.248	27.748	27.944	27.992	27.991
28.092	28.092	28.094	28.199	28.664	30.167	41.940	41.202	40.833	40.756	40.755	40.692	40.684	40.615	40.547	40.483	40.421	40.361	40.730	29.692	28.577	28.307	28.198	29.194	28.142
28.243	28.244	28.295	28.396	28.546	28.794	41.624	41.265	41.119	40.901	40.827	40.928	40.757	40.761	40.767	40.704	40.649	40.247	38.313	28.164	28.462	28.454	28.398	29.345	28.394
28.394	28.394	28.445	28.446	28.395	28.344	41.334	41.118	41.046	41.045	41.045	40.971	40.975	40.980	40.912	40.993	41.221	42.028	30.504	29.216	28.809	28.652	29.598	29.595	28.545
28.545	28.545	28.495	28.446	28.346	29.143	40.973	41.046	41.046	41.117	41.045	41.118	41.120	41.052	41.129	41.064	40.994	40.978	28.696	28.853	28.903	28.750	28.747	29.695	28.744
28.694	28.695	28.596	29.498	28.350	27.997	40.317	40.694	40.975	41.118	41.262	41.262	41.265	41.269	41.275	41.144	40.665	38.609	29.223	28.760	28.903	29.949	29.996	29.944	28.994
28.994	28.845	28.847	28.701	28.511	27.980	38.459	40.636	41.197	41.336	41.406	41.436	41.408	41.556	41.562	41.736	42.653	30.934	29.569	29.209	29.151	29.097	29.094	29.092	29.092
29.141	29.142	29.096	29.101	29.111	29.528	30.899	42.776	41.994	41.766	41.693	41.693	41.767	41.699	41.704	41.634	41.551	29.196	29.354	29.352	29.339	29.343	29.341	29.339	29.339
29.398	29.389	29.392	29.348	29.353	29.356	29.393	42.334	42.051	41.909	41.907	41.938	41.909	41.985	41.923	41.519	39.432	29.936	29.363	29.501	29.544	29.549	29.586	29.594	29.594
29.681	29.683	29.637	29.594	29.503	29.361	28.962	41.338	41.550	41.837	41.979	42.192	42.264	42.409	42.698	43.552	31.597	30.311	29.951	29.892	29.886	29.833	29.879	29.377	29.876
30.022	30.023	29.979	29.938	29.852	29.579	28.926	39.298	41.351	41.913	42.194	42.405	42.617	42.690	42.692	42.687	30.130	30.192	30.236	30.191	30.176	30.172	30.169	30.167	30.167
30.360	30.361	30.366	30.375	30.293	30.318	30.607	31.617	42.976	42.414	42.623	42.930	43.039	43.182	42.780	40.638	29.792	30.395	30.479	30.556	30.560	30.503	30.576	30.456	30.504
30.743	30.697	30.749	30.758	30.820	30.840	30.871	30.510	40.553	42.093	42.777	43.397	43.876	44.219	45.252	32.897	31.567	31.113	31.051	30.947	30.893	30.890	30.840	30.939	30.839
31.029	31.077	31.128	31.193	31.337	31.496	31.667	32.103	32.960	42.195	43.180	44.190	44.639	44.936	44.793	31.523	31.582	31.527	31.377	31.323	31.271	31.221	31.172	31.171	31.123
31.406	31.407	31.457	31.603	31.751	31.997	32.293	32.733	33.446	34.141	44.037	45.651	45.860	45.381	43.125	31.494	31.915	31.897	31.796	31.696	31.599	31.503	31.502	31.454	31.454
31.688	31.688	31.784	31.879	32.070	32.354	32.731	33.151	33.748	34.557	35.609	48.514	48.168	48.931	35.335	33.596	32.827	32.446	32.255	32.020	31.924	31.830	31.735	31.599	31.698
31.828	31.922	31.969	32.109	32.342	32.621	32.945	33.265	33.808	34.216	34.179	46.519	48.910	49.451	34.248	33.672	33.171	32.804	32.526	32.340	32.108	32.015	31.922	31.975	31.875
31.968	31.968	32.061	32.246	32.431	32.707	33.121	33.073	34.151	34.818	35.872	39.009	52.392	50.768	34.286	33.795	33.344	32.981	32.661	32.431	32.292	32.154	32.061	32.014	31.968

GRID SPACING: 1 IN. X 1 IN.; AUGER SPEED: 24.30 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2; BULK DENSITY: 45.58 LB/FT^3 (DISTURBED), 48.86 LB/FT^3 (UNDISTURBED)

Figure F-14. Computed air velocities over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-16

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0342	0.0341	0.0335	0.0320	0.0280	0.0320	0.0335	0.0342	0.0345	0.0346	0.0347	0.0347	0.0346	0.0345	0.0343	0.0341	0.0338	0.0335	0.0330	0.0325	0.0320	0.0317	0.0317	0.0319	0.0320
0.0689	0.0688	0.0684	0.0677	0.0670	0.0678	0.0685	0.0690	0.0693	0.0694	0.0694	0.0694	0.0692	0.0690	0.0686	0.0682	0.0677	0.0670	0.0661	0.0651	0.0638	0.0626	0.0633	0.0639	0.0641
0.1039	0.1039	0.1036	0.1034	0.1032	0.1034	0.1037	0.1040	0.1042	0.1043	0.1043	0.1042	0.1039	0.1036	0.1031	0.1025	0.1017	0.1007	0.0995	0.0978	0.0954	0.0909	0.0949	0.0965	0.0969
0.1391	0.1391	0.1390	0.1389	0.1389	0.1388	0.1390	0.1391	0.1393	0.1393	0.1393	0.1391	0.1388	0.1383	0.1377	0.1369	0.1359	0.1347	0.1333	0.1317	0.1301	0.1291	0.1299	0.1306	0.1309
0.1744	0.1744	0.1743	0.1741	0.1740	0.1740	0.1741	0.1743	0.1744	0.1744	0.1743	0.1741	0.1738	0.1732	0.1725	0.1715	0.1703	0.1689	0.1672	0.1652	0.1634	0.1638	0.1646	0.1653	0.1655
0.2099	0.2097	0.2095	0.2093	0.2091	0.2090	0.2091	0.2093	0.2095	0.2096	0.2096	0.2093	0.2089	0.2083	0.2074	0.2063	0.2050	0.2033	0.2013	0.1984	0.1934	0.1976	0.1995	0.2004	0.2006
0.2453	0.2452	0.2449	0.2445	0.2440	0.2436	0.2437	0.2444	0.2447	0.2449	0.2449	0.2447	0.2442	0.2435	0.2426	0.2414	0.2399	0.2382	0.2363	0.2345	0.2336	0.2345	0.2355	0.2362	0.2365
0.2811	0.2809	0.2805	0.2797	0.2785	0.2773	0.2784	0.2794	0.2801	0.2805	0.2805	0.2803	0.2793	0.2790	0.2780	0.2766	0.2750	0.2730	0.2709	0.2690	0.2696	0.2708	0.2719	0.2726	0.2728
0.3173	0.3171	0.3165	0.3153	0.3131	0.3092	0.3128	0.3149	0.3159	0.3163	0.3164	0.3162	0.3157	0.3148	0.3137	0.3122	0.3103	0.3079	0.3048	0.2999	0.3047	0.3071	0.3085	0.3093	0.3096
0.3540	0.3539	0.3533	0.3525	0.3513	0.3502	0.3509	0.3518	0.3523	0.3527	0.3527	0.3524	0.3519	0.3509	0.3497	0.3481	0.3461	0.3437	0.3412	0.3409	0.3429	0.3447	0.3460	0.3467	0.3469
0.3911	0.3910	0.3906	0.3900	0.3893	0.3887	0.3887	0.3889	0.3892	0.3893	0.3892	0.3899	0.3883	0.3874	0.3861	0.3845	0.3823	0.3792	0.3738	0.3783	0.3810	0.3828	0.3843	0.3847	0.3849
0.4287	0.4286	0.4282	0.4276	0.4269	0.4263	0.4260	0.4260	0.4261	0.4262	0.4261	0.4258	0.4252	0.4243	0.4230	0.4215	0.4197	0.4179	0.4171	0.4184	0.4200	0.4215	0.4226	0.4232	0.4234
0.4667	0.4665	0.4660	0.4653	0.4644	0.4634	0.4626	0.4629	0.4630	0.4632	0.4632	0.4629	0.4624	0.4615	0.4602	0.4586	0.4567	0.4550	0.4560	0.4576	0.4593	0.4606	0.4617	0.4623	0.4625
0.5051	0.5049	0.5043	0.5034	0.5020	0.5002	0.4984	0.4992	0.5000	0.5005	0.5007	0.5005	0.5000	0.4991	0.4979	0.4961	0.4934	0.4884	0.4938	0.4967	0.4988	0.5003	0.5013	0.5019	0.5021
0.5442	0.5440	0.5433	0.5420	0.5401	0.5370	0.5311	0.5355	0.5374	0.5383	0.5385	0.5395	0.5391	0.5373	0.5362	0.5349	0.5335	0.5331	0.5350	0.5372	0.5391	0.5405	0.5416	0.5422	0.5424
0.5840	0.5838	0.5831	0.5813	0.5800	0.5778	0.5756	0.5758	0.5764	0.5769	0.5771	0.5771	0.5767	0.5760	0.5749	0.5734	0.5720	0.5736	0.5755	0.5781	0.5800	0.5814	0.5825	0.5831	0.5834
0.6247	0.6245	0.6237	0.6224	0.6206	0.6185	0.6164	0.6154	0.6154	0.6158	0.6161	0.6162	0.6159	0.6153	0.6140	0.6117	0.6069	0.6132	0.6169	0.6195	0.6216	0.6231	0.6241	0.6243	0.6250
0.6663	0.6661	0.6652	0.6639	0.6618	0.6592	0.6562	0.6535	0.6540	0.6548	0.6555	0.6558	0.6558	0.6554	0.6547	0.6539	0.6539	0.6567	0.6596	0.6620	0.6640	0.6655	0.6665	0.6673	0.6675
0.7090	0.7087	0.7078	0.7062	0.7039	0.7006	0.6959	0.6882	0.6922	0.6941	0.6953	0.6961	0.6964	0.6962	0.6954	0.6946	0.6970	0.7001	0.7030	0.7054	0.7074	0.7089	0.7099	0.7106	0.7109
0.7527	0.7524	0.7515	0.7499	0.7475	0.7443	0.7401	0.7352	0.7334	0.7344	0.7359	0.7372	0.7380	0.7378	0.7367	0.7318	0.7393	0.7439	0.7472	0.7497	0.7516	0.7531	0.7541	0.7547	0.7550
0.7976	0.7973	0.7964	0.7949	0.7926	0.7895	0.7852	0.7792	0.7704	0.7738	0.7769	0.7793	0.7809	0.7816	0.7818	0.7826	0.7862	0.7898	0.7927	0.7951	0.7969	0.7982	0.7992	0.7998	0.8000
0.8435	0.8433	0.8425	0.8411	0.8391	0.8364	0.8327	0.8277	0.8212	0.8138	0.8199	0.8228	0.8253	0.8262	0.8263	0.8296	0.8334	0.8366	0.8393	0.8415	0.8431	0.8443	0.8451	0.8456	0.8458
0.8904	0.8902	0.8896	0.8885	0.8870	0.8848	0.8819	0.8783	0.8737	0.8683	0.8621	0.8590	0.8720	0.8720	0.8677	0.8764	0.8813	0.8846	0.8870	0.8888	0.8902	0.8912	0.8918	0.8922	0.8924
0.9382	0.9380	0.9376	0.9369	0.9359	0.9343	0.9324	0.9300	0.9271	0.9238	0.9209	0.9209	0.9232	0.9248	0.9256	0.9289	0.9318	0.9340	0.9357	0.9370	0.9380	0.9387	0.9392	0.9395	0.9396
0.9865	0.9864	0.9862	0.9858	0.9853	0.9845	0.9835	0.9823	0.9807	0.9787	0.9754	0.9697	0.9759	0.9796	0.9801	0.9819	0.9832	0.9844	0.9852	0.9859	0.9864	0.9868	0.9870	0.9872	0.9872
1.0351	-1.0351	-1.0351	-1.0351	-1.0351	-1.0351	-1.0351	-1.0351	-1.0351	-1.0351	-1.0351	-1.0351	-1.0351	-1.0351	-1.0351	1.0351	1.0351	-1.0351	-1.0351	-1.0351	-1.0351	1.0351	-1.0351	1.0351	-1.0351

GRID SPACING: 1 IN. X 1 IN.; AUGER SPEED: 24.30 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2 BULK DENSITY: 45.42 LB/FT^3 (DISTURBED), 49.60 LB/FT^3 (UNDISTURBED)

Figure F-15. Computed air pressures over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-18

25.148	25.073	24.787	24.048	35.222	38.512	39.704	40.199	40.435	40.540	40.571	40.550	40.492	40.359	40.269	40.098	39.889	39.636	39.314	38.935	38.530	39.236	23.903	23.989	24.026
25.159	25.378	25.469	25.395	27.472	41.407	40.760	40.630	40.605	40.621	40.615	40.577	40.513	40.439	40.309	40.146	39.937	39.679	39.345	38.908	39.313	37.631	23.829	24.057	24.128
25.517	25.553	25.557	25.849	26.100	41.302	40.984	40.829	40.757	40.705	40.683	40.657	40.595	40.509	40.409	40.244	40.073	39.835	39.544	39.110	38.270	35.522	23.861	24.329	24.429
25.636	25.637	25.673	25.734	25.775	41.094	40.987	40.907	40.860	40.830	40.776	40.726	40.651	40.608	40.514	40.397	40.233	40.038	39.939	39.965	40.609	27.092	25.540	25.106	25.020
25.665	25.671	25.669	25.663	25.650	40.944	40.896	40.891	40.896	40.889	40.880	40.947	40.789	40.716	40.613	40.511	40.379	40.202	40.010	39.763	39.554	25.360	25.417	25.359	25.339
25.695	25.633	25.667	25.613	25.562	40.805	40.821	40.871	40.919	40.945	40.959	40.962	40.926	40.863	40.772	40.679	40.551	40.399	40.152	39.502	36.918	24.941	25.448	25.582	25.601
25.780	25.749	25.698	25.604	25.403	40.522	40.649	40.913	40.956	41.041	41.085	41.090	41.044	41.002	40.955	40.857	40.777	40.737	40.885	41.704	27.963	26.466	26.053	25.949	25.917
25.896	25.840	25.794	25.629	25.312	39.817	40.397	40.842	41.075	41.193	41.249	41.261	41.231	41.176	41.121	41.033	40.901	40.737	40.535	40.441	26.057	26.148	26.176	26.163	26.155
26.111	26.084	26.027	25.347	25.333	37.624	40.409	41.139	41.376	41.451	41.475	41.460	41.440	41.400	41.323	41.224	41.067	40.775	40.036	37.600	25.566	26.170	26.329	26.372	26.386
26.343	26.355	26.397	26.575	27.113	28.803	43.170	42.242	41.911	41.786	41.729	41.711	41.678	41.637	41.596	41.523	41.446	41.419	41.895	29.352	27.095	26.766	26.695	26.660	26.657
26.564	26.512	26.675	26.726	26.945	27.193	42.865	42.421	42.175	42.049	41.972	41.939	41.935	41.911	41.832	41.890	41.793	41.319	38.936	26.707	27.032	27.011	26.973	26.957	26.944
26.759	26.762	26.767	25.774	26.776	26.737	42.472	42.334	42.235	42.195	42.170	42.162	42.166	42.192	42.224	42.302	42.605	43.640	29.379	27.940	27.481	27.308	27.231	27.201	27.203
26.932	26.923	26.893	26.836	26.722	26.558	42.064	42.121	42.248	42.323	42.381	42.422	42.444	42.459	42.459	42.426	42.339	42.334	27.394	27.551	27.535	27.503	27.467	27.447	27.447
27.172	27.154	27.104	26.991	26.777	26.394	41.347	41.959	42.267	42.502	42.625	42.638	42.759	42.784	42.784	42.690	42.139	35.529	26.995	27.505	27.690	27.716	27.723	27.717	27.719
27.462	27.453	27.399	27.285	27.051	26.465	39.082	41.970	42.612	42.955	42.974	43.041	43.093	43.164	43.272	43.594	44.576	30.009	28.626	28.132	28.038	28.010	28.012	28.023	28.020
27.814	27.797	27.799	27.794	27.830	28.335	27.926	44.685	43.739	43.460	43.412	43.442	43.493	43.526	43.513	43.428	43.403	28.133	28.310	28.313	28.316	28.313	28.311	28.317	28.321
28.206	28.202	28.142	28.183	28.188	28.229	28.235	44.170	43.789	43.703	43.740	43.927	43.995	43.943	43.871	43.337	40.593	27.765	28.337	28.579	28.625	28.640	28.641	28.639	28.643
28.625	28.724	28.595	28.512	28.447	28.246	27.951	43.107	43.441	43.752	43.999	44.212	44.408	44.626	44.978	46.026	31.031	29.559	29.150	29.047	29.019	29.018	29.012	29.009	29.010
29.095	29.088	29.065	29.003	28.892	28.603	27.863	43.619	43.138	43.970	44.377	44.672	44.900	45.014	44.999	45.003	29.322	29.457	29.452	29.433	29.413	29.401	29.400	29.379	29.391
29.580	29.577	29.585	29.587	29.590	29.635	29.920	31.016	45.358	44.710	44.908	45.250	45.543	45.625	45.119	42.449	29.047	29.667	29.830	29.849	29.831	29.806	29.791	29.784	29.773
30.085	30.037	30.110	30.143	30.203	30.276	30.299	29.971	42.327	44.139	45.198	45.977	46.551	47.120	48.277	32.607	31.077	30.543	30.402	30.314	30.266	30.211	30.170	30.154	30.151
30.555	30.574	30.615	30.737	30.939	31.026	31.326	31.933	32.733	44.431	45.976	47.007	47.541	47.674	47.637	31.032	31.122	31.034	30.874	30.777	30.685	30.613	30.557	30.525	30.515
30.966	30.990	31.076	31.195	31.332	31.640	32.026	32.600	33.433	34.185	45.961	49.919	49.114	48.540	45.533	31.040	31.478	31.455	31.326	31.132	31.053	30.951	30.986	30.945	30.834
31.349	31.362	31.434	31.582	31.793	32.090	32.491	33.039	33.737	34.634	35.849	52.527	52.083	52.943	35.435	33.416	32.539	32.077	31.781	31.550	31.373	31.253	31.172	31.116	31.096
31.576	31.618	31.706	31.851	32.092	32.394	32.781	33.272	33.927	34.292	34.163	45.963	52.976	53.699	34.275	33.529	32.839	32.430	32.090	31.874	31.619	31.478	31.374	31.316	31.292
31.709	31.730	31.927	31.992	32.226	32.542	32.945	33.443	34.074	34.909	35.193	39.712	57.035	55.340	34.260	33.624	33.065	32.602	32.232	31.945	31.741	31.590	31.434	31.418	31.393

GRID SPACING: 1 IN. X 1 IN.; AUGER SPEED: 24.30 IN./MINUTE; AVERAGE FLOW RATE: 35.0 CFM/FT^2; BULK DENSITY: 45.42 LB/FT^3 (DISTURBED), 49.60 LB/FT^3 (UNDISTURBED)

Figure F-16. Computed air velocities over a 26 in. deep by 24 in. wide cross section of the auger-stirred corn mass of Test R-18