RESISTANCE TO AIR FLOW THROUGH SHELLED CORN

by

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TABLE OF CONTENTS

DEFINITION OF SYMBOLS

The definition of symbols given in Table 1 will be used throughout this manuscript except where otherwise stated.

Table 1. Definition of symbols

Symbol	Description	Units
A	Constant in Ergun's equation	---
a	Material constant	---
B	Constant in Ergun's equation	---
b	Material constant	---
D	Particle diameter	Length
D_c	Average channel diameter	Length
D_e	Equivalent diameter	Length
D_p	Effective diameter	Length
d	Particle density	lb/ft^3
E	Fractional void volume	---
f_k	Ergun's friction factor (kinetic)	---
f_m	Matthies' friction factor	---
f_v	Ergun's friction factor (viscous)	---
g	Gravitational acceleration	ft/sec^2
K_1	Constant	$lb\text{-}sec/ft^4$
K_2	Constant	$lb\text{-}sec^2/ft^5$
k	Constant	---
L	Height of bed	ft
m	Moisture content %	---
NR_e	Modified Reynolds' number	
P	Pressure	lb/ft^2
P	Pressure drop	lb/ft^2
Q	Cubic feet per minute (cfm.) per unit length of duct	$ft^3/min/ft$
r	Radial distance from center of bin	ft
S	Surface area of particle	ft^2
S_v	Specific surface	ft^2/ft^3
U	Apparent velocity of fluid	ft/sec
U_e	Actual velocity of fluid	ft/sec
ρ	Density of fluid	lb/ft^3
γ	Bulk density of bed	lb/ft^3
μ	Viscosity of fluid	$lb\text{-}sec/ft^2$
ϕ	Shape factor	---

INTRODUCTION

With the advent of mechanization of farming, grain production has increased tremendously especially in the United States. As a part of modern farming development, grain harvesting, handling, drying and storage have been highly mechanized. Proper storage is necessary in order to widen the scope of grain distribution without lowering the market quality of grain.

According to Saul (21), the maximum moisture content for safe storage of field shelled corn for one year is 13% w.b. Mechanical harvesting of corn begins at about 28% moisture content wet basis. In order to reduce the moisture content to the safe storage level in the available time, heated air or unheated air is passed through grain. Saul and Lind (22) have discussed maximum safe drying time. Hukill (11) discussed various factors that determine the number of cubic feet of air necessary for drying. They are: permissible drying time, initial moisture content and wet bulb depression. The quantity of grain and the cubic feet per minute per bushel combine to give an estimate of total cubic feet per minute (cfm) required.

Aeration of grain is another common practice in grain storage. This is generally done in order to prevent grain temperature gradient between the center of the bin and the outside which, according to Robinson, Hukill and Foster (20) could result in undesirable moisture movement. The size of the storage determines the total number of cubic feet per minute required. Aeration can also be estimated in terms of number of air changes required. Thompson and Isaacs (28) and Zink (29) have discussed various methods of measuring the void volume in grain.

After air flow rate through grain has been estimated, the resistance that the system offers to air flow is given the next consideration. Air flow rate and pressure drop are necessary for computing the horsepower required to drive the fan.

Shedd (24) has done extensive experimental work on air resistance through grain. His plots for air flow vs. pressure drop, Figure 1, for most of the common grains, covers the common range of air flow rates and has been used by agricultural engineers for many years. His results are for loose fill of clean grain and it is necessary to make allowances for condition of grain according to Shedd's recommendations.

OBJECTIVES

The object of the present work is to attempt to explain the effects on air resistance through grain of some of the variables that were not fully explained by Shedd and other earlier workers (10, 12, 13, 27) such as moisture content, fractional void volume, grain size, and surface of grain. In order to do this effectively it will be necessary to review some of the methods adopted in other fields of study, especially in chemical engineering, with an aim to finding a theoretical or empirical equation that can be correlated with Shedd's data and the data of the present investigation. Such an equation would help in filling the gap and even extending the range of Shedd's work.

Since variations in fractional void volume and grain size of a given type of grain are often a result of change in moisture content of the grain, the objectives of this study can be summarized in two objectives as follows:

1. To find the effect of moisture content on resistance to air flow through shelled corn.
2. To find a mathematical equation correlating grain parameters that can be measured such as fractional void volume, kernel average size, with air flow rate and pressure drop.

$$\frac{dP}{dL} = \frac{32\mu U_e}{D_c^2} \tag{5}$$

where,

U_e = actual fluid velocity

D_c = channel diameter.

Ergun added kinetic energy term. Equation 5 then became:

$$\frac{dP}{dL} = \frac{32\mu U_e}{D_c^2} + \frac{\frac{1}{2}\rho U_e^2}{D_c g} \tag{6}$$

Using relationships for cylindrical channels, Ergun eliminated the number of channels per unit area and their size in favor of specific surface and the fractional void volume. This led to Equation 7:

$$\frac{dP}{dL} = \frac{2(1-E)^2\mu U S_v^2}{E^3} + \frac{1/8(1-E)\rho U^2 S_v}{gE^3} \tag{7}$$

where, S_v is the specific surface of solids, i.e. surface area per unit volume of solids. All the coefficients of Equation 7 have theoretical significance.

Discussing the nature of flow through granular material, Ergun said, "For a packed bed the flow path is sinuous and the stream lines converge and diverge. The kinetic energy losses, which occur only once for the capillary, occur with a frequency that is statistically related to the number of particles per unit length. For these reasons a correction factor must be applied to each term. These factors may be designated by A and B." Applying factors A and B, Equation 7 becomes:

They decided that the ratio $\frac{E}{1-E}$ was not significant and could be ignored. The remaining expression was plotted in a manner like Blake. Their data and Blake's data showed good correlation over a small range.

Like Blake, Burke and Plummer did not recognize the additivity of both viscous and turbulent energy losses as suggested later by Ergun. This fact limited the range of their correlation.

The assumption of fluid flow through conduits was also used by Chilton and Colburn (6) who considered turbulence energy losses in terms of contraction and expansion losses.

Kozeny (14) was the first to treat the granular bed as a system of equal-sized parallel channels. He assumed the granular bed to be equivalent to a group of parallel channels such that the total internal surface and the free internal volume are equal to the total surface of the particles and the void volume respectively, of the randomly packed bed. His final equation was of the form:

$$U = \frac{E^3 \Delta Pg}{k \mu S^2 L} \tag{4}$$

where, S is the surface per unit packed volume. Carman (5) found that the method of Blake for viscous flow leads to Kozeny's equation, thus providing a theoretical basis for Blake's method.

Ergun and Orning (9) using an earlier observation by Reynolds (19, p. 83) considered the energy loss in fluid flow through granules as a sum of simultaneous viscous and kinetic energy losses. Using Kozeny's assumption of equal-sized parallel channels, Ergun expressed the viscous energy term by the following expression:

μ = viscosity of fluid

ρ = density of fluid.

Plotting the first term against the second, Blake found points fell over a wide range. He reasoned that the particle diameter was not sufficient to describe the material. He replaced D by the ratio of fractional void volume and surface area per cubic foot of free space, S/E. Equation 1 then became:

$$\frac{\Delta P}{L} \frac{gE^3}{\rho U^2} = F \left[\frac{\rho U}{S \mu g} \right] \tag{2}$$

where, E is fractional void volume. For the plot of Equation 2, data for glass rings fell close to one curve but data for larger rings, about three times larger in diameter, showed a significant difference from glass rings. Blake was unable to explain this difference.

Burke and Plummer (4) in their attempt to give Blake's approach a theoretical basis assumed that total force exerted by the fluid in a given system is the sum of the separate forces acting on individual particles suspended in the air stream. Their final equation was of the form:

$$\frac{P}{L} = k \frac{\rho U^2 S}{gE^3} \left[\frac{\mu SEg}{\rho U(1-E)} \right]^{2-n} \tag{3}$$

where,

k = constant

n = 1 for viscous flow

n = 2 for turbulent flow.

LITERATURE REVIEW

Resistance to fluid flow through granular material has been a subject of intensive study. Many of the earlier workers developed equations that were good for either laminar or turbulent flow. Recent workers have developed equations that have been found applicable over a wide range of velocities.

As most authorities agree the factors to be considered are 1) rate of fluid flow, 2) viscosity and density of fluid, 3) fractional void volume and orientation of particles, 4) size, shape and surface of particles. Some of the above factors are not susceptible to complete and exact mathematical analysis and various workers have used simplifying assumptions or analogies so that they could utilize some of the general equations representing the forces exerted by the fluids in motion to arrive at a useful expression correlating these factors.

Some of the various approaches will be discussed in brief.

Blake (2) assumed that flow through granular material can be treated like flow in circular pipes. He developed the following dimensionless groups:

$$\frac{\Delta P \; Dg}{LU^2 \rho} = F \left[\frac{\rho \; DU}{g \mu} \right] \qquad (1)$$

where,

ΔP = pressure drop

L = length of the column

D = particle diameter

U = fluid apparent velocity

$$\frac{dP}{dL} = 2A\frac{(1-E)^2\mu}{E^3} S_v{}^2U + \frac{B}{8}\frac{(1-E)\rho}{E^3 g} U^2 S_v \qquad (8)$$

Integrating, he got:

$$\frac{\Delta P}{L} = \frac{(1-E)^2}{E^3} 2A\mu S_v{}^2 U + \frac{(1-E)}{E^3}\frac{B\rho U^2}{8g} S_v \qquad (9)$$

Continuing this work, Ergun (8) developed a comprehensive equation which has been found very useful. It is based on Equation 9 above and is of the form:

$$\frac{\Delta P}{L} = k_1\frac{(1-E)^2}{E^3}\frac{\mu U}{D_p{}^2} + k_2\frac{1-E}{E^3}\frac{\rho U^2}{D_p g} \qquad (10)$$

where, D_p is the effective diameter defined by:

$$D_p = \frac{6}{S_v}$$

From Equation 10, Ergun derived friction factors as follows:

$$f_v = k_1 + k_2\frac{NR_e}{(1-E)} \qquad (11)$$

where,

$$f_v = \frac{\Delta P}{L\mu}\frac{D_p{}^2}{U}\frac{E^3}{(1-E)^2}$$

and,

NR_e = modified Reynolds' number $\frac{\rho U D_p}{\mu g}$

$$f_k = k_2 + k_1 \frac{1-E}{NR_e} \tag{12}$$

where,

$$f_k = \frac{\Delta Pg}{L} \frac{D_p}{\rho U^2} \frac{E^3}{(1-E)}$$

Using the method of Least Squares, Ergun used his data and that of other previous workers to determine values of k_1 and k_2. He found $k_1 = 150$ and $k_2 = 1.75$. His plot for Equation 11 checked closely with data of Burke and Plummer (4) and of Morcom (18).

Recently Leva, in his book on Fluidization (16, p. 45), discussed flow through fixed beds. Assuming the nature of velocity, length of fluid path and hydraulic radius of granular bed, he modified open-conduit flow equations to Kozeny-Carman type equations that apply to laminar and turbulent flow in granular beds. His equations are of the form:

$$\Delta P = \frac{200\ UL\mu(1-E)^2}{D_p{}^2\phi^2 E^3 g} \tag{13}$$

for laminar flow, and,

$$\frac{\Delta P}{L} = \frac{3.50(\rho U)^{1.9}(\mu)^{0.1}(1-E)^{1.1}}{D_p{}^{1.1}\phi^{1.1}\ E^3 g\ \rho} \tag{14}$$

for turbulent flow.

Ergun's equation is also discussed in Leva's book.

Bunn (3) developed an empirical equation for one-dimensional flow relating pressure drop and air flow rate through steel shot as follows:

$$\frac{\Delta P}{L} = a(e^{bQ^2/(\Delta P/L)}-1) \tag{15}$$

In his attempt to develop an equation applicable to two-dimensional flow, he assumed that 1) air flowed normal to the isopressure surfaces, and 2) that the differential form of Equation 15 described the air behavior in the direction normal to the isopressure surfaces. He combined Equation 15 with the two-dimensional steady mass continuity equation to obtain an equation for predicting pressures in two-dimensional flows. His equation was found to have a good correlation with the observed data.

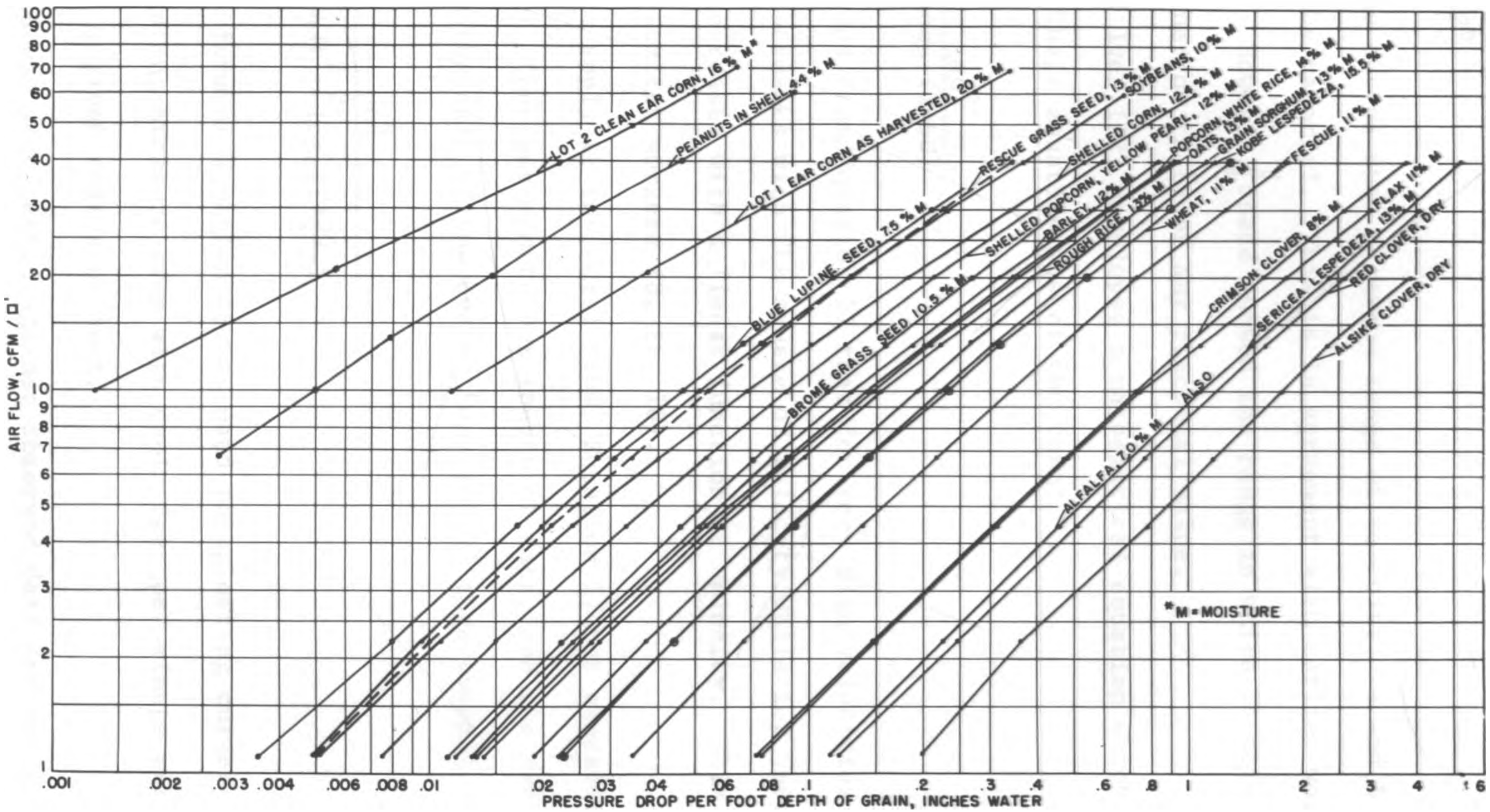
The workers discussed so far dealt mainly with non-biological materials. Some of the materials they used had regular shapes such as spheres, cylinders, rings (2, 4, 8) and variables such as specific volume, effective diameter could be determined fairly accurately. This was necessary in order to test the theoretical or semi-theoretical equations they developed.

Some of the equations were shown to have limitations with regard to size and size mixtures. Blake (2) found that his data for rings of different sizes did not fall on the same line. Carman (5) pointed out that Kozeny's equation had some important limitations when applied to materials of non-uniform sizes.

In biological materials, non-uniformity of size and presence of foreign materials is often important. This fact reduces many theoretical analysis to mere approximations of the actual facts when applied to these materials. A theoretical equation is, however, useful as a means of explaining the effects of various factors.

Up to now, Shedd's experimental curves (Figure 1) have been widely used in estimating pressure drop in grains. Correction for the condition of grain is necessary as Shedd recommended. Shedd reported that the

Figure 1. Shedd's curves for resistance of loosely filled, clean, dry grains and seeds to air flow



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
FESCUE, 11% M
BLUE LUPINE SEED, 7.5% M
SHELLED POPCORN
BARLEY, 12% M
ROUGH RICE, 13% M
WHEAT, 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
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
.001
.002
.003
.004
.006
.008
.01
.02
.03
.04
.06
.08
.1
.2
.3
.4
.6
.8
1
2
3
4
6

Ramsin equation,

$$U = aP^b \qquad (16)$$

can describe the curves over a narrow range of velocity. a and b are constants for the material. This is in agreement with earlier work by Henderson (10). However, Shedd showed the range in which Equation 16 applies is too narrow to be of any practical value.

Hukill and Ives (12) developed a mathematical equation which satisfies Shedd's data. Their equation was of the form:

$$\frac{\Delta P}{L} = \frac{aU^2}{\log_e (1+bU)} \qquad (17)$$

They observed from Equation 17 that for very high velocities the pressure drop increases with the square of velocity while for very low velocities it increases with a linear function of velocity. This is in agreement with earlier workers (8, 16, 18).

In order to apply it to radial flow, Equation 17 was expressed in terms of Q, cubic feet per minute per length of duct, and the radial distance r from the axis of the duct. Equation 17 then became:

$$\frac{dP}{dr} = \frac{aQ^2}{4\Pi^2 r^2 \log_e(1+\frac{bQ}{2\,r})} \qquad (18)$$

Integrated form of Equation 18 was used for plotting curves for radial flow relating pressure drop with cubic feet per minute per foot of duct length for a given radius of duct.

Equation 18 was also tested against observed data and was found to have good correlation except at points near the duct surface, for which the necessary correction was suggested.

The results of this work has made it possible to use Shedd's data for radial flow systems. Shedd worked with parallel flow only.

Matthies (17) has reported significant work on biological materials. He developed an equation of the form:

$$P = kf_m \frac{1}{E^4} \frac{L}{D} \frac{U^2}{2g} \tag{19}$$

where, k is a material constant, f_m friction factor, a function of modified Reynolds' number. Matthies' equation differs from equations of other workers in that it does not contain viscosity and is a function of the fourth power of fractional void volume. At best it can be compared with the kinetic energy loss terms of other workers.

One of the latest attempts to find a theoretical equation to describe pressure drops in biological materials was made by Bakker-Arkema *et al.* (1). They used cherry pits which have an almost spherical shape and correlated their data with both Matthies' and Ergun's equations. A good fit was obtained with Matthies' equation but a modification of Ergun's equation was found necessary in order to fit the data. They recommended use of Ergun's equation with the modification, as it was simpler to use.

From the literature studied it appears that most approaches adopted by several workers in developing equations applicable to fluid flow through granular materials, are based on either of the two basic assumptions:

1. The assumption that flow in granular materials is similar to flow through round pipes and has both laminar and turbulent

range of fluid flow. This assumption leads to Leva's equation. His state of flow factor n has a value of n = 1 for laminar flow and n = 2 for completely turbulent flow.

2. The assumption that granular bed can be considered to consist of equal-sized parallel channels and that the total energy loss is the sum of viscous and turbulent energy losses which occur simulataneously. The concept of equal-sized parallel channels was introduced by Kozeny while the additive nature of the two energy losses was first recognized by Morcom (18). This assumption leads to Ergun's equation.

Morcom was the first to recognize the fact that the transition between laminar and turbulent flow is best described by the sum of the viscous and turbulent energy losses. He said, "It is known that pressure loss through a granular bed is proportional to the fluid velocity at low flow rates and approximately to the square of velocity at high flow rates. Theoretical considerations indicate that the transition from one to the other is gradual, and may be expressed by denoting the pressure loss as the sum of two terms, proportional respectively to the first and the second power of the fluid velocity."

Good correlation obtained in the transition flow rates as reported by Ergun, support the Morcom concept.

The common flow rates in grain drying would fall in the transition range of flow rates as defined by Morcom. That is between modified Reynolds' number NR_e = 10 and NR_e = 400. On this basis, Ergun's equation is preferable to Leva's equation in grain drying considerations.

ACQUISITION OF DATA

Analysis of the Problem

As stated above, one of the objectives of this study was to find the effect of moisture content on pressure drop in shelled corn. Literature review does not show any conclusive attempt to determine the effect of moisture content on resistance to air flow through biological materials. Shedd (24) observed that 20% or higher moisture grain had less resistance to air flow than the same grain dried to lower moisture content and filled in the same way. Shedd found also that the bulk density is less at higher moisture but offers no further explanation as to why moisture content has an effect on pressure drop. As is generally agreed, void volume is an important variable in pressure drop calculations. Fractional void volume can be calculated knowing bulk density and particle density. Bulk density alone cannot fully explain the variation of pressure drop.

In order to explain the causes of the effect of moisture content, it is necessary to measure the properties of grain which are known to have an effect on pressure drop and show how they vary with moisture content.

Ergun's Equation 10, whose derivation gives theoretical meaning to various properties of the material can be used as a basis for theoretical considerations. There are difficulties, however, in using Ergun's equation because the effective diameter used in that equation is a function of specific surface which cannot be easily measured or computed for irregular shaped materials such as shelled corn.

By definition, effective diameter is given by:

$$D_p = \frac{6}{S_v}$$

where, S_v is the ratio of surface area of particles to the volume of particles, known as specific surface. Specific surface varies from one material to another depending on the shape and size of the material. For a sphere D_p represents the actual diameter of the sphere. For a given volume, say one cubic foot, the surface area is smallest for a spherical shape. Therefore spherical shape assumes the smallest value of specific surface and the largest value of effective diameter. For a given particle volume the smaller the effective diameter the larger is the departure from a spherical shape.

Specific surface is a function of particle size. Consequently, large size particles have small specific surface while small size particles have a large specific surface. The specific surface of a size mixture of spheres would lie somewhere in between the two.

In the case of irregular shaped materials for which specific surface cannot be measured, another function may be substituted for effective diameter. Since effective diameter is a function of particle size and particle shape it would be appropriate to substitute for it a function of average particle size and shape factor.

The diameter of a spherical volume equal to the volume of a particle of arbitrary shape is a convenient indicator for average particle size of irregular shaped material. This diameter is called equivalent diameter. It will be assumed that the relation between effective diameter as defined in Ergun's equation and equivalent diameter can be expressed by a factor of shape, size distribution and foreign matter for a particular material as follows:

$$D_p = \frac{D_e}{\phi}$$

in this discussion, ϕ will be referred to as shape factor.

Since equivalent diameter can be easily measured, and shape factor can be determined empirically as will be shown below, substituting $\frac{D_e}{\phi}$ for D_p in Ergun's Equation 10 would render this equation applicable to irregular shaped materials such as shelled corn.

The second objective of this work was to fit a modified Ergun's equation to data of samples of shelled corn and determine whether variation from sample to sample, of shape, size distribution, and foreign matter is small enough to allow application of modified Ergun's equation to field shelled corn.

Shape factor

Ergun's equation is given by the relationship:

$$\frac{\Delta P}{L} = 150\frac{(1-E)^2}{E^3}\frac{\mu U}{D_p^2} + 1.75\frac{(1-E)}{E^3 g}\frac{\rho U^2}{D_p} \qquad (10)$$

where, D_p is defined as:

$$D_p = \frac{6}{S_v}$$

Substituting $\frac{D_e}{\phi}$ for D_p the modified form of Ergun's equation is obtained as follows:

$$\frac{\Delta P}{L} = 150\ \phi^2 \frac{(1-E)^2}{E^3} \frac{\mu U}{D_e^2} + 1.75\ \phi \frac{(1-E)}{E^3 g} \frac{\rho U^2}{D_e} \tag{20}$$

Tests can be carried out for a given sample in the test bin with air flow rate and pressure drop as the only variables in the modified Ergun equation. Under these circumstances this equation can be reduced to the following form:

$$\frac{\Delta P}{L} = K_1 U + K_2 U^2 \tag{21}$$

where,

$$K_1 = 150\ \phi^2 \frac{(1-E)^2}{E^3} \frac{\mu}{D_e^2} \tag{22}$$

and,

$$K_2 = 1.75\ \phi \frac{(1-E)}{E^3} \frac{\rho}{g} \frac{1}{D_e} \tag{23}$$

For several values of velocity and the corresponding values of pressure drop, coefficients of Equation 21 can be determined using curvilinear regression analysis of the second order polynomial as discussed by Snedecor (26). Substituting these values in Equations 22 and 23 the value of the shape factor ϕ can be calculated since other parameters can be obtained or measured. This procedure can be repeated for several samples of corn. The average value of ϕ can then be considered as the shape factor for the material.

Friction factor

Equation 20 can be transformed as follows:

$$\frac{\Delta P}{LU} \frac{E^3}{(1-E)^2} \frac{D_e^2}{\phi^2} = 150 + 1.75 \frac{1}{\phi} \frac{\rho U D_e}{g(1-E)} \qquad (24)$$

By defining a friction factor,

$$f_v = \frac{\Delta P}{LU} \frac{\phi E^3}{(1-E)^2} D_e^2$$

and modified Reynolds' number as,

$$NR_e = \frac{\rho U D_e}{g}$$

Equation 24 can be reduced to,

$$f_v = 150 + 1.75 \frac{NR_e}{(1-E)\phi} \qquad (25)$$

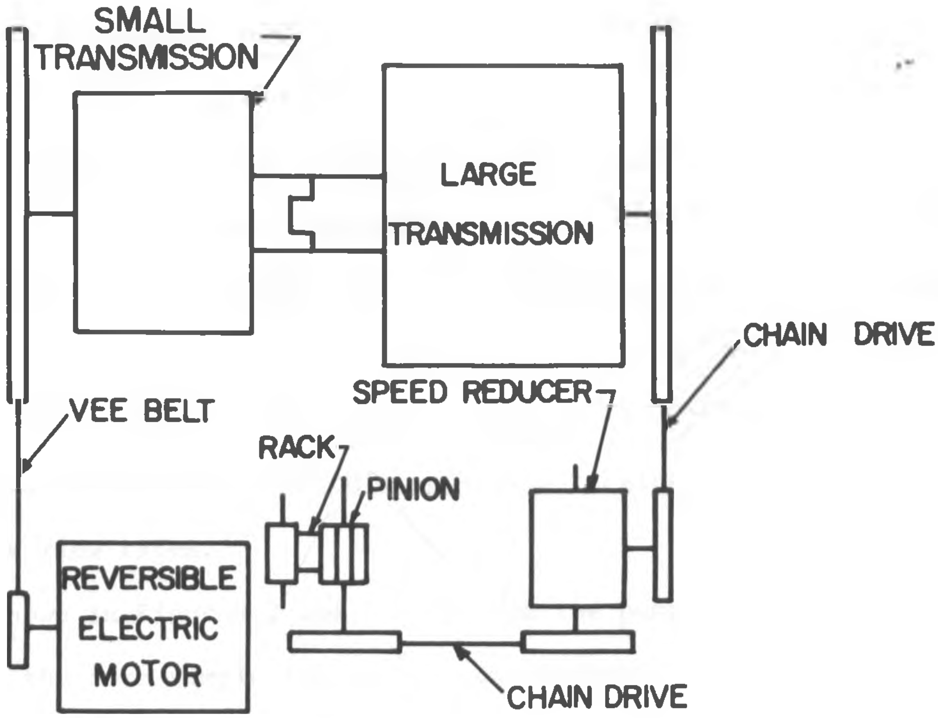
Equation 25 expresses a linear relationship between f_v and $\frac{NR_e}{(1-E)\phi}$.

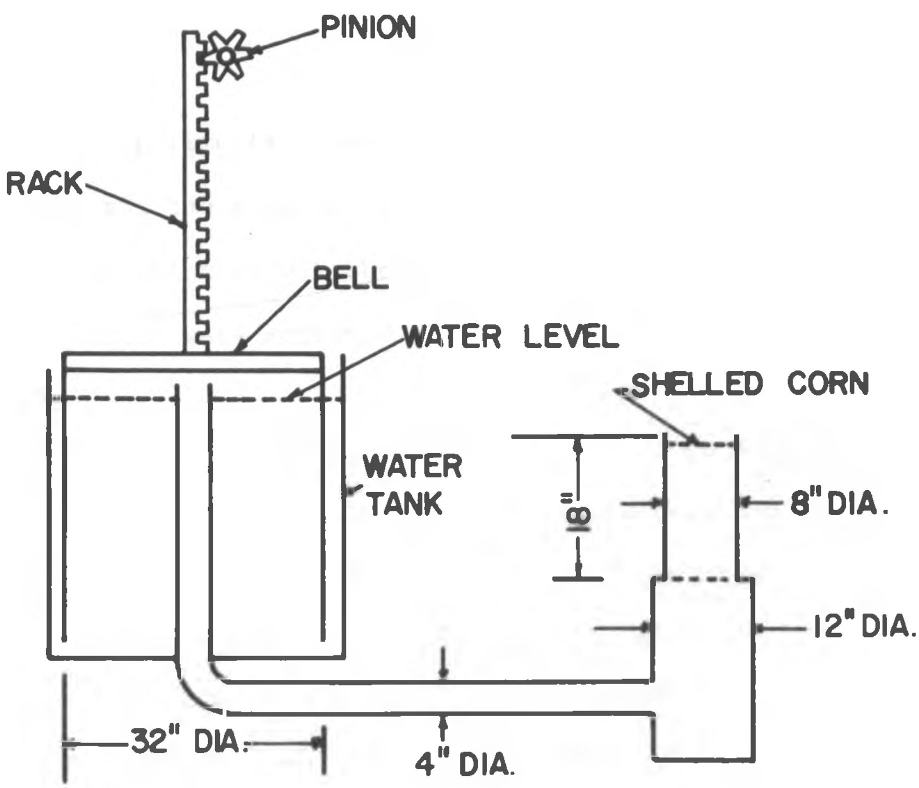
Equipment

Shedd's apparatus

In the experiments it was necessary to maintain a constant air flow rate. The air pump used was basically the same as one originally used by Shedd (25). The schematic diagram of Shedd's apparatus as modified by Bunn (3) is shown in Figure 2. It consists of an open topped cylindrical water tank about 4 feet high, a stand pipe of 4-inch diameter through the

Figure 2. Schematic diagram of Shedd's apparatus for delivering a constant volume of air


SMALL TRANSMISSION
LARGE TRANSMISSION
CHAIN DRIVE
SPEED REDUCER
VEE BELT
RACK
PINION
REVERSIBLE ELECTRIC MOTOR
CHAIN DRIVE


PINION
RACK
BELL
WATER LEVEL
SHELLED CORN
WATER TANK
18"
8" DIA.
12" DIA.
32" DIA.
4" DIA.

bottom of the tank with open end extending above the water surface to serve as an air outlet (and inlet) and a bell driven up and down at known speed by a driving mechanism.

The driving mechanism consists of a reversible electric motor, a vee-belt from motor to a small transmission which is connected in series to a large transmission, a roller-chain drive from the large transmission to a worm gear speed reducer, another roller-chain drive from speed reducer to a pinion driving a rack attached to the bell. A wide range of air flow rates could be obtained with this apparatus ranging from 43 cfm. to some fairly low flow rates.

As shown in Figures 2 and 3, air from the pump passed through the plenum to the corn sample loaded in a bin 8 inches in diameter and 18 inches deep.

Dryer

In pressure drop experiments it was necessary to have a uniform moisture sample. For all the samples tested the first test was done at the moisture content at which it was obtained from the field. All other levels of moisture content were achieved using the dryer shown in Figures 5 and 6.

This dryer consisted of drying compartment insulated by asbestos walls, 4 (33 inches long by 20 inches wide and 6 inches deep) drying trays in the drying compartment, intersection duct connecting the heater unit to drying compartment, electric heater unit, centrifugal fan and temperature control unit. The drying temperature range was between 90°F and 105°F. The air flow rate was about 345 cubic feet per minute. The depth of shelled corn in the drying trays was 1½ inches. The 4 trays made it

Figure 3. Shedd's apparatus showing the air pump, air duct, and the sample bin

Figure 4. Plenum and test bin of Shedd's apparatus

Figure 5. Dryer assembly showing dryer cabinet, intersection air duct, electric heater unit, and the temperature control

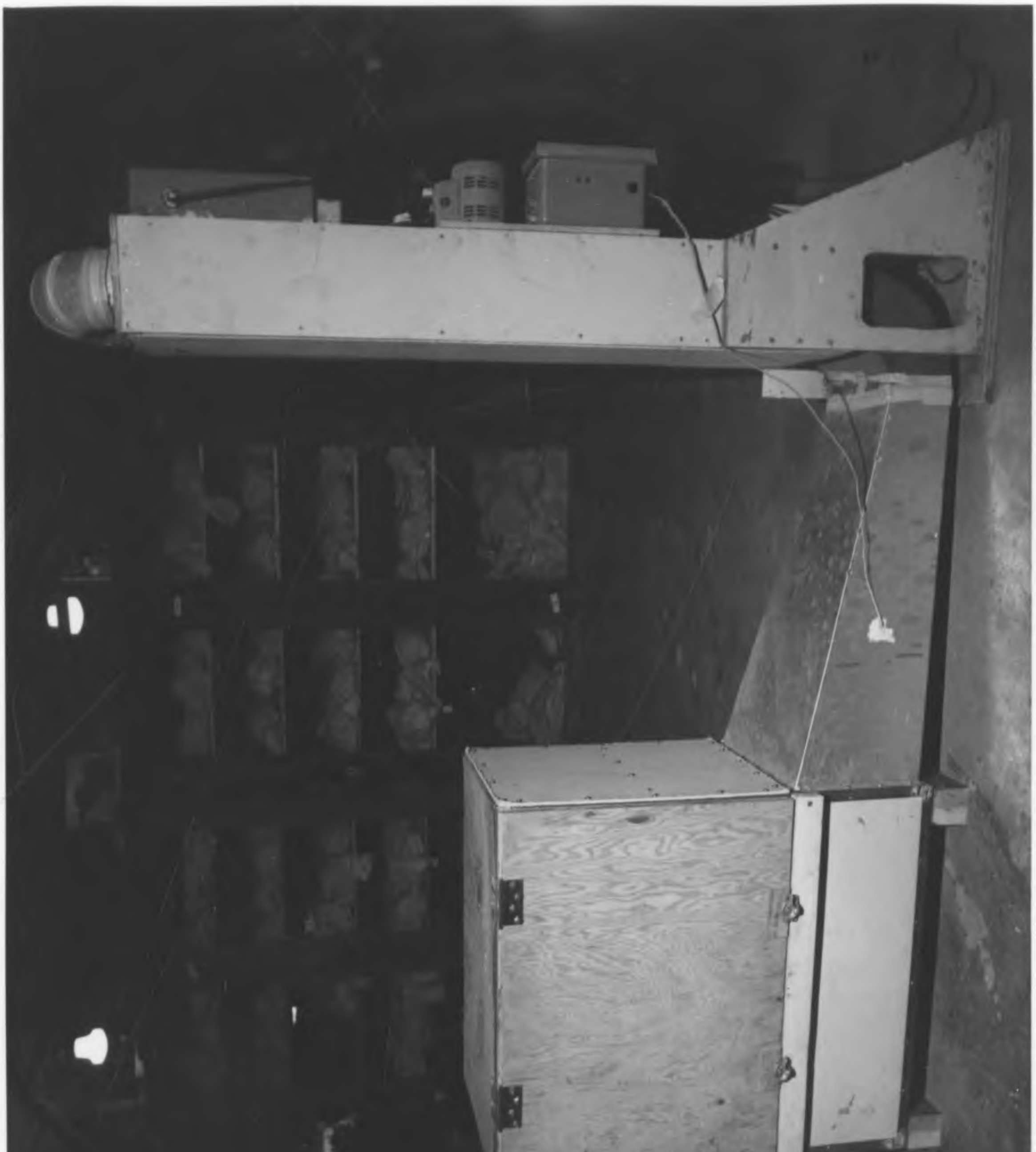


Figure 6. Four drying trays inside the dryer cabinet

possible to dry 4 samples of shelled corn to different moisture levels simultaneously.

When the approximate moisture content desired was approached the sample was removed from the dryer and stored in the bucket under cover for about 24 hours in order to achieve uniform moisture content in the kernel.

Micromanometer

Most of the air pressure drops were measured using a micromanometer which enabled readings to the nearest one thousandth of an inch of water to be taken. This micromanometer, Figure 7, which uses the same principle as the one described by Shedd (23), consists of 2 tubes, say A and B, filled with water. Tube A is attached rigidly to the manometer frame, while tube B is attached to a carriage which can be moved vertically by means of a micrometer. When air pressure is applied to the top of tube B, the water level will be forced downwards in tube B and upwards in tube A. By moving tube B downward the water can be lowered to position of no pressure in tube A. The distance tube B was moved downward will measure the pressure.

For high air flow rates, a regular U-tube oil manometer was used.

Density bottle

As shown in Figures 8 and 9, this equipment consisted of open top glass jar $2\frac{1}{2}$ inches in diameter, and $2\frac{1}{4}$ inches deep; a steel perforated disc inside the glass jar and held horizontally by 3 steel screws extending from the lid and a steel pointer fixed to the lid. The mercury level was determined by the pointer.

Figure 7. Micromanometer

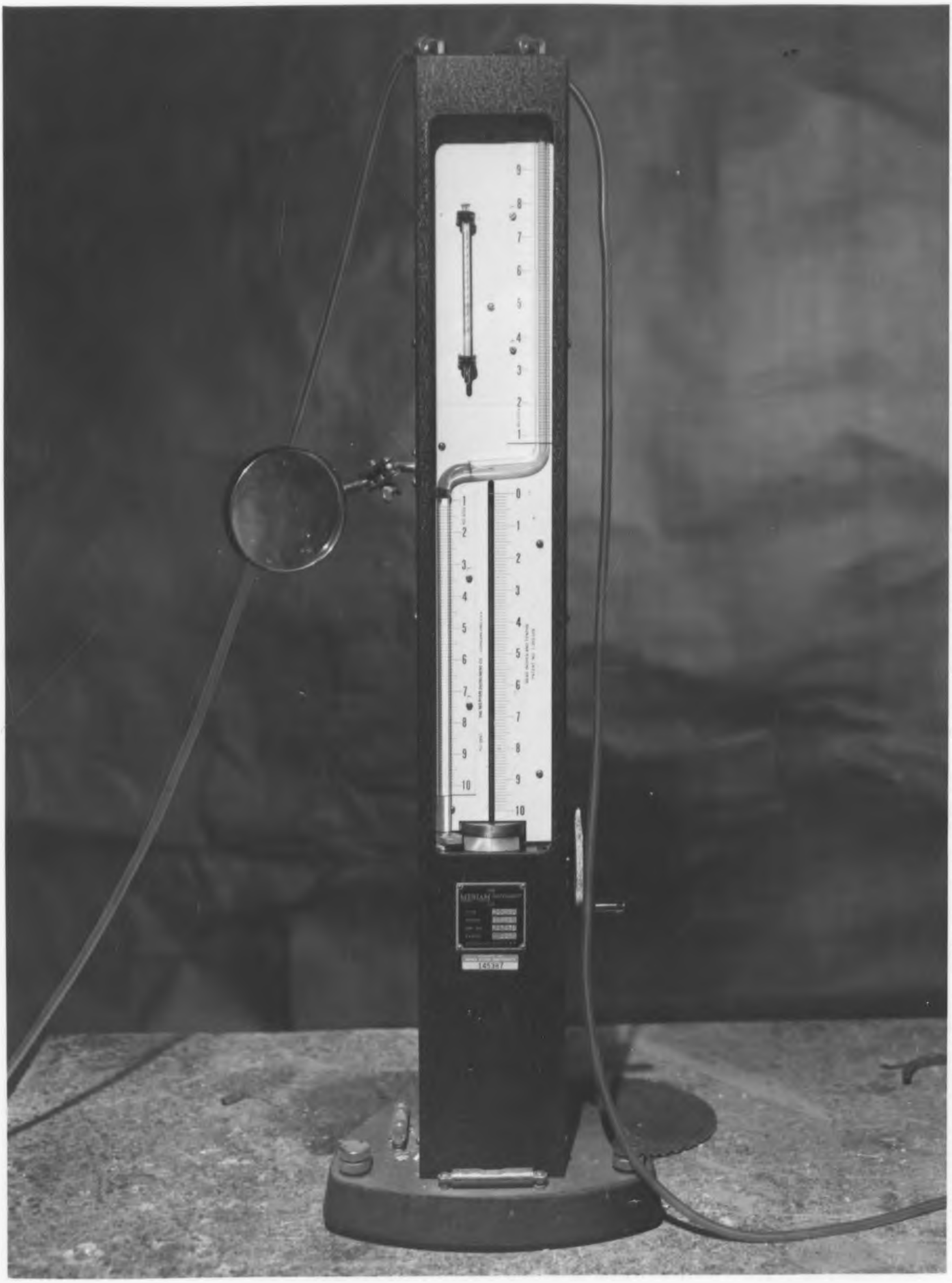


Figure 8. Density bottle. Mercury fills the void space up to the level indicated by the pointer

Figure 9. Top view of the density bottle, showing the hole through which mercury is poured using a funnel

Measurements

In order to show the relation between pressure drop and the variables that are being investigated, that is, flow rate, moisture content, fractional void volume and kernel size, it was necessary to hold constant one or more variables while varying the rest.

Air flow rate

Air flow rate required was adjusted using Shedd's apparatus (Figure 2). Air flow rate stayed constant when pressure drop was being taken.

Pressure drop

The micromanometer was used for all the pressure drops except at very high velocities. With this micromanometer, Figure 7, it was possible to read to the nearest one thousandth of an inch of water. For high velocities, pressure drops were measured to the nearest one tenth of an inch using an ordinary oil manometer and then converted to inches of water.

Moisture content

Field shelled corn at field moisture content or after drying in the dryer, Figure 5, was covered in a bucket for about 24 hours in order to achieve uniform moisture content for the whole grain. A sample of 100 grams was then drawn and dried in the oven for 72 hours at 103°C.

Kernel density and kernel size

The volume of the density bottle, Figure 8, was determined by filling it with mercury of known specific volume and weighing the mercury. About 100 grams of shelled corn was counted, weighed and then introduced into the density bottle. After replacing the lid, mercury of known temperature was poured into the bottle until the mercury level reached the pointer. The weight of the bottle containing corn and mercury was taken. The difference between weight of mercury filling the kernel density bottle alone and weight of mercury contained in the bottle with corn, multiplied by the specific volume of mercury, gave the volume occupied by the kernels. The weight of the kernels divided by their volume gave the density of the kernels.

The volume of the kernels divided by number of kernels in the sample gave the kernel average size in cubic centimeters. The diameter of a sphere of equal volume to the kernel average volume was the equivalent diameter.

Bulk density

Measuring the weight and the volume of shelled corn in the test bin, Figure 4, and dividing the former by the latter, the bulk density was obtained.

Fractional void volume

Kernel density and bulk density were combined to give fractional void volume as follows:

$$\gamma = (1-E)d \tag{26a}$$

where,

γ = bulk density

E = fractional void volume

d = kernel density.

Expressing Equation 26a in terms of fractional void volume, we obtain:

$$E = 1 - \frac{\gamma}{d} \qquad (26b)$$

Procedure

The procedure followed in acquiring the necessary data included measuring pressure drops through shelled corn at various levels of moisture contents holding air flow rate constant at 8.93 cfm. per square foot. Measurements for fractional void volume and kernel size were made for all the samples tested. This procedure was repeated for 30 different samples of shelled corn. For every sample, fractional void volume was varied 3 times from loose fill through intermediate fill to packed fill.

For 13 samples, air flow rate was varied 11 times from 123.64 cfm. per square foot to 4.6 cfm. per square foot. This was done for packed fill only.

Six batches of shelled corn (XL 45) were obtained from the field sheller. Two batches of Cargill variety were obtained from ear corn cold storage and were shelled, using an experimental sheller at the U.S.D.A. grain storage laboratory.

Initial moisture content of shelled corn tested varied between 28 percent and 21 percent. Each sample was tested at its initial moisture content and approximately through 25 percent (if initial moisture content was about 28 percent), 21 percent, 15 percent, 11 percent, and 8 percent. All moisture contents were calculated on wet basis. The table of results is given in the Appendix.

Analysis of Data

Moisture content effect

A plot of fractional void volume and moisture content, Figures 10 and 11, showed a non-linear trend which suggested that a polynomial of second degree could be fitted to the data. The regression analysis was done using the OMNITAB regression routine on the IBM 360.

For packed fill the prediction equation was found to be as follows:

$$E = 36.4 - .195m + .0084m^2 \tag{27}$$

The standard deviation of the mean of prediction was .78. For loose fill, the prediction equation is given by:

$$E = 41.2 - .238m + .0126m^2 \tag{28}$$

The corresponding standard deviation of the mean of prediction was .87.

A similar plot of particle size vs. moisture content, Figure 12, showed a non-linear trend also. Accordingly, a polynomial of the second order was fitted. The following prediction equation was determined:

$$D_e = .68 + .0095m - .0015m^2 \tag{29}$$

The standard deviation of the mean of prediction was .027 cm. Table 2 gives the standard deviations of coefficients of Equations 27, 28 and 29.

In order to show the effect of other variables of moisture content except void volume, a plot of pressure drop vs. moisture content for fractional volume fixed at 39 percent was made as shown in Figure 13. It is evident that surface friction and kernel size had a relatively small effect on pressure drop since no increase or decrease in pressure drop was observed in this plot.

Figure 10. A plot of fractional void volume vs. moisture content for loose filled shelled corn

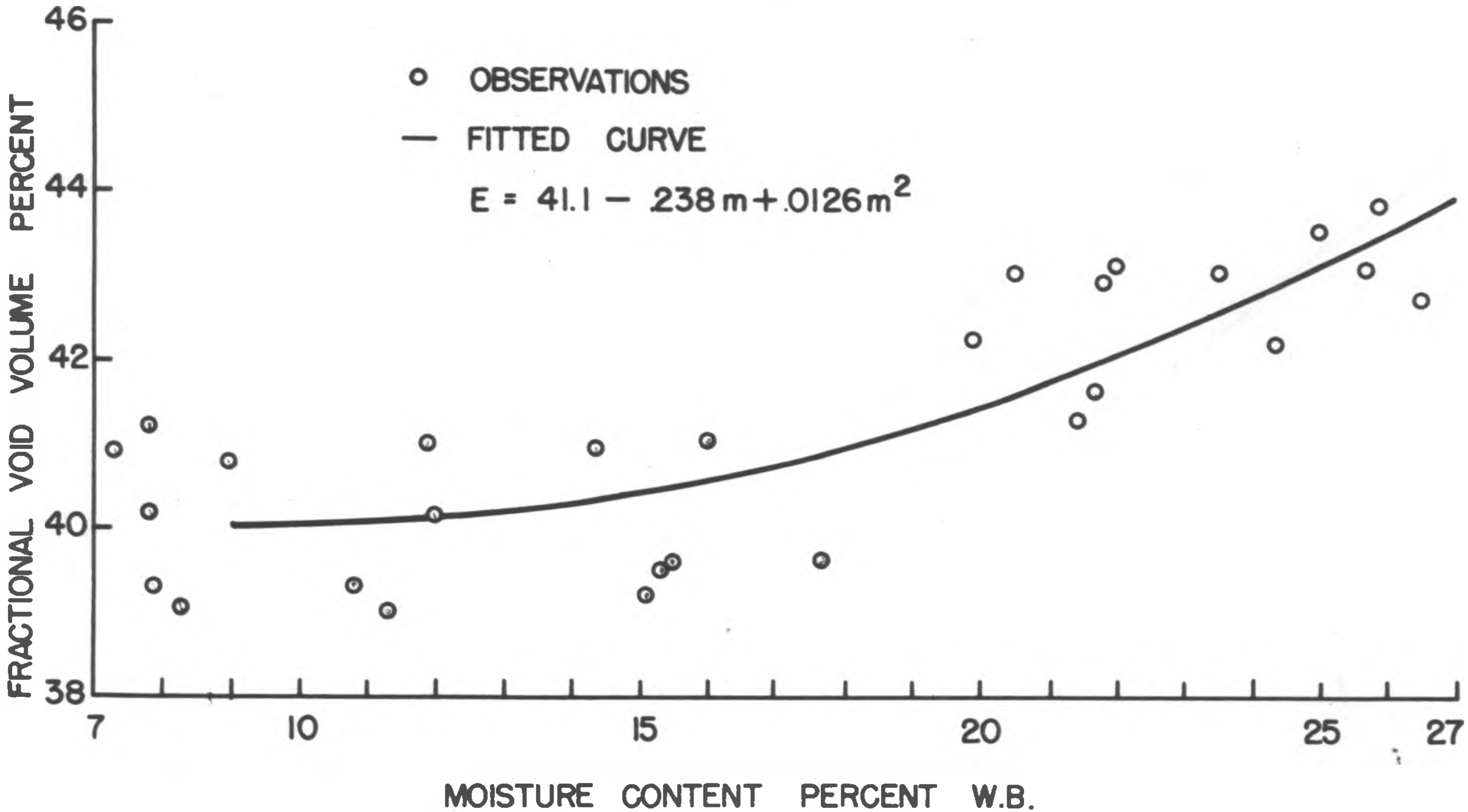

OBSERVATIONS
FITTED CURVE
E = 41.1 − .238 m + .0126 m²
FRACTIONAL VOID VOLUME PERCENT
46
44
42
40
38
7
10
15
20
25
27
MOISTURE CONTENT PERCENT W.B.

Figure 11. A plot of fractional void volume vs. moisture content for packed filled shelled corn

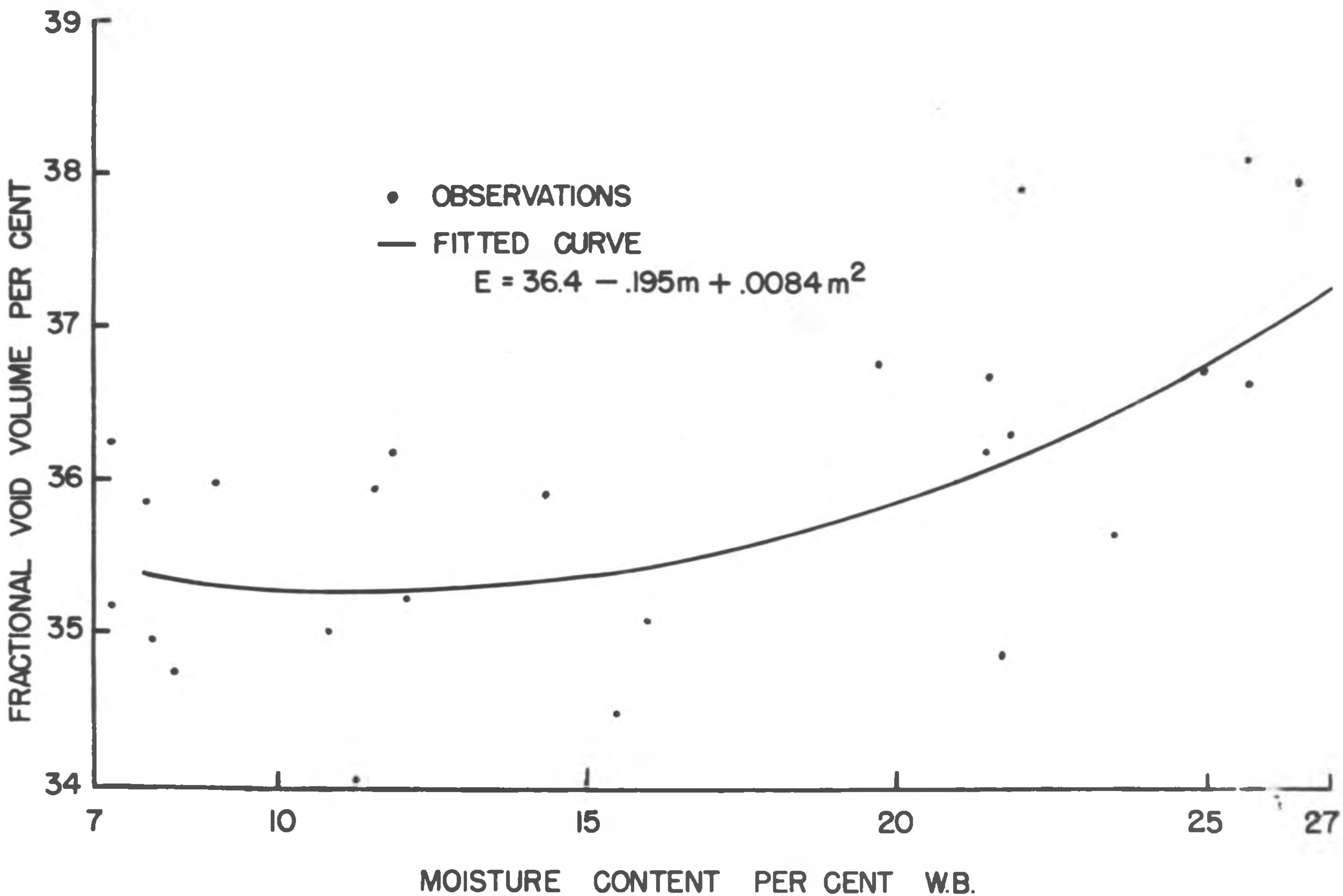

39
38
37
36
35
34
FRACTIONAL VOID VOLUME PER CENT
OBSERVATIONS
FITTED CURVE
E = 36.4 − .195m + .0084m2
7
10
15
20
25
27
MOISTURE CONTENT PER CENT W.B.

Figure 12. A plot of equivalent diameter vs. moisture content

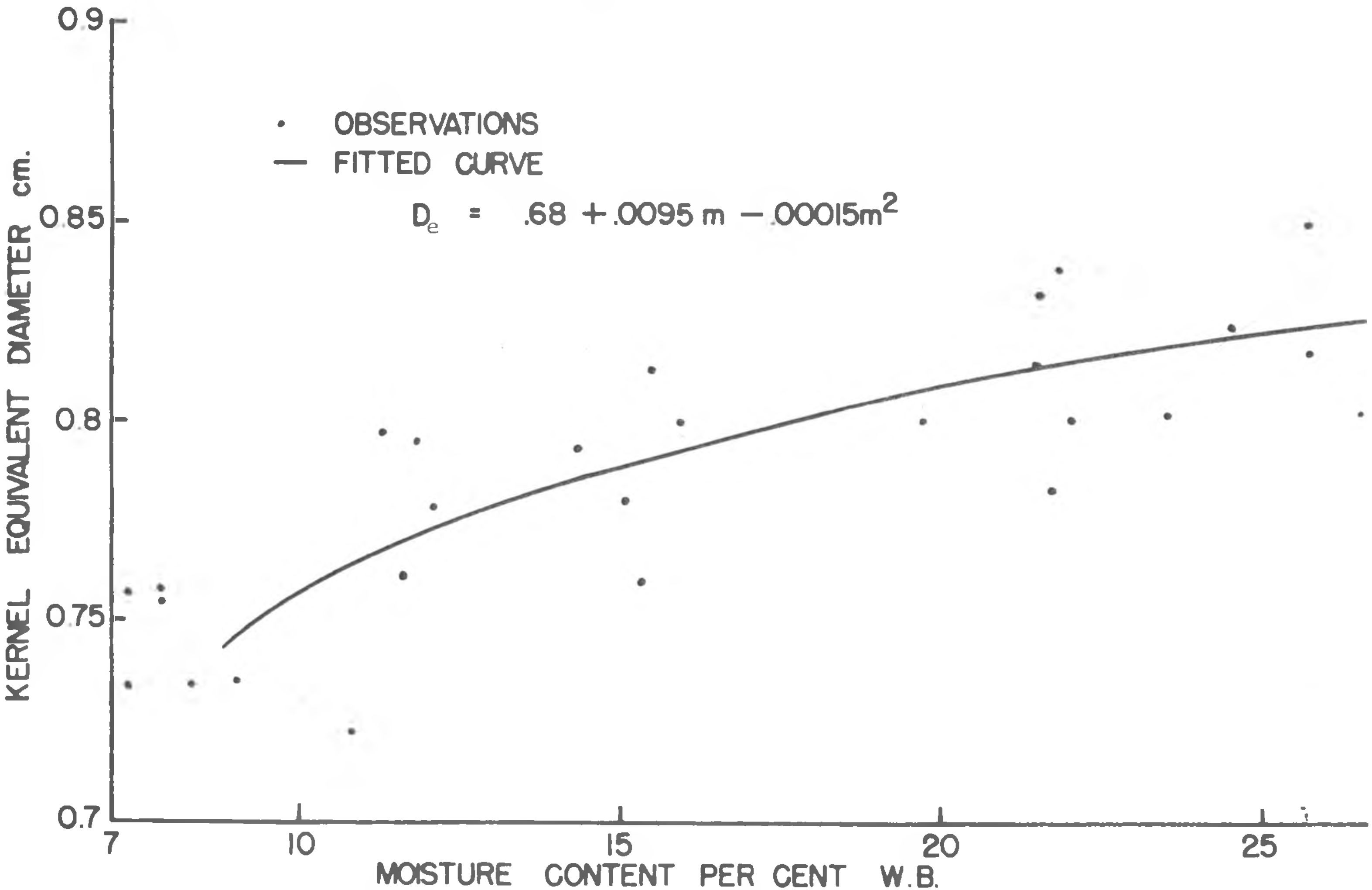

OBSERVATIONS
FITTED CURVE
$D_e = .68 + .0095\,m - .00015m^2$
KERNEL EQUIVALENT DIAMETER cm.
0.9
0.85
0.8
0.75
0.7
7
10
15
20
25
MOISTURE CONTENT PER CENT W.B.

Figure 13. A plot of pressure drop per foot depth vs. moisture content of shelled corn at constant fractional void volume of 39 percent

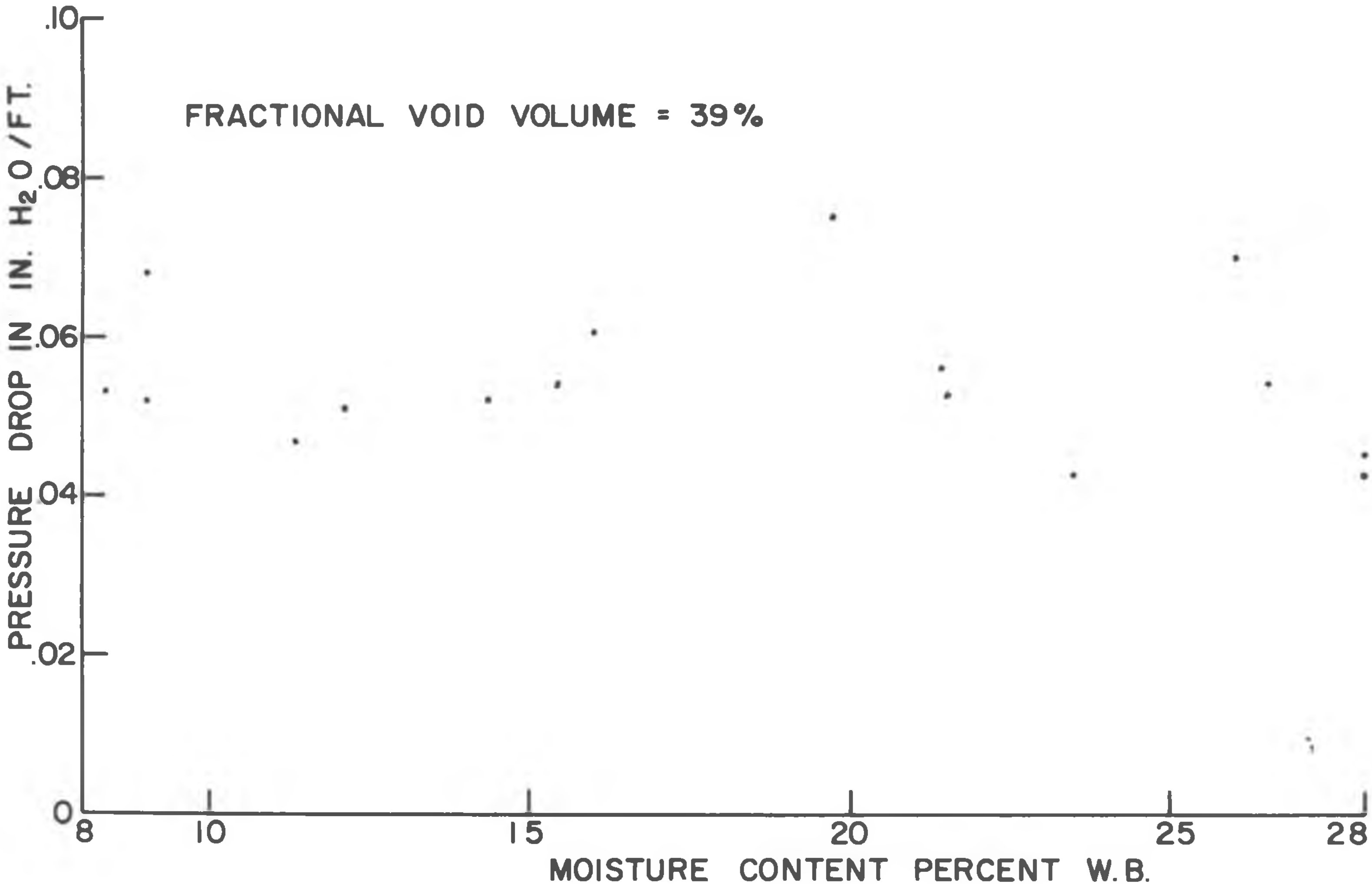

FRACTIONAL VOID VOLUME = 39%
PRESSURE DROP IN IN. H_2O/FT.
.10
.08
.06
.04
.02
0
8
10
15
20
25
28
MOISTURE CONTENT PERCENT W.B.

Figure 14. A plot of friction factor f_v vs. $\frac{N_{Re}}{1-E}\frac{1.02}{1.9}$. The theoretical curve is drawn using the relation:

$$f_v = 150 + 1.75 \frac{N_{Re}}{(1-E)} \frac{1.02}{1.9}$$

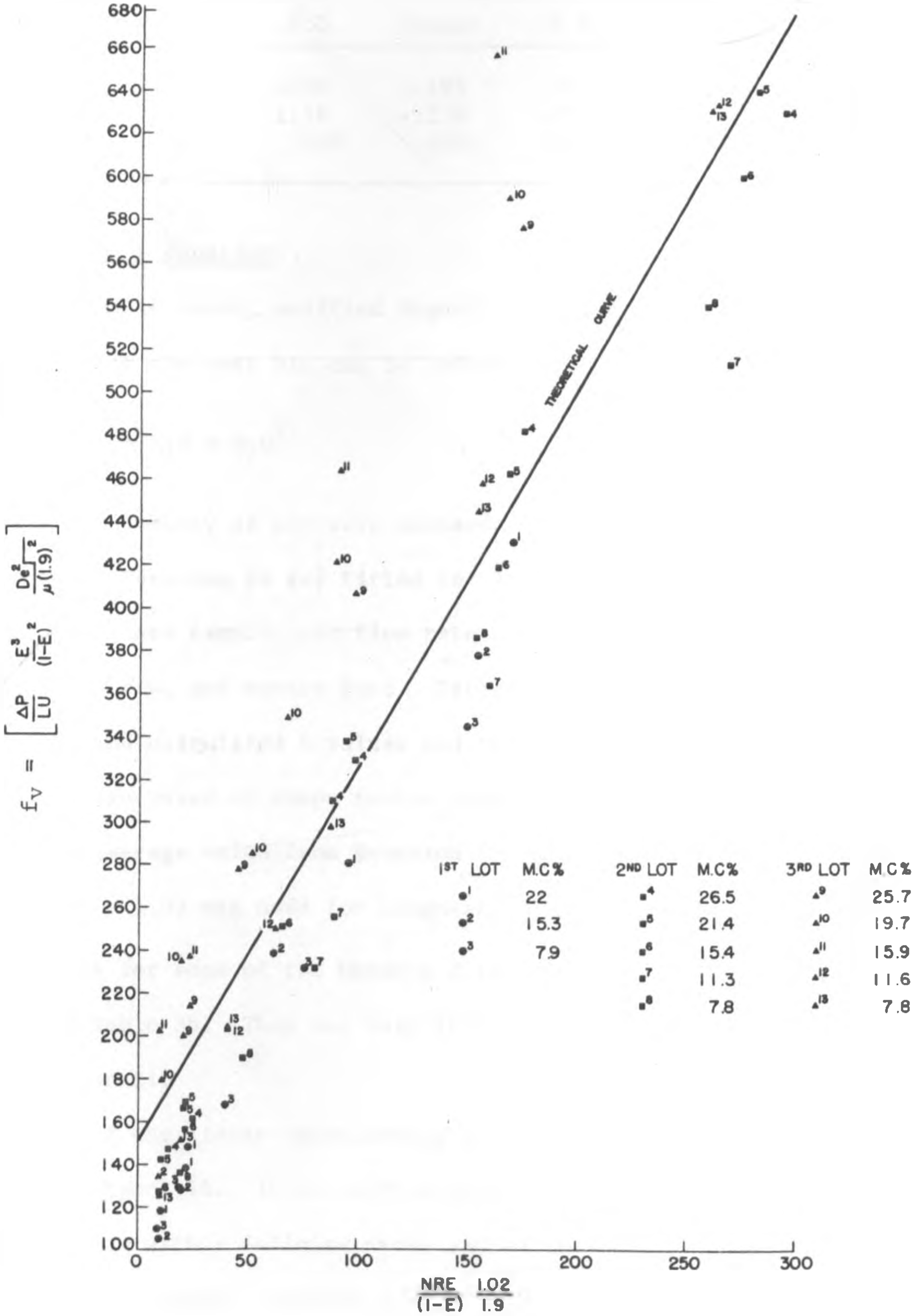

$f_V = \left[\frac{\Delta P}{LU} \; \frac{E^3}{(1-E)^2} \; \frac{De^2}{\mu(1.9)}\right]^2$
$\frac{NRE}{(1-E)} \; \frac{1.02}{1.9}$
THEORETICAL CURVE
1ST LOT M.C%
22
15.3
7.9
2ND LOT M.C%
26.5
21.4
15.4
11.3
7.8
3RD LOT M.C%
25.7
19.7
15.9
11.6
7.8

Table 2. Intercept, linear and quadratic coefficients of Equations 27, 28 and 29 and their corresponding standard deviations

Equation No.	Intercept	S.D.	Linear	S.D.	Quadratic	S.D.
27	36.4	1.08	-.195	.14	.0084	.004
28	41.2	1.18	-.238	.15	.0126	.0043
29	.68	.029	.0095	.0037	.00015	.00011

Modified Ergun's equation

As discussed above, modified Ergun's equation for given sample of shelled corn in the test bin can be reduced to the following form:

$$\Delta P/L = K_1U + K_2U^2 \tag{21}$$

Viscosity and density of air were assumed to remain constant for all the experiments. Equation 21 was fitted to the data of each one of the 13 samples. For each sample, air flow rate was varied 10 to 11 times from 123.64 to 4.6 cfm. per square foot. Table 3a gives the values of statistical and calculated K values and the corresponding shape factors, ϕ. The average value of shape factor determined from Equation 22 was 1.9 and the average value from Equation 23 was 1.95. Taking ϕ = 1.9, a ratio = $\frac{1.95}{1.9}$ = 1.02 was used for computation purposes.

K values for some of the Shedd's data were determined and are included in Table 3b. They may help in extrapolating outside Shedd's data using Equation 21.

A plot of the linear relationship of the modified Ergun's equation is shown in Figure 14. It is quite evident that each sample is describing a straight line with a definite slope and an intercept. Some samples show a marked deviation from the theoretical line given by the relation:

Table 3a. Empirical and calculated K values and the corresponding ϕ values

Sample No.	E	D_e(cm)	Empirical $K_1(10^{-5})$	S.D.(10^{-5})	Calculated $K_1(10^{-5})$	ϕ^2	Empirical $K_2(10^{-5})$	S.D.(10^{-5})	Calculated $K_2(10^{-5})$	ϕ
1	.3791	.801	478	7.78	188	2.54	18.7	.135	9.52	1.99
2	.3491	.760	788	63	293	2.69	23.7	1.09	13.33	1.78
3	.3519	.734	799	23.9	304	2.63	23.6	.41	14.32	1.65
4	.3795	.825	791	66.5	176	4.49	15.4	.65	9.11	1.69
5	.3619	.814	930	39.4	221	4.21	20.0	.39	10.95	1.82
6	.3447	.813	969	29.7	270	3.59	23.6	.29	13.03	1.82
7	.3403	.797	864	42.4	296	2.92	22.6	.42	13.90	1.63
8	.3496	.758	914	49.2	293	3.12	23.5	.48	13.29	1.77
9	.3810	.817	986	66.6	177	5.57	18.4	.65	9.07	2.02
10	.3678	.805	911	17.0	211	4.32	28.6	.17	10.49	2.73
11	.3507	.800	1,016	24.1	260	3.91	28.5	.24	12.46	2.28
12	.3593	.761	911	65.7	260	3.50	24.9	.64	12.02	2.08
13	.3584	.755	898	46.5	253	3.55	25.6	.46	12.20	2.1

mean of ϕ^2 = 3.62
standard deviation = .87
S.D. = standard deviation

mean of ϕ = 1.95
standard deviation = .3

$$\phi^2 = \frac{K_1(\text{Empirical})}{K_1(\text{Calculated})} \qquad \phi = \frac{K_2(\text{Empirical})}{K_2(\text{Calculated})}$$

where,

$$\text{Calculated } K_1 = 150\frac{(1-E)^2}{E^3}\frac{\mu}{D_e^2}(.192) \text{ and Calculated } K_2 = 1.75\frac{(1-E)}{E^3}\frac{\rho}{gD_e}(.192)$$

(.192) = Conversion factor from lb/ft^2 to in. H_2O

Table 3b. K values for Shedd's data in Figure 1

	$K_1(10^{-5})$	S.D.(10^{-5})	$K_2(10^{-5})$	S.D.(10^{-5})
Shelled corn	435	13.9	21.9	.285
Soya bean	429	19.2	11.6	.39
Rough rice	1,307	83.1	28.4	3.38
Wheat	1,992	38.2	31.8	1.16
Alfalfa	10,298	24.2	65.9	7.3

$$f_v = 150 + 1.75 \frac{NR_e}{1-E\ \phi} 1.02 \qquad (30)$$

The large deviation is an indication that shape, size distribution and foreign matter varied from one sample to the other. Estimates of these factors were not made and no quantitative evaluation of any of them will be made here.

DISCUSSION OF RESULTS

Moisture Content

Looking at Figures 10 and 11, it is evident that fractional void volume, for a given method of loading, increases with moisture content. The fitted curves for the packed and loose fill data are given by Equations 27 and 28, respectively. The scatter in Figures 10 and 11 shows that these equations are mere approximations. They would be used, however, when it is necessary to show how fractional void volume would be expected to vary as shelled corn is being dried. It is necessary to point out that these equations are not applicable to batch drying systems because as shelled corn is being dried in a batch dryer it changes from originally wet packed corn to relatively loose dry corn. The other consideration is that the equation for predicting pressure, demands very accurate measurements of void volume and in this situation Equations 27 and 28 would be inadequate.

However, for rough estimates, Equations 27 and 28 may be used to compute the variation in fractional void volume as corn is dried. Using Equation 27, it was estimated that fractional void volume reduction for shelled corn dried from 28 percent moisture content to 18 percent moisture content for packed fill is about 2 percent. The corresponding increase in pressure drop per foot depth would be about 24 percent.

With regard to variation of kernel size with moisture content, Equation 29, above, is the fitted curve for the data. Similar to Equations 27 and 28, only approximate values can be predicted using this equation.

As was mentioned in earlier paragraphs, moisture content can be used as an indicator for pressure drop if good relationship can be shown to exist between moisture content and fractional void volume and kernel size. Since it appears that this is not the case, it can be concluded that moisture content alone cannot be used for accurate pressure drop prediction in shelled corn.

Modified Ergun's Equation

A plot of linear relationship given by Equation 30 is shown in Figure 14. It is evident that data for different samples do not fall on one curve. However, data from one sample show a definite slope and intercept. This is an indication that pressure drop is a sum of two terms proportional to velocity and the square of velocity, respectively. This can be shown as follows:

For a given sample, Ergun's equation reduces to the form:

$$\frac{\Delta P}{L} = K_1 U + K_1 U^2 \qquad (21)$$

Dividing by velocity, we get:

$$\frac{\Delta P}{LU} = K_1 + K_2 U \qquad (21a)$$

The relationship given by Equation 21a is linear and is of the form of single sample curves in Figure 14.

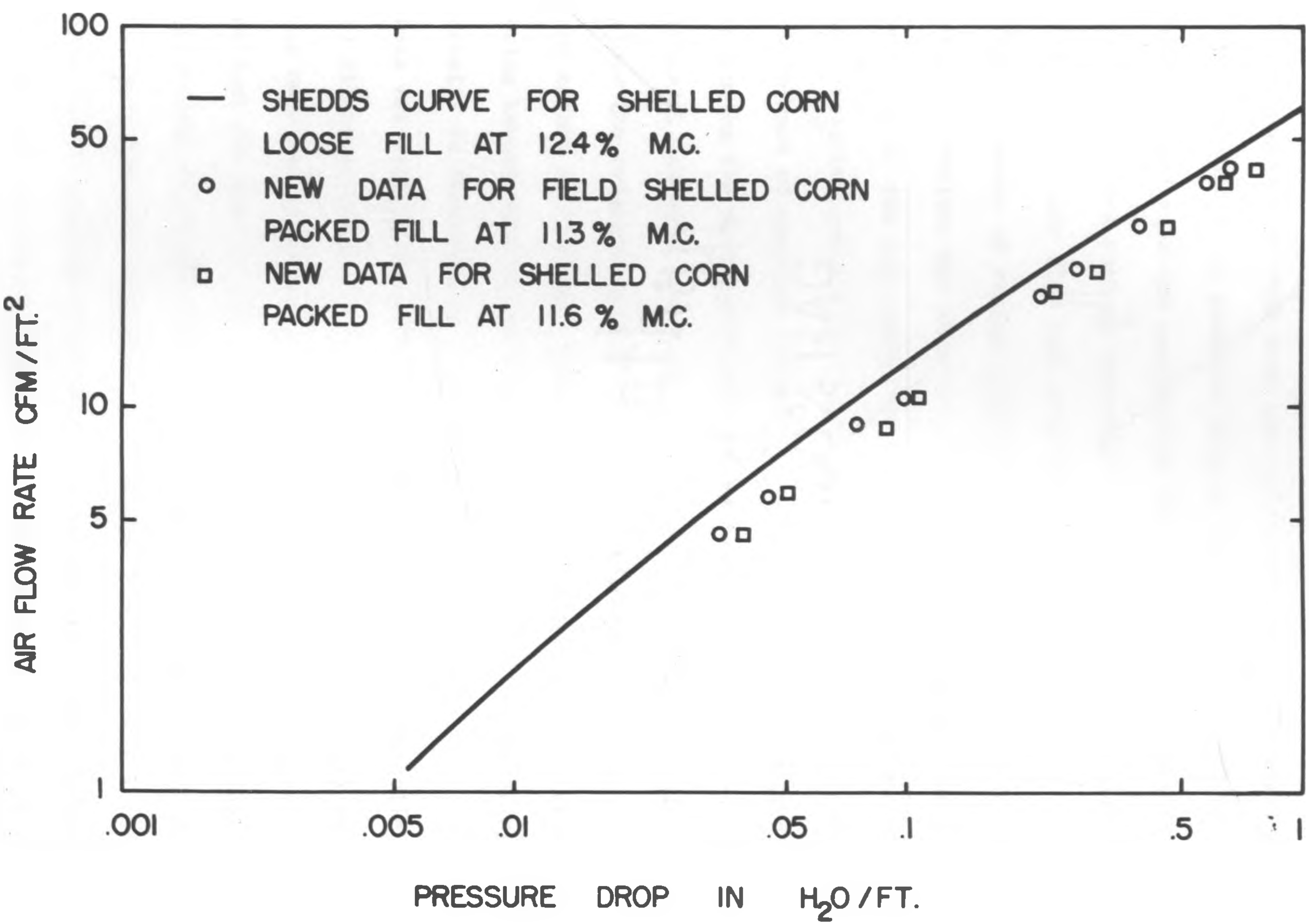
As was mentioned in the procedure above, most of the data for correlating modified Ergun's equation were taken for packed fill. For each sample, however, two points were observed at loose and at intermediate fills. Fractional void volume of loose fill was about 6 percent higher than that of packed fill. The range of fractional void volume variation among packed filled corn samples was 4 percent. The points from loose fill and intermediate fill were included in Figure 14 and were found to fall on the corresponding single sample lines. This gave an indication that the fractional void volume functions in the modified Ergun's Equation 20, i.e. $\frac{(1-E)^2}{E^3}$ and $\frac{(1-E)}{E^3}$ are valid.

A comparison between Shedd's curve for loose fill of clean shelled corn in Figure 1 and the data of present investigation which was packed fill, is shown in Figure 15. Shedd's data show lower values of pressure drop (about 30 percent lower) as would be expected for loose fill.

As mentioned in the analysis of the problem, a departure from the theoretical curve may be attributed to sample variation of any of the following factors, namely: shape, size distribution and foreign matter. Table 3a shows how the shape factor varied. However, not all of the deviations from the theoretical line may be attributed to the above factors. It was estimated that error of 1 percent in determining kernel density would result in about 2 percent error in fractional void volume. Two percent error in fractional void volume in turn may account for 24 percent error in pressure drop. The fractional void volume function takes a third power and hence a small error in its determination becomes important in pressure drop calculations.

The actual error of fractional void volume was not estimated but it is the opinion of the author that possibilities for testing modified Ergun's equation are limited by the accuracy of fractional void volume determinations.

Figure 15. A comparison between Shedd's data for loose fill of clean shelled corn and packed fill of field shelled corn of present investigation


100
50
10
5
1
.001
.005
.01
.05
.1
.5
1
SHEDDS CURVE FOR SHELLED CORN
LOOSE FILL AT 12.4 % M.C.
NEW DATA FOR FIELD SHELLED CORN
PACKED FILL AT 11.3 % M.C.
NEW DATA FOR SHELLED CORN
PACKED FILL AT 11.6 % M.C.
AIR FLOW RATE CFM / FT.²
PRESSURE DROP IN H₂O / FT.

SUMMARY AND CONCLUSION

1. The objectives of this work were 1) to determine the effect of moisture content on pressure drop in shelled corn and 2) to find a mathematical equation correlating the material parameters that can be easily measured such as fractional void volume and equivalent diameter and air flow rate with pressure drop.
2. Thirty samples of various moisture contents were tested for pressure drop at constant air flow rate of 8.93 cfm. per square foot. The analysis of the data showed no increase or decrease in pressure drop with moisture content, if fractional void volume is held constant. The effect of moisture content can, therefore, be determined by measuring the fractional void volume variation it produces. Moisture content, however, cannot be used to predict fractional void volume since the relation between the two is influenced by kernel shrinkage and method of filling. Fractional void volume can be determined using kernel density and bulk density. A method of measuring kernel density is described in this work.
3. Data for fitting the modified Ergun's Equation 20 were collected from 13 different samples. An attempt to fit the data to this equation was made but large deviations from the theoretical curve were evident for some of the samples. This was attributed to possible variations in shape, size distribution or foreign matter. Due to the fact that the fractional void volume function takes a third power, error in determining fractional void volume may result in large deviations. Estimates showed this to be the case and it is the opinion of the author that inaccuracies in measuring fractional

void volume may have had a large contribution to the deviations.

4. Substitution for effective diameter in Ergun's equation by a function of equivalent diameter and shape factor is considered useful until satisfactory methods for measuring specific surface are available. An empirical method for determining shape factor is described in this work.

5. Having determined that one or more of the factors, shape, size distribution and foreign matter, may vary from one corn sample to the other, it can be concluded that the next stage of this investigation is to measure those factors and show how they influence the shape factor ϕ.

SUGGESTED FUTURE WORK

1. Now that the results of this work show, shape, size distribution and foreign matter to be variables in field shelled corn, it seems that further attempts to perfect the application of modified Ergun's equation should consider measuring the effects of these variables on shape factor ϕ.
2. An accurate method of measuring fractional void volume is necessary in order to minimize error since fractional void volume is a high power function.

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APPENDIX: TABLE OF RESULTS

Table 4. Loose fill data for regressing (1) moisture content on fractional void volume and (2) moisture content on corn kernel equivalent diameter

Sample No.	m(%)	E(%)	D_e(cm)	d($\frac{gm}{cc}$)	γ($\frac{gm}{cc}$)
1	25.7	43.05	.850	1.17	.664
2	25.0	43.46	.824	1.16	.635
3	21.5	43.03	.832	1.18	.674
4	14.3	40.88	.793	1.18	.700
5	12.1	40.20	.778	1.18	.708
6	9.0	20.82	.735	1.20	.709
7	28.3	44.22	.791	1.19	.661
8	23.5	42.96	.825	1.16	.664
9	17.7	39.56	.771	1.19	.718
10	8.3	38.98	.739	1.21	.734
11	27.6	43.43	.856	1.16	.654
12	21.8	42.89	.837	1.17	.667
13	11.8	40.98	.795	1.19	.700
14	7.3	40.92	.757	1.20	.709
15	22.0	43.13	.801	1.19	.675
16	15.3	39.48	.760	1.20	.728
17	7.9	39.25	.734	1.21	.732
18	21.7	41.56	.783	1.18	.689
19	15.1	39.19	.780	1.18	.720
20	10.8	39.36	.722	1.19	.724
21	26.5	42.65	.825	1.17	.671
22	21.4	41.27	.814	1.18	.693
23	15.4	39.64	.813	1.18	.711
24	11.3	38.88	.797	1.20	.731
25	7.8	40.17	.758	1.21	.724
26	25.7	43.79	.817	1.18	.661
27	19.7	42.23	.801	1.19	.688
28	15.9	41.04	.800	1.19	.701
29	11.6	39.95	.761	1.22	.714
30	7.8	41.24	.755	1.22	.718

Table 5. Packed fill data for regressing moisture content on fractional void volume

Sample No.	m(%)	E(%)	D_e (cm)	d $(\frac{gm}{cc})$	γ $(\frac{gm}{cc})$
1	25.7	36.62	.850	1.17	.739
2	25.0	36.71	.824	1.16	.731
3	21.5	36.69	.832	1.18	.749
4	14.3	35.90	.793	1.18	.759
5	12.1	35.22	.778	1.18	.767
6	9.0	35.98	.735	1.20	.767
7	28.3	37.22	.791	1.19	.744
8	23.5	35.65	.825	1.16	.749
9	8.3	34.76	.734	1.21	.790
10	27.6	36.59	.856	1.16	.733
11	21.8	36.30	.837	1.17	.744
12	11.8	36.17	.795	1.19	.757
13	7.3	36.25	.757	1.20	.765
14	22.0	37.91	.801	1.19	.737
15	15.3	34.91	.760	1.20	.783
16	7.3	35.19	.734	1.21	.781
17	21.7	34.86	.783	1.18	.768
18	15.1	34.80	.780	1.18	.772
19	10.8	35.01	.722	1.19	.776
20	26.5	37.95	.825	1.17	.726
21	21.4	36.19	.814	1.18	.735
22	15.4	34.47	.813	1.18	.772
23	11.3	34.03	.797	1.20	.789
24	7.8	34.96	.758	1.21	.787
25	25.7	38.10	.817	1.18	.728
26	19.7	36.78	.805	1.19	.735
27	15.9	35.07	.800	1.19	.772
28	11.6	35.93	.761	1.22	.781
29	7.8	35.84	.755	1.22	.784

Table 6. Data for fitting linear relationship of modified Ergun's equation

$$f_v = 150 + 1.75 \frac{NR_e}{1-E} \frac{1.02}{\phi}$$

Sample No.	m(%)	$d(\frac{gm}{cc})$	$\gamma(\frac{gm}{cc})$	D_e(cm)	$\frac{\Delta P}{L}$	E	$\frac{E^3}{(1-E)^2}$	U	f_v	$\frac{NR_e}{(1-E)} \frac{1.02}{1.9}$
1	22.0	1.19	.675	.801	.0336	.4313	.2481	8.93	147.55	22.70
	22.0	1.19	.711	.801	.0436	.4010	.1797	8.93	137.74	21.55
	22.0	1.19	.737	.801	1.36	.3791	.1413	73.32	411.45	170.76
	22.0	1.19	.737	.801	.5235	.3791	.1413	41.39	280.56	96.40
	22.0	1.19	.737	.801	.4394	.3791	.1413	37.23	261.80	86.70
	22.0	1.19	.737	.801	.3023	.3791	.1413	29.39	228.16	68.45
	22.0	1.19	.737	.801	.2026	.3791	.1413	22.58	199.03	52.58
	22.0	1.19	.737	.801	.1596	.3791	.1413	19.33	183.15	45.02
	22.0	1.19	.737	.801	.0708	.3791	.1413	10.91	143.95	25.41
	22.0	1.19	.737	.801	.0547	.3791	.1413	8.93	135.88	19.72
	22.0	1.19	.737	.801	.0318	.3791	.1413	5.83	121.00	17.35
	22.0	1.19	.737	.801	.0245	.3791	.1413	4.60	118.14	10.71

U(cfm/ft^2)

$$\frac{\Delta P}{L} \left[\frac{in.\ H_2O}{ft}\right]$$

$$f_v = \left[\frac{1}{(1.9)^2} \frac{E^3}{(1-E)^2} \frac{\Delta P}{LU} D_e^2\right]$$

Table 6. (Continued)

Sample No.	m(%)	d($\frac{gm}{cc}$)	γ($\frac{gm}{cc}$)	D_e(cm)	$\frac{\Delta P}{L}$	E	$\frac{E^3}{(1-E)^2}$	U	f_v	$\frac{NR_e}{(1-E)}$ $\frac{1.02}{1.9}$
2	15.3	1.20	.728	.760	.0481	.3948	.1680	8.93	127.90	20.24
	15.3	1.20	.757	.760	.0615	.3707	.1286	8.93	125.17	19.46
	15.3	1.20	.783	.760	1.85	.3491	.1004	73.32	357.59	154.53
	15.3	1.20	.783	.760	.7278	.3491	.1004	41.39	248.33	87.24
	15.3	1.20	.783	.760	.6137	.3491	.1004	37.23	233.91	78.47
	15.3	1.20	.783	.760	.4943	.3491	.1004	29.39	238.66	61.94
	15.3	1.20	.783	.760	.2835	.3491	.1004	22.58	177.38	44.89
	15.3	1.20	.783	.760	.2251	.3491	.1004	19.33	164.61	40.74
	15.3	1.20	.783	.760	.1007	.3491	.1004	10.91	130.55	22.99
	15.3	1.20	.783	.760	.0755	.3491	.1004	8.93	119.20	18.82
	15.3	1.20	.783	.760	.0446	.3491	.1004	5.83	107.85	12.29
	15.3	1.20	.783	.760	.0341	.3491	.1004	4.60	105.01	9.70
3	7.9	1.21	.732	.734	.0535	.3925	.1638	8.93	129.34	19.49
	7.9	1.21	.760	.734	.0669	.3693	.1266	8.93	125.00	18.76
	7.9	1.21	.781	.734	1.85	.3519	.1037	73.32	344.86	149.89
	7.9	1.21	.781	.734	.7470	.3519	.1037	41.39	246.67	84.61
	7.9	1.21	.781	.734	.6317	.3519	.1037	37.23	231.91	76.11
	7.9	1.21	.781	.734	.4428	.3519	.1037	29.39	205.92	60.08
	7.9	1.21	.781	.734	.2957	.3519	.1037	22.58	178.99	46.17
	7.9	1.21	.781	.734	.2377	.3519	.1037	19.33	168.07	39.52
	7.9	1.21	.781	.734	.1073	.3519	.1037	10.91	134.42	22.30
	7.9	1.21	.781	.734	.0748	.3519	.1037	8.93	114.48	18.25
	7.9	1.21	.781	.734	.0478	.3519	.1037	5.83	112.06	11.92
	7.9	1.21	.781	.734	.0370	.3519	.1037	4.60	109.94	9.40

Table 6. (Continued)

Sample No.	m(%)	d($\frac{gm}{cc}$)	γ($\frac{gm}{cc}$)	D_e(cm)	$\frac{\Delta P}{L}$	E	$\frac{E^3}{(1-E)^2}$	U	f_v	$\frac{NR_e}{(1-E)}$ $\frac{1.02}{1.9}$
4	26.5	1.70	.671	.825	.0365	.4265	.2359	8.93	160.56	23.19
	26.5	1.70	.692	.825	.0438	.4085	.1948	8.93	159.11	22.49
	26.5	1.70	.726	.825	3.3	.3795	.1420	123.64	628.99	296.22
	26.5	1.70	.726	.825	1.5	.3795	.1420	73.32	482.38	175.97
	26.5	1.70	.726	.825	.5767	.3795	.1420	41.39	328.69	99.33
	26.5	1.70	.726	.825	.4903	.3795	.1420	37.23	309.77	89.35
	26.5	1.70	.726	.825	.3410	.3795	.1420	29.39	274.29	70.54
	26.5	1.70	.726	.825	.2299	.3795	.1420	22.58	238.83	34.19
	26.5	1.70	.726	.825	.1849	.3795	.1420	19.33	224.64	46.39
	26.5	1.70	.726	.825	.0826	.3795	.1420	10.91	177.35	26.19
	26.5	1.70	.726	.825	.0608	.3795	.1420	8.93	160.79	21.44
	26.5	1.70	.726	.825	.0367	.3795	.1420	5.83	146.61	13.99
	26.5	1.70	.726	.825	.0269	.3795	.1420	4.60	135.15	11.04
5	21.4	1.18	.753	.814	4.2	.3619	.1164	123.64	638.73	284.71
	21.4	1.18	.753	.814	1.8	.3619	.1164	73.32	462.34	168.82
	21.4	1.18	.753	.814	.7423	.3619	.1164	41.39	337.79	95.30
	21.4	1.18	.753	.814	.6270	.3619	.1164	37.23	317.03	85.72
	21.4	1.18	.753	.814	.4317	.3619	.1164	29.39	275.52	67.68
	21.4	1.18	.753	.814	.2879	.3619	.1164	22.58	239.66	52.00
	21.4	1.18	.753	.814	.2307	.3619	.1164	19.33	224.56	44.52
	21.4	1.18	.753	.814	.1042	.3619	.1164	10.91	179.27	25.13
	21.4	1.18	.753	.814	.0786	.3619	.1164	8.93	166.06	20.57
	21.4	1.18	.753	.814	.0455	.3619	.1164	5.83	147.19	13.42
	21.4	1.18	.753	.814	.0345	.3619	.1164	4.60	141.53	10.60
	21.4	1.18	.693	.814	.0456	.4127	.2038	8.93	168.72	22.34
	21.4	1.18	.719	.814	.0575	.3907	.1606	8.93	167.65	21.53

Table 6. (Continued)

Sample No.	m(%)	d$(\frac{gm}{cc})$	$\gamma(\frac{gm}{cc})$	D_e(cm)	$\frac{\Delta P}{L}$	E	$\frac{E^3}{(1-E)^2}$	U	f_v	$\frac{NR_e}{(1-E)}$ $\frac{1.02}{1.9}$
6	15.4	1.18	.772	.813	4.8	.3447	.0954	123.64	598.84	267.93
	15.4	1.18	.772	.813	2.0	.3447	.0954	73.32	419.42	164.20
	15.4	1.18	.772	.813	.8223	.3447	.0954	41.39	305.31	92.69
	15.4	1.18	.772	.813	.6967	.3447	.0954	37.23	288.35	83.37
	15.4	1.18	.772	.813	.4805	.3447	.0954	29.39	251.34	65.82
	15.4	1.18	.772	.813	.3213	.3447	.0954	22.58	218.96	50.57
	15.4	1.18	.772	.813	.2565	.3447	.0954	19.33	203.54	43.29
	15.4	1.18	.772	.813	.1140	.3447	.0954	10.91	160.36	24.43
	15.4	1.18	.772	.813	.0861	.3447	.0954	8.93	148.03	20.00
	15.4	1.18	.772	.813	.0504	.3447	.0954	5.83	132.61	13.06
	15.4	1.18	.772	.813	.0383	.3447	.0954	4.60	127.98	10.30
	15.4	1.18	.711	.813	.0505	.3964	.1710	8.93	156.30	21.70
	15.4	1.18	.742	.813	.0653	.3701	.1278	8.93	151.05	20.81
7	11.3	1.20	.789	.797	4.5	.3403	.0906	123.64	512.16	269.63
	11.3	1.20	.789	.797	1.9	.3403	.0906	73.32	364.36	159.89
	11.3	1.20	.789	.797	.7540	.3403	.0906	41.39	256.04	90.26
	11.3	1.20	.789	.797	.6215	.3403	.0906	37.23	233.53	81.19
	11.3	1.20	.789	.797	.4309	.3403	.0906	29.39	205.39	64.10
	11.3	1.20	.789	.797	.2879	.3403	.0906	22.58	178.66	51.34
	11.3	1.20	.789	.797	.2302	.3403	.0906	19.33	167.41	42.15
	11.3	1.20	.789	.797	.1037	.3403	.0906	10.91	133.65	23.19
	11.3	1.20	.789	.797	.0808	.3403	.0906	8.93	126.61	19.47
	11.3	1.20	.789	.797	.0465	.3403	.0906	5.83	111.14	12.71
	11.3	1.20	.789	.797	.0346	.3403	.0906	4.60	105.51	10.03
	11.3	1.20	.731	.797	.0469	.3888	.1573	8.93	120.28	21.02
	11.3	1.20	.762	.797	.0604	.3629	.1177	8.93	123.61	20.17

Table 6. (Continued)

Sample No.	m(%)	$d(\frac{gm}{cc})$	$\gamma(\frac{gm}{cc})$	D_e(cm)	$\frac{\Delta P}{L}$	E	$\frac{E^3}{(1-E)^2}$	U	f_v	$\frac{NR_e}{(1-E)}$ $\frac{1.02}{1.9}$
8	7.8	1.21	.787	.758	4.7	.3496	.1010	123.64	539.48	260.11
	7.8	1.21	.787	.758	2.0	.3496	.1010	73.32	386.27	154.24
	7.8	1.21	.787	.758	.7752	.3496	.1010	41.39	265.56	87.07
	7.8	1.21	.787	.758	.6542	.3496	.1010	37.23	248.52	78.32
	7.8	1.21	.787	.758	.4562	.3496	.1010	29.39	220.11	61.83
	7.8	1.21	.787	.758	.3045	.3496	.1010	22.58	190.29	47.50
	7.8	1.21	.787	.758	.2406	.3496	.1010	19.33	176.76	40.66
	7.8	1.21	.787	.758	.1080	.3496	.1010	10.91	139.17	22.95
	7.8	1.21	.787	.758	.0838	.3496	.1010	8.93	132.07	18.78
	7.8	1.21	.787	.758	.0480	.3496	.1010	5.83	116.45	12.27
	7.8	1.21	.787	.758	.0370	.3496	.1010	4.60	113.61	9.67
	7.8	1.21	.724	.758	.0477	.4017	.1811	8.93	136.01	20.43
	7.8	1.21	.757	.758	.0637	.3744	.1341	8.93	134.50	19.54
9	25.7	1.18	.728	.817	4.0	.3810	.1443	123.64	760.19	294.57
	25.7	1.18	.728	.817	1.8	.3810	.1443	73.32	576.61	174.67
	25.7	1.18	.728	.817	.7190	.3810	.1443	41.39	407.16	98.60
	25.7	1.18	.728	.817	.6096	.3810	.1443	37.23	383.63	88.70
	25.7	1.18	.728	.817	.4230	.3810	.1443	29.39	336.55	70.02
	25.7	1.18	.728	.817	.2859	.3810	.1443	32.58	296.54	53.80
	25.7	1.18	.728	.817	.2287	.3810	.1443	19.33	277.72	46.05
	25.7	1.18	.728	.817	.1034	.3810	.1443	10.91	221.23	26.00
	25.7	1.18	.728	.817	.0761	.3810	.1443	8.93	200.05	21.28
	25.7	1.18	.728	.817	.0446	.3810	.1443	5.83	178.87	13.89
	25.7	1.18	.728	.817	.0336	.3810	.1443	4.60	171.81	10.96
	25.7	1.18	.661	.817	.0440	.4379	.2658	8.93	213.60	24.42
	25.7	1.18	.695	.817	.0580	.4090	.1959	8.93	207.52	22.29

Table 6. (Continued)

Sample No.	m(%)	d($\frac{gm}{cc}$)	γ($\frac{gm}{cc}$)	D_e(cm)	$\frac{\Delta P}{L}$	E	$\frac{E^3}{(1-E)^2}$	U	f_v	$\frac{NR_e}{(1-E)}$ $\frac{1.02}{1.9}$
10	19.7	1.19	.753	.805	5.5	.3678	.1245	123.64	875.90	284.18
	19.7	1.19	.753	.805	2.2	.3678	.1245	73.32	591.83	168.52
	19.7	1.19	.753	.805	.8878	.3678	.1245	41.39	422.17	95.14
	19.7	1.19	.753	.805	.7218	.3678	.1245	37.23	380.74	85.58
	19.7	1.19	.753	.805	.5214	.3678	.1245	29.39	349.18	67.55
	19.7	1.19	.753	.805	.3520	.3678	.1245	22.58	305.78	51.90
	19.7	1.19	.753	.805	.2818	.3678	.1245	19.33	286.05	44.42
	19.7	1.19	.753	.805	.1276	.3678	.1245	10.91	228.84	25.07
	19.7	1.19	.753	.805	.0970	.3678	.1245	8.93	213.06	20.53
	19.7	1.19	.753	.805	.0557	.3678	.1245	5.83	187.41	13.40
	19.7	1.19	.753	.805	.0419	.3678	.1245	4.60	179.52	10.58
	19.7	1.19	.688	.805	.0820	.4223	.2257	8.93	215.46	22.46
	19.7	1.19	.719	.805	.1022	.3963	.1708	8.93	212.45	21.49
11	15.9	1.19	.772	.800	5.6	.3507	.1023	123.64	949.78	274.98
	15.9	1.19	.772	.800	2.3	.3507	.1023	73.32	657.70	163.08
	15.9	1.19	.772	.800	.9155	.3507	.1023	41.39	464.38	92.06
	15.9	1.19	.772	.800	.7749	.3507	.1023	37.23	437.07	82.80
	15.9	1.19	.772	.800	.5378	.3507	.1023	29.39	382.43	65.37
	15.9	1.19	.772	.800	.3509	.3507	.1023	22.58	334.11	50.22
	15.9	1.19	.772	.800	.2879	.3507	.1023	19.33	310.99	42.99
	15.9	1.19	.772	.800	.1305	.3507	.1023	10.91	250.05	24.26
	15.9	1.19	.772	.800	.1002	.3507	.1023	8.93	235.34	19.86
	15.9	1.19	.772	.800	.0575	.3507	.1023	5.83	205.93	12.96
	15.9	1.19	.772	.800	.0442	.3507	.1023	4.60	201.72	10.23
	15.9	1.19	.701	.800	.0519	.4104	.1988	8.93	237.32	21.86
	15.9	1.19	.728	.800	.0672	.3877	.1554	8.93	183.01	21.06

Table 6. (Continued)

Sample No.	m(%)	$d(\frac{gm}{cc})$	$\gamma(\frac{gm}{cc})$	D_e(cm)	$\frac{\Delta P}{L}$	E	$\frac{E^3}{(1-E)^2}$	U	f_v	$\frac{NR_e}{(1-E)}$ $\frac{1.02}{1.9}$
12	11.6	1.22	.781	.761	4.9	.3593	.1130	123.64	633.55	265.08
	11.6	1.22	.781	.761	2.1	.3593	.1130	73.32	457.56	157.20
	11.6	1.22	.781	.761	.7810	.3593	.1130	41.39	300.78	88.74
	11.6	1.22	.781	.761	.6621	.3593	.1130	37.23	283.18	79.82
	11.6	1.22	.781	.761	.4604	.3593	.1130	29.39	249.58	63.01
	11.6	1.22	.781	.761	.3086	.3593	.1130	22.58	217.58	48.41
	11.6	1.22	.781	.761	.2460	.3593	.1130	19.33	203.18	41.44
	11.6	1.22	.781	.761	.1116	.3593	.1130	10.91	163.19	23.39
	11.6	1.22	.781	.761	.0877	.3593	.1130	8.93	156.79	19.15
	11.6	1.22	.781	.761	.0506	.3593	.1130	5.83	137.59	12.50
	11.6	1.22	.781	.761	.0388	.3593	.1130	4.60	134.39	9.86
	11.6	1.22	.714	.761	.0476	.3995	.1768	8.93	133.43	20.43
	11.6	1.22	.746	.761	.0632	.3880	.1560	8.93	156.31	20.05
13	7.8	1.22	.784	.755	5.0	.3584	.1118	123.64	629.54	262.64
	7.8	1.22	.784	.755	2.1	.3584	.1118	73.32	445.67	155.75
	7.8	1.22	.784	.755	.7936	.3584	.1118	41.39	297.63	87.92
	7.8	1.22	.784	.755	.6715	.3584	.1118	37.23	280.49	79.08
	7.8	1.22	.784	.755	.4729	.3584	.1118	29.39	249.32	62.44
	7.8	1.22	.784	.755	.3177	.3584	.1118	22.58	218.15	47.96
	7.8	1.22	.784	.755	.2543	.3584	.1118	19.33	204.14	41.06
	7.8	1.22	.784	.755	.1145	.3584	.1118	10.91	162.06	23.17
	7.8	1.22	.784	.755	.0879	.3584	.1118	8.93	152.71	18.97
	7.8	1.22	.784	.755	.0505	.3584	.1118	5.83	134.01	12.38
	7.8	1.22	.784	.755	.0377	.3584	.1118	4.60	126.22	9.77
	7.8	1.22	.718	.755	.0476	.4124	.2031	8.93	150.89	20.71
	7.8	1.22	.750	.755	.0632	.3862	.1529	8.93	150.88	19.83