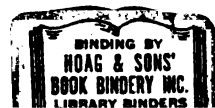




AIRFLOW-PRESSURE DROP
CHARACTERISTICS OF PACKED BEDS
OF BIOLOGICAL PARTICLES

Thesis for the Degree of M. S.
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THESIS



ABSTRACT

AIRFLOW-PRESSURE DROP CHARACTERISTICS OF PACKED BEDS OF BIOLOGICAL PARTICLES

by Richard J. Patterson

The resistance to airflow of randomly packed beds of plastic spheres, cherry pits, shelled corn and navy beans was determined in the airflow range of 10 to 120 cfm per square foot. The effect of bed porosity, product moisture content and air temperature on the pressure drop was evaluated for shelled corn and navy beans.

Three semitheoretical relationships, the Leva, Matthies and Ergun equations, each describing the pressure drops through randomly packed beds, are tested and their value in predicting pressure drops through grain beds evaluated. A new equation, the modified Ergun equation, is proposed for predicting the airflow resistance in beds of biological products:

$$\frac{\Delta P}{h} = k_E \left[150 \frac{(1-\epsilon)^2}{\epsilon^3} \mu \frac{u}{d^2 g} + 1.75 \frac{1-\epsilon}{\epsilon^3} \frac{\rho u^2}{dg} \right]$$

where k_E is the modified Ergun product constant.

The values of k_E were determined for beds of cherry pits, shelled corn and navy beans. The results for beds containing no fines are:

k_E for cherry pits - 1.1 to 1.2

k_E for shelled corn - 3.7 to 4.5

k_E for navy beans - 1.8 to 2.0

Adding fines to a bed of biological particles increases the k_E value according to the percentage of fines in the bed.

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**AIRFLOW-PRESSURE DROP CHARACTERISTICS
OF PACKED BEDS OF BIOLOGICAL PARTICLES**

By

Richard J. Patterson

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LIST OF SYMBOLS

a	product constant, dimensionless
a'	in. H_2O per ft.
a''	product constant, in. H_2O per ft.
b	product constant, dimensionless
b'	in. H_2O , min sq per ft ³
b''	product constant, in H_2O , min sq per ft ³
d	particle diameter, ft.
eq.	subscript, equivalent
f	friction factor, $f(Re)$
g	conversion factor, lb _m ft per lb _f sec sq
h	bed height, ft
k	product constant, dimensionless
n	state-of-flow factor, $f(Re)$
u	superficial air velocity, ft per sec
ΔP	pressure drop, lb per sq ft, or in. H_2O
μ	air viscosity, lb per ft sec
ϵ	porosity, dimensionless decimal
ϕ	particle shape factor, dimensionless
ρ	air density, lb per cu ft
ρ_p	product bulk density, lb per cu ft
Re	Reynolds number, dimensionless
E	as subscript, Ergun
L	as subscript, Leva
M	as subscript, Matthies

I. INTRODUCTION

The resistance to airflow through a packed bed of biological particles is a function of the air and bed characteristics. These include air temperature, air relative humidity, bed particle moisture content, bed particle diameter, bed porosity and the percentage of intermixed fine material. All influence the resistance to airflow and, therefore, should be taken in account when predicting the pressure drop through a bed of biological particles.

A good deal of empirical data has been published on the pressure drop through beds of biological materials. An example of such data is that published in the American Society of Agricultural Engineers Yearbook (1969) entitled Data D 272 (figure 1). Unfortunately, such data does not reflect the effects of the above mentioned bed and air characteristics (except as stated in a footnote). This data is, therefore, only reliable for pressure drop-airflow conditions closely resembling those for which the data was obtained. For researchers, designers and operators of drying and cooling equipment and processes, data in the form of ASAE D 272 is of limited value.

The chemical engineering profession has been the source of rather extensive investigations into the pressure drop-airflow relationships of beds of nonbiological particles and several relationships have evolved which adequately describe the air and bed parameters.

The purpose of this investigation is to test three of these semitheoretical relationships, Leva, Matthies and Ergun, on beds composed of biological particles, namely cherry pits, corn and navy beans.

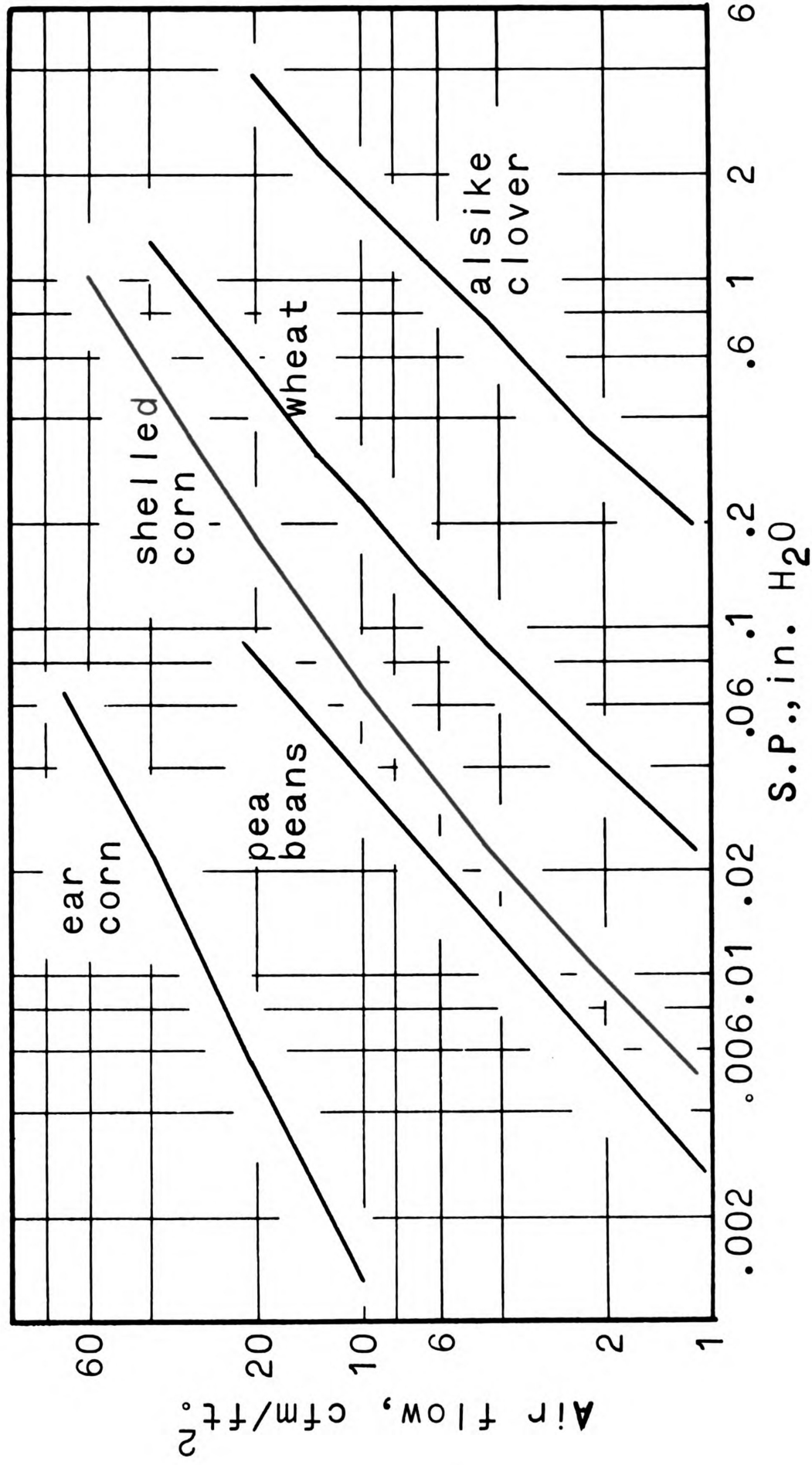


Figure 1. Resistance of grains and seeds to airflow.

II. REVIEW OF LITERATURE

2.1 General

The static pressure requirements of a fan, providing air circulation for drying or cooling a fixed bed of biological particles, is a function of the specific resistance of the bed material to airflow. Since 1948, empirical data on the airflow-static pressure relationship of a number of biological products has been published in graphical form in the American Society of Agricultural Engineers Yearbook. A disadvantage of this data is that each curve is representative of the static pressure-airflow relationship for a particular product under only one set of bed conditions. Since the actual static pressure depends on a number of bed parameters such as, bed porosity, product moisture content and the percentage of "fines" in the bed, one curve does not adequately represent the possible range of static pressure requirements for a bed of a particular product.

Empirical airflow-static pressure data for a large number of biological products is available in the literature (Table 1). When such data is represented by a log-log plot, the resulting curves are almost straight lines which are reasonably well described by the following equation:

$$\frac{\Delta P}{h} = a u^b \quad (1)$$

Equation (1) is called the Ramsin equation. Hall (1957) has published the values of the product constants a and b for a number of grains.

Table 1. Emperical pressure drop-airflow data on biological products available in the literature.

<u>Product</u>	<u>Reference</u>
alfalfa	Shedd (1953)
apples	Borrero (1967)
barley	Hukill, et al. (1955)
carrot seed	Lawton (1965)
cherry pits	Bakker-Arkema, et al. (1969)a
clover seed	Lawton (1965)
cotton seed	Nissing (1958)
coffee beans	Wang, et al. (1968)
hay	Day (1964)a
grass seed	Osborn (1961)
macadamia nuts	Wang, et al. (1968)
oats	Osborn (1961)
onion	Lawton (1965)
pea beans	Shedd (1953)
potatoes	Matthies (1956)
rape	Lawton (1965)
rice	Stirniman, et al. (1931)
shelled corn	Shedd (1953)
sorghum	Hukill, et al. (1955)
soybeans	Hukill, et al. (1955)
sugarbeets	Matthies (1956)
wheat	Shedd (1953)

The pressure drop data are properly described by equation (1) only over a relatively narrow airflow range. Hukill, et al. (1955) proposed an empirical relationship between the airflow rate and the pressure drop which has good accuracy throughout the full range of air velocities used for cooling and drying fixed beds of biological products. The equation has the following form:

$$\frac{\Delta P}{h} = \frac{a'u^2}{\ln(1+bu)} \quad (2)$$

A third empirical relationship between the pressure drop and the airflow through a fixed bed has been proposed by Bunn, et al. (1963):

$$\frac{\Delta P}{h} = a'' [\exp. (b''u^2h/\Delta P) - 1] \quad (3)$$

Equations (2) and (3) describe the airflow-static pressure relationship of biological products well as long as the bed and product conditions are the same as those for which the product constants were originally determined. However, the empirical nature of the equations does not provide an understanding of the importance of the bed parameters affecting the pressure drop. For instance, none of the empirical equations contain terms for the bed porosity or bed particle diameter, both variables which considerably affect the pressure drop. For this reason the use of pure empirical equations was rejected in favor of semitheoretical relationships in this study.

A number of theoretical studies on the pressure drops of fluids flowing through porous media, such as a packed bed, have been made by chemical engineers. Two different approaches can be taken in analyzing fluid flow through a fixed bed. The bed can either be

regarded as consisting of a bundle of channels of varying hydraulic diameter (Barth, 1954) or as a collection of submerged particles (Carman, 1937). The first case leads to an internal flow problem, the second to an external flow analysis. The treatment of fluid permeation as an internal flow phenomenon within a set of channels has been more successful and has been the basis of very useful semitheoretical relationships.

LeClair, et al. (1968) recently solved the Navier-Stokes equations for axisymmetric flows around spherical particles in a bed (the external flow analysis). Numerical results were presented in the form of surface vorticity, pressure distributions and standing vortex ring dimensions. Although the agreement between the predicted drag and the experimental data for packed beds was satisfactory, the practical use of this analytical analysis for predicting pressure drops through beds of biological products cannot be recommended at this time because the required parameters (pressure distributions, surface vorticity, etc.) of such beds are not known.

A number of semitheoretical internal flow type expressions, each containing certain experimentally determined coefficients, have been developed for calculating the resistance of a fixed bed to airflow. A review of the available methods has recently been made by Yen (1967). Three airflow-static pressure relationships, the so-called Ergun, Leva and Matthies equations will be reviewed in detail since they are tested experimentally in this thesis.

2.2 Ergun Equation

A significant study on fluid flow through fixed beds of granular solids was published by Ergun (1952). He confirmed an observation first made by Reynolds (1900) that the total energy loss in a packed bed should be treated as the sum of the viscous and kinetic energy losses. Reynolds had found that at a low air-flow rate (laminar flow) the resistance offered by friction to the airflow is proportional to the product of the airflow to the first power times the viscosity of the air. At high flow rates (turbulent flows), the contributions of the viscous forces to the hydraulic resistances in a packed bed become negligible compared to the kinetic energy dissipation. Reynolds' investigation also showed that, in the turbulent airflow range, the static pressure loss is proportional to the product of the air density and the square of the air velocity. Since the airflow rates in fixed beds of biological particles take place mainly in the transition zone between laminar and turbulent flow (Matthies, 1956), the total resistance of the bed can best be treated as the sum of the separate (laminar and turbulent) resistances.

When the equations for the pressure drop for laminar flow (the so-called Blake-Kozeny equation) and for turbulent flow (the so-called Burke-Plummer equation) are added, the result is:

$$\Delta P = k_1 \frac{(1-\epsilon)^3}{\epsilon^3} \mu \frac{h}{d^2} \frac{u}{g} + k_2 \frac{1-\epsilon}{\epsilon^3} \frac{h}{d} \frac{\rho u^2}{g} \quad (4)$$

On the basis of experimental results, Ergun determined that $k_1 = 150$ and $k_2 = 1.75$. Anderson (1963) critically evaluated the Ergun equation with experiments. He found the constant k_1 to be a function

of bed porosity and k_2 a function of the tortuosity factor and the Reynolds number. Yen (1967) compared several available methods for predicting packed bed pressure drops and concluded that the error range of the Ergun equation is between -67 and +46 percent.

2.3 Leva equation

Leva (1949) developed a relationship for laminar as well as turbulent flow through packed beds of spherical and nonspherical particles. Leva's equations are based on the Hagen-Poiseuille law for isothermal laminar flow and on a modified friction factor analysis for turbulent flow. Leva's correlation has the following form:

$$\Delta P = f_L \frac{2}{\phi^{3-n}} \frac{(1-\epsilon)^{3-n}}{\epsilon^3} \frac{h}{d} \frac{\rho u^2}{g} \quad (5)$$

The terms f_L , the (Leva) friction factor and n , the state-of-flow factor, are functions of the bed-particle Reynolds number. In addition, f_L depends on the surface characteristics of the bed particles. The values of f_L and n are read from graphs given in Leva's paper. Because of the necessity to find f_L and n graphically for each fluid velocity, Leva's equation cannot be programmed on a computer as easily as Ergun's equation. Yen (1967) found the error range of the Leva equation to be between -57 and +63 percent.

2.4 Matthies equation

The first significant semitheoretical study on the pressure drop of air through packed beds of biological products was published by Matthies (1956). Matthies investigated and described, by way of a semitheoretical equation, the pressure drop through beds of most common grains as well as through potatoes and sugar beets. The

equation proposed by Matthies, which is based on earlier work by Fehling (1939), is:

$$\Delta P = k_M f_M \frac{1}{\epsilon^4} \frac{h}{d} \frac{\rho u^2}{2g} \quad (6)$$

The value of k_M , a product constant, is a function of the shape, size and distribution and surface characteristics of the bed particles. For smooth spheres k_M is equal to one while for agricultural products this value varies from 1.05 for peas to 3.8 for oats. Matthies found that the k_M values for columns of wheat and rye were 1.8 and 2.7, respectively. No reliable data on corn was presented.

The use of the equation (6) is rather involved because f_M , the friction factor, is a function of the bed particle Reynolds number and is based on known pressure drops through a packed bed of spheres.

2.5 Bed depth and wall effects

It is often assumed (Hall, 1957) that there exists a linear relationship between the pressure drop through a bed and the bed depth. Under certain circumstances, however, the pressure drop of the successive layers of a deep bed will change as the bed height is increased (Sheldon, et al., 1960). Matthies (1956) found that the resistance to airflow per foot of bed depth remained constant for 13 percent moisture content corn, but increased for 34 percent moisture content corn as the bed depth was increased from one to ten feet. This increase, which became evident at bed depths over five feet, resulted from a change in shape of the corn kernels and a decrease in porosity of the lower bed layers due to the pressure exerted by the grain above.

It has been observed that there will be a region of relatively high porosity adjacent to the internal wall surface of a packed bed due to the difference between the radii of curvature of the bed wall and the bed particles. Chiam (1962) presents evidence that the effect of a container wall causes a cyclic variation, with distance from a cylindrical wall, of the local porosity, extending from three to four particle diameters into the bed. The effect of the wall increases the overall voidage and errors in determination of the bulk mean porosity, unless the ratio of the wall to particle diameter (D_w/D_p) is large. It is generally concluded that the wall effect is negligible for regular particles if $D_w/D_p > 10$, with a somewhat higher limit for irregular particles (Haughey, et al., 1969). Since the D_w/D_p ratio in the experiments performed in this study were well above ten, it was not necessary to compensate for the wall effect.

III. EXPERIMENTAL

3.1 Bed Materials

The semitheoretical expressions were tested on beds composed of various materials. Beds of acetate spheres were used to calibrate the experimental set-up and to verify the results of investigations made by previous researchers. Two lots of spheres, having diameters of 0.250 in. and 0.375 in. with a size tolerance of plus or minus 0.005 in. and a sphericity of 0.005, were purchased commercially.

The cherry pits used in this study were acquired from a Michigan processor of red tart cherries. The pits had an initial moisture content ranging between 45 and 50 percent wet basis and were stored in closed containers at 40 degrees F. until used for testing purposes.

The cherry pits were sized and an equivalent diameter determined using a Tyler Rotap sizer. The pits ranged in size from 0.250 in. to 0.371 in. in diameter with an average of 0.031 in..

The corn and navy beans were purchased at a local commercial elevator. The corn was of the yellow dent type graded as No. 2. The specific variety was unknown. It was screened using a screen with round openings of 0.187 in. in diameter. Material passing through these openings was considered as "Fines".

The navy beans were of the Michelite variety and were graded as choice hand picked. A screen with slotted openings of dimensions 0.187 in. by 0.75 in. was used to remove all split beans. A screen with round openings of 0.343 in. in diameter was used to remove excessively enlarged or deformed beans.

The screened lots of corn and navy beans were each divided into three additional lots for purposes of moisture content adjustment. In the case of corn, the three lots were adjusted to moisture contents of approximately 16, 19 and 24 percent wet basis. Likewise, the navy beans were adjusted to moisture contents of approximately 15, 18 and 25 percent wet basis. The moisture contents were adjusted by adding predetermined amounts of water to each lot of product. Each lot was then agitated in a cement mixer, placed in sealed containers and stored at 40 degrees F. until used in performing a test.

Moisture content determinations of the cherry pits, corn and navy beans were made using an air oven. Samples were exposed to temperatures controlled at 210 degrees F. for a period of twenty-four hours. Samples, approximately seventy-five grams in initial weight, were weighed using a balance reading to 0.01 grams.

The equivalent particle diameter, determined by Bakker-Arkema, et al. (1969)b, of corn at 16 percent moisture content wet basis and navy beans at 15 percent moisture content wet basis was 0.03222 and 0.02224 feet respectively. For the higher moisture content lots of corn and navy beans the equivalent particle diameter was adjusted according to the information presented by Pabis, et al. (1962). The compensation for variation in particle diameter due to a temperature change was adjusted based on the information given by Ekstrom, et al. (1966). Table 2 gives the values for equivalent particle diameter at various moisture contents and temperatures for the corn and navy beans used in this study.

Table 2. Equivalent particle diameter of cherry pits, navy beans and corn at various temperatures and moisture contents.

Product	Moisture Content, % W.B.	Temperature, °F	Equivalent Diameter, Feet
Cherry pits	45	76	0.02600
Navy beans	15	85	0.02224
Navy beans	15	120	0.02228
Navy beans	18	85	0.02250
Navy beans	25	85	0.02309
Corn	16	85	0.03222
Corn	16	120	0.03227
Corn	19	85	0.03259
Corn	24	85	0.03321

3.2 Porosity Determination

One of the more important characteristics of a fixed bed, which influences the pressure drop-airflow relationship, is the bed porosity. Therefore, in order to relate bed porosity to pressure drop and airflow, a porosity measurement was required of the same fixed bed for which pressure drop and airflow data were taken.

The porosities of the beds used in the investigation were determined by two different methods. In the first studies, using acetate spheres and cherry pits as bed materials, the porosity was determined using the water displacement method. By slowly submerging the bed of particles into a water-filled container, a volume of water was displaced equal to the volume of the submerged bed particles. Porosity is then equal to the difference in volume between the bed particles and the test bed volume. This method was satisfactory in the case of acetate spheres and cherry pits since

the spheres were impervious to water and the cherry pits were sufficiently high in initial moisture content to prevent further absorption of water.

In the studies involving corn and navy beans, use of the water displacement method of porosity determination was unsatisfactory. These relatively low moisture content products tended to absorb the water, resulting in inaccurate porosity determinations. Consequently, a device for determining porosity was constructed similar to that described by Day (1964)b. This instrument, termed an air comparison pycnometer, was constructed to enable the entire bed of product, as it was used to collect pressure drop and airflow data, to be placed in it while porosity determinations were made. The air comparison pycnometer used in this study is shown in Figure 2. Basically, the pycnometer consisted of two containers, a manometer and connecting tubing with valves. The container designed to hold the test bed was constructed of 8 in. diameter steel pipe cut to a length of 24 in. (1 in Fig. 2). A steel plate was welded to one end to form the bottom. A machined ring was welded to the inside top edge of the steel pipe, forming an opening into the container of 7 in. diameter. A circular steel plate served as the container lid. Slots were filed to a depth of 0.25 in. in the inside edge of the container opening 180 degrees apart. The edge of the container lid was also filed to a depth of 0.25 in., perpendicular to its radius, at points 180 degrees apart. A rubber gasket was shaped to fit the lid edge to provide a good sealing surface. Under test conditions the container lid was slipped into the container, rotated 90 degrees

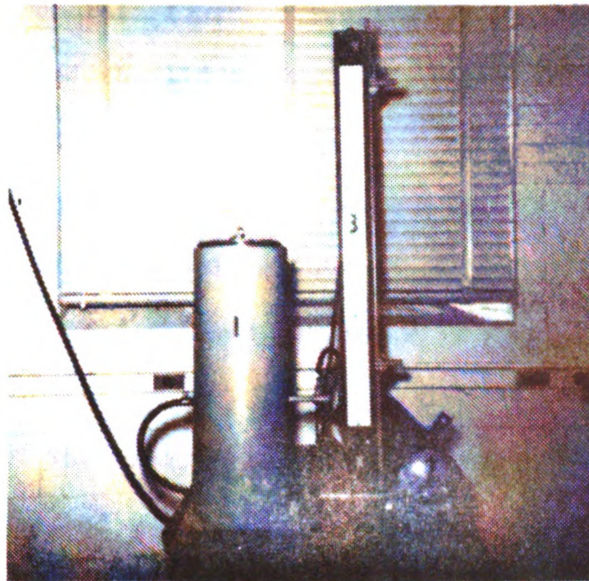


Figure 2. Porosity determination instrumentation.

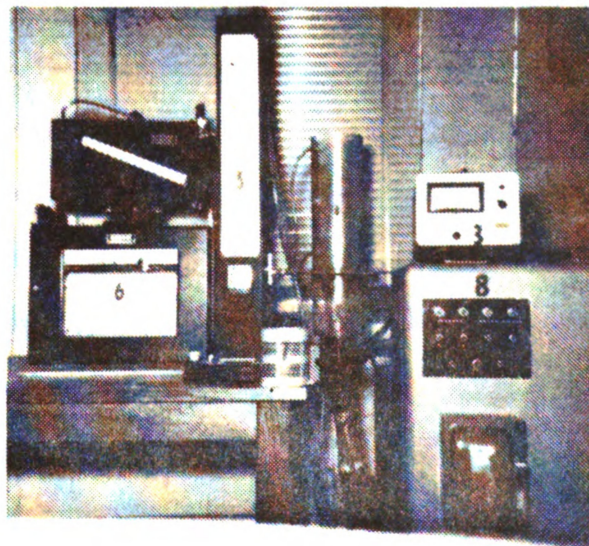


Figure 3. Pressure drop determination instrumentation.

and then the container was pressurized. The pressure inside the container forced the lid outward against the retainer ring, forming an airtight seal.

The second container, a pressurized gas storage tank, served as a reference volume into which the pressurized air of the first container was allowed to expand (2 in Fig. 2). The manner in which the porosity of a bed was determined is the same as that used by Day. The manometer used to indicate the pressures within the pycnometer had a range of 35 in. of mercury reading to 0.05 in..

3.3 Apparatus (Figure 3)

The test bed, in which the various materials were placed to determine their pressure drop-airflow characteristics, was constructed from a plexiglas cylinder with dimensions of 15.50 in. in height and 5.56 in. in inside diameter (1 in Fig. 3). The total test bed volume was 376.67 cubic in.. The floor of the test bed was constructed of sheet metal having round perforations 0.14 in. in diameter, totaling 33 percent of the entire floor area.

Pressure taps were attached to the test bed wall at six inch intervals beginning approximately 1.5 in. above the bed floor. The pressure taps were attached by first drilling a hole 0.25 in. in diameter to a depth of approximately 0.1875 in. at the desired point on the test bed wall. The tap was then inserted into the opening and secured by applying a plexiglas solvent. When the solvent had dried sufficiently, a 0.125 in. diameter hole was drilled through the tap extending into the interior of the test bed. The interior bed wall was sanded lightly to remove any burrs that may have resulted

from the drilling. This method of pressure tap attachment insured a smooth intersection between the pressure tap opening and the interior test bed wall. The pressure drop through the test bed was measured with an inclined manometer reading to 0.01 in. of water (2 in Fig. 3).

During the performance of a pressure drop-airflow test, the test bed was supported on a base constructed of plexiglas materials (4 in Fig. 3). It provided an airtight seal between the test bed and the incoming supply of air. Provision was made for the attachment of temperature and humidity sensing devices which were positioned directly beneath the test bed and in the incoming airstream. Thermocouples were used to sense air temperature and were connected to a continuous recording potentiometer (6 in Fig. 3). Relative humidity was measured with an electric hygrometer (3 in Fig. 3).

Measurements of airflow to the test bed were made using a laminar flow element and a micromanometer (9 and 5 in Fig. 3). The pressure differential, created by the measuring section of the laminar flow element was related to the total airflow through the element. One in. of water pressure differential across the measuring section corresponded to approximately 5 cfm air. The micromanometer, indicating the pressure differential, had a range of 0 to 10 in. of water, reading to 0.001 in.. The laminar flow element was attached directly to the inlet of the base supporting the test bed. Flexible tubing provided the connection between the laminar flow element and the fan circulating the air to the test bed.

Conditioned air was supplied by a conditioning unit capable of controlling temperature and humidity (8 in Fig. 3). The air was circulated by a fan equipped with a variable speed motor. An auto-transformer (7 in Fig. 3) was used to regulate the speed of the series wound motor driving the fan.

A computer program was written to accept the collected data and provide values for airflow, air velocity and bed porosity. Most important, however, it was written to compute values for bed pressure drop, as predicted by the semitheoretical relationships, to compare these values to the experimentally obtained data and to plot the results if desired. The program is given in the appendix of this paper.

3.4 Procedure

A test schedule was developed to provide for maximum use of bed materials and to allow for a minimum of adjustment of the test apparatus. A set of standard test conditions was set up to provide a basis of comparison for establishing the effect of the variables to be investigated.

Prior to each set of tests the air conditioning unit was started to allow the desired air conditions to stabilize. A check was periodically made on all of the measuring instrumentation to be sure it was properly adjusted.

The bed material selected for a given test was placed into the test bed by one of two methods. Very porous beds were created by placing a section of metal tubing, approximately 4 in. in inside diameter, into the test bed and allowing it to rest on the test bed

floor. The bed material was then poured into the metal tubing. By slowly raising the metal tubing the bed material was allowed to flow out, thus filling the test bed in a very porous manner.

Test beds of greater density were created through a process of repeated filling and packing. After each fill of approximately five in. the bed was vibrated to bring about settling of the bed material. Through the use of an established method of filling test beds of nearly the same porosity could be attained.

Once the test bed was prepared in the desired manner and placed on its base, actual pressure drop-airflow testing could begin (late in the study the test bed was weighed before beginning an airflow-pressure drop test). At this time the variable speed fan was adjusted to obtain the desired airflow and readings of bed pressure drop, air relative humidity, air temperature and airflow were recorded. The fan speed was then readjusted, at approximately 2.5 cfm intervals, and the data recording process repeated. The testing proceeded in this manner until the pressure drop through the test bed was approximately 4 in. of water column.

When the pressure drop-airflow data had been collected, the bed of material was measured for porosity. This entailed removal of the test bed from its base support and placing it into the air comparison pycnometer. The pycnometer chamber containing the test bed was then pressurized to approximately 30 in. mercury. Two minutes were allowed, after pressurization was completed, for the system to come to equilibrium. The mercury level, on the manometer indicating the pycnometer pressure, was then recorded. The valve

connecting the two pycnometer chambers was then opened permitting the pressure within to equalize. Again two minutes were allowed for equilibrium to be reached before the mercury level was noted and recorded.

The procedure of pressurizing and expanding the air within the pycnometer was repeated three times for each bed of test material. An average of the three pressure readings was calculated and read into the computer for purposes of porosity determination.

Adjustment of the air conditioning unit, filling of the test bed, recording of pressure drop-airflow data and porosity measurement of the test bed material constituted the data collection procedure. This information was then punched on computer cards in a form compatible with the program given in the appendix of this paper.

IV. RESULTS AND DISCUSSION

4.1 Spheres

Figure 4 shows the effect of particle diameter on the pressure drop through two fixed beds of uniformly dimensioned smooth acetate spheres of different diameter. As expected, the smaller particles ($d = 0.0280$ ft.) offer more resistance to a given airflow than do the larger bed particles ($d = 0.0312$ ft.).

In order to check the accuracy of the experimental measuring devices, the data of Figure 4 was plotted on a Matthies plot (section 4.4) as shown in Figure 5. It can be seen that the experimentally obtained data points given by two curves in Figure 4 are represented well by one curve in Figure 5, the Matthies curve. Since the Matthies curve was checked by a number of investigators (Burke, et al. 1928; Fehling, 1939; and Kling, 1940) using beds composed of uniformly dimensioned spheres, it can be accepted as an accurate representation of pressure drops through beds of spheres. The fact that the pressure drop data obtained in this study, on beds composed of uniform acetate spheres, agreed with the accepted data from the literature, verifies the accuracy of the experimental set-up.

Pressure drop data obtained using beds composed of biological products unfortunately, do not fall on the Matthies curve due to their nonspherical character. Beds of irregularly shaped particles as compared to smooth spheres will have a different distribution of points of contact, a different voidage distribution and a resulting increase in resistance to airflow at the rough particle edges. Therefore, the pressure drop data of beds composed of biological products (all irregular in shape) can be expected to fall above the Matthies curve for spheres given in Figure 5.

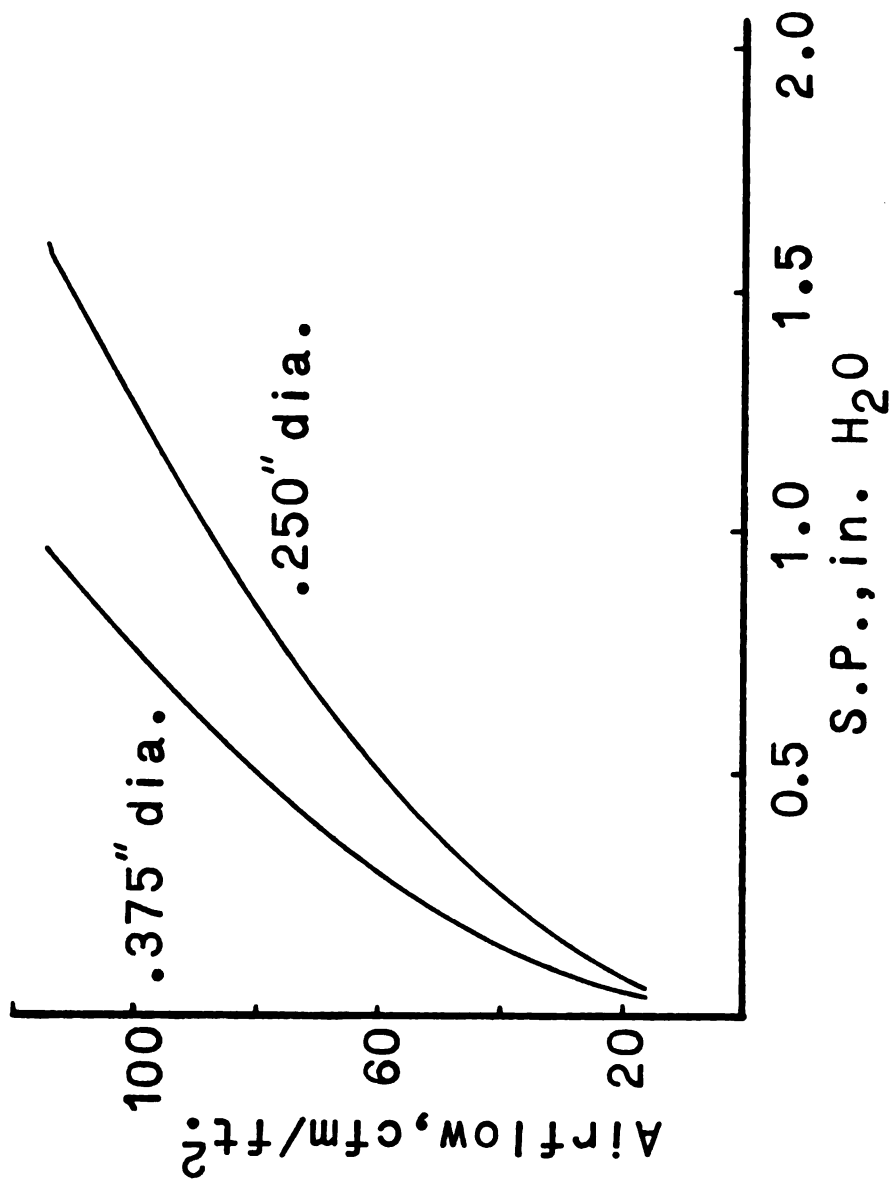


Figure 4. Static pressure drop through beds of smooth spheres of two diameters.

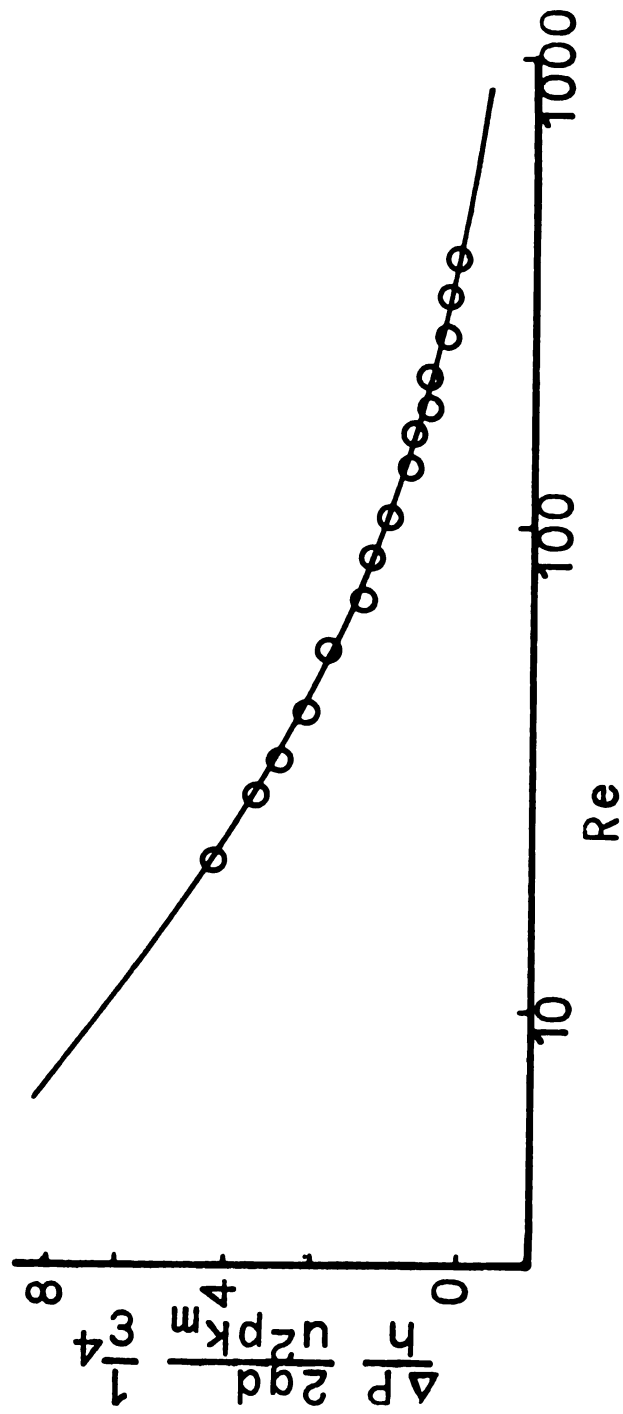


Figure 5. Matthies plot of the pressure drop through spheres of two diameters.

The Leva and Ergun equations agree reasonably well with the Matthies equation in predicting the pressure drop through beds of uniformly sized spheres (Figure 6).

4.2 Biological products

The experimental results of tests performed to determine the resistance to airflow through randomly packed beds of cherry pits, corn and navy beans are given in Figures 7 through 11. The effect of bed porosity and bed particle moisture content is illustrated.

Porosity more than any other bed parameter, affects the amount of power required to circulate air through a bed of particles, (see Figures 7, 8 and 9). As illustrated by Figure 7, a decrease in bed voidage from 0.42 to 0.33 increased the required static pressure, at an airflow of 100 cfm per square foot, from 0.9 to 2.3 in. water column. This amounts to an increase of over 100 percent. Similar observations can be made regarding the effect of bed porosity on pressure drops through beds of corn and navy beans.

The porosity of a bed of biological particles is related to the method of loading. A grain bin loaded by a method of mechanical elevation and free fall will result in a bed of a different voidage than one loaded by a pneumatic method. Matthies (1956) compared these two modes of filling a commercial sized grain bin with shelled corn and measured a range of porosities from 0.44 (mechanical loaded) to 0.34 (pneumatically loaded). Figure 8 reflects the variation in resistance to airflow through two beds of corn with different porosities.

The range of porosities for beds of biological products, measured by Matthies (1956), was found to be between 0.32 and 0.50. Thompson, et al. (1967) measured values for grain voidage between 0.39 and 0.64 percent.

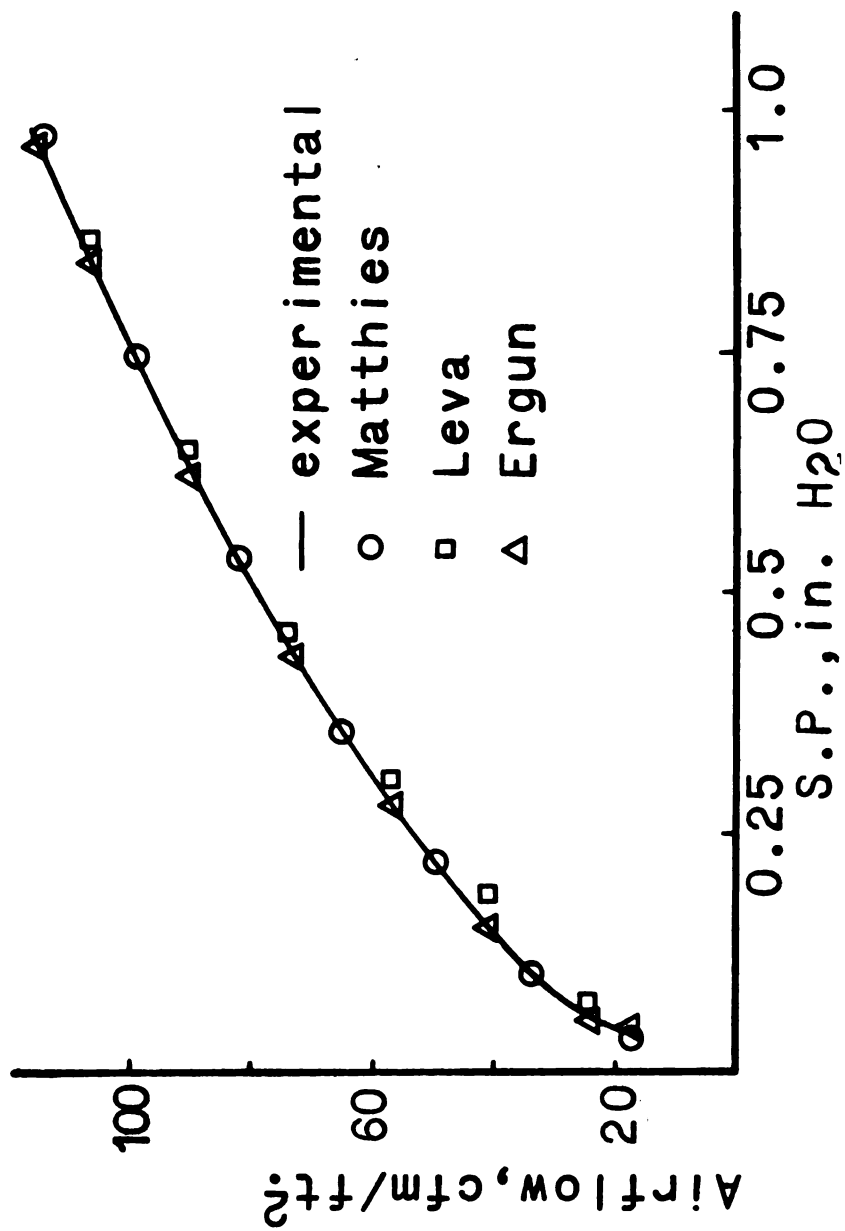


Figure 6. Resistance to airflow through a bed of smooth spheres as given by the Leva, Matthies, and Ergun equations.

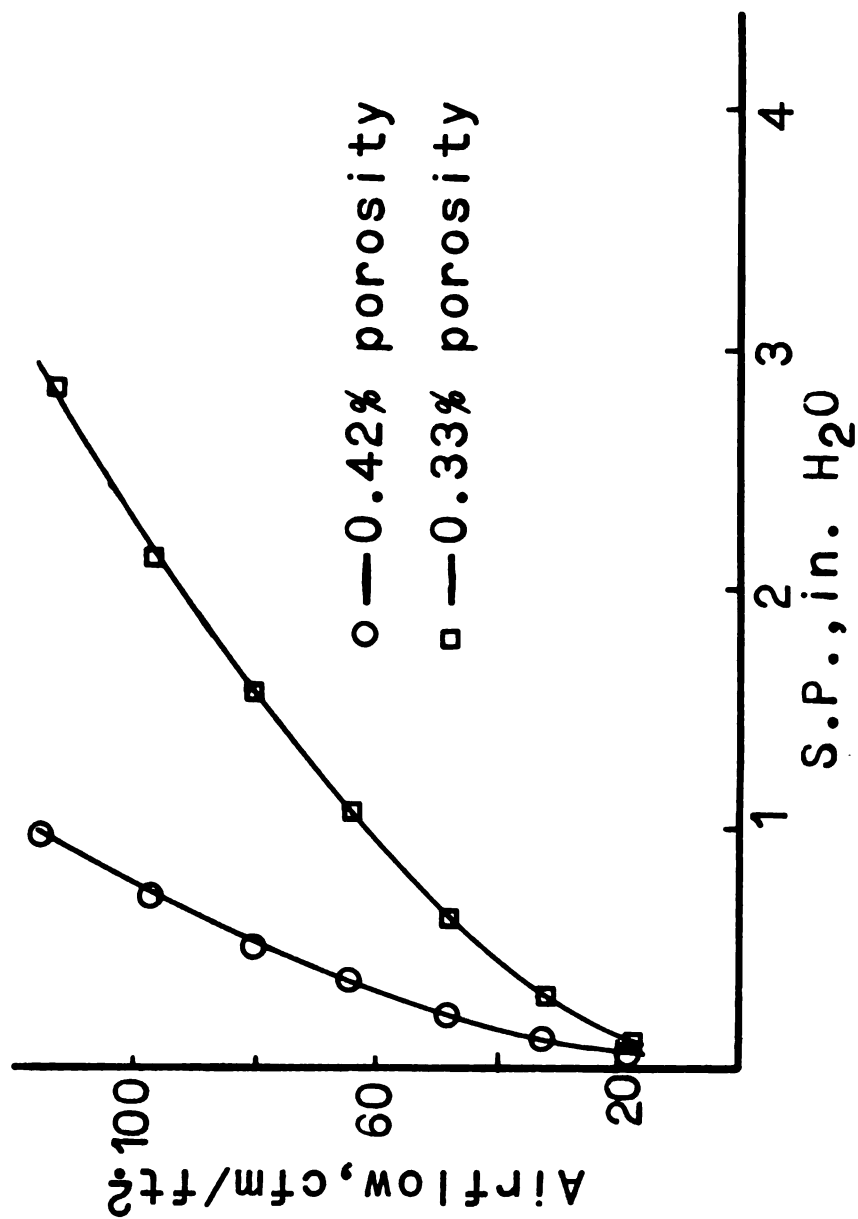


Figure 7. Resistance to airflow through a bed of cherry pits at two porosities.

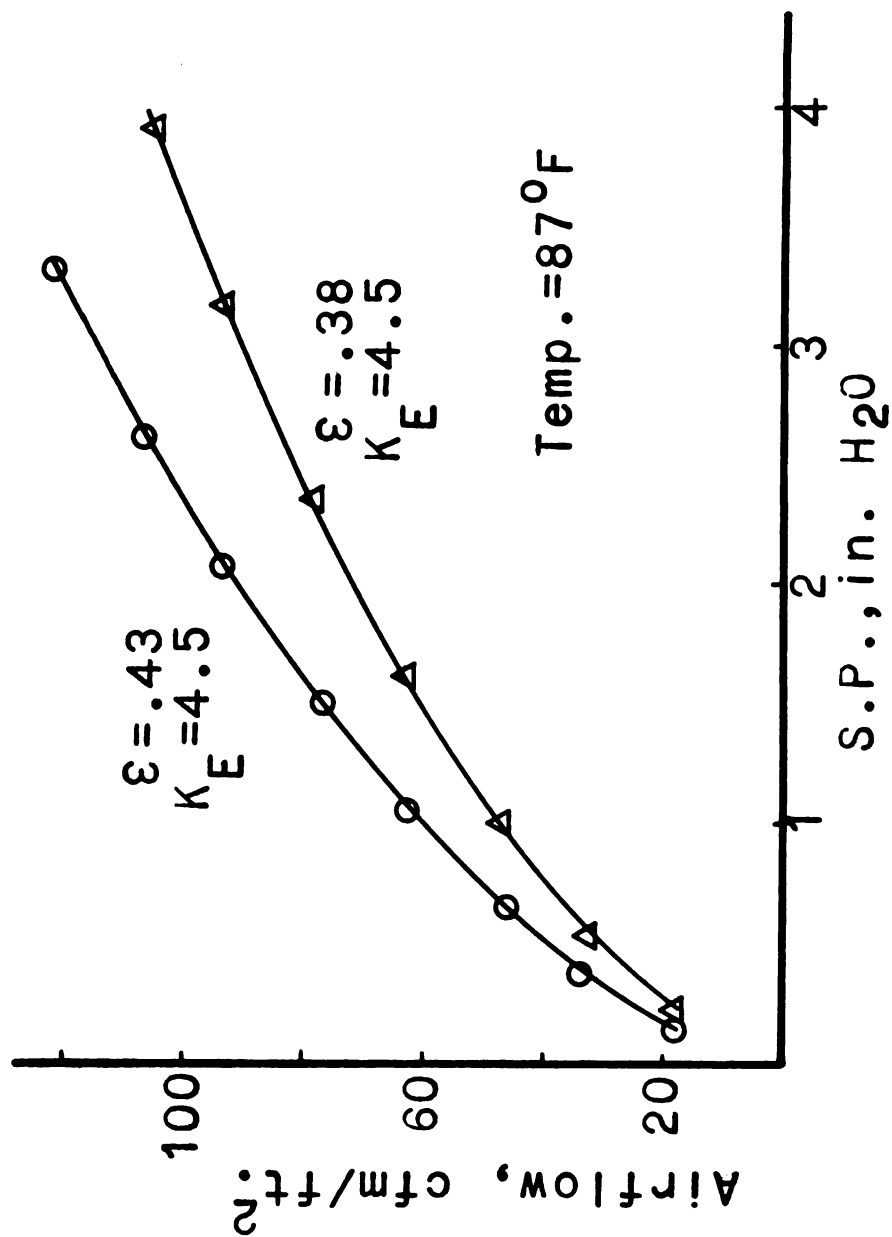


Figure 8. The effect of porosity on the pressure drop through corn.

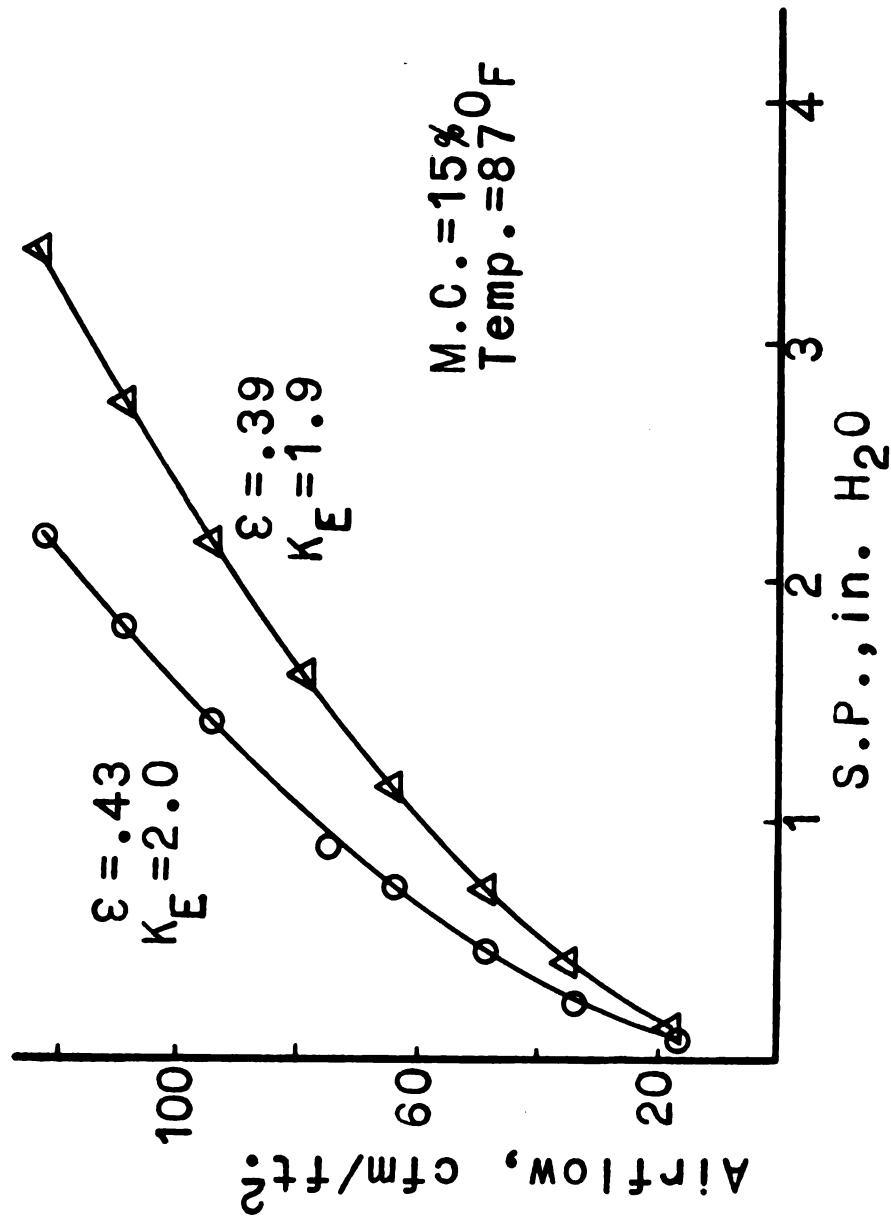


Figure 9. The effect of porosity on the pressure drop through navy beans.

The porosity ranges studied in this thesis for cherry pits, corn and navy beans can be expected to be representative of situations encountered in actual conditioning operations. The porosity range for cherry pits was between 0.33 and 0.42, between 0.33 and 0.43 for corn and between 0.35 and 0.43 for navy beans. Thus a much narrower overall range of bed porosities is observed with randomly packed beds of irregularly shaped biological products than with beds of uniformly dimensioned spheres where voidage values between 0.26 and 0.47 were measured (Haughey, et al., 1969).

The effect of moisture content of the bed particles on the resistance to airflow through a bed is minor compared with the porosity effect. In addition, it is not certain what effect a change in moisture content will have. For corn, as shown in Figure 10, the pressure drop decreases with a decrease in moisture content while Figure 11 shows the opposite trend for navy beans. The result for corn does not agree with the findings of Shedd (1953) who made the general statement that "the resistance pressure for a given rate of airflow is less for a lot of grain at 20 percent or higher moisture than for the same lot of grain and the same method of filling after drying to a lower moisture content". Pressure drop data on corn at different moisture contents published by Matthies (1956), however, agree with the findings of this study. Aas, et al. (1960) also found that the trend of the moisture content effect on the pressure drop is dependent on the grain and the moisture content range being tested.

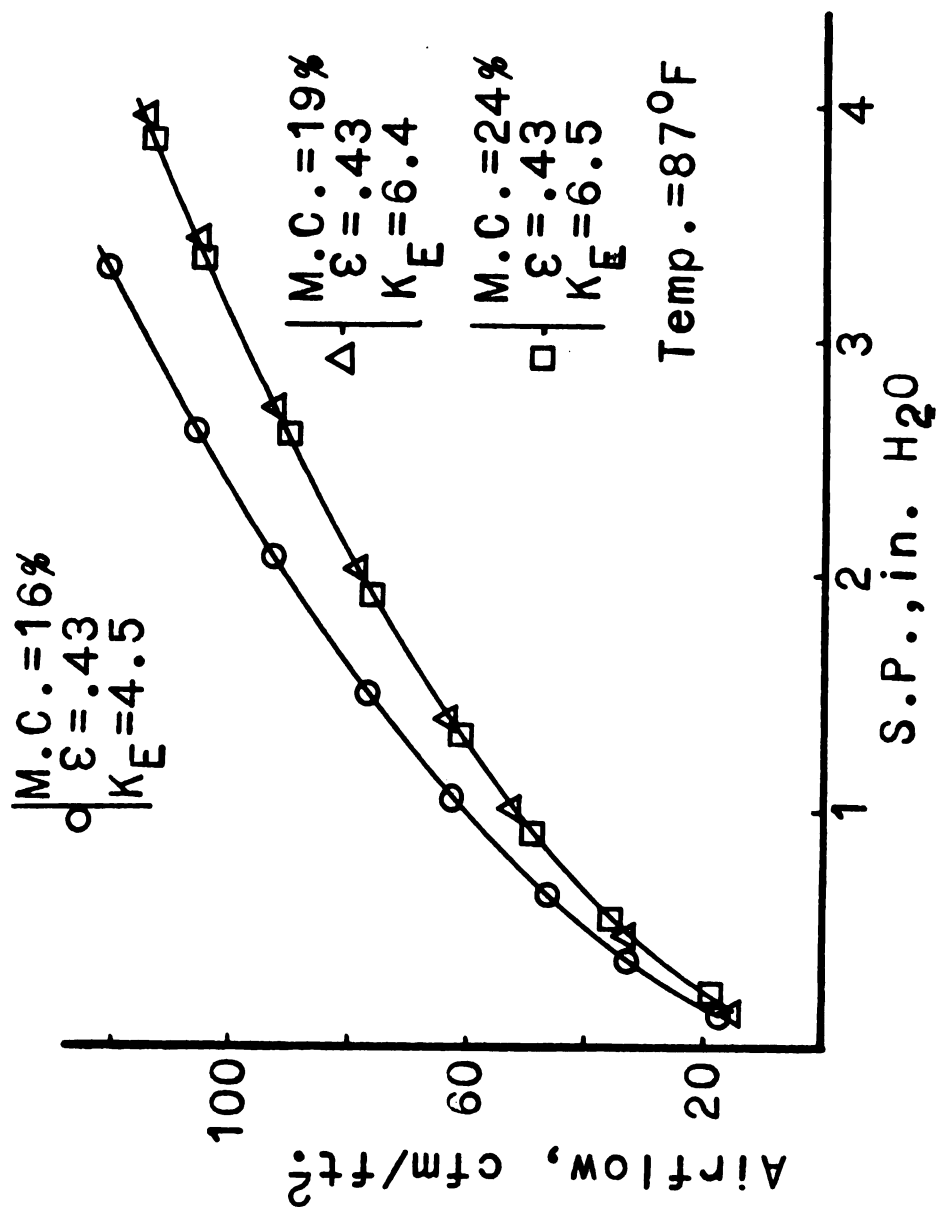


Figure 10. The effect of moisture content on the pressure drop through corn.

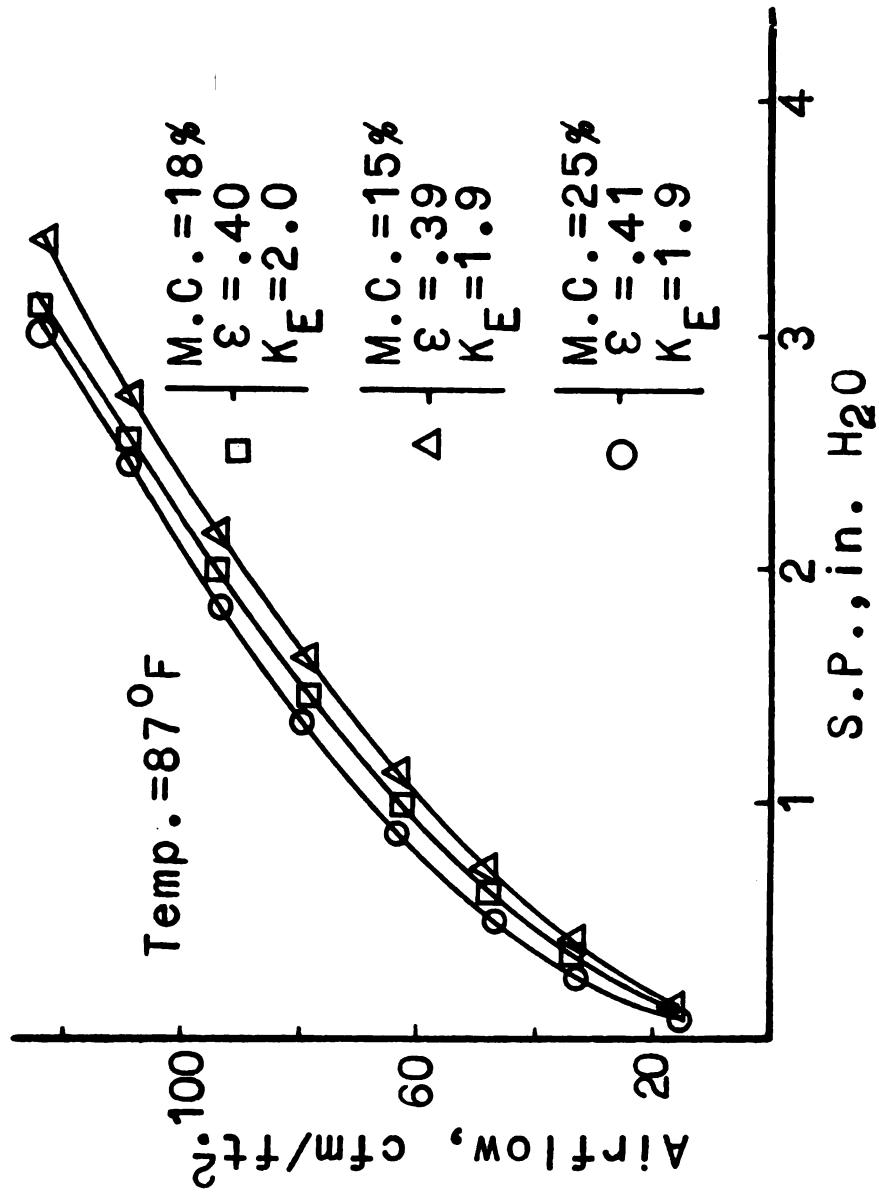


Figure 11. The effect of moisture content on the pressure drop through navy beans.

Figures 12 and 13 illustrate the effect of air temperature on the resistance to airflow through beds of corn and navy beans. In both cases increased air temperatures resulted in increased static pressure at the same airflow. At the same time the beds of corn and navy beans became less porous at the higher temperature. This decrease in porosity, resulting in greater resistance to airflow, may be explained by an increase in bed particle diameter due to expansion with increased temperature.

The effect of bed porosity, air temperature and particle moisture content on the pressure drop through beds of grain has been illustrated above. These facts, however, are not sufficiently accounted for by the airflow-pressure drop data (ASAE D 272) recognized and published by the American Society of Agricultural Engineers. Figure 1 is representative of ASAE D 272. While this data is accurate as presented, it will unfortunately, hold only for beds of products similar to those used to obtain this data. Although it is indicated in a footnote to this graph, that a curve gives reliable data for only loosely filled beds of relatively dry (and clean) grain, no specific mention is made as to how these curves should be corrected in case these standard conditions are not prevailing. As an example, notice in Figure 14 the difference illustrated by a log-log plot of the pressure drop requirements of two beds of cherry pits. The two beds differ only in porosity. If it were desired to add information pertaining to the pressure drop through cherry pits to ASAE D 272, the question might well be asked which line of Figure 14 should this be.

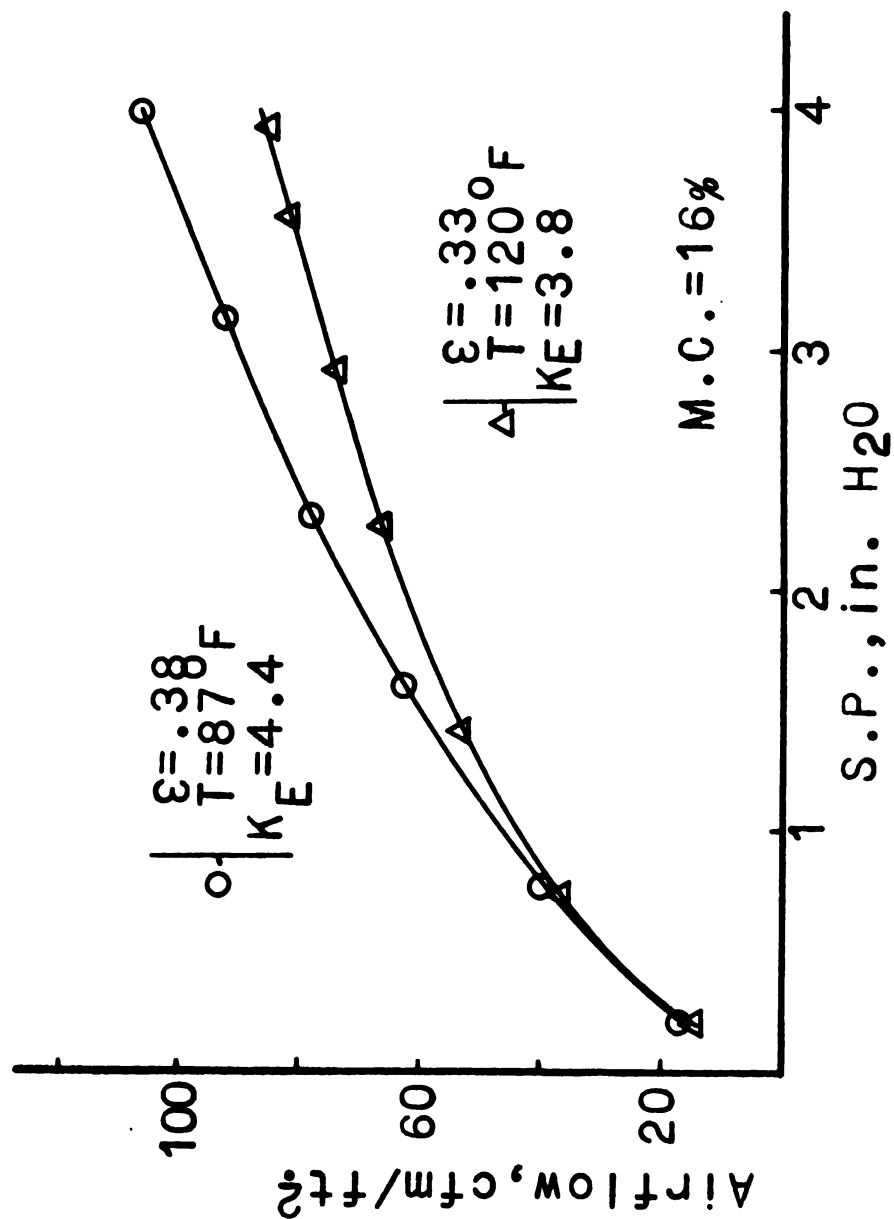


Figure 12. The effect of air temperature on the porosity and the pressure drop through corn.

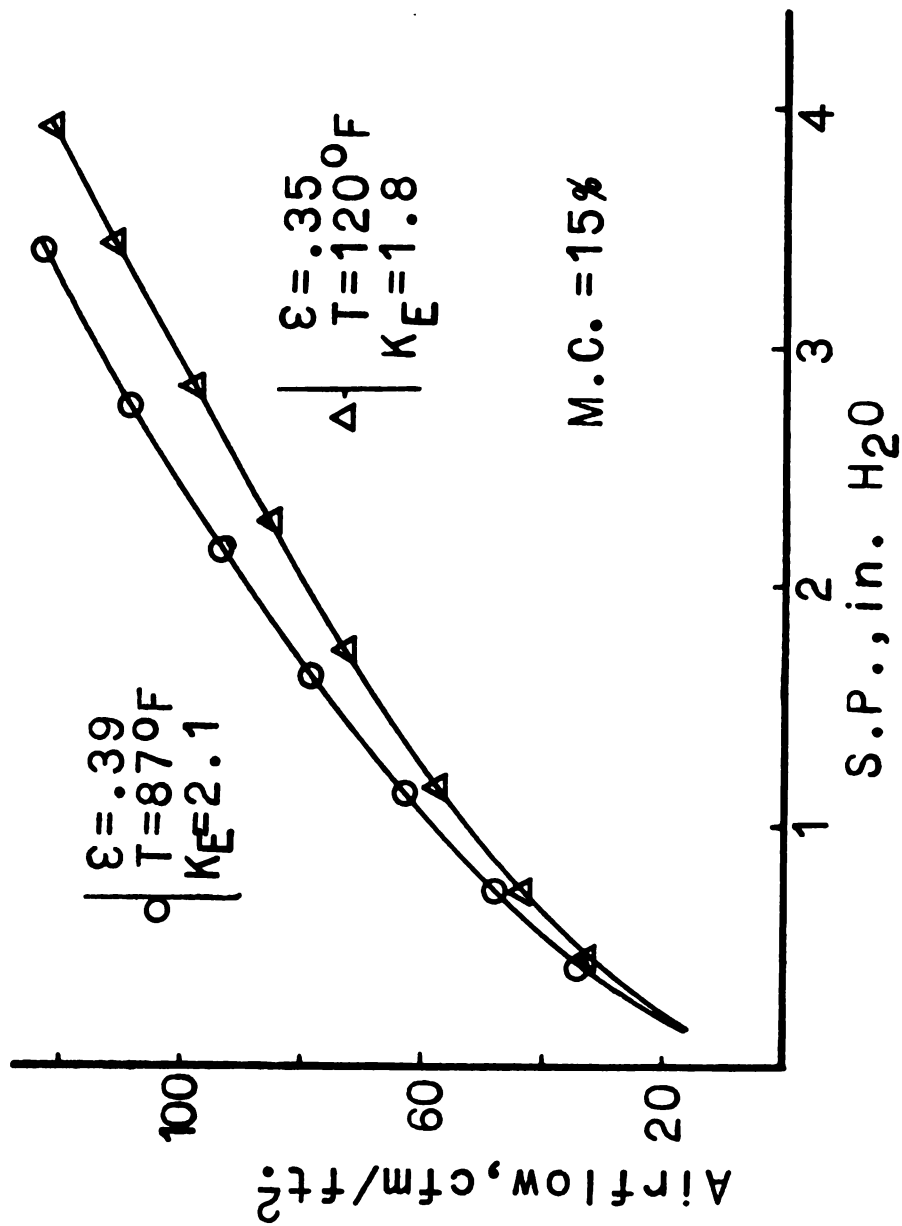


Figure 13. The effect of air temperature on the porosity and the pressure drop through navy beans.

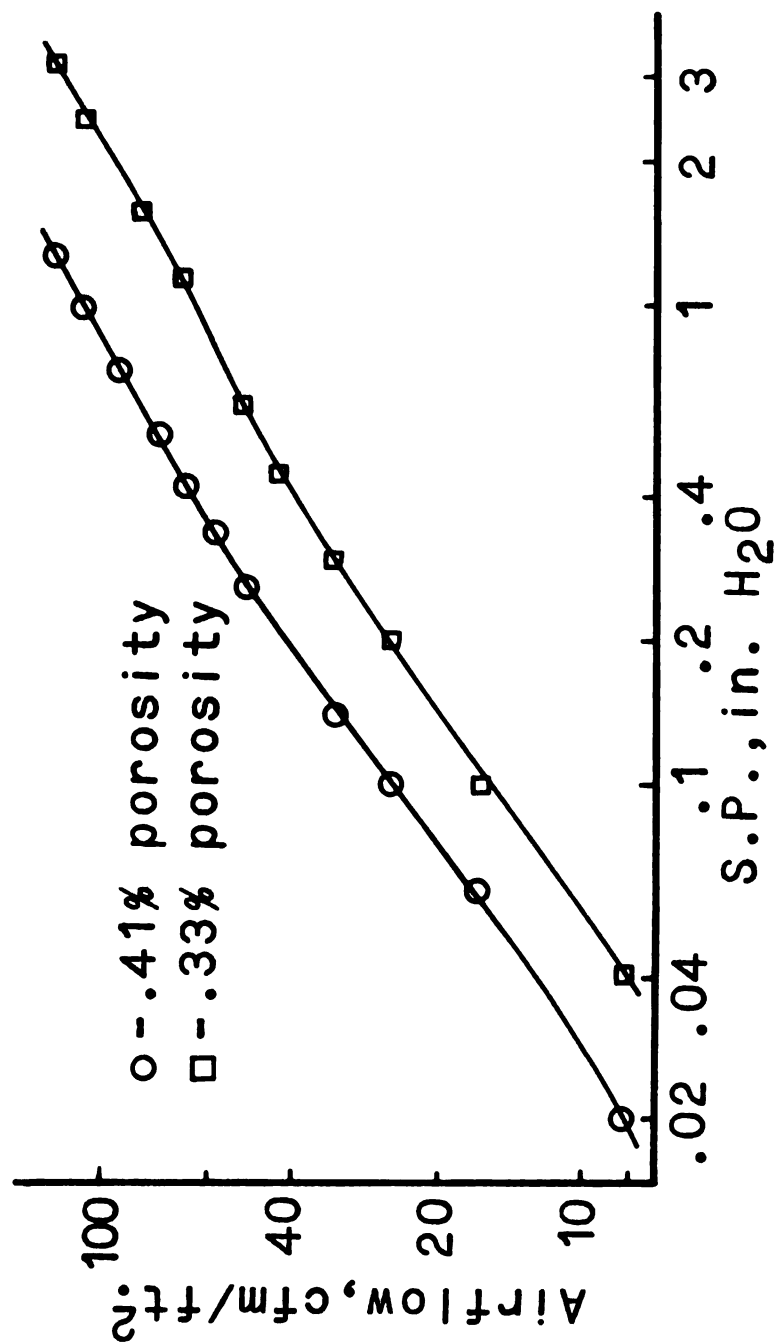


Figure 14. Resistance to airflow of cherry pits at two different bed porosities.

It is obvious that the ASAE D 272, in its present form, does not adequately represent the probable range of pressure drop-airflow characteristics of a bed of a given biological material.

The lines on Figures 1 and 14 are not completely straight. This means that the Ramsin equation does not exactly describe the data points in these figures. In addition, the product constants, a and b , would vary not only from product to product, but also from porosity to porosity (Figure 14) and from moisture content to moisture content.

It has long been recognized that the presence of foreign material (fines) intermixed with grain tends, in general, to increase the resistance to airflow if the foreign material is of a smaller equivalent diameter than that of the grain. Figure 15 illustrates this for beds of 16 percent moisture corn intermixed with various percentages of fines. (Fines were considered as material passing through a 0.1875 in. diameter round-hole dockage sieve.)

It has been previously illustrated with corn that with an increase in bed porosity, a decrease in pressure drop would result. This is not the case when the increase in voidage is a result of the addition of fines as illustrated in Figure 15. In this case, a bed containing 10 percent fines and having a porosity of 0.43 requires a lower static pressure than a bed with 40 percent fines and a voidage of 0.49.

The importance of keeping the percentage of fines to a minimum is illustrated well in Figure 15. Here it is indicated that a bed with 20 percent fines will require a static pressure, at 60 cfm per square foot airflow, of 3 in. water column per foot of depth which is three times as high as a bed of corn containing no fines.

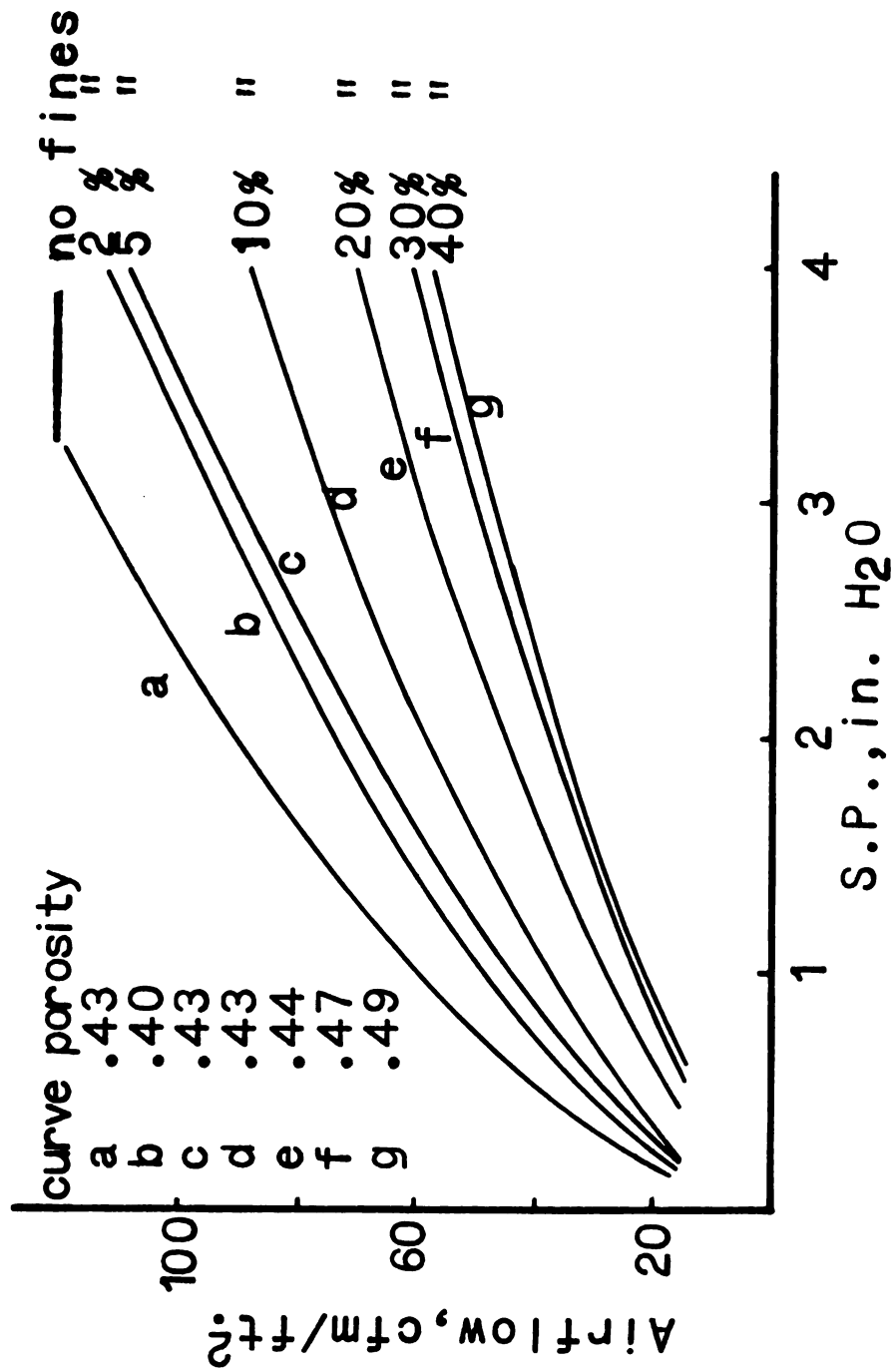


Figure 15. Resistance to airflow through beds of corn containing various percentages of fines.

4.3 Leva Equation

To calculate the resistance to airflow through a bed of particles using the Leva equation the terms f_L , the Leva friction factor, and n , the state-of-flow factor, both functions of the Reynolds number, were found. Table 3 shows the values of f_L and n as they were obtained for a test using cherry pits as bed material. The table also shows the calculated and experimental values for pressure drop ($\Delta P/h$). It is evident that the theoretical and experimental data do not agree. For this reason the ratio between the experimental and the theoretical values was calculated (last column in Table 3) and the average determined. This average was called k_L , the Leva product constant for cherry pits. The average k_L for this test was 1.2.

The pressure drop data calculated using the Leva equation was obtained using the following relationship:

$$\frac{\Delta P}{h} = k_L \left[f_L \frac{2}{3-n} \frac{(1-\epsilon)^{3-n}}{\epsilon^3} \frac{\rho u^2}{d_g} \right] \quad (7)$$

where Φ , the particle shape factor for cherry pits was taken to be 1.1.

Table 3. Values of n and f_L , as functions of the Reynolds number, and $\Delta P/h$ for the pressure drop through a bed of cherry pits (porosity = 0.42) as given by the Leva Equation.

<u>Re</u>	<u>n</u>	<u>f_L</u>	<u>$(\Delta P/h)_L$</u>	<u>$(\Delta P/h)_{exp.}$</u>	<u>$\frac{(\Delta P/h)_{exp}}{(\Delta P/h)_L}$</u>
63.4	1.58	1.69	0.06	0.08	1.41
84.5	1.68	1.48	0.10	0.12	1.28
105.6	1.72	1.38	0.14	0.18	1.30
126.7	1.75	1.30	0.19	0.24	1.25
147.9	1.80	1.25	0.26	0.32	1.24
169.0	1.82	1.19	0.32	0.40	1.23
190.1	1.84	1.16	0.40	0.50	1.23
211.2	1.85	1.13	0.48	0.60	1.23
232.4	1.86	1.10	0.56	0.70	1.21
253.5	1.86	1.08	0.66	0.82	1.20
274.6	1.87	1.06	0.75	0.94	1.20
295.7	1.88	1.04	0.88	1.10	1.21
316.9	1.89	1.03	0.99	1.24	1.21

Although the modified version of the Leva equation predicted the pressure drop through beds of cherry pits satisfactorily, testing the equation on beds of additional kinds of biological products was not conducted because of the relative complexity involved in finding the proper values of f_L , n and ϕ .

4.4 Matthies Equation

To calculate the pressure drop through a bed of particles at a certain airflow using the Matthies equation, one has to know the values for k_M and f_M . The friction factor f_M , like f_L , is a function of the Reynolds number. The various values obtained for f_M for a particular test on cherry pits are given in Table 4 along with values for k_M . The Matthies product constant, k_M , would not be expected to vary a great deal if the Matthies equation properly describes the pressure drop through a cherry pit bed. As expected, the values for k_M in Table 3 are approximately the same for the various Reynolds number values. The average k_M for this particular test was 1.09.

Matthies (1956) obtained k_M values for a number of agricultural products. They varied from 1.05 for peas, to 2.70 for barley to 3.80 for oats. For spheres k_M is equal to one and since cherry pits are nearly spherical, a k_M for cherry pits of approximately one would be expected. As indicated in the previous paragraph, this is the case.

Table 4. Values of f_m , as a function of Reynolds number, and $(\Delta P/h)$ for the pressure drop through a bed of cherry pits (Porosity = 0.42) as given by the Matthies Equation.

<u>Re</u>	<u>f_M</u>	<u>$(\Delta P/h)$ exp.</u>	<u>$(\Delta P/h)_M$</u>	<u>$\frac{(\Delta P/h) \text{ exp.}}{(\Delta P/h)_M}$</u>
63.4	1.69	0.08	0.08	1.09
84.5	1.48	0.12	0.12	1.05
105.6	1.38	0.18	0.16	1.08
126.7	1.30	0.24	0.22	1.06
147.9	1.25	0.32	0.30	1.08
169.0	1.19	0.40	0.36	1.09
190.1	1.16	0.50	0.46	1.10
211.2	1.13	0.60	0.56	1.10
232.4	1.10	0.70	0.64	1.09
253.5	1.08	0.82	0.74	1.09
274.6	1.06	0.94	0.86	1.09
295.7	1.04	1.10	0.98	1.12
316.9	1.03	1.24	1.12	1.11

In comparing the Leva and Matthies equations it can be said that both predict pressure drops through beds of cherry pits adequately, but the Matthies equation is easier to use.

4.5 Ergun and Modified Ergun Equation

Table 5 contains the calculated pressure drop data, as given by the Ergun equation, and the experimental pressure drop data for a bed composed of cherry pits at various airflow rates. Along with this data the ratio of these last two values is given. It was found that the Ergun equation always predicts a value for the pressure drop through cherry pits which is low by 15 to 20 percent. For this reason the Ergun equation was modified to:

$$\frac{\Delta P}{h} = k_E \left[150 \frac{(1-\epsilon)^2}{\epsilon^3} \mu \frac{u}{d^2 g} + 1.75 \frac{1-\epsilon}{\epsilon^3} \frac{\rho u^2}{dg} \right] \quad (8)$$

where k_E is the Ergun product constant. For the bed of cherry pits analyzed in Table 5 the average value of k_E was 1.17.

The Ergun equation is the combination of an equation for laminar flow and an equation for turbulent flow (Section 2.2). The data of a typical pressure drop-airflow test as given by the Ergun equation is plotted in Figure 16. The proportion of the total pressure drop contributed by the laminar and the turbulent portion of the Ergun equation is illustrated. At the low end of the airflow range, 0.29 feet per second, the laminar portion of the total pressure drop through the bed is approximately 55 percent. As airflow increases to 2.65 feet per second the laminar contribution to total bed resistance has decreased to approximately 13 percent. The fact that the Ergun equation contains terms for both laminar and turbulent airflow emphasizes its suitability in describing the air circulation requirements of most drying and cooling operations.

Comparing the results of the Leva, Matthies and Ergun equations (Tables 3, 4 and 5) illustrates that any one of these relationships is able to describe and, therefore, predict with comparable accuracy, the resistance to airflow of packed beds of cherry pits. However, they do differ with respect to ease of use. Leva's equation is the most difficult to use (ϕ , f_L and n values have to be found first) followed by the Matthies equation (f_M has to be determined as a function of the Reynolds number). Comparatively, the modified Ergun equation has no special terms requiring additional calculations. Thus, on the basis of its simplicity plus its satisfactory prediction characteristics, it was decided to use the modified Ergun equation for the remainder of the pressure drop tests.

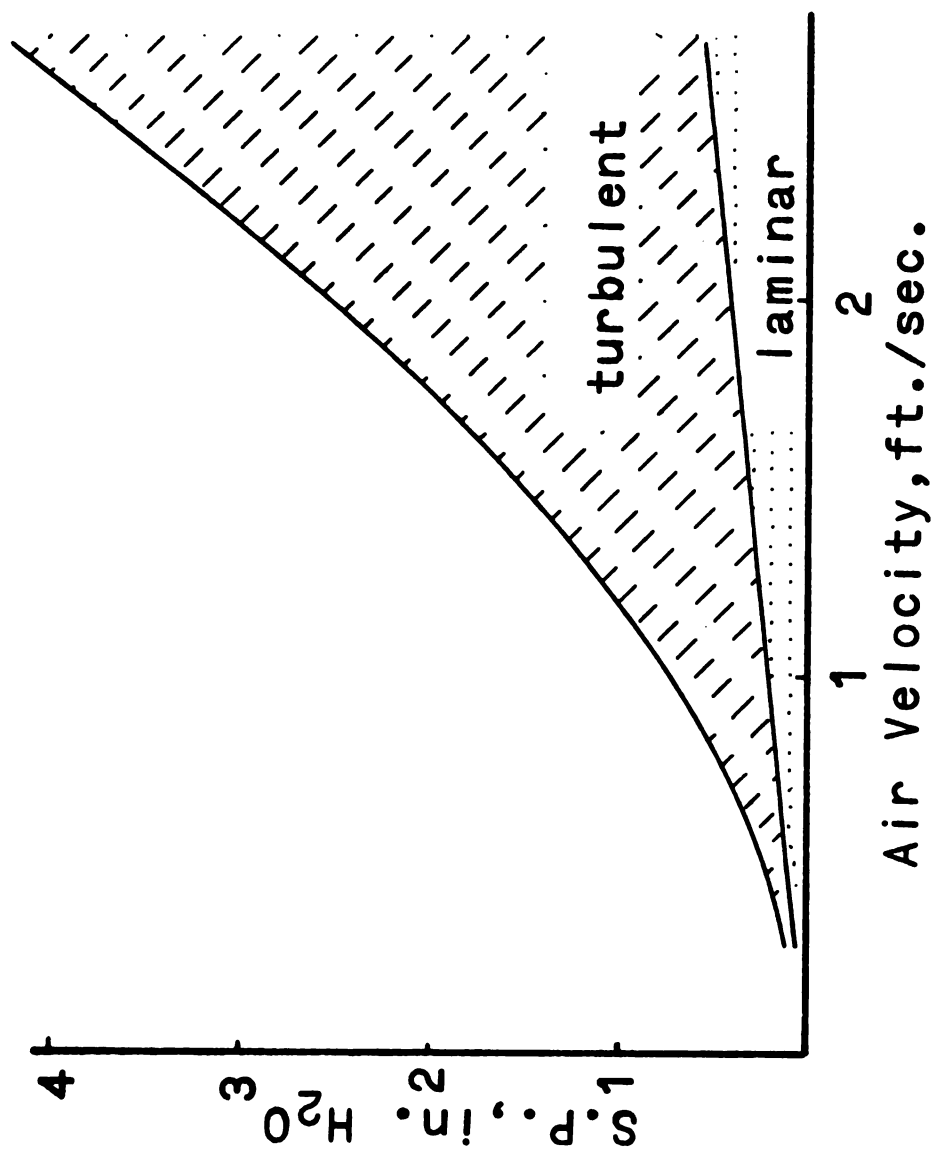


Figure 16. The laminar and turbulent air flow contribution to total bed resistance.

Table 5. Values of $(\Delta P/h)$, at various air velocities for the pressure drop through a bed of cherry pits (porosity = 0.42) as given by the Ergun Equation.

<u>u, ft./min.</u>	<u>$(\Delta P/h)_E$</u>	<u>$(\Delta P/h)_{Exp.}$</u>	<u>$\frac{(\Delta P/h)_{Exp.}}{(\Delta P/h)_E}$</u>
24.3	0.06	0.08	1.21
32.4	0.10	0.12	1.15
40.5	0.14	0.18	1.19
48.6	0.20	0.24	1.16
56.7	0.26	0.32	1.19
64.8	0.34	0.40	1.17
72.9	0.42	0.50	1.19
81.1	0.50	0.60	1.18
89.2	0.60	0.70	1.16
97.3	0.70	0.82	1.16
105.4	0.82	0.94	1.14
113.5	0.94	1.10	1.17
121.6	1.08	1.24	1.16

4.6 k_E Values

The Ergun product constants, k_E for corn and navy beans are given in Table 6. The data is for three moisture contents, three porosity ranges and two air temperatures. Each k_E value is based on three tests. The data shows, in the case of navy beans, that the k_E values are consistent for beds containing no fines. This means that the modified Ergun equation, with a k_E value between 1.8 and 2.0, will predict correctly the effect of moisture content, bed porosity and air temperature on the pressure drop through beds of navy beans.

For beds of corn the results are not as consistent. Although the modified Ergun equation does predict rather accurately the effect of porosity and air temperature (with a k_E between 3.7 and 4.5), a change in bed particle moisture content from 16 to the 19 to 24 per-cent moisture content range increased the k_E value from about 4.0 to

Table 6. k_E and k_E' values for corn and navy beans at different product moisture contents, bed porosities, air temperatures and percentages of fines.

<u>Product</u>	<u>MC, %</u>	<u>d. ft. eq.</u>	<u>temp. °F</u>	<u>ϵ</u>	<u>k_E</u>	<u>k_E'</u>	<u>Comments</u>
corn	16.01	.032	87	0.43	4.5	1.9	normal fill
"	16.01	.032	87	0.38	4.5	2.8	dense fill
"	16.01	.032	120	0.33	3.7	3.9	see text
"	19.07	.033	87	0.43	6.4	2.6	normal fill
"	23.71	.033	87	0.43	6.5	2.6	normal fill
beans	14.88	.022	87	0.43	2.0	1.3	normal fill
"	14.88	.022	87	0.39	1.9	2.1	normal fill
"	14.88	.022	115	0.35	1.8	2.5	see text
"	18.30	.023	87	0.40	2.0	1.8	normal fill
"	25.01	.023	87	0.41	1.9	1.6	normal fill
corn	16.01	0.032	87	0.40	5.7	3.0	2% fines
"	16.01	0.032	87	0.43	6.6	2.8	5% fines
"	16.01	0.032	87	0.43	10.4	4.3	10% fines
"	16.01	0.032	87	0.44	17.6	6.3	20% fines
"	16.01	0.032	87	0.47	30.4	8.3	30% fines
"	16.01	0.032	87	0.49	42.2	9.2	40% fines
beans	14.88	.022	87	0.41	2.7	3.0	10% splits

NOTE: The values for k_E' are based on $d_{eq} = 0.02$ ft., $\epsilon = 0.40$, air temperature is 100°F and air relative humidity is 50 percent.

6.5. It is not well understood why one value for k_E in the modified equation predicts accurately the pressure drop through navy beans while different values have to be used for corn to accomplish the same thing.

Increasing the percentage of fines in a bed results in larger k_E values due to the larger pressure drop in the beds. For corn the value of k_E increased from 5.7 at 2 percent fines to 9.2 at 40 percent fines.

4.7 k_E' Values

The modified Ergun equation is simple to use once the different parameters in the equation are known. Unfortunately the value of ϵ , the porosity, of a bed of grain is difficult to determine. Since it is possible that there exists some linear or non-linear relationship between the porosity of a grain bed and its bulk density, it might be advisable to replace the ϵ by some value e which is a function of the bulk density of the bed.

A further simplification in the use of equation (8) could be made by writing it in the following form:

$$\frac{\Delta P}{h} = k_E' (M u + N u^2) \quad (9)$$

$$\text{where } M = 150 \frac{(1-e)^2}{e^3} \mu \frac{1}{d^2 g}$$

$$N = 1.75 \frac{1-e}{e^3} \frac{\rho}{dg}$$

It is suggested that the values of M and N be calculated at arbitrarily defined standard conditions. For instance, the standard conditions could be chosen as: an equivalent diameter of 0.02 ft., a

porosity of 0.40 and drying air conditions of 100°F and 50 percent relative humidity. Under these circumstances the values of M and N would be 0.1604 and 0.3356 respectively. Equation (9) would then be:

$$\frac{\Delta P}{h} = k_E' (0.1604 u + 0.3356 u^2) \quad (10)$$

In calculating the k_E' values at other porosities or bulk densities, moisture contents and air temperatures, the values for M and N would be kept constant. The result is that the k_E' values will reflect the bulk density, the moisture content and the air property effects. For each crop a range of values for k_E' will thus be obtained.

Table 6 contains in addition to the k_E values, the k_E' data. It is clear that unlike the k_E values, k_E' will be affected especially by the bed voidage (or bulk density).

Although equation (10) is easier to use than the modified Ergun equation, it is purely empirical in nature. For this reason the use of the modified Ergun equation, using k_E rather than k_E' and replacing the porosity value with the proper bulk density term, is preferred.

Bed porosity, a difficult parameter to measure, is not as well understood as the term bulk density. For this reason a number of porosity and bulk density readings were made on beds of corn and navy beans in order to see if there exists a consistent relationship between porosity and bulk density. If such a relationship can be found, the porosity term in the modified Ergun equation could be replaced by a bulk density term. Table 7 shows the results. The data indicates that for navy beans the product of the porosity and the bulk density is fairly constant within the 14.88 to 25.01 moisture

Table 7. Porosity and bulk density values of beds of corn and navy beans at 50°F at different moisture contents.

<u>Corn</u>		Bulk Density, lb/ft ³	Bulk Porosity x Density
<u>Mc, % wb</u>	<u>ε</u>		
16.01	.4704	46.42	21.80
16.01	.4439	48.42	21.50
16.01	.4269	49.74	21.30
19.07	.5366	42.62	22.80
19.07	.5062	44.77	22.60
19.07	.4881	46.11	22.50
23.71	.5585	40.93	22.80
23.71	.5304	43.03	22.80
23.71	.5140	44.31	22.80
<u>Beans</u>		Bulk Density, lb/ft ³	Bulk Porosity x Density
<u>Mc, % wb</u>	<u>ε</u>		
14.88	.4805	50.14	24.10
14.88	.4576	51.97	23.70
14.88	.4313	54.18	23.20
18.30	.4898	49.56	24.20
18.30	.4685	51.26	24.00
18.30	.4479	52.65	23.60
25.01	.4953	47.74	23.80
25.01	.4809	49.41	23.70
25.01	.4568	51.12	23.40

moisture content range. For corn this product is constant between 19.07 and 23.7 percent moisture but increases slightly between 16.01 and 19.07 percent moisture content.

If the product of the porosity and the bulk density of a bed is assumed to be constant for a particular product and is called y , the term ϵ in the Ergun equation (Equation 8) can be replaced by $y/\text{bulk density}$. For navy beans the value of y would be 23.70. For corn y would have the value of 21.50 in the low moisture content range and of 22.70 above 19.07 percent moisture content. The value of 21.50 (resulting in a lower calculated ϵ) should be chosen if one value of y is to be used for the full moisture content range.

Finally, the modified Ergun equations for corn and navy beans would take the form:

for corn:

$$\frac{\Delta P}{h} = k_E \left[150 \frac{\left(1 - \frac{22.0}{\rho_p}\right)^2}{\left(\frac{22.0}{\rho_p}\right)^3} \mu \frac{u}{d^2 g} + 1.75 \frac{\left(1 - \frac{22.0}{\rho_p}\right)}{\left(\frac{22.0}{\rho_p}\right)^3} \frac{\rho_p u^2}{dg} \right] \quad (12)$$

for beans:

$$\frac{\Delta P}{h} = k_E \left[150 \frac{\left(1 - \frac{24.0}{\rho_p}\right)^2}{\left(\frac{24.0}{\rho_p}\right)^3} \mu \frac{u}{d^2 g} + 1.75 \frac{\left(1 - \frac{24.0}{\rho_p}\right)}{\left(\frac{24.0}{\rho_p}\right)^3} \frac{\rho_p u^2}{dg} \right] \quad (13)$$

where ρ_p is the bulk density of the bed product expressed in pounds per cubic foot. The results of applying Equations 12 and 13 to predict the pressure drop through beds of corn and navy beans are shown in Figure 17.

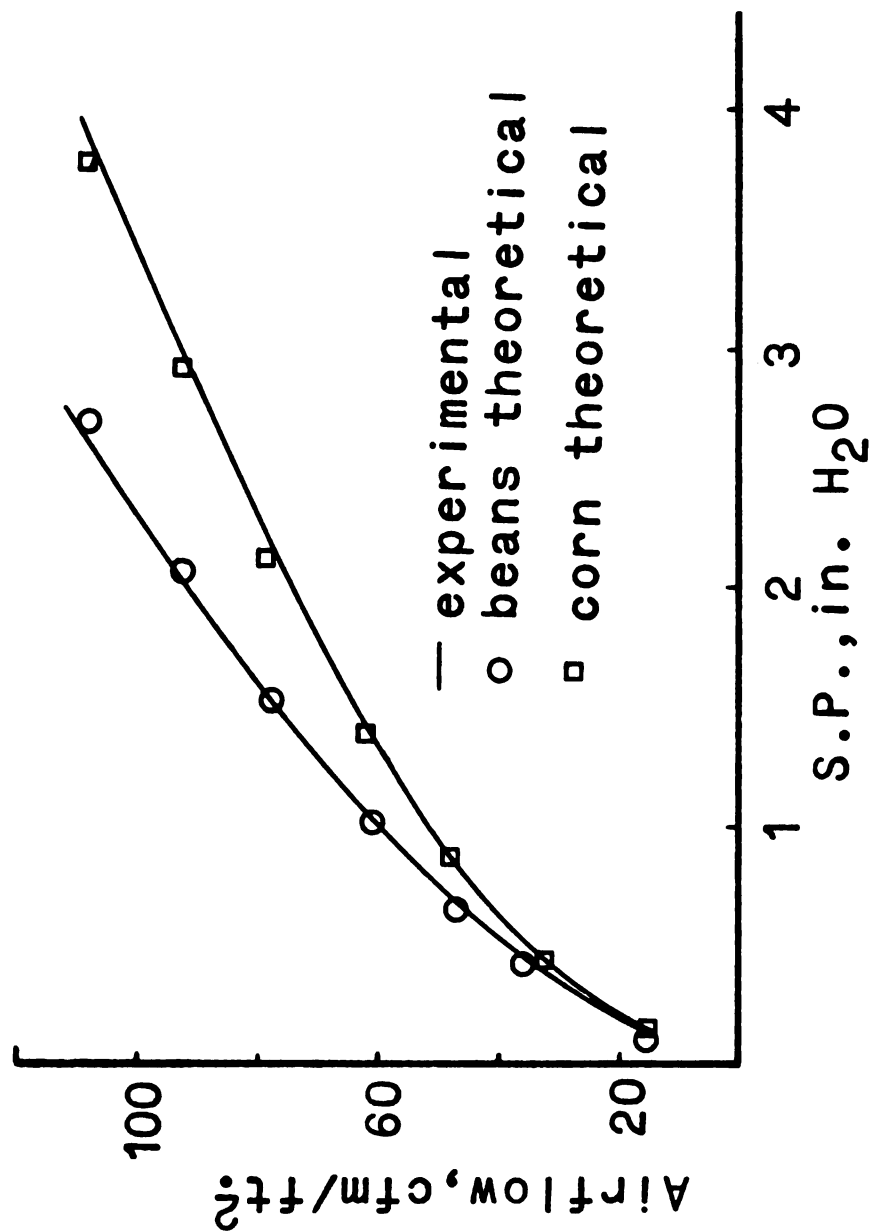


Figure 17. Resistance to airflow of corn and navy beans as given by the modified Ergun equation.

V. SUMMARY AND CONCLUSIONS

Three semitheoretical relationships were tested for their ability to accurately predict the pressure drop through fixed beds composed of biological particles at various airflow rates. Bed particles consisted of cherry pits, corn and navy beans. The cherry pits were tested at one air temperature and one moisture content. The corn and navy beans were tested at two air temperatures, three moisture contents and with various percentages of intermixed fines. The experimental set up was verified by comparing experimentally obtained data, on resistance to airflow through beds of uniformly dimensioned acetate spheres, with data of previous investigators.

The three relationships predicted the resistance to airflow through beds of cherry pits with equal accuracy. The Ergun equation proved to be the least difficult to work with because of the required use of independently calculated terms in the Leva and Matthies equation. Consequently the Leva and Matthies relationships were not tested on beds of corn and navy beans.

The Ergun equation was modified to include a product constant to compensate for the nonspherical nature of the bed particles. The results are given which indicate the ability of the modified Ergun equation to predict the resistance to airflow through beds of corn and navy beans. The effect of particle moisture content, bed porosity and air temperature are discussed.

Suggestions for Further Study

1. Find k_E values for other grains.
2. Further investigate the effect of grain moisture content on the k_E values.
3. Determine experimentally the pressure drops at bed depths over 10 feet.
4. Expand the range of airflow rates beyond the 10 to 130 cfm/ft.² range.
5. Determine the effect of moisture content and product temperature on the equivalent diameter of grains.

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APPENDIX

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PROGRAM DESPER
C  AFDELTP =PRESSURE DIFFERENTIAL ACROSS.
C      MEASURING SECTION OF LAMINAR FLOW ELEMENT.
C  EXBDELTP=PRESSURE DIFFERENTIAL ACROSS TEST BED.
C  CFM      =AIRFLOW CUBIC FEET PER MINUTE PER SQUARE FEET.
C  TEMP     =AIR TEMPERATURE AT TEST BED ENTRANCE.
C  TEMPCOR  =CORRECTION FACTOR USED IN CALCULATING AIRFLOW.
C  DELTPE   =PRESSURE DIFFERENTIAL GIVEN BY ERGUN.
C  DMAIRFLO=DIMENSIONLESS AIRFLOW.
C  RE       =REYNOLDS NUMBER DIVIDED BY ONE MINUS EPSILON.
C  U        =AIR VELOCITY.
C  AMU      =AIR VISCOSITY.
C  EK       =CONSTANT IN MODIFIED ERGUN EQUATION.
C  DELTPKE  =PRESSURE DIFFERENTIAL GIVEN BY ERGUN EQUATION CON-
      TAINING EK.
C  ROONE    =AIR SPECIFIC VOLUME.
C  RH       =AIR RELATIVE HUMIDITY.
C  PS       =SATURATION PRESSURE.
C  EKP      =CONSTANT IN MODIFIED ERGUN EQUATION CONTAINING CON-
      STANTS M AND N.
C  DELTPMN  =PRESSURE DIFFERENTIAL GIVEN BY ERGUN EQUATION CON-
      TAINING CONSTANTS M AND N.
C  DELTPKEP=PRESSURE DIFFERENTIAL GIVEN BY ERGUN EQUATION CON-
      TAINING CONSTANTS M,N, AND EKP.
C  TESTNO   =TEST NUMBER
C  IA       =NUMBER OF DATA POINTS FOR A GIVEN TEST.
C  H        =HEIGHT OF TEST BED OVER WHICH PRESSURE DIFFERENTIAL
      WAS MEASURED.
C  D        =EQUIVALENT PARTICLE DIAMETER.
C  PF       =FINAL PRESSURE READING IN POROSITY MEASUREMENT.
C  DELTP    =DIFFERENCE BETWEEN INITIAL AND FINAL PRESSURE READING
      IN POROSITY MEASUREMENT.
C  SUMEK    =SUM OF EK VALUES FOR A GIVEN TEST.
C  SUMEKP   =SUM OF EKP VALUES FOR A GIVEN TEST.
C  EPS      =POROSITY VALUE.
C  EKMEAN   =MEAN VALUE OF CONSTANT EK FOR A GIVEN TEST.
C  EKPMEAN  =MEAN VALUE OF CONSTANT EKP FOR A GIVEN TEST.
      DIMENSION AFDELTP(20),EXBDELTP(20),CFM(20),TEMP(20),TEMPCOR(160)
      DIMENSION DELTPE(20), DMAIRFLO(20), RE(20), U(20), AMU(170)
      DIMENSION EK(20), DELTPKE(20), ROONE(20), RH(20), PS(160)
      DIMENSION EKP(20), DELTPMN(20), DELTPKEP(20)
      READ(60,8)PS
      READ(60,8)TEMPCOR
8  FORMAT(10F5,4)
      READ(60,6)AMU
6  FORMAT(10F5,5)
001 READ(60,9)TESTNO,IA,H,D,PF,DELTP
9  FORMAT(F3,0,12,F5.0,3F10.0)
      IF(TESTNO.LE.0) GO TO 002

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      READ(60,7) (AFDELTP(I),I=1,IA)
      READ(60,7) (EXBDELTP(J),J=1,IA)
      READ(60,7) (TEMP(N),N=1,IA)
      READ(60,7) (RH(M),M=1,IA)
7  FORMAT(15F5.0)
      K=0
      SUMEK=0
      SUMEKP=0
      IC=0
      EPS=1-((1144.1639-((893.46*PF)/DELTP))/3/6.67)
20 DO 203 L=1,IA
      K=K+1
      CFM(K)=((-0.00408754+5.55090626*AFDELTP(K)-0.009/1439*AFDELTP(K)**
13+0.00056478*AFDELTP(K)**4)*TEMPCOR(TEMP(K)))/0.168759
      U(K)=CFM(K)/(60)
      DELTPMN(K)=(H*((.160386662*U(K))+(.33556465*(U(K)**2))))
      EKP(K)=(EXBDELTP(K))/(DELTPMN(K))
      SUMEKP=SUMEKP+EKP(K)
      ROONE(K)=(53.35*(TEMP(K)+460))/(144*(14.696-(RH(K)*PS(TEMP(K)))))
      DELTPE(K)=(150*((1-EPS)**2)*AMU(TEMP(K))*0.000672*H*U(K))/((EPS**3
1)* (D**2)*32.2*5.204)+(1.75*(1-EPS)*H*(U(K)**2))/((EPS**3)*D*32.2*5
1.204*ROONE(K))
      RE(K)=((D*U(K))/(AMU(TEMP(K))*0.000672*ROONE(K)))/(1-EPS)
      EK(K)=(EXBDELTP(K))/(DELTPE(K))
203 SUMEK=SUMEK+EK(K)
      EKMEAN=SUMEK/IA
      EKPMEAN=SUMEKP/IA
      DO 300 L=1,IA
      IC=IC+1
204 DELTPKE(IC)=EKMEAN*DELTPE(IC)
      DELTPKEP(IC)=EKPMEAN*DELTPMN(IC)
300 DMAIRFLO(IC)=(DELTPE(IC)*32.2*ROONE(IC)*D*(EPS**3)*5.204)/H*EKME
1AN*(U(IC)**2)*(1-EPS))
      PRINT 13
13 FORMAT(1H1)
      PRINT 12
12 FORMAT(*BED DEPTH PTCL. DIA. FINAL P. DELTA P. EKMEAN POROSI
1TY TESTNO EKPMEAN*)
      WRITE(61,10)H,D,PF,DELTP,EKMEAN,EPS,TESTNO,EKPMEAN
10 FORMAT(F10.1,F10.6,2F10.2,2F10.5,F10.0,F10.3,*-*)
      PRINT 23
23 FORMAT(*-*,5X,*EK DELTPKE XBDELTP DELTPE CFM U AFDELTP
1TEPCOR DAIRFLO RE TEMP RH ROONE AMU PS*)
      J=0
      DO 301 L=1,IA
      J=J+1
301 WRITE(61,36)EK(J),DELTPE(J),EXBDELTP(J),DELTPE(J),CFM(J),U(J),AFD
1ELTP(J),TEPCOR(TEMP(J)),DMAIRFLO(J),RE(J),TEMP(J),RH(J),ROONE(J),
1AMU(TEMP(J)),PS(TEMP(J))
36 FORMAT(7F8.3,F8.4,5F8.3,F8.6,F8.4)
      PRINT 24
24 FORMAT(*-*,* EKP DELTPMN DELTPKEP*)
      J=0
      DO 302 L=1,IA

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      J=J+1
302 WRITE(61,37)EKP(J),DELTPMN(J),DELTPKEP(J)
37  FORMAT(3F8.3)
      CALL PLOT(0.0,0.0,0,100.,100.)
      CALL PLOT (23.,0.0,3)
      CALL PLOT(0.0,-30.,2)
      CALL PLOT(0.0,0.0,0)
      CALL GRAPH1 (EXBDELTP,CFM,IA,5H06X06,4HAUTO,26HAIRFLOW VS PRESSURE
1DROP.,16HBED PRESS DROP.,16HAIRFLOW IN CFM.,)
      CALL GRAPH1 (DELTPKE,CFM,IA,7HOVERLAY,4HSAME)
      CALL GRAPH1 (DELTPE,CFM,IA,7HOVERLAY,4HSAME)
      GO TO 001
002 END

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