PRESSURE DROP
IN
SPOUTED BEDS

- by -

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I

ABSTRACT

The present work contains the result of an investigation on pressure drop in spouted beds. Six inch columns with a 0.5" air inlet orifice were used during the course of the investigation. The spouting medium was air. The gas flow rates vary from 84 to 1077 pounds per hour per square foot of column cross section. Particle diameters ranging from 0.079" to 0.25" were studied. Porosities of the packings vary from 0.358 to 0.525.

Correlations for the packed bed region and for the spouting point are presented.

A six inch spouting unit consisting of four stages was also studied. Necessary gas flow rates to achieve spouting in each stage seems to indicate that the spouting bed technique can be improved by using several stages instead of one.

II

INTRODUCTION

Large coarse particles are satisfactorily agitated in a spouted Bed whereas in a fluidized bed they present the tendency to rise up as slugs.

The spouted bed technique makes use of a high pressure drop orifice located at the column base instead of the distributor plate used in the fluidized bed. The air inlet orifice tends to stabilize the system.

Spouting occurs when a bed of solid particles is brought into a continuously agitated condition by an upward stream of fluid. The particles are carried upwards in a central core. Above the bed the particles fall back into the annular space around the spout and move uniformly downwards. A continuous circulation of the solids and a good fluid-solid contact are achieved.

It has been established that a particular packing has a limiting spoutable bed depth (13) which depends upon the column diameter and upon the air inlet orifice.

The present investigation intends to correlate pressure drops in the beds with the experimental variables. Column diameter and air inlet orifice were held constant on account of the scope of the investigation.

III

HISTORICAL REVIEW

K.B. Mathur and P.E. Gishler (13) studied the effect of column diameter, cone angle and orifice size on spouting. This work was continued by B. Thorley, J. Klassen, P.E. Gisler and K.B. Mathur (17).

A. AIR FLOW REQUIREMENTS FOR SPOUTING

Mathur and Gishler (13) experimenting in columns ranging in diameter from 4 to 12 inches derived the following correlation for the minimum air flow required for spouting

$$v = \left(\frac{d_p}{d_c}\right)\left(\frac{d_i}{d_c}\right)^{1/3} \sqrt{\frac{2 g_c L (\rho_s - \rho_f)}{\rho_f}} \qquad (1)$$

Further work was conducted by Gishler and co-workers in a 24 inch diameter Plexiglass column. Provisions were made in the column for changing the cone angle and the air inlet orifice.

It was found that lower superficial velocities for spouting are required with steeper cones. The effect of cone angle in a 24 inch column is more pronounced than in a 6 inch column.

Equation (1) was modified as follows:

$$v = \left(\frac{d_p}{d_c}\right)\left(\frac{d_i}{d_c}\right)^{c} \sqrt{\frac{2 g_c L (\rho_s - \rho_f)}{\rho_f}} \qquad (2)$$

Where:

$c = 0.23$ for 45° cone angle

$c = 0.13$ for 85° " "

B. AIR FLOW PATTERN

Data obtained from a moving packed bed in a 4 inch diameter column in which the flow of particles and air was kept at the same order of magnitude as in the annulus of the spouted bed, showed that this region is essentially a loosely packed bed. Error would be introduced in this method of determining the distribution of the flow of air when an homogeneous orientation of the particles is not established.

Column diameter.- Results of an investigation carried out in columns ranging in diameter from 6 to 24 inches showed that the percentage of air flow through the annulus increases with the diameter of the column. Variables such as (d_c/d_i), (L/d_c), cone angle and air flow were held constant.

Bed depth.- The percentage of air flow through the annulus increases with decreasing bed depth.

Air inlet orifice.- The percentage of air flow through the annulus increases with increasing air inlet diameter.

Cone angle.- The percentage of air flow through the annulus increases with increasing included cone angle.

Air flow.- Increasing air flows above the minimum required for spouting were found to reduce the percentage of air flow through the annulus. The air in excess remains essentially within the spout.

C. SOLIDS FLOW PATTERN

Solids flow in the annulus.- It has been observed that the vertical component of the velocity does not change appreciably across the radius of the annulus. It was found that particles in the part of the bed above the cone are transferred from the annulus into the spout by direct removal of particles from the interface. This is due to collisions between the upward moving particles and the downward moving particles in the annulus, along the spout boundary.

Within the cone, the horizontal component of the static pressure on the particles in the annulus is high because of the thrust due to the cone wall. The particles would travel across the interface under this driving force and carried upwards by the air stream.

The particle velocity at the wall, in the split column, was taken as to be the direct measurement of the solids flow in the annulus.

An equation that shows qualitatively the relationship between the number of collisions and other variables has been proposed by the same authors (17).

$$d_w = \pi d_s \, dL \, (n_1); \text{ or} \tag{3}$$

$$d_w = \pi d_s \, dL \, f(N \; V_p) \tag{4}$$

d_s = spout diameter, ft.

Effect of column diameter.- If (d_c/d_i), (L/d_c) and cone angle were held constant it was found that the flow of solids is higher in the 24 inch column than in the 6 inch column. Higher kinetic energies available in the higher rates of air flow for spouting is probably the cause of this effect in the 24" column.

Effect of bed depth.- Higher kinetic energies would cause the linear increase of particle velocity with bed depth observed in the 6 inch column and in the 24 inch column.

The gradient of the particle velocity vs. bed level curve is higher for deeper beds. This is due, in part, to the increase in spout diameter with bed depth. The data of the 24 inch column did not show a gradient with bed levels up to 5 feet; indication that the cross flow in the region above the cone is not sufficient to show marked differences in the particle velocities at wall. A definite gradient in the particle velocity at wall was observed in the case of a 6 foot bed depth.

Effect of cone angle.- The data obtained for the six inch diameter column indicates that there is no appreciable effect of cone angle on the cross flow. The data for the 24 inch diameter column indicates that the cross flow per unit height above the cone decreases with increasing cone angles.

Effect of increasing air flow above the minimum spouting.-

The cross flow per unit height increases with increasing flow.

Solids flow in the spout.- Particle velocity obtained from a 24 inch diameter split column indicates that the particle velocity in the spout increases with air flow rate above the minimum spouting. This is due to the greater impulse received by the particles within the cone and to the lifting action of the air in the spout above the cone. A 16 mm Western Electric Fantax Cine Camera, at about 2000 frames per second was used for this determination.

Estimation of the spout diameter.- The diameter of the spout is apparently not related to the diameter of the air inlet orifice in any simple way. Nevertheless, an empirical correlation has been developed in order to predict the diameter of the spout

$$ds = K\left(\frac{d_i}{d_c}\right)^m \left(\frac{V_i}{V_{im}}\right)^{0.8} L^{0.22} \qquad (5)$$

24 inch column	6 inch column
K = 1.58	K = 0.72
m = 0.15	m = 0.0

ds = average spout diameter, inches

A 24 inch column diameter provided with 45° and 60° cone angles and a 6 inch column diameter with a 60° cone angle were used in this investigation.

Void Space in the spout.- It was found that the voids in the spout decrease with increasing flow rates above the minimum required for spouting, since the solids flow rate increases considerably without a substantial increase in the particle velocity in the spout.

At corresponding positions, the percentage of voids in the spout is higher in the 24 inch column than in the 6 inch diameter column.

A series of equations aimed to predict the particle velocity in the spout have been proposed by the same authors.

Solids turnover.- It has been observed that higher kinetic energies produced higher turnover rate. Attempts to correlate kinetic energy and solids turnover rate led to the following empirical relationship:

$$W = K_2 \left(\frac{d_i}{d_c}\right)^{-0.25} \left(\frac{L}{d_c}\right)^{1.0} \left(\frac{V_i}{V_{im}}\right)^{1.23} \qquad (6)$$

24" column K_2	cone angle (degrees)	6" column K_2
1.85	45	0.15
1.24	60	0.15
1.27	85	0.18

It was observed that the highest solids turnover rate is obtained with the maximum bed depth, a small air inlet orifice and a high air flow.

IV

THEORETICAL PRINCIPLES

The purpose of this section is to present a review of the theory of flow of non-adsorbable gases through beds of different packings.

The flow of a fluid through packings includes porosities ranging from zero to 100 per cent. Zero represents the impervious solid and 100% represents an empty conduit.

Poiseuille (15) carried out experiments on capillary tubes and established laminar flow relations through conduits.

Reynolds (16) showed experimentally that there are two types of flow - laminar and turbulent. He deriveda dimensionless group, known as Reynolds number, which defines the condition of the system and predicts the type of flow. He also showed that the resistance to flow is a function of that dimensionless group.

Darcy (6) stated the concept of laminar flow through a porous bed. His equation is the equivalent of Poiseuille's relation for conduit and may be stated as follows:

$$v = \frac{dV}{Adt} = K_1 \frac{\triangle P}{\mu L} \qquad (7)$$

Blake (1) presented the following correlation for streamline flow

$$\frac{\triangle P}{L} \; \frac{g_c \, \rho_f \, \delta^3}{G^2 \; a} = f\left(\frac{G}{\mu a}\right) = K\left(\frac{G}{\mu a}\right)^{-1.0} \qquad (8)$$

In order to derive his equation Blake made use of the Dupuit's (8) assumption that the effective path diameter is proportional to the void volume per unit of surface area and that the velocity in the pore space is inversely proportional to the porosity of the bed.

Carman introduced the concept of shape factor. Its importance in helping to understand the phenomenon of fluid flow through porous bed has been stressed by several authors.

For spherical particles, the specific surface was transformed to particle diameter by means of the following relationship

$$a = \frac{6\,(1 - \delta)}{D_p} \qquad (9)$$

For nonspherical particles

$$\phi_s = \frac{6\,(1 - \delta)}{a \quad D_p} \qquad (10)$$

Where ϕ_s is defined as

$$\phi_s = \frac{a_p}{a} \qquad (11)$$

Max Leva (10) derived an equation in which the shape factor is directly related to the dimensions of the packing particles.

$$\lambda = 0.205 \frac{s}{vp^{2/3}} \qquad (12)$$

The shape factor has been presented in literature in various ways. They may be related as follows

$$\lambda = \frac{1}{s} = \frac{1}{\psi} \tag{13}$$

Kozeny (9), assumed that the granular bed is equivalent to a group of parallel similar channels such that the total internal surface and the total internal volume are equal to the particle surface and the pore volume in the bed itself. He further assumed that the tortuous passage is longer than the depth of the bed, and the channel velocity higher than if straight vertical channel existed. He proposed the following correlation for streamline flow

$$\frac{\Delta P}{L} \; \frac{g_c \; \rho_f \; \delta^3}{G^2 a} = 5\left(\frac{G}{\mu a}\right)^{-1.0} \tag{14}$$

or

$$\frac{\Delta P}{L} = \frac{180G \; (1-\delta)^2 \mu}{\phi_s{}^2 D_p{}^2 \; g_c \; \delta^3 \rho_f} \tag{15}$$

Carman (4) proved the validity of the correlation proposed by Kozeny and derived the following expression for turbulent flow

$$\frac{\Delta P}{L} = \frac{G^2 \; a}{g_c \; \rho_f \; \delta^3} \; 0.4 \; \left(\frac{G}{\mu a}\right)^{-0.1} \tag{16}$$

or

$$\frac{\Delta P}{L} = \frac{2.9\, G^{1.9}\, \mu^{0.1}\, (1-\delta)^{1.1}}{D_p^{1.1}\, g_c\, \rho_s^{1.1}\, \rho_f\, \delta^{3}} \tag{17}$$

Max Leva (10) derived a general theoretical equation for fluid flow in packed beds, by establishing the analogy of this latter and the fluid flow in empty pipes

$$\frac{\Delta P}{L} = \frac{K}{g_c}\left(\frac{D_p G}{\mu}\right)^{n} \frac{\mu^2}{\rho_f}\, \frac{\lambda^{3-n}}{D_p^{3}}\, \frac{(1-\delta)^{3-n}}{\delta^{3}} \tag{18}$$

Theoretical derivation of Equation (18) is included in the Appendix.

<u>Fluidized Beds</u>.- When the fluid is admitted at the bottom of the column, a small pressure drop will be registered. The pressure drop will increase when the fluid flow is increased until a point of maximum pressure drop is reached.

Parent, Yagol and Steiner (14) reported that the pressure drop at fluidization was approximately equal to the weight of the solids per unit cross section of the bed.

$$\frac{\Delta P}{L} = (1-\delta)(\rho_s - \rho_f) \tag{19}$$

The bed expands as the fluid flow is increased. The percentage of voids in the bed increases and the pressure drop remains constant.

When the fluid has reached a certain velocity an internal motion of the particles in the bed is established and fluidization begins.

Carman's equation has been modified by assuming constant pressure drop for the fluidized bed. Substituting equation (19) in equation (15) for K = 200, the following relationship is obtained

$$G = \frac{0.005\ D_p^2\ g_c\ \rho_f(\ \rho_s - \rho_f)\,\delta^3}{\mu\ \lambda^2\ (1-\delta)} \qquad (20)$$

The bed will experienced a further expansion with an additional increase in the fluid flow and the motion of the particles is intensified. At this stage, an increase of the air flow will cause a greater agitation and considerable fluctuation of the top of the bed. If still more air is admitted, large bubbles will rise up and the slugging condition will have been established. Slugging is more pronounced in columns with small diameter.

Uneven distribution of the fluid flow over the cross sectional area of a fixed bed or a fluidized bed will bring about the effect called channeling. This phenomenon decreases the interfacial area. If the channel is large enough as to form a pipe the pressure drop will be lower than that predicted from the weight of the bed, although fluidization still occurs.

Materials with greater tendency to channel show that the ΔP versus flow relation deviate most widely from the theoretical.

When a liquid is used as the fluidizing medium, particulate fluidization occurs. This type of fluidization is characterized by a continuous and uniform expansion of the bed with increasing velocity of the fluid, until the particles are widely separated and behave as individuals particles.

When a gas is used instead of a liquid, aggregative fluidization occurs. Some of the gas flows around the particles, some flows through the bed, and the top of the bed gives the appearance of a boiling liquid. A downward movement of the solids takes place at the walls of the container.

Lewis and co-workers (12) reported that the pressure drop calculated from equation (19) may be as low as 20% when electrostatic effects are present. Electrostatic charges have been observed in experiments on aggregative fluidization. These charges may be needed for fluidization of small particles. The bed collapses (2) when the fluid is ionized and therefore the charges are lost.

<u>Pressure deficiency ratio, in fluidization</u>.-

Defined as

$$X_D = \frac{\Delta P - \Delta P_D}{\Delta P} \tag{21}$$

When the point of maximum pressure drop is reached ($\Delta P = wt./A$), the pressure drop will fall sharply to a minimum value ΔP_D.

Max Leva and coworkers (11) reported that X_D would be the equivalent fractional length of unfluidized bed. X_D can be used with caution to compare qualitatively the channeling of various beds. Large values of X_D would indicate a greater tendency to channeling.

Less resistance to fluid flow, in a narrow column, is offered near to the wall and greater to the center. This effect indicates that increased channeling tendencies are to be expected when columns of small diameter are operated.

X_D decreases sharply with increasing values of D_p. Large particle diameters would imply less channeling tendencies.

V

EXPERIMENTAL DETAILS

A. EQUIPMENT

Four columns were used during the course of the present investigation. (Figure 1)

1. A six inch diameter column with a 60° cone angle
2. A six inch diameter column with a flat bottom
3. A four inch diameter column with a 60° cone angle
4. A six inch diameter split column with a flat bottom.

The three first columns are made of Pyrex glass. The other one is made of Aluminum.

The spouting medium, air, was supplied from a compressor and either of two rotameters metered the flow rate. The pipes leading to the columns were provided with a two foot calming section of brass pipe. The equipment also consisted of a filter for the air, pipes, fittings and valves to control the air flow rate. Static pressures relative to atmospheric pressure were read off three vertical manometers. These manometers were connected to pressure taps located above the orifice plates. A mercury manometer and a gauge measured the static pressures in the stage spouting unit. Mercury thermometers graduated in degrees Fahrenheit were used to measure the air temperature at different points.

A flow sheet of the spouted apparatus is shown on Fig. 2. Details of the pressure taps appear on Figures 3 and 4.

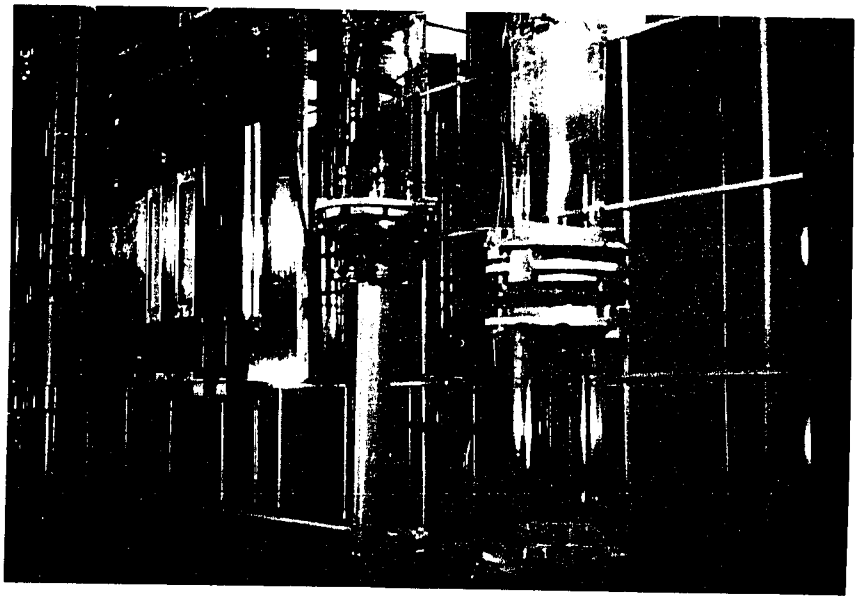

Fig 1.- Columns and Panel Board

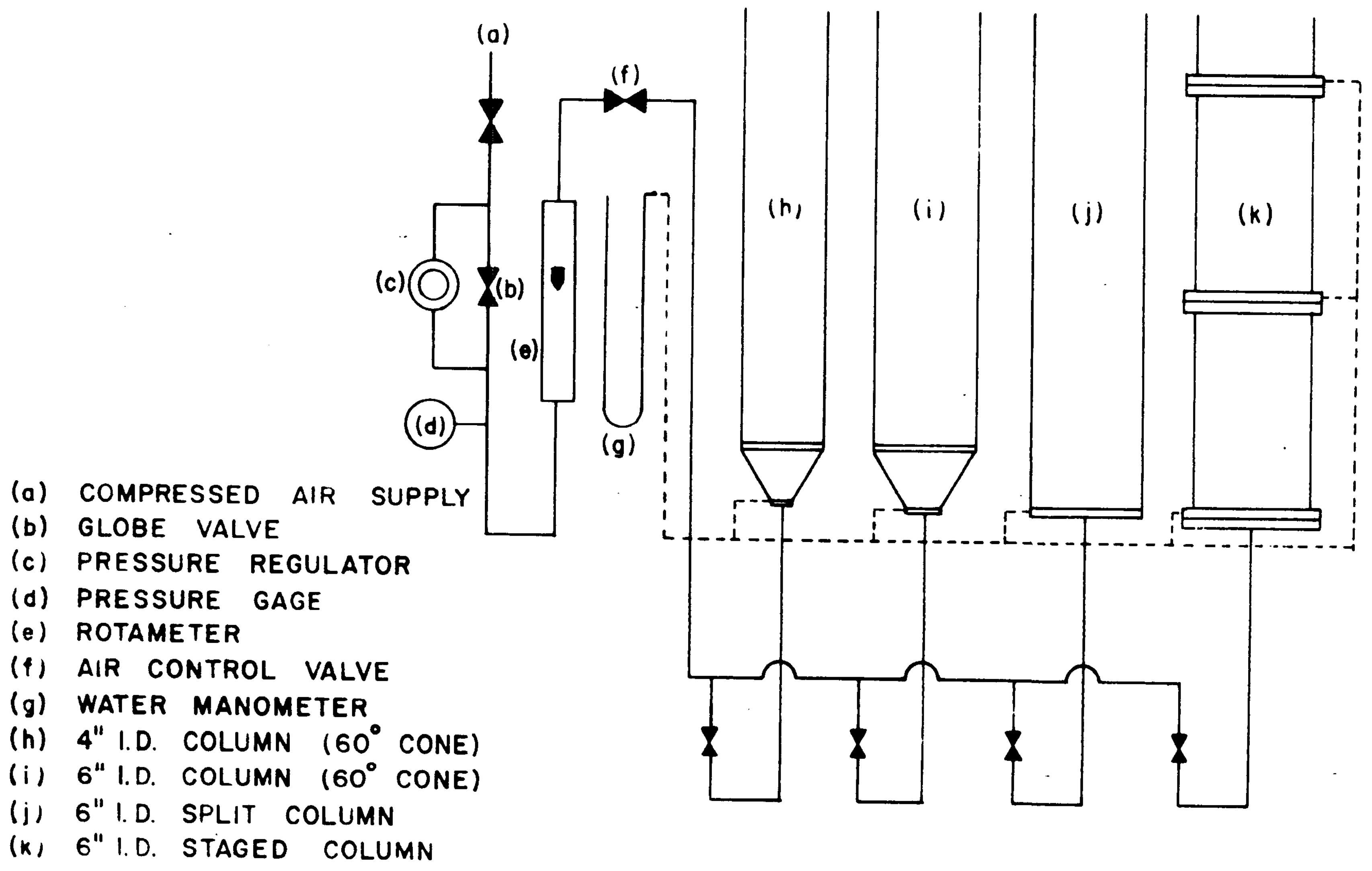

FIG. 2 FLOW SHEET OF SPOUTED BED APPARATUS

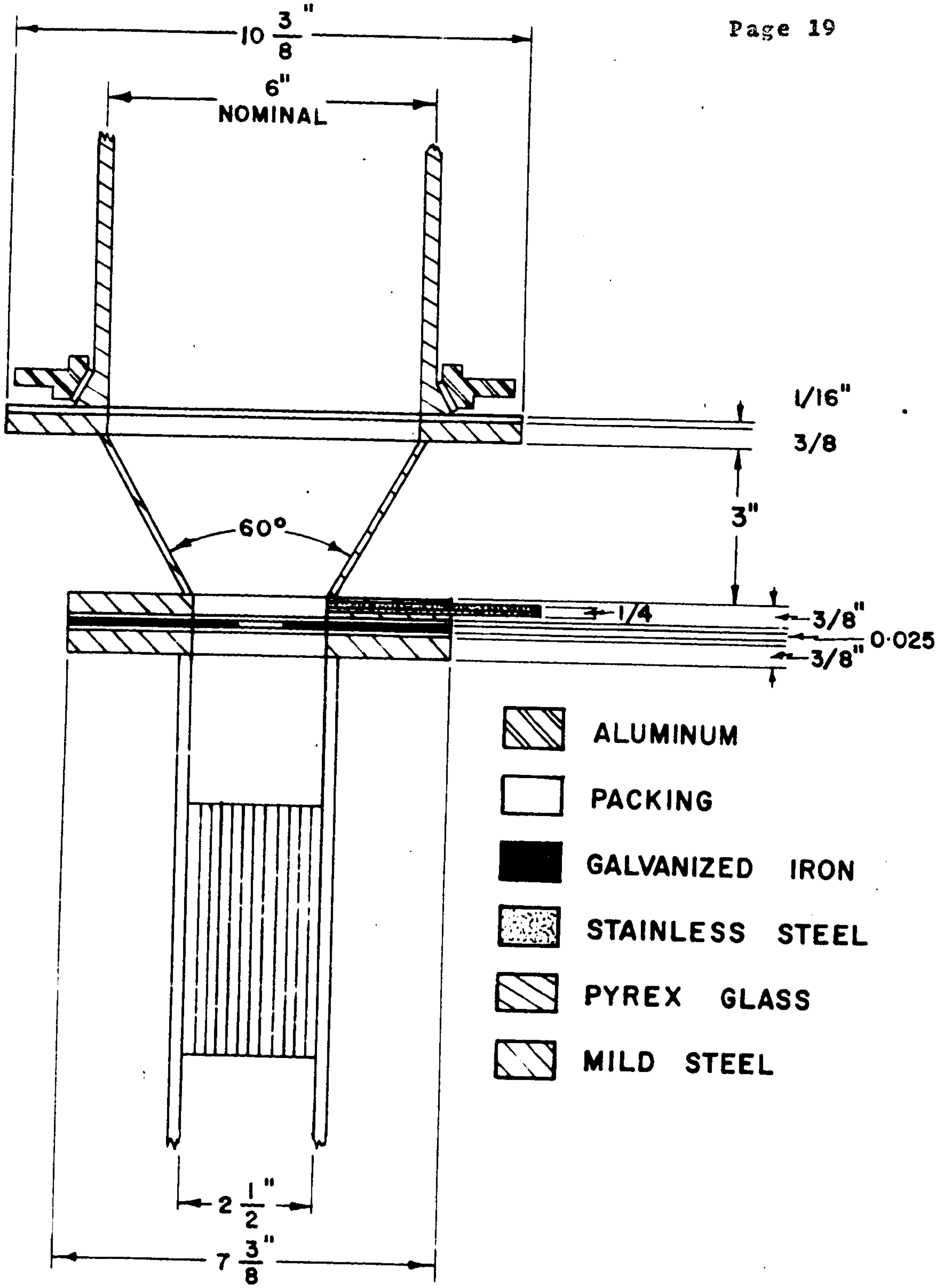

FIG. 3 PRESSURE TAP ARRANGEMENT
6" COLUMN WITH CONE

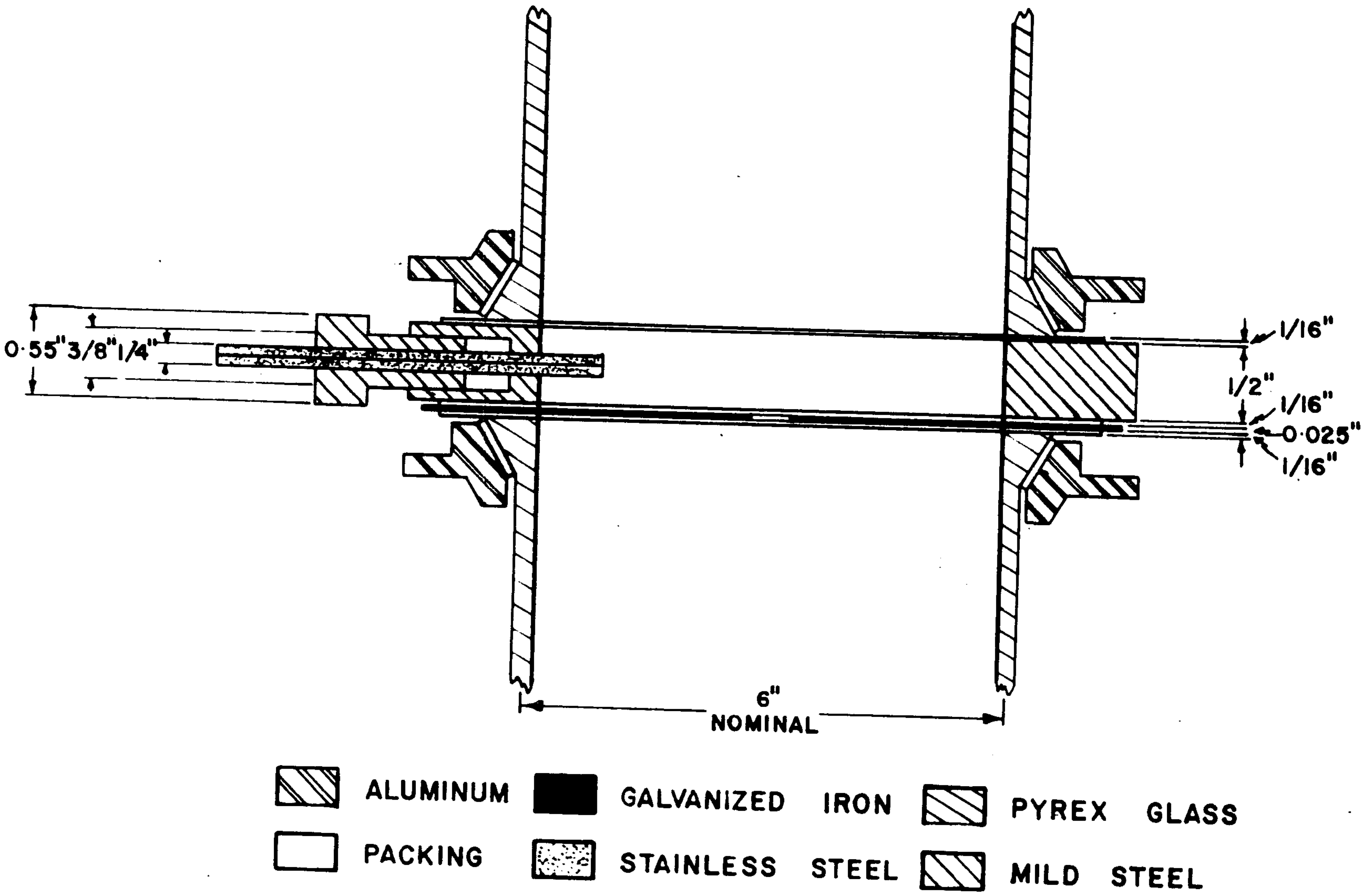

FIG. 4 PRESSURE TAP ARRANGEMENT
6" FLAT BOTTOM COLUMN

Compressor and motor.- Figure 5

The compressor was obtained from Ingersoll Rand, Type 30, Model 71 T D, size 5-$\frac{1}{2}$ & 3$\frac{1}{2}$ x 4, serial Number 30 T, 137027. Piston displacement is 53 C.F.M., speed 965 R.P.M., discharge pressure is 100 p.s.i.g. Its delivery at 100 p.s.i.g. is 40 C.F.M., B. H. P. is 10.4. The capacity of the receiver is 20 x 63 (80 gallons).

The motor is 10 HP and operates on three phase, 60 cycles and 550 volts. Its speed is 1740 R.P.M. at full load. Frame 324.

The moisture in the compressed air was eliminated by a cooling unit installed at the inlet of the receiver.

Instrumentation and control.- Figure 6

The board is made of a $\frac{1}{2}$" piece of plywood 4 feet by 2.8 feet. On the left hand side were placed the rotameters, the controlling valves and the gauges. On the right hand side were mounted four vertical manometers.

B. METHODS OF CALCULATION

The standard flow conditions chosen for this work were: 14.7 p.s.i.a., and 70°F.

Rotameters.-

Two rotameters manufactured by Brooks Rotameter Company were used to measure the air flow rate. These rotameters metered the flow with an accuracy of 1%.

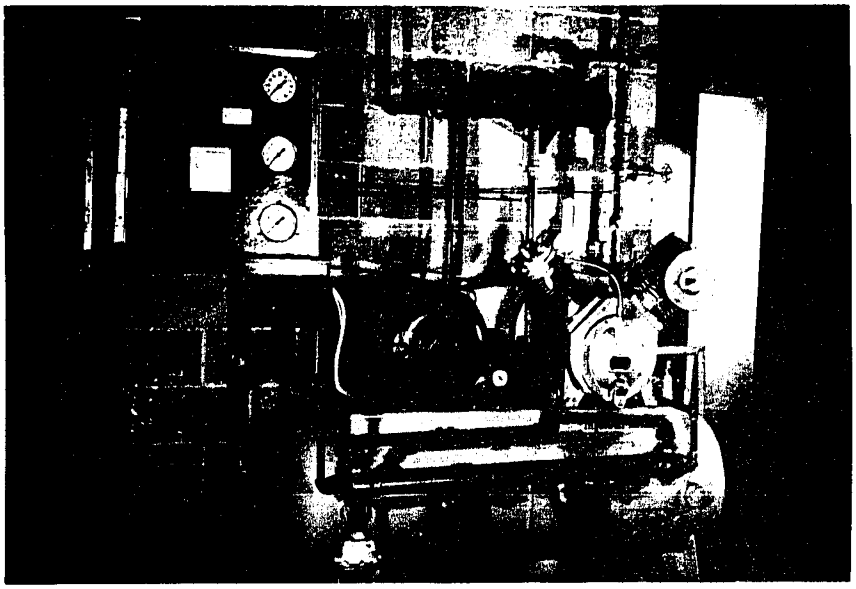

Fig 5.- Compressor

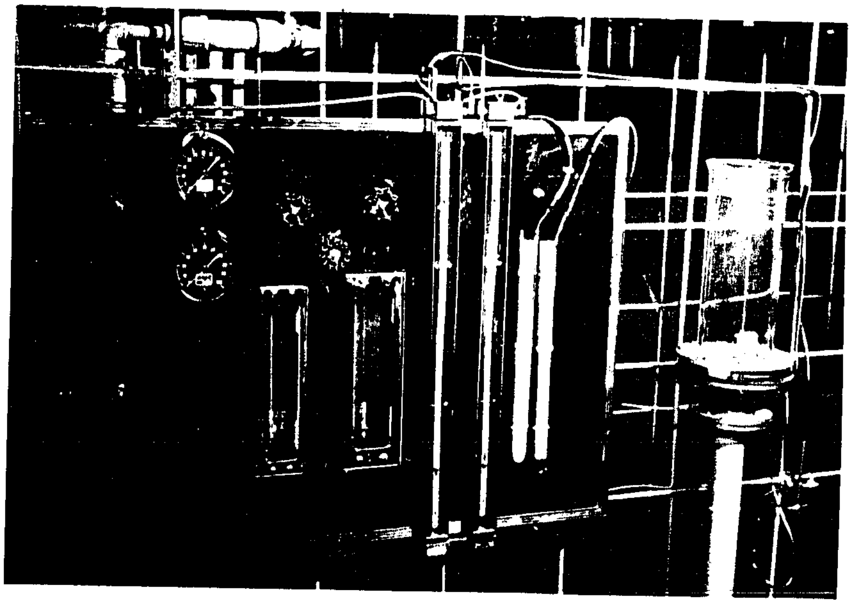

Fig 6.- Panel Board

Characteristics:

<u>Rotameter (1)</u>.- Tube size 12M - 25 - 1, SER-14185

SCFM at 14.7 p.s.i.a. and 70°F

The air flow rate was converted to the standard flow conditions with the aid of the following equation (7)

$$q_s = q_m \sqrt{\frac{P}{P_o}} \sqrt{\frac{T}{T_o}} \qquad (22)$$

Example of calculation

gauge pressure = 40 p.s.i. $\quad P_o = 14.7$

rotameter reading = 10 C.F.M. $\quad T_o$ and $T = 70°F$

$$q_s = 10 \sqrt{\frac{14.7 + \text{gauge pressure}}{14.7}} = 10 \sqrt{\frac{14.7 + 40}{14.7}}$$

$$q_s = 10 \times 1.93 = 19.3$$

<u>Rotameter (2)</u>.- Tube size R-9M-25-2, SER-11532-1

SCFM at 80°F and 40 p.s.i.g.

Correction factor

$$q_{s_1} = q_M \sqrt{\frac{80 + 460 \quad (T_o)}{40 + 14.7 \quad (P_o)}} \quad \sqrt{\frac{\text{gauge pressure} + 14.7 \ (P)}{70 + 460 \ (T)}}$$

q_{s_1} = C.F.M. at 14.7 p.s.i.a. and 80°F.

T_o = 540°R ; P_o = 54.7

$$q_{s_1} = q_M \times 3.14 \times \sqrt{\frac{P}{T}}$$

For all practical purposes $q_{s_1} = q_s$

Example of calculation

gauge pressure = 40 psi.

rotameter reading = 10 ; T = 530°R

$$q_s = 10 \times 3.14 \sqrt{\frac{54.7}{530}} = 10$$

Mass velocity conversion factors.-

6 inch. diameter column.- Inside diameter = 5.875" (average).

$$G = q_s \frac{ft^3}{min.} \times 60 \frac{min.}{hr.} \times 0.075 \frac{lbs.}{ft^3} \times \frac{1}{0.188\ ft^2} = 23.9\ q_s$$

6 inch diameter split column.- Inside diameter = 6.2"

$$G = q_s \frac{ft^3}{min.} \times 60 \frac{min.}{hr.} \times 0.075 \frac{lbs.}{ft^3} \times \frac{1}{0.2096\ ft^2} = 42.92\ q_s$$

Modified Reynolds number.-

$$Re = \frac{G\ D_p}{\mu} \qquad (23)$$

Example of calculation.- Table 6

SCFM = 10 ; $G = 23.9 \times 10 \frac{lbs}{hr. \times sq.ft.}$; Re = 64.5

Pressure drop

Pressure drop data presented in Tables 6-19 are the average value of four different runs.

In order to determine pressure drops due to the solids alone, data were collected for the empty columns at different flow rates, (Figures 19 and 20).

The bed was allowed to spout for 1½ minutes before each run.

Example of calculation

Table 6, L = 4"; 6 inch diameter column, 60° cone angle

Manometer reading = 1.14 inches of water; 10 SCFM.

Correction factor for empty column = -0.1 (Figure 19)

$1.14 - (-0.1) = 1.24$ inches of water

$$1.24 \text{ inches of water} \times 5.2 \ \frac{\text{lbs/ft}^2}{\text{inch of water}} = 6.45 \ \frac{\text{lbs}}{\text{ft}^2}$$

$$\text{Pressure drop per foot} = \frac{6.45 \ \frac{\text{lbs}}{\text{ft}^2}}{\frac{4}{12} \ \text{ft}} = 19.35 \ \frac{\text{lbs}}{\text{ft}^2\text{-ft}}$$

<u>Absolute density of the packing</u>.- (Table 1)

The absolute density was determined by the method of liquid displacement of a known weight of the particles (5).

The tests were carried out in pycnometers and liquids such as water, benzene or ethyl alcohol were used in these determinations.

With knowledge of the number of particles used in each test and the amount of liquid displaced, the volume of one particle and the diameter of an sphere (D_p) of equivalent volume were determined, as follows

$$\frac{\text{Volume displaced}}{\text{number of particles}} = \text{volume of one particle } (v_p) \qquad (24)$$

$$D_p = \sqrt[3]{\frac{6 \ v_p}{\pi}} = \sqrt[3]{\frac{6}{M \ \rho_s \ \pi}} \qquad (25)$$

Example of calculation

Number of particles of old wheat = 60; wt. = 2.1155 gms

C_2H_5 OH displaced = 1.1665 cc ;

$$\text{absolute density} = \frac{2.1155}{\frac{1.1665}{0.7843}} = 1.4224 \frac{\text{gs}}{\text{cc}}$$

$$D_p = \sqrt[3]{\frac{6}{\pi \times 1.4224 \times 28.3}} = 0.3625 \text{ cm.} = 0.1431''$$

Kozeny corrections for voidage

Pressure drops were taken to a common basis of 40% voidage. This voidage was arbitrarily chosen. The following factor made possible this correction

$$\frac{(1-\delta)^{3-n}}{\delta^3}$$

Example of calculation

For laminar flow.- Packing: old wheat

$$\left(\frac{\Delta P}{L}\right)_{40} = \left(\frac{\Delta P}{L}\right) \frac{(1-0.4)^2}{(0.4)^3} \times \frac{(0.3935)^3}{(0.6065)^2} = 0.9318 \left(\frac{\Delta P}{L}\right)$$

For transitional flow: Packing: old wheat

$$\left(\frac{\Delta P}{L}\right)_{40} = \left(\frac{\Delta P}{L}\right) \frac{(1-0.4)^{1.75}}{(0.40)^3} \times \frac{(0.3935)^3}{(0.6065)^{1.75}} = 0.933 \left(\frac{\Delta P}{L}\right)$$

Bulk density of the packing (Table 1)

A 6 inch diameter column and a 6 inch diameter split column were used for this work. Known quantities of the packings were dumped into the column in a slow and steady stream. The height of the column was recorded before and after two minutes of spouting. Results of the investigation presented in Table 15 represent the average value of four determinations. Data were reproduced within ±1% average deviation.

Porosities (Table 1)

Porosities were calculated from the absolute density and the after spouting bulk density, as follows

$$\delta = 1 - \frac{\rho_b}{\rho_s} \qquad (26)$$

Shape factor (Table 1)

Shape factors for normal packings evaluated from the Brownell's sphericity vs. porosity chart, (3), are similar to those calculated from equation (12).

Surface areas could not be calculated with the necessary accuracy from the dimensions of the particles, thus, it has been preferred to use the Brownell's data in the present calculations.

Table 1

PHYSICAL CHARACTERISTICS OF PACKINGS

PACKINGS	D_p(in.)	δ	$\frac{(1-\delta)^2}{\delta^3}$	$\frac{(1-\delta)^{1.75}}{\delta^3}$	ρ_s	ρ_b	ρ_{bs}	λ_C	λ
OLD WHEAT	0.1431	0.3935	6.037	6.86	88.76	56.6	53.83	1.03	1.075
NEW WHEAT	0.1496	0.42	4.55	5.196	86.51	51.82	50.17	1.091	1.19
BARLEY	0.1537	0.4741	2.595	3.048	82.22	45.53	43.24	1.245	1.141
RAPE SEED	0.079	0.399	5.686	6.45	68.93	42.63	41.43	-	1.11
OATS	0.1458	0.525	1.559	1.88	76.58	39.16	36.38	1.552	1.60
VETCHES	0.1713	0.3921	6.13	6.934	88.14	54.6	53.58	1.12	1.075
SPLIT PEAS	0.1732	0.358	8.983	10.03	87.87	57.54	56.42	-	1.0
PEAS	0.2239	0.3975	5.78	6.56	87.77	53.11	52.88	1.0	1.075
SMALL PELLETS (polyethylene)	0.131	0.406	5.272	5.977	57.35	35.47	34.07	1.14	1.11
BIG PELLETS (polyethylene)	0.2016	0.406	5.272	5.977	57.35	35.34	34.07	1.08	1.11
SOY BEANS	0.25	0.3743	7.47	8.4	76.05	47.58	47.58	-	1.058
WHITE MILLET SEED	0.0894	0.3929	6.077	6.9	76.0	48.36	46.14	-	1.075

VI

DISCUSSION OF RESULTS

A. VISUAL OBSERVATIONS

The effect of column diameter on spouting was qualitatively observed using a four inch column diameter. It was noted that this column tends to deviate the central core towards the sides of the container. This undesirable effect becomes more pronounced with higher bed depths.

Slugging.-

This condition describes the effect of large bubbles of air passing through the bed. These bubbles are even able to separate the bed into two sections. While part of the bed is raised like a solid piston and acts as a packed bed, the bottom section may even be spouting.

The six inch diameter column did not show either the tendency to deviate the central core towards the sides of the container or the slugging effect in the range of particle diameters and air flow rates studied.

Considerable fluctuation of the top of the bed at high bed depths was observed in the six inch diameter split column.

B. PRESENTATION OF RESULTS

In order to gain an insight into the effect of pressure drop in spouted beds, plots of pressure drop vs. air flow rate were prepared (Figures 7 and 8)from data presented in Tables 6 and 17.

As the gas flow rate increases the pressure drop increases because of friction through the bed until the point of maximum

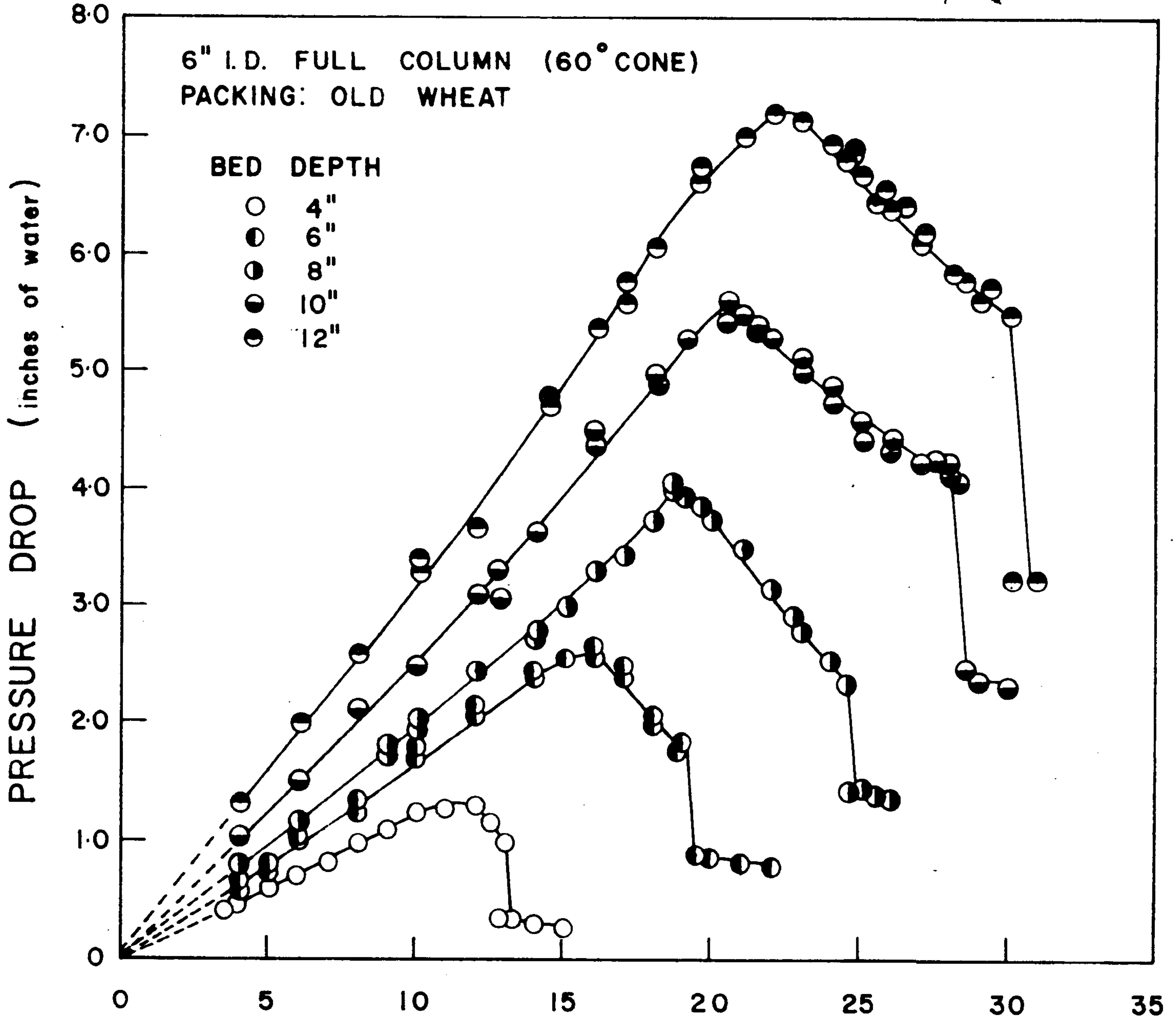

FIG. 7 PRESSURE DROP vs AIR FLOW RATE

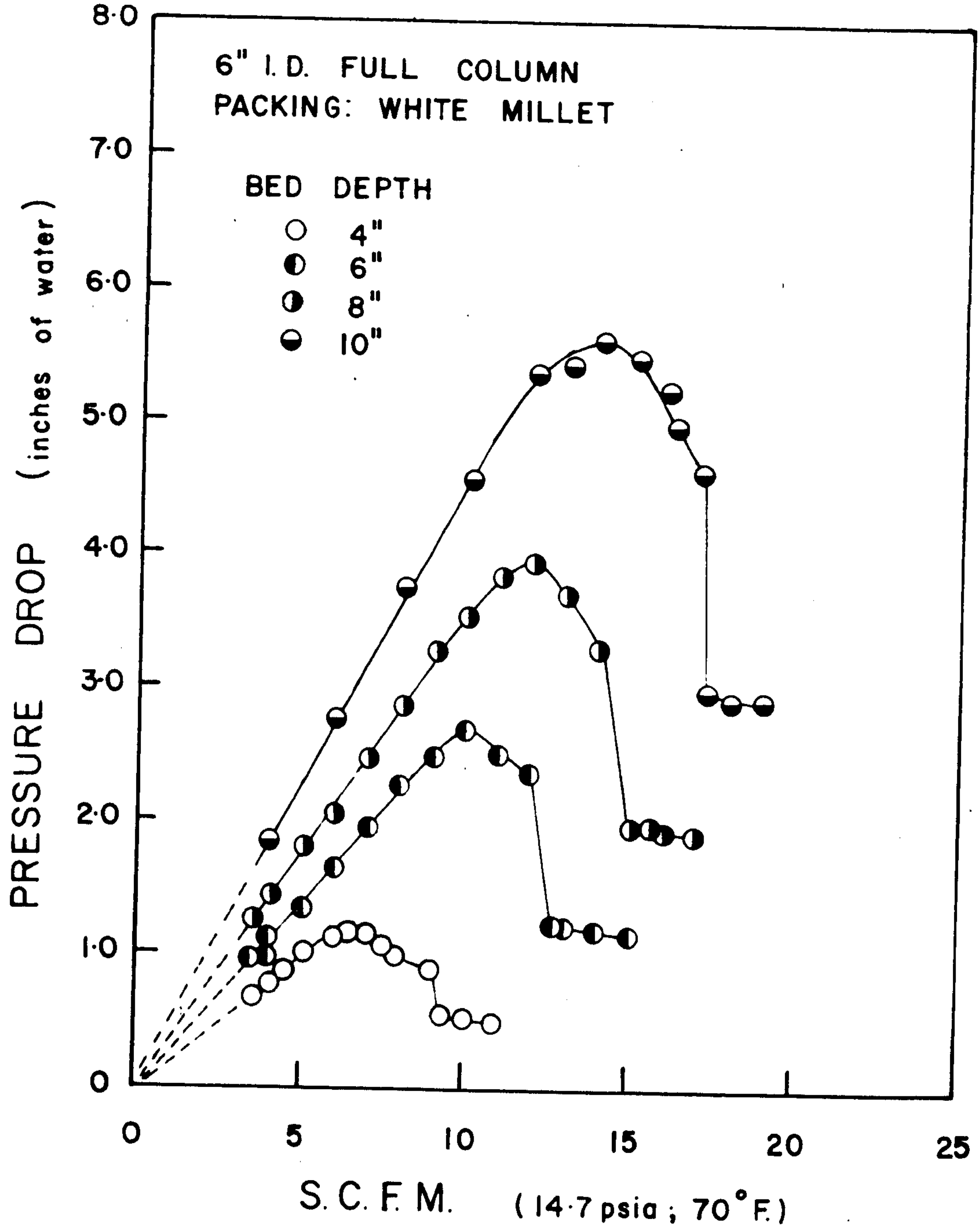

FIG. 8 PRESSURE DROP vs AIR FLOW RATE

pressure drop is reached. This section of the curve represents the flow of the fluid stream through a packed bed. Deviations from linearity prior to the point of maximum pressure drop are small and have not been taken into account.

At the point of maximum pressure drop, the internal spout has experienced a considerable development, whereas the bed is just beginning to expand (Fig. 9). Further increase in the gas flow rate beyond this point will bring about a decrease in pressure drop and an increase in the height of the bed until a sudden and sharp decrease in pressure drop will indicate that the spout has broken through the top of the bed (Figure 10).

The shape of the pressure drop curves at various bed depths is similar. The points of maximum pressure drop (ΔP_M) and pressure drop at spouting (ΔP_s) are easily distinguished from other points along the curve.

Unreliable values for pressure drop in the bed were obtained with a pressure tap located below the orifice plate. Small pressure drops in the bed are completely masked by the pressure drops through the orifice.

Pressure drop data obtained with the pressure tap located above the orifice plate was easily reproduced. A similar technique for measuring pressure drops in fluidized beds was used by Wilhelm and Kwauk (18).

Maximum pressure drop

A plot of the logarithm of the maximum pressure drop for

Fig. 9.- Internal spout at the point of maximum pressure drop

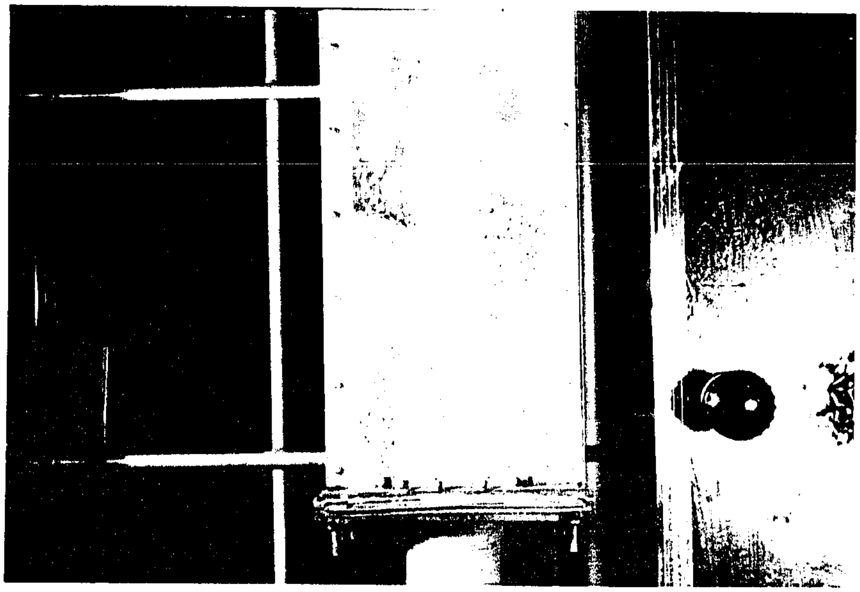

Fig. 10.- Internal spout has broken up through the top of the bed

different packings and bed depths against the logarithm of the modified Reynolds number produced a series of straight lines with slopesof unity (Figure 11), and thus

$$\frac{\Delta P_M}{L} \approx \frac{G\ D_p}{\mu} \tag{26}$$

Straight lines with slopes of unity were also obtained when pressure drops in the packed bed region were plotted against Reynolds number (Figure 12).

Pressure drop data from Figure (11) at Reynolds number 90 and modified by introducing the shape factor was corrected to 40% voids (Table 20) and plotted against respective particle diameters (Figure 13). The slope of the straight line is equal to -3.0, indicating that

$$\frac{\Delta P_M}{L} \approx \frac{1}{D_p^3} \tag{27}$$

Insofar, as the evidence of pressure drop is concerned the behaviour of the spouted bed up to the point of maximum pressure drop is similar to that of a packed bed with viscous flow.

A general correlation covering all the variables was not developed experimentally because derivation of relationships such as pressure drop versus fluid density and pressure drop versus fluid viscosity were beyond the scope of the present work.

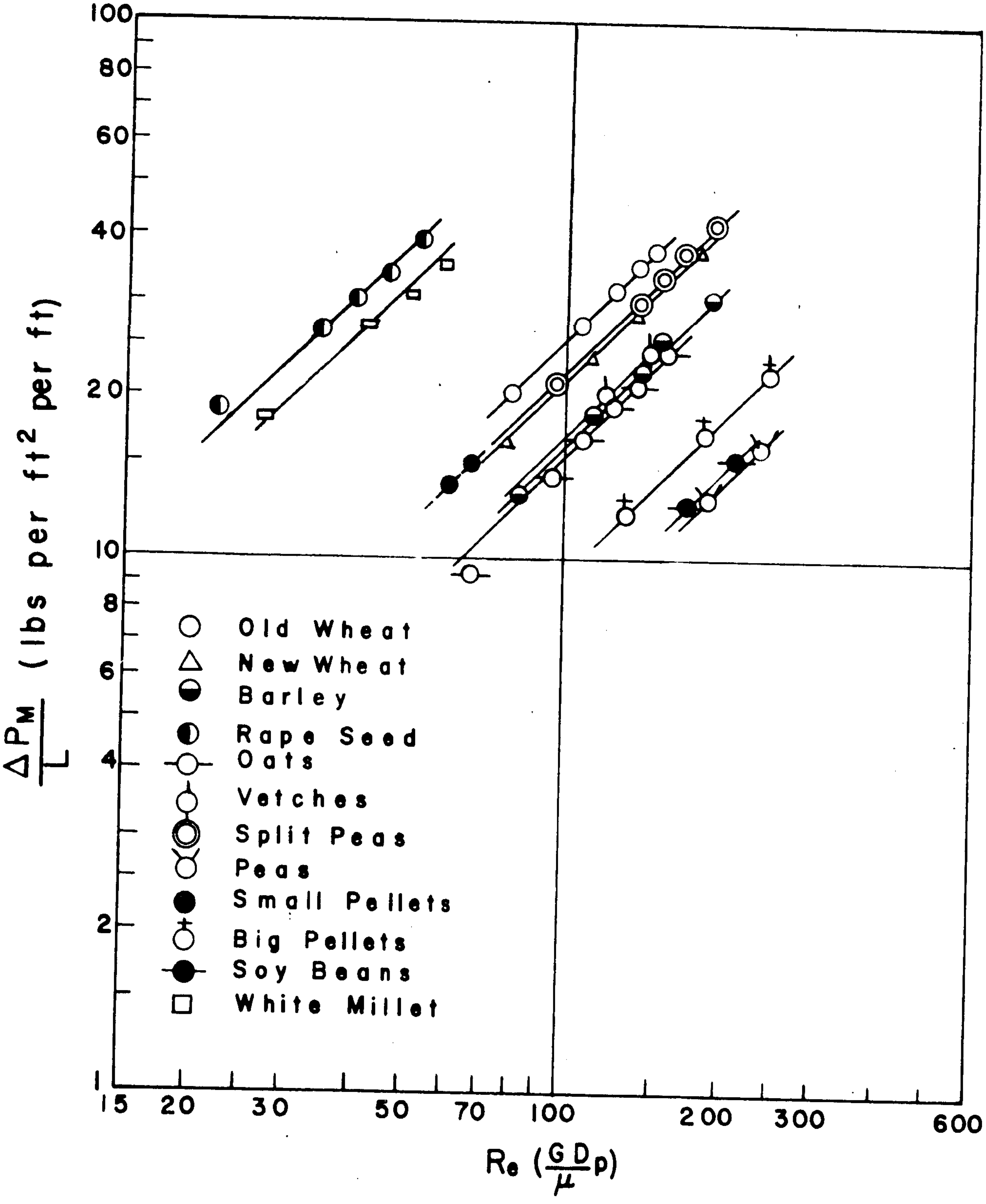

Fig. 11 MAXIMUM PRESSURE DROP

VS MODIFIED REYNOLDS NUMBER

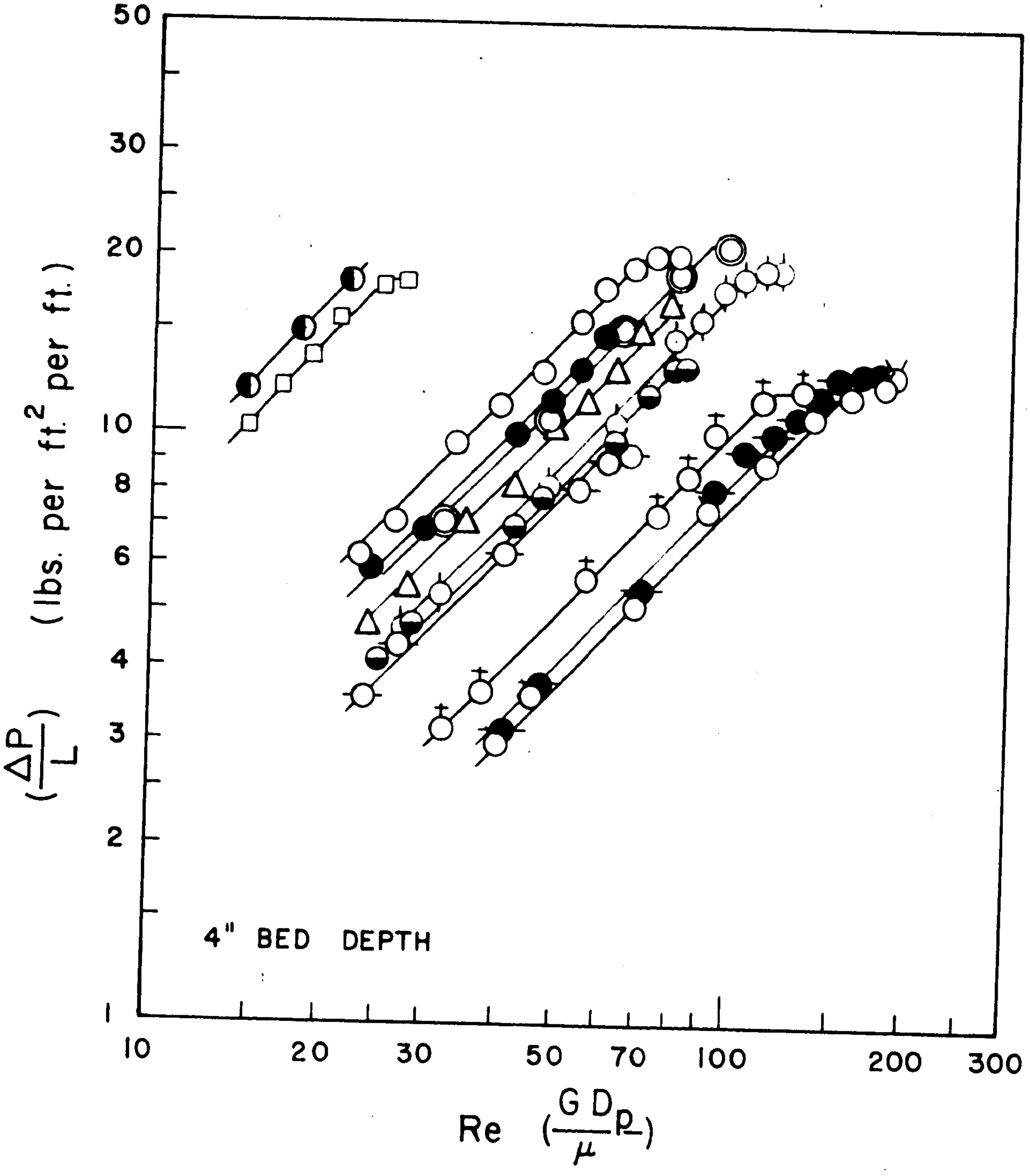

FIG. 12 PRESSURE DROP vs MODIFIED REYNOLDS NUMBER

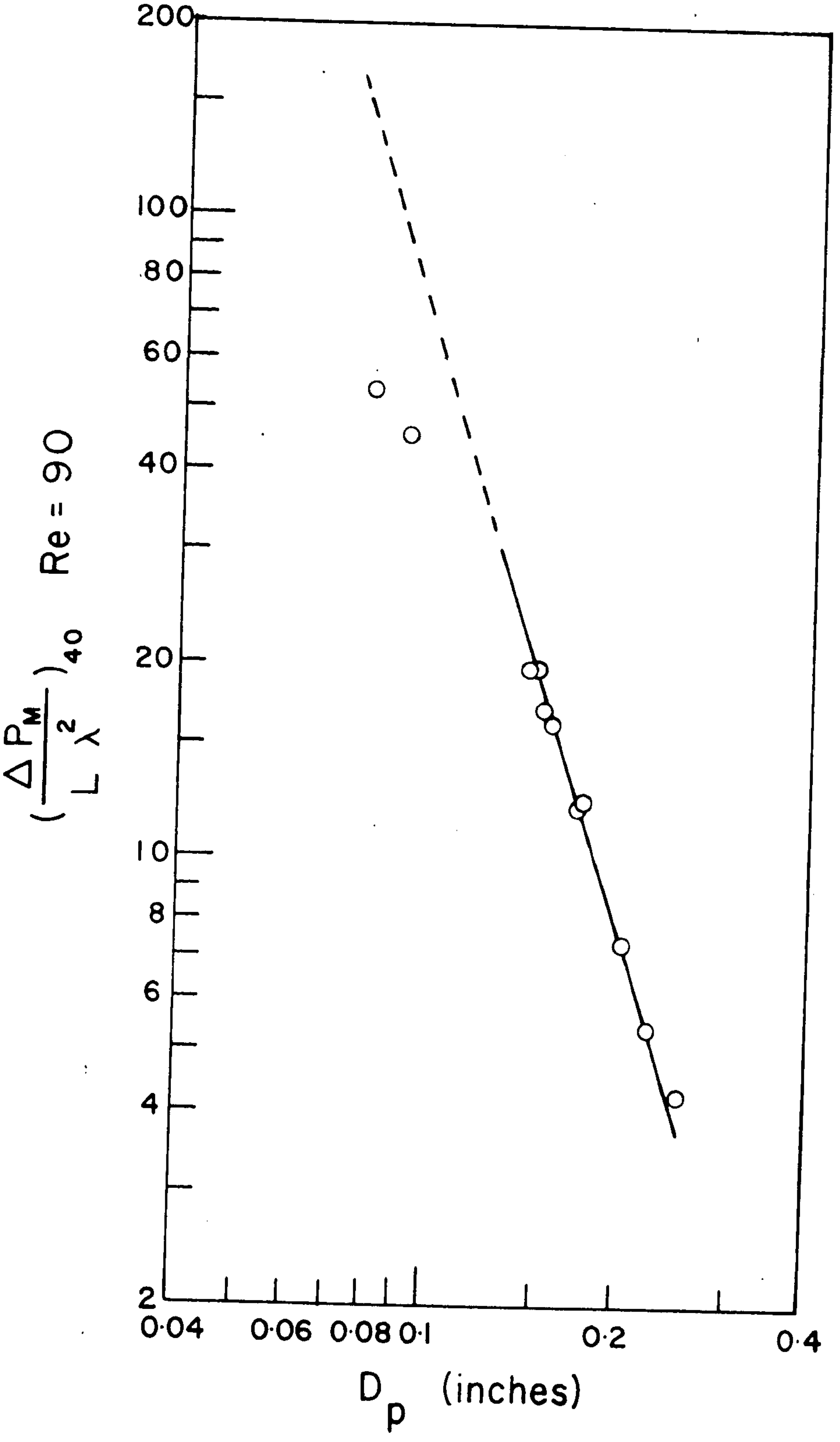

FIG. 13 MAXIMUM PRESSURE DROP
vs PARTICLE DIAMETER

The value of $n = 1$ was substituted in the general equation (18), and the following correlation was obtained.

$$\frac{\Delta P_M}{L} = \frac{K\, G\, \lambda^2\, (1-\delta)^2}{D_p^2\, \rho_f\, g_c\, \delta^3}$$

The physical characteristics of the packings, the fluid properties and the data on maximum pressure drop for the six inch diameter column with 60° degree cone and the six inch diameter split column (Tables 6-18)made possible the evaluation of K (Table 2).

The values of K for rape seed and white millet are considerably lower than the values for the rest of the packings. Small pellets also present a low value for K.

The six inch diameter column with flat bottom produced low values for pressure drop, whenever small bed depths were tested. This effect could indicate a distortion of the pattern of flow in the bed due to the "dead section" of packing formed at the bottom of the column. With increasing bed depths; this dead section of packing gradually becomes insignificant in relation to the total amount of packing material.

Spouting Point

Graphical presentation of the pressure drop data at spouting (tables 6-17,19) in the form of log $\Delta P_s / L$ vs. log Re may be observed in Figures 14 and 15.

Table 2

CONSTANT K

PACKED BED REGION

PACKINGS	6" column 60° cone angle L (in.)	K	6" split column L (in.)	K
OLD WHEAT	4-12	1038.1	4-20	915.5
NEW WHEAT	4-12	1059.7	4-16	995.6
BARLEY	4-12	1105.4	4-16	1109.6
RAPE SEED	4-12	515.0	-	-
OATS	4-14	1168.9	4-16	1099.3
VETCHES	4- 5.5	1093.2	4-10	923.8
SPLIT PEAS	4- 8.0	1218.0	4-20	1010.4
PEAS	4- 5.0	1127.0	4- 7	1025.6
SMALL PELLETS	4- 4.85	758.0	-	-
BIG PELLETS	4- 8.0	1113.6	4-10	956.0
SOY BEANS	4- 5.5	1239.0	4- 8	1116.1
WHITE MILLET	4-10	611.8	4-22	516.2

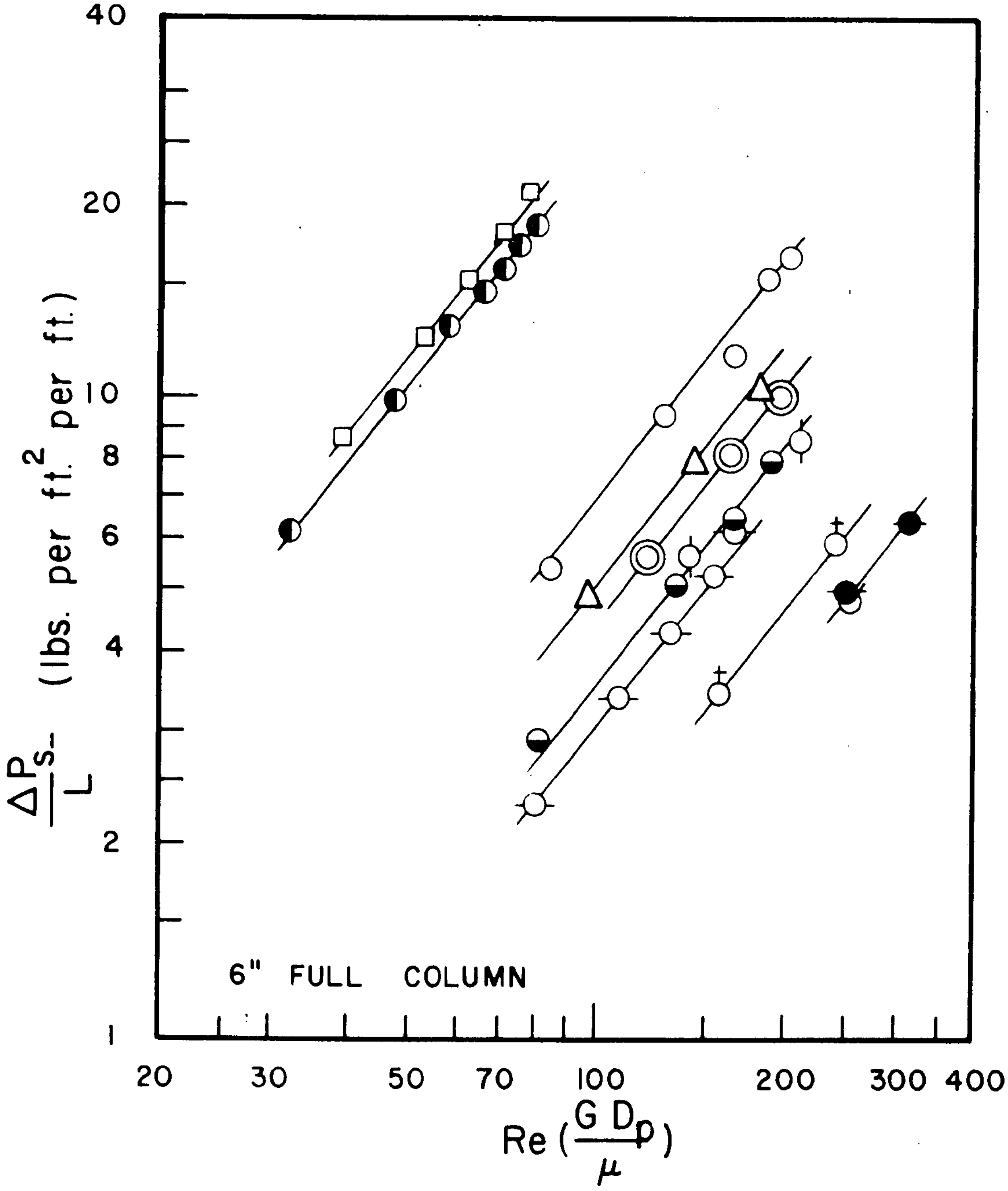

FIG. 14 PRESSURE DROP AT THE SPOUTING POINT vs MODIFIED REYNOLDS NUMBER

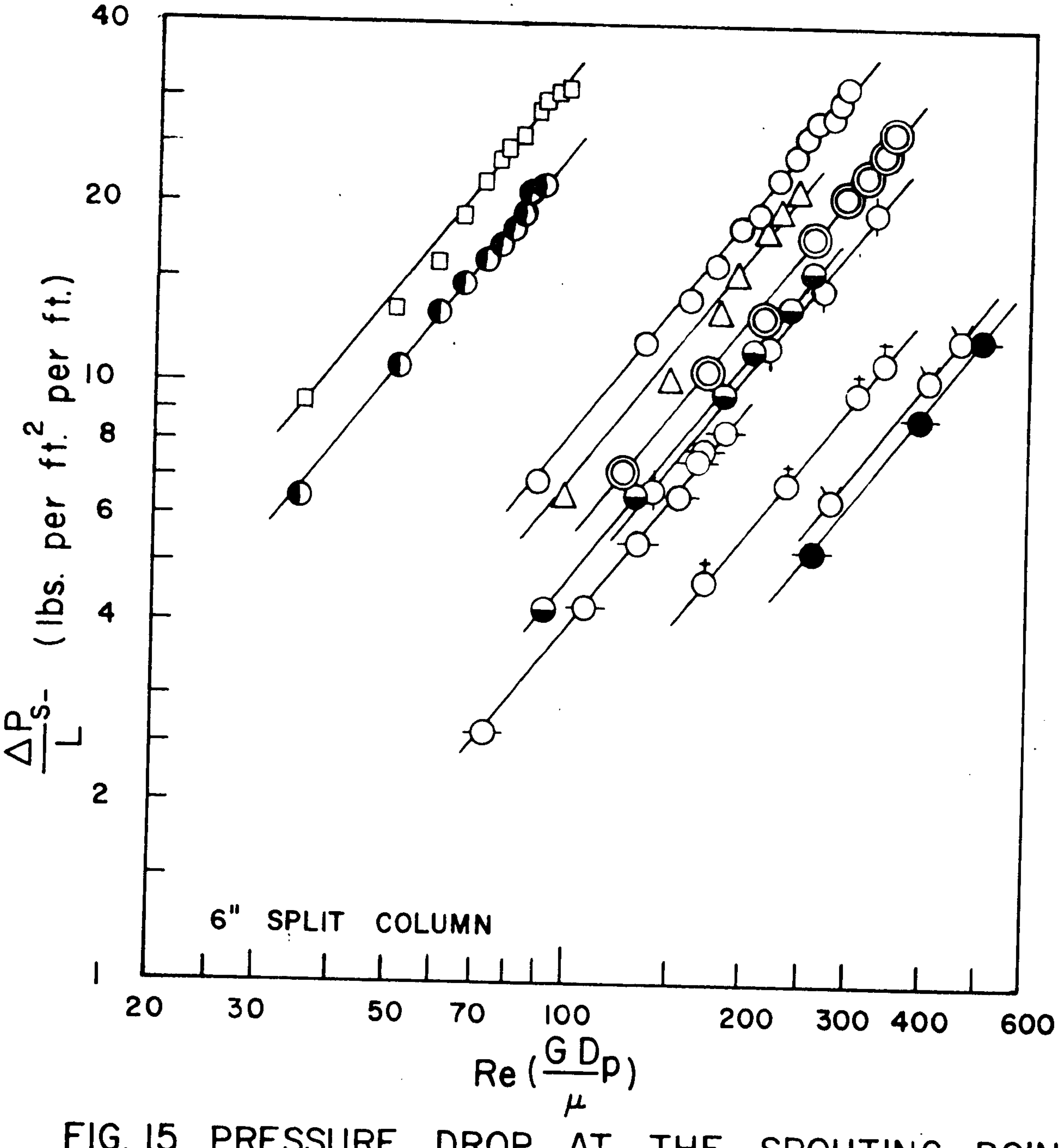

FIG. 15 PRESSURE DROP AT THE SPOUTING POINT vs MODIFIED REYNOLDS NUMBER

Straight lines of slope of 1.25 for different packings indicate the variation of pressure drop with the gas flow rate, hence

$$\frac{\Delta P_s}{L} \approx \left(\frac{G \quad D_p}{\mu}\right)^{1.25} \qquad (28)$$

A straight line with slope of -3.0 (Figure 16) shows the effect of particle diameter on pressure drop. The 6 inch diameter column and the six inch diameter split column behave similarly.

Pressure drop versus Reynolds number relationship characterized for n = 1.25 indicates that transitional flow exists at the spouting point, within the range of conditions studied.

By substitution of n = 1.25 in the general equation (18), the following correlation is obtained:

$$\frac{\Delta P_s}{L} = K\,G^{1.25}\,\frac{\mu^{0.75}}{g_c\,\rho_f}\left(\frac{\lambda}{D_p}\right)^{1.75}\frac{(1-\delta)^{1.75}}{\delta^{3}} \qquad (29)$$

Calculated values of K are presented in Table 3. Although white millet seed behaved as most of the packings, pressure drop data for rape seed packing deviate widely from them.

Stage Spouting

The result of the investigation on stage spouting presented in Tables 4 and 5 indicates that considerable reductions in the necessary amount of air to spout a certain bed depth is

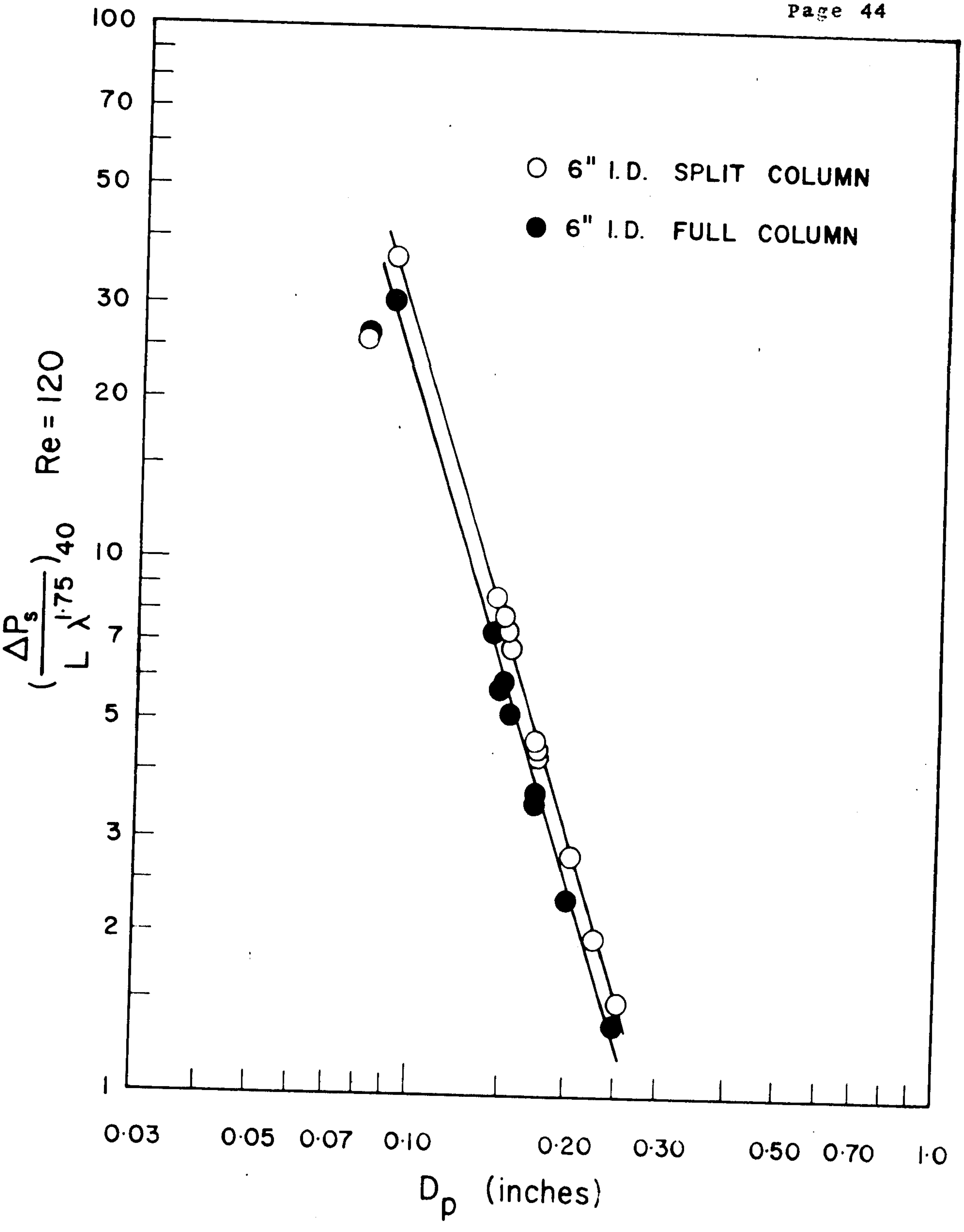

FIG. 16 PRESSURE DROP AT THE SPOUTING POINT vs PARTICLE DIAMETER

Table 3

CONSTANT K

TRANSITIONAL FLOW

	6" column 60° cone angle		6" split column	
PACKINGS	L (in.)	K	L (in.)	K
OLD WHEAT	4-12	78.1	4-28	89.9
NEW WHEAT	4-10	74.8	4-16	96.5
BARLEY	4-10	73.7	4-18	90.0
RAPE SEED	4-16	49.9	4-22	47.6
OATS	4-12	71.3	4-16	85.0
VETCHES	4- 5.5	67.7	4-10	83.7
SPLIT PEAS	4- 6.75	67.8	4-18	84.8
PEAS	4	72.6	4- 7	81.8
SMALL PELLETS	4	72.1	4- 5	58.5
BIG PELLETS	4- 6	71.3	4-10	79.5
SOY BEANS	4- 5.5	73.1	4- 8	80.0
WHITE MILLET SEED	4-12	78.2	4-26	88.0

Table 4

AIR FLOW REQUIRED (SCFM) FOR SPOUTING OLD WHEAT PACKING IN A STAGE SPOUTING UNIT.

L = 4" in each stage

STAGE NUMBER (FROM BOTTOM TO TOP)

	1	2	3	4
SINGLE COLUMN	13.4	-	-	-
TWO STAGE UNIT (second stage: empty)	14.0	-	-	-
TWO STAGE UNIT	14.3 (1.85)	13.7	-	-
THREE STAGE UNIT	15.0 (3.75)	14.5 (1.85)	14.0	-
FOUR STAGE UNIT	16.0 (5.90)	15.0 (3.75)	15.0 (1.85)	14.5

L = 6" in each stage

STAGE NUMBER (FROM BOTTOM TO TOP)

	1	2	3
SINGLE COLUMN	21.0	-	-
TWO STAGE UNIT (second stage: empty)	23.2	-	-
TWO STAGE UNIT	23.6 (4.45)	21.0	-
THREE STAGE UNIT	26.0 (5.25)	23.0	22.5

In brackets: static pressures -inches of mercury-.

Table 5

STAGE SPOUTING

AIR FLOW RATE AT SPOUTING (S.C.F.M.)

PACKING MATERIAL: OLD WHEAT

L (in.) (1)	Single unit (2)	L=4" in each stage (3)	L=6" in each stage (4)	% $\frac{(2)-(3)}{(2)}$	% $\frac{(2)-(4)}{(2)}$
4	13.4	13.4	-	-	-
6	21.0	-	21.0	-	-
8	27.3	14.3	-	47.6	-
12.0	30.5	15.0	23.6	50.8	22.6
16.0	34.3	16.0	-	53.8	-
18.0	36.3	-	26.0	-	28.4

achieved when using several stages instead of one (Figure 17). However, as the bed depth is increased in each stage in order to make up for the depth of a single column bed the reduction of air for spouting tends to be lessen due to the fact that mass velocity at spouting varies exponentially with respect to bed depth.

When the air inlet orifices were provided with screens in order to keep constant levels in each stage, the particles of wheat carried upwards by the spout had the tendency to plug the screens causing a constant increase in the static pressure of each stage. It was observed that static pressures ranging from seven to eight pounds per square inch brought complete collapse to the spouts. This static pressure could create a limit to the number of stages that can be spout in a stage spouting unit.

With extrapolation of the straight lines in Figure (18) to about 14 inches of mercury a limited number of stages is obtained as follows:

Bed depth equal to 4 inches . . . . 6 stages
Bed depth equal to 6 inches . . . . 4 stages

The total of twenty-four inches, in bed depth, is approximately equal to the limiting spoutable bed depth of old wheat packing in a single column.

Transfer of material from one stage to the next above was obtained when the screens were removed from the air inlet orifices. A countercurrent flow of solids was also established in a two stage spouting unit.

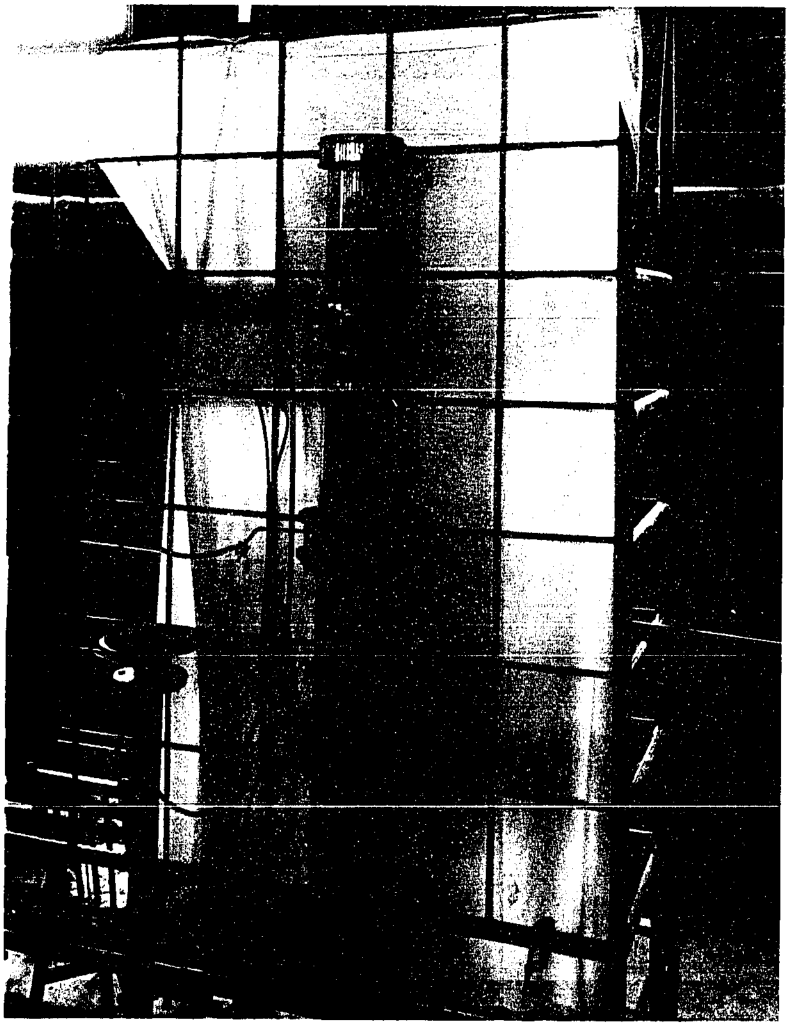

Fig 17.- Stage spouting unit in operation

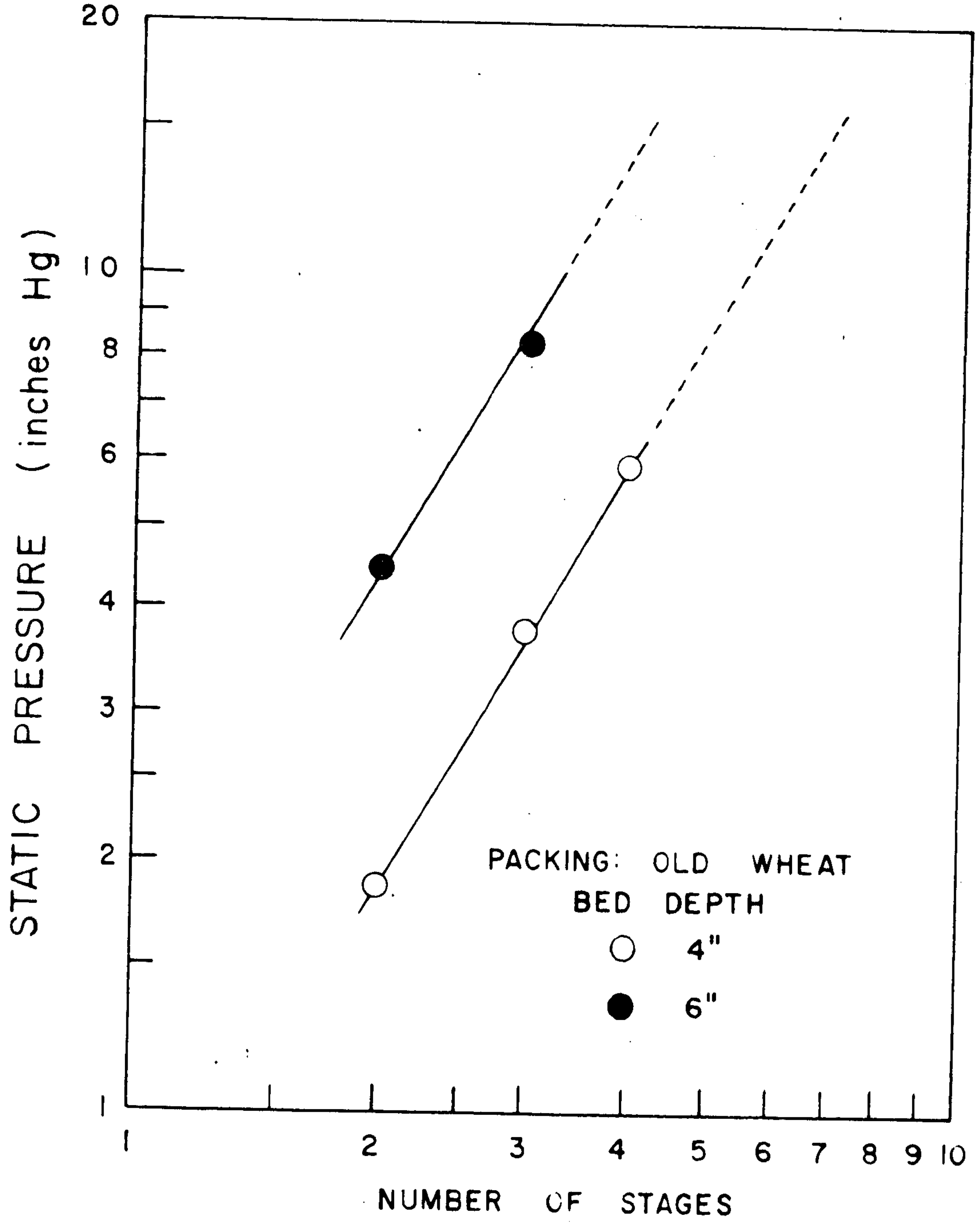

FIG. 18 STATIC PRESSURE IN THE FIRST STAGE OF A STAGEWISE SPOUTING UNIT

CONCLUSIONS

1.- The general equation for pressure drop in packed beds (Equation 18) can be applied to the study of pressure drop in spouted beds.

2.- Variations of the pressure drop in spouted beds up to its maximum value represent the flow of fluid through packed beds. In this work the laminar flow condition is covered. The following equation has been derived in the present work:

$$\frac{\Delta P}{L} = \frac{1120\, G \mu \lambda^2 \ (1-\delta)^2}{D_p^{\,2}\, \rho_f \ \ g_c \delta^3} \ ;$$

for the six inch diameter column with sixty degree cone angle.

The average value of K equals to 1120 does not hold for packings such as rape seed, white millet and small pellets of polyethylene.

3.- The result of the investigation on pressure drop at spouting indicates that transitional flow prevails at this point. Data have been correlated as follows:

$$\frac{\Delta P}{L} = 74\, G^{1.25} \frac{\mu^{0.75}}{g_c \ \rho_f} \left(\frac{\lambda}{D_p}\right)^{1.75} \frac{(1-\delta)^{1.75}}{\delta^{3}}$$

for the six inch diameter column with sixty degree cone angle.

4.- The behaviour of the spouted bed presents some similarities to the behaviour of a channel bed in fluidization.

5.- Preliminary investigation on stage spouting shows that when several stages are used instead of one a substantial decrease in the air flow rate for spouting a certain bed depth is achieved.

VIII

RECOMMENDATIONS

1.- A study of the change of porosity in the spouted bed would throw more light into the insight of this technique.

2.- Pressure drop measurements in the six inch diameter column varying the air inlet orifice and the cone angle should be taken in order to determine the effect of these variables on the correlations derived in this work.

3.- It would be most useful to conduct a study on pressure drop in spouted beds using columns of different diameters. The result of this investigation would show the effect of (D_p/d_c) on spouting.

4.- An investigation on stage spouting aimed to determine the maximum number of stages for a certain packing and for a certain stage bed depth should be conducted as a continuance of this work.

5.- It would also be very useful to continue the study on countercurrent flow of solids in a stage spouting unit.

IX

NOMENCLATURE

A	total cross sectional area of bed, sq.ft.
D_p	diameter of the equivalent volume sphere of a packing particle, in.
G	mass velocity of fluid flowing, based on cross sectional area of column, lbs/sq.ft. x hr.
K_1	constant of permeability, dependent upon the nature of the bed, cu. ft./(sec)(sec).
K_2	constant, lbs./sec.
L	length of bed, ft.
M	number of packing particles per gram
N	number of particles in the spout increment dl
P	gauge pressure 14.7 p.s.i.a.
P_o	pressure at standard conditions, p.s.i.a.
R_e	modified Reynolds number
S	surface area of particle of arbitrary shape, sq.ft.
V	volume of fluid flowing through the bed, cu.ft.
V_i	inlet air velocity, ft/sec.
V_{im}	inlet air velocity, minimum spouting, ft./sec.
V_p	particle velocity in the spout, ft/sec.
T	working temperature, ^oR
T_o	temperature at standard conditions, ^oR
W	solids turnover, lbs./sec.
X_D	channeling factor
a	surface area of particles per unit volume of packed bed, sq.ft./cu. ft.

a_p	surface area per unit packed space of spheres of equal volume, sq.ft/cu.ft.
d_c	column diameter, inches
d_i	air inlet diameter, inches
d_L	incremental height of bed, ft.
d_p	particle diameter, inches
f	function of
g_c	conversion factor, 4.17×10^8 ft./hr.^{2}
n	slope of the lines when plotting P/L vs. Re
n_1	number of effective collisions per second per sq.ft. of interfacial area
q	flow of air
	Subscripts are as follows:
	m metered
	s at standard conditions
t	time, sec.
v	velocity of the fluid based on total cross sectional area, ft./sec.
v_p	volume of a packing particle
w	number of particles transferred across the interface
δ	bed voidage
ΔP	pressure drop across entire bed (lbs./ft.^{2})
	Subscripts are as follows:
	D minimum for channeling
	M maximum
	S at spouting

λ	$1/\phi_s$ particle shape factor
λ_c	shape factor calculated from Carman's equation
μ	fluid viscosity, lbs./sec. x ft. or lbs./hr. x ft.
ρ	density, lbs./cu. ft.
	Subscripts are as follows:
	b bulk
	bs bulk, after spouting
	s solids
	f fluid
ϕ_s	Carman's shape factor
ψ	Sphericity = $1/\lambda$

X

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XI

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XII

APPENDIX

The appendix of this thesis contains:

1. The calibration curves for empty columns
2. The pressure drop data for the six inch diameter column with 60° cone and for the six inch diameter split column
3. The theoretical derivation of the equation for fluid flow through packed beds.

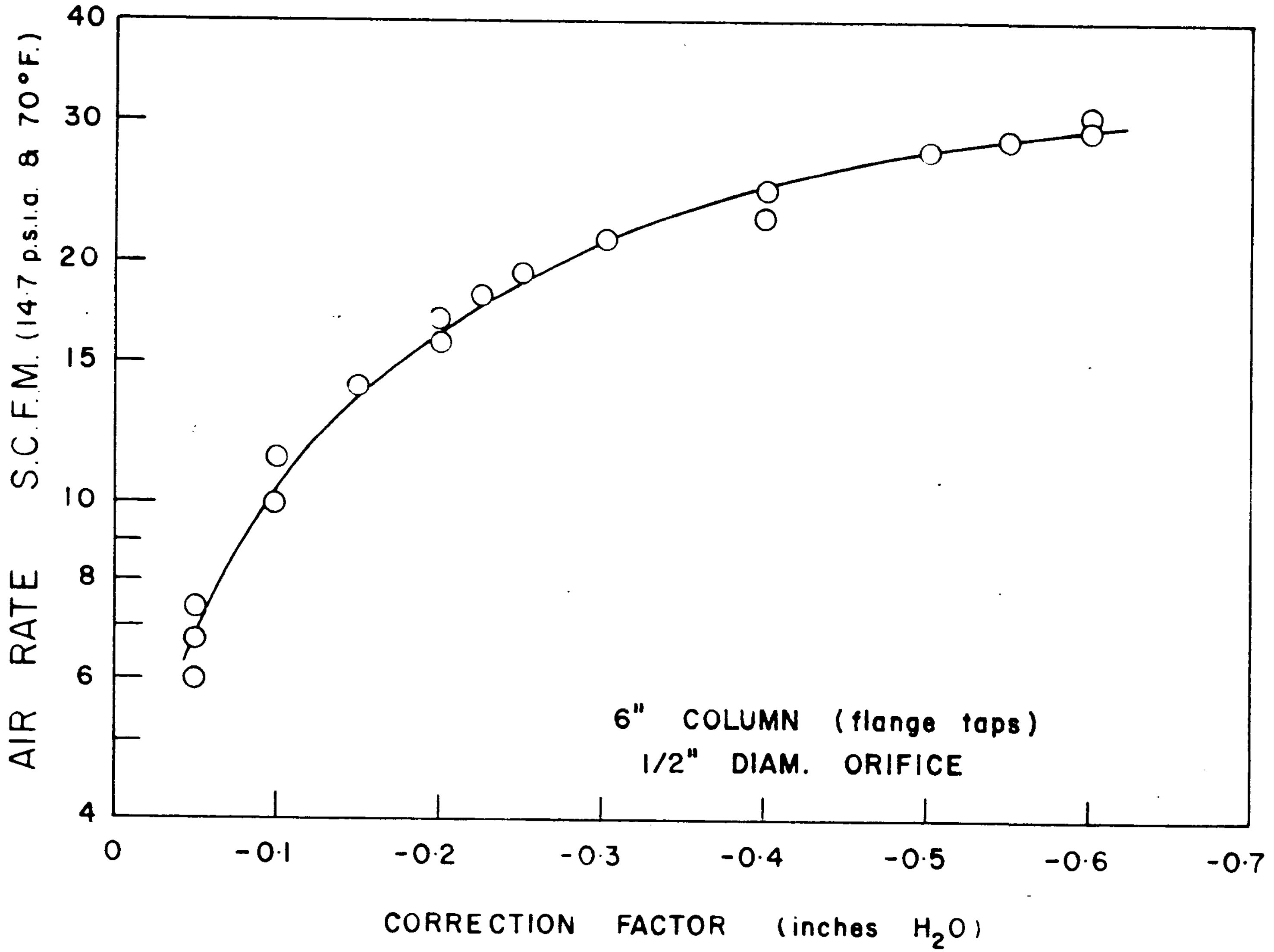

FIG. 19 CORRECTION FACTOR vs AIR RATE

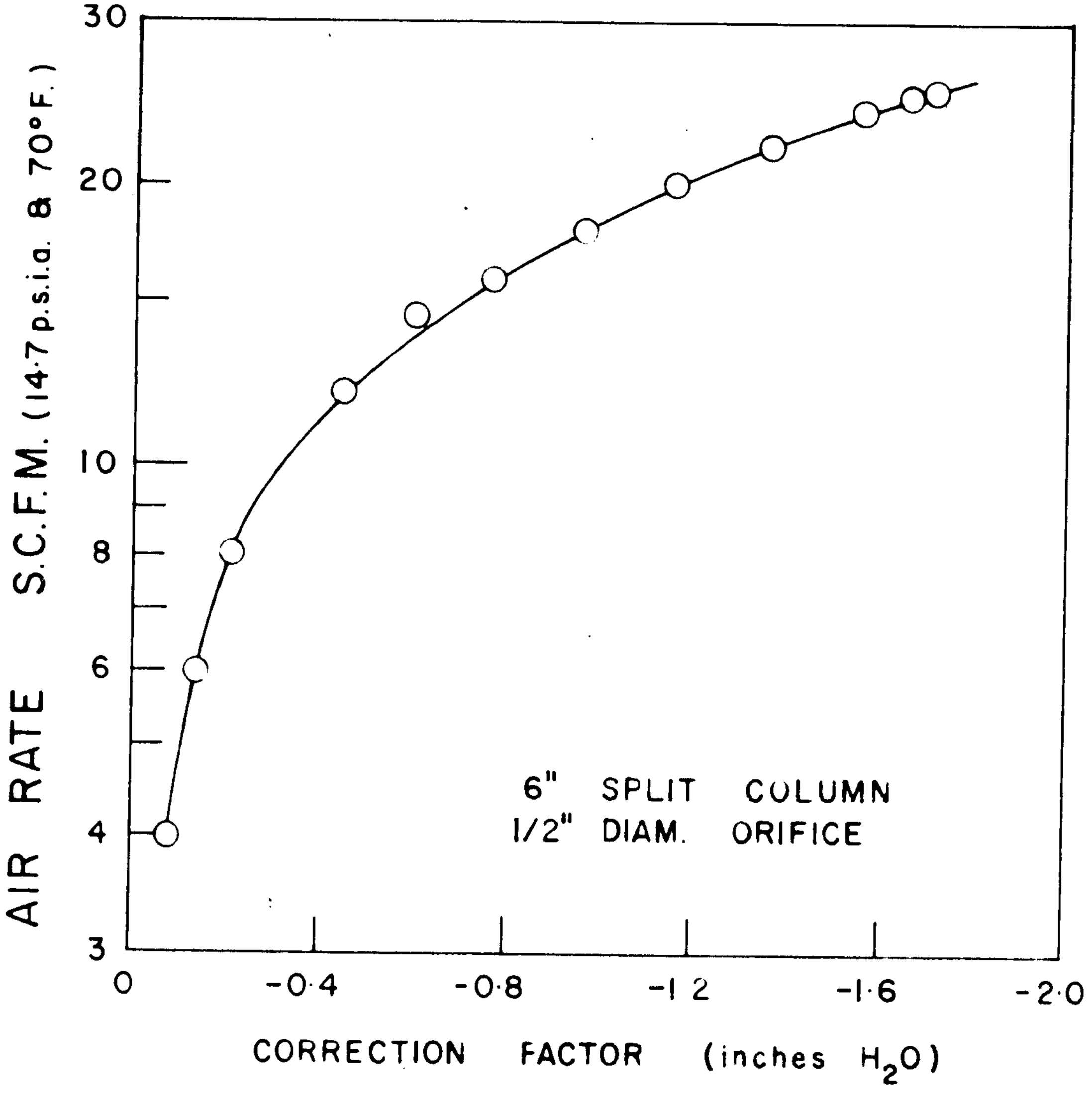

FIG. 20 CORRECTION FACTOR vs AIR RATE

TABLE 6

OLD WHEAT

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=8"	L=10"	L=12"
3.5	83.7	22.6	6.24	-	-	-	-
4.0	95.6	25.8	7.02	6.95	6.25	6.70	7.08
5.0	119.5	32.3	9.66	8.50	-	-	-
6.0	143.4	38.7	11.22	10.90	9.15	9.50	10.48
7.0	167.3	45.2	12.80	-	-	-	-
8.0	191.2	51.6	15.6	13.0	10.53	13.40	13.90
9.0	215.1	58.1	17.3	-	14.22	-	-
10.0	239.0	64.5	19.35	17.7	15.90	15.60	17.80
11.0	262.9	71.0	20.1	-	-	-	-
12.0	286.8	77.5	20.3 M	22.5	19.20	19.50	19.20
12.5	298.8	80.7	17.94	-	-	-	-
12.8	306.0	82.6	5.46 S	-	-	-	-
14.0	334.6	90.3	4.80	25.5	21.45	22.80	-
14.5	346.6	93.6	-		-	-	24.96
15.0	358.5	96.8	4.40	26.5	23.40	-	-
16.0	382.4	103.3	-	27.6 M	25.75	27.50	28.10
17.0	406.3	109.7	-	25.0	26.90	-	30.16
18.0	430.2	116.2	-	20.80	29.25	31.20	31.72
18.6	444.5	120.0	-	-	31.80 M	-	-
19.0	454.1	122.6	-	16.60	30.80	33.10	-
19.5	466.1	125.9	-	9.50 S	-	-	34.60
20.0	478.0	129.1	-	9.40	29.30	-	-
20.5	490.0	132.3	-	-	-	35.00 M	-

TABLE 6 (continued)

OLD WHEAT

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=8"	L=10"	L=12"
21.0	501.9	135.5	-	8.80	27.30	34.30	36.66
21.5	513.9	138.8	-	-	-	33.70	-
22.0	525.8	142.0	-	8.6	24.60	33.10	37.44 M
23.0	549.7	148.4	-	-	21.85	32.20	37.20
24.0	573.6	154.9	-	-	19.90	31.20	36.14
24.5	585.6	158.7	-	-	18.33	-	-
25.0	597.5	161.3	-	-	11.42 S	29.0	34.84
25.5	609.5	164.6	-	-	11.00	-	-
26.0	621.4	167.8	-	-	10.60	27.1	33.20
27.0	645.3	174.2	-	-	-	26.5	31.72
28.0	669.2	180.7	-	-	-	25.9	30.42
28.2	674.0	182.0	-	-	-	25.6	-
28.5	681.2	184.0	-	-	-	15.6 S	-
29.0	693.1	187.1	-	-	-	15.0	29.40
30.0	717.0	193.6	-	-	-	14.7	28.60
30.5	729.0	196.8	-	-	-	-	16.90 S

TABLE 7

NEW WHEAT

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=8"	L=10"	L=12"
3.5	83.7	23.7	4.68	5.02	-	-	-
3.8	90.8	25.7	-	-	5.82	-	-
4.0	95.6	27.1	5.46	5.66	-	-	-
4.4	105.2	29.8	-	-	6.55	-	-
5.0	119.5	33.8	7.02	-	-	-	-
6.0	143.4	40.6	8.10	8.32	-	-	-
6.6	155.7	44.10	-	-	10.11	-	-
7.0	167.3	47.30	10.14	-	-	-	-
8.0	191.2	54.10	11.22	11.64	-	-	-
8.8	210.3	59.5	-	-	12.72	-	-
9.0	215.1	60.9	12.96	-	-	-	-
10.0	239.0	67.64	14.82	15.60	-	-	-
11.0	262.9	74.4	16.53 M	-	16.85	-	-
12.0	286.8	81.2	15.30	18.72	-	-	-
13.0	310.7	87.9	13.42	-	-	-	-
13.1	313.1	88.6	-	-	21.30	-	-
13.5	322.7	91.3	12.48	-	-	-	-
14.0	334.6	94.7	4.98 S	21.94	-	-	-
15.0	358.5	101.5	4.37	-	-	-	-
15.3	365.7	103.5	-	-	25.90	-	-
16.0	382.4	108.2	4.37	23.50 M	-	-	-
17.0	406.3	115.0	-	22.68	-	-	-
17.5	418.3	118.4	-	-	27.70	-	-

Table 7 (continued)

NEW WHEAT

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=8"	L=10"	L=12"
18.0	430.2	121.80	-	21.42	-	-	-
19.0	454.1	128.5	-	20.60	-	-	-
19.7	470.8	133.2	-	-	28.22 M	-	-
20.0	478.0	135.3	-	18.20	-	-	-
20.8	497.1	140.7	-	-	28.10	-	-
20.9	499.5	141.4	-	8.0 S	-	-	-
21.9	523.4	148.1	-	-	27.70	-	-
22.0	525.8	148.8	-	7.6	-	-	-
23.0	549.7	155.6	-	7.28	26.90	-	-
23.3	556.9	157.6	-	-	-	34.92 M	-
24.1	576.0	163.0	-	-	26.10	-	-
25.2	602.3	170.5	-	-	25.50	-	-
25.4	605.9	171.5	-	-	-	-	37.18 M
25.7	614.2	173.8	-	-	23.40	-	-
26.0	621.4	175.9	-	-	23.40	-	-
26.2	626.2	177.2	-	-	10.87 S	-	-
28.5	681.2	193.0	-	-	-	12.4 S	-

Table 8

BARLEY

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=8"	L=10"	L=12"
3.5	83.7	24.3	4.15	3.55	-	-	-
4.0	95.6	27.7	4.75	4.16	-	-	-
4.4	105.2	30.5	-	-	5.17	5.13	-
6.0	143.4	41.6	6.0	5.52	-	-	-
6.6	157.8	45.8	7.8	-	7.16	7.85	-
8.0	191.2	55.5	-	8.31	-	-	-
8.8	210.3	61.0	9.8	-	9.60	9.73	-
10.0	239.0	69.3	11.8	11.24	-	-	-
11.0	262.9	76.3	13.1 M	-	12.56	13.36	-
11.5	274.9	79.7	2.94 S	-	-	-	-
12.0	286.8	83.2	2.65	13.32	-	-	-
13.0	310.7	90.1	2.50	13.94	-	-	-
13.1	313.1	90.8	-	-	15.60	16.66	-
14.0	334.6	97.0	-	15.40	-	-	-
15.0	358.5	104.0	-	16.44	-	-	-
15.3	365.7	106.1	-	-	19.58	20.59	-
16.0	382.4	110.9	-	18.20 M	-	-	-
17.0	406.3	117.8	-	16.64	-	-	-
17.5	418.3	121.3	-	-	21.84	22.46	-
18.0	430.2	124.8	-	14.57	-	-	-
18.5	442.2	128.2	-	13.00	-	-	-
18.6	444.5	128.9	-	-	22.16	-	-

Table 8 (continued)

BARLEY

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=8"	L=10"	L=12"
19.0	454.1	131.7	-	5.31 S	-	-	-
19.5	466.1	135.2	-	4.68	-	-	-
19.7	470.8	136.5	-	-	22.38 M	25.15	-
20.5	490.0	142.1	-	4.47	-	-	-
20.8	497.1	144.2	-	-	20.51	-	-
21.4	511.5	148.3	-	-	-	25.78 M	-
21.9	523.4	151.8	-	-	19.34	25.27	-
22.5	537.8	156.0	-	-	18.64	-	-
23.0	549.7	159.4	-	-	17.24	24.34	-
23.5	561.7	162.9	-	-	6.72 S	-	-
24.1	576.0	167.0	-	-	-	22.46	-
24.6	588.0	170.5	-	-	6.40	-	-
25.2	602.3	174.7	-	-	6.16	21.03	-
26.3	628.6	182.3	-	-	-	20.59	-
26.6	635.7	184.4	-	-	-	-	30.94 M
26.9	642.9	186.4	-	-	-	8.26 S	-
28.4	694.4	196.9	-	-	-	7.86	
29.4	718.8	203.8	-	-	-	7.74	

Table 9

RAPE SEED

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=8"	L=10"	L=12"	L=14"	L=16"
3.5	83.7	12.7	-	9.25	9.40	9.20	8.62	-	-
4.0	95.6	14.7	11.7	10.58	11.36	11.50	10.20	-	-
5.0	119.5	18.1	14.82	-	-	-	-	-	-
6.0	143.4	21.7	18.24 M	16.06	15.60	16.0	14.58	-	-
7.0	167.3	25.3	17.94	18.0	-	-	-	-	-
8.0	191.2	28.9	16.38	21.55	21.45	19.15	17.42	-	-
8.5	203.2	30.7	14.04	-	-	-	-	-	-
8.8	210.3	31.8	6.24 S	-	-	-	-	-	-
9.5	227.1	34.4	-	26.62 M	-	-	-	-	-
10.0	239.0	36.2	5.93	25.48	28.86	28.50	24.66	-	-
11.0	262.9	39.8	5.77	23.40	30.50 M	-	-	-	-
12.0	286.8	43.4	-	22.36	29.48	31.0	28.34	-	-
12.9	308.3	46.7	-	10.0 S	-	-	-	-	-
13.0	310.7	47.0	-	-	27.53	33.13	31.98	-	-
13.5	322.7	48.8	-	9.67	-	-	-	-	-

Table 9 (continued)

RAPE SEED

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=8"	L=10"	L=12"	L=14"	L=16"
14.0	334.6	50.6	-	9.46	24.96	38.70 M	35.0	-	-
14.5	346.6	52.4	-	-	-	38.06	-	-	-
15.0	358.5	54.2	-	-	23.48	37.44	37.44	-	-
15.7	375.2	56.8	-	-	13.11 S	-	-	-	-
16.0	382.4	57.9	-	-	-	35.57	43.50 M	-	-
16.5	394.4	59.7	-	-	12.71	-	-	-	-
17.0	406.3	61.5	-	-	12.48	31.20	-	-	-
18.0	430.2	65.1	-	-	-	14.72 S	37.80	-	-
19.0	454.1	68.7	-	-	-	14.35	35.30	-	-
19.2	458.8	69.4	-	-	-	-	16.17 S	-	-
20.0	478.0	72.3	-	-	-	-	15.34	-	-
20.4	488.8	74.0	-	-	-	-	-	17.5 S	-
21.0	501.9	75.9	-	-	-	-	15.08	-	-
21.6	516.2	78.1	-	-	-	-	-	-	18.8 S

Table 10

OATS

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=8"	L=10"	L=12"	L=14"
3.5	83.7	23.1	3.60	3.44	3.90	3.88	3.80	-
4.0	95.6	26.4	4.38	4.16	4.43	4.71	4.63	-
6.0	143.4	39.6	6.24	6.04	5.85	6.65	6.60	-
8.0	191.2	52.8	8.10	8.52	8.34	8.23	7.90	-
9.0	215.1	59.4	9.06	-	-	-	-	-
10.0	239.0	66.0	9.36 M	11.02	11.07	11.23	10.71	-
11.0	262.9	72.6	8.73	-	12.48	-	-	-
11.5	274.9	75.9	7.95	-	-	-	-	-
11.85	283.2	78.2	2.50 S	-	-	-	-	-
12.0	286.8	79.2	2.34	12.68	13.65	13.92	13.42	-
13.0	310.7	85.8	2.04	13.94	14.90	15.35	-	-
14.0	334.6	92.4	1.86	14.14 M	16.07	17.10	16.54	-
15.0	358.5	99.0	-	13.84	16.85	18.10	-	-
16.0	382.4	105.5	-	12.48	17.16 M	18.72	17.10	-
16.35	390.8	107.9	-	3.64 S	-	-	-	-
16.5	394.4	108.9	-	3.42	-	-	-	-
17.0	406.3	112.1	-	3.12	16.38	19.0	-	-
17.5	418.3	115.5	-	3.02	-	-	-	-
18.0	430.2	118.7	-	-	15.84	19.40 M	18.8	-
19.0	454.1	125.3	-	-	-	19.03	19.8	-
19.5	466.1	128.6	-	-	4.45 S	-	-	-
20.0	478.0	131.9	-	-	4.29	18.41	21.0 M	-

Table 10 (continued)

OATS

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=8"	L=10"	L=12"	L=14"
21.0	501.9	138.5	-	-	3.98	17.78	20.7	-
22.0	525.8	145.1	-	-	-	16.97	20.38	-
22.1	527.2	145.5	-	-	-	-	-	24.0M
22.5	537.8	148.4	-	-	-	16.72	-	-
22.9	547.3	151.1	-	-	-	5.50 S	-	-
23.0	549.7	151.7	-	-	-	-	19.24	-
23.5	561.7	155.0	-	-	-	5.18	-	-
24.0	573.6	158.3	-	-	-	5.05	18.30	-
24.5	585.6	161.6	-	-	-	-	6.45 S	-
25.0	597.5	164.9	-	-	-	4.68	6.14	-
26.4	631.0	174.2	-	-	-	-	5.98	-

Table 11

VETCHES

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=5.5"
3.5	83.7	27.1	4.68	-
3.9	93.2	30.2	-	4.36
4.0	95.6	31.0	5.31	-
4.4	105.2	34.1	-	4.54
5.5	131.5	42.6	-	6.58
6.0	143.4	46.5	7.80	-
6.6	157.7	51.1	-	7.37
7.7	184.0	59.6	-	8.62
8.0	191.2	62.0	10.44	-
8.8	210.3	68.1	-	10.56
9.9	236.6	76.7	-	12.48
10.0	239.0	77.4	14.82	-
10.5	251.0	81.3	-	13.05
11.0	262.9	85.2	15.75	-
12.0	286.8	92.9	17.64	-
12.6	301.1	97.6	-	15.67
13.0	310.7	100.7	18.57	-
14.0	334.6	108.4	19.02	-
14.7	351.3	113.8	-	19.64
15.0	358.5	116.2	19.20 M	-
16.0	382.4	123.9	18.72	-
16.8	401.5	130.1	-	21.10
17.0	406.3	131.6	15.60	-

Table 11 (continued)

VETCHES

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=5.5"
18.0	430.2	139.4	5.46 S	-
18.5	442.2	143.3	5.46	-
18.9	451.7	146.4	-	24.0 M
19.0	454.1	147.1	5.31	-
20.0	478.0	154.9	5.16	-
21.0	501.9	162.6	-	21.0
23.1	552.1	178.9	-	19.3
25.2	602.3	195.1	-	17.25
26.6	635.7	206.0	-	8.74 S
27.3	652.5	211.4	-	8.29
29.4	702.7	227.7	-	7.94

Table 12

SPLIT PEAS

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=6.75"	L=8"
3.5	83.7	27.43	4.46	5.62	-	-
4.0	95.6	31.33	7.02	6.76	-	-
6.0	143.4	47.0	10.92	10.54	-	-
8.0	191.2	62.7	15.12	12.16	-	-
10.0	239.0	78.3	18.72	17.58	-	-
12.0	286.8	94.0	21.06 M	19.76	-	-
13.0	310.7	101.8	20.13	-	-	-
14.0	334.6	109.7	18.87	25.14	-	-
15.0	358.5	117.5	15.30	-	-	-
15.5	370.0	121.1	5.62 S	-	-	-
15.9	380.0	124.5	5.46	-	-	-
16.0	382.4	125.3	-	26.30	-	-
16.5	394.4	129.2	4.83	-	-	-
17.0	406.3	133.1	4.68	27.88	-	-
17.2	411.1	134.7	-	30.0 M	-	-
18.0	430.2	141.0	-	28.6	-	-
19.0	454.1	148.8	-	26.88	33.20 M	-
20.0	478.0	156.6	-	24.76	-	-
21.0	501.9	164.5	-	8.22 S	-	-
21.1	504.3	165.3	-	-	-	37.5 M
21.5	513.9	168.4	-	7.70	-	-
22.0	525.8	172.3	-	7.70	-	-
23.0	549.7	180.1	-	7.38	-	-
25.4	606.0	198.6	-	-	10.26 S	-
24.0	573.6	188.0	-	7.08	-	-

Table 13

<u>PEAS</u>

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=5"
3.9	93.2	39.6	2.97	2.75
4.4	105.2	44.7	3.60	3.34
6.6	157.7	67.1	5.16	5.0
8.8	210.3	89.4	7.50	6.74
10.5	251.0	106.7	-	8.11
11.0	262.9	111.8	9.06	8.61
12.6	301.1	128.1	-	9.73
13.1	313.1	133.2	10.92	10.36
14.7	351.3	149.4	-	11.23
15.3	365.7	155.5	11.70	-
16.8	401.5	170.8	-	12.85
17.5	418.3	177.9	12.48	13.20
18.0	430.2	183.0	12.96 M	-
18.9	451.7	192.1	-	14.0
19.7	470.8	200.2	12.30	14.5
20.8	497.1	211.4	11.70	-
21.0	501.9	213.5	-	15.0
21.9	523.4	222.6	10.92	16.0
22.5	537.8	228.7	-	16.3 M
23.0	549.7	233.8	8.58	-
24.1	576.0	245.0	7.80	-
24.5	585.6	249.1	5.0 S	-
26.3	628.6	267.3	4.53	-
27.4	654.9	278.5	4.20	-

Table 14

SMALL PELLETS

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=4.85"
3.5	83.7	20.8	4.68	4.95
4.0	95.6	23.7	5.94	5.79
5.0	119.5	29.6	6.87	7.10
6.0	143.4	35.6	7.80	8.36
7.0	167.3	41.5	10.14	9.53
8.0	191.2	47.4	11.40	11.83
9.0	215.1	53.3	12.96	13.76
10.0	239.0	59.3	13.74 M	14.40
11.0	262.9	65.2	12.63	15.00 M
11.6	277.2	68.7	4.68 S	-
12.0	286.8	71.1	4.68	-
13.0	310.7	77.0	4.20	-

Table 15

BIG PELLETS

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=8"
3.5	83.7	31.9	3.12	-	-
3.9	93.2	35.5	-	3.66	-
4.0	95.6	36.4	3.75	-	-
4.4	105.2	40.1	-	3.82	-
6.0	153.4	54.6	5.76	-	-
6.6	157.7	60.1	-	5.50	-
8.0	191.2	72.9	7.32	-	-
8.8	210.3	80.1	-	7.30	-
9.0	215.1	82.0	8.28	-	-
10.0	239.0	91.1	9.18	-	-
11.0	262.9	100.2	-	9.34	-
12.0	286.8	109.3	10.59	-	-
13.1	313.1	119.3	-	10.08	-
14.0	334.6	127.5	12.0 M	-	-
15.0	358.5	136.6	10.92	-	-
15.3	365.7	139.3	-	13.36	-
16.0	382.4	145.7	8.58	-	-
16.4	392.0	149.4	-	13.52	-
17.0	406.3	154.8	3.74 S	-	-
17.5	418.3	159.4	-	15.08	-
18.0	430.2	163.9	3.12	-	-
19.0	454.1	173.0	2.82	-	-

Table 15 (continued)

BIG PELLETS

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=8"
19.7	470.8	179.4	-	17.06 M	-
21.9	523.4	199.4	-	14.56	-
24.1	576.0	219.5	-	11.96	-
25.8	616.6	235.0	-	-	22.08 M
26.0	621.4	236.8	-	6.14 S	-
27.3	652.5	248.6	-	5.62	-
28.4	678.8	258.6	-	5.30	-

Table 16

SOY BEANS

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=5.5"
3.5	83.7	39.6	3.12	-
4.0	95.6	45.2	3.75	3.52
4.6	109.9	52.0	-	3.75
6.0	143.4	67.8	5.46	-
6.8	162.5	76.9	-	6.01
8.0	191.2	90.4	8.10	-
9.0	215.1	101.7	9.51	-
9.1	217.5	102.9	-	8.28
10.0	239.0	113.0	10.14	-
11.0	262.9	124.4	10.92	-
11.4	272.5	128.9	-	10.0
12.0	286.8	135.7	11.30	-
13.0	310.7	147.0	11.54	-
13.7	327.4	154.9	-	11.91
14.0	334.6	158.3	11.85	-
15.0	358.5	169.6	12.00 M	-
16.0	382.4	180.9	11.85	13.96
17.0	406.3	192.2	10.61	-
18.0	430.2	203.5	9.83	-
18.25	436.2	206.3	-	14.65 M
19.0	454.1	214.8	9.05	-
19.4	463.7	219.3	-	14.41

Table 16 (continued)

SOY BEANS

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=5.5"
20.0	478.0	226.1	8.58	-
20.5	490.0	231.8	-	14.19
21.0	501.9	237.4	7.50	-
21.6	516.2	244.2	4.83 S	13.72
22.0	525.8	248.7	4.68	-
22.8	544.9	257.8	-	12.70
23.0	549.7	260.0	4.37	-
23.9	571.2	270.2	-	11.0
25.1	599.9	283.8	-	9.5
27.5	657.3	310.9	-	6.46 S
27.9	666.8	315.4	-	6.24
30.5	729.0	344.8	-	5.79

Table 17

WHITE MILLET SEED

Pressure drop (pounds per square foot per foot).

SCFM	G	Re	L=4"	L=6"	L=8"	L=10"	L=12"
3.5	83.7	14.2	10.14	10.10	9.94	-	-
4.0	95.6	16.2	12.0	11.6	11.34	11.60	-
4.5	107.6	18.2	13.41	-	-	-	-
5.0	119.5	20.2	15.90	13.94	14.04	-	-
6.0	143.4	24.2	17.64	17.16	16.0	17.28	-
6.5	155.4	26.3	18.24 M	-	-	-	-
7.0	167.3	28.3	17.94	20.28	19.26	-	-
7.5	179.3	30.3	16.53	-	-	-	-
7.9	188.8	31.9	15.60	-	-	-	-
8.0	191.2	32.3	-	23.60	22.38	23.50	-
9.0	215.1	36.4	14.04	25.80	25.60	-	-
9.4	224.7	38.0	8.73 S	-	-	-	-
10.0	239.0	40.4	8.28	28.08 M	27.70	28.39	-
11.0	262.9	44.4	7.80	26.10	30.10	-	-
12.0	286.8	48.5	-	24.76	30.66 M	33.44	-
12.7	303.5	51.3	-	12.68 S	-	-	-
13.0	310.7	52.5	-	12.68	28.86	33.82	-
14.0	334.6	56.6	-	12.50	25.74	35.0 M	-
15.0	358.5	60.6	-	12.16	15.40 S	34.20	-
15.6	372.8	63.0	-	-	15.40	-	-
16.0	382.4	64.6	-	-	15.06	32.76	-
17.0	406.3	68.7	-	-	14.82	28.76	-
17.2	411.1	69.5	-	-	-	18.47 S	-
18.0	430.2	72.7	-	-	-	18.16	-
18.5	442.2	74.7	-	-	-	-	21.21 S
19.0	454.1	76.7	-	-	-	18.04	-

Table 18

Maximum pressure drop in a 6 inch diameter split column

Pressure drop (Pounds per square foot - per foot)

PACKINGS	L=4"	L=6"	L=8"	L=10"	L=12"	L=14"	L=16"	L=18"	L=20"	L=22"	L=24"
OLD WHEAT	14.8 (7.0)	21.5 (10.0)	29.2 (13.0)	38.3 (14.5)	40.9 (15.0)	43.5 (16.0)	44.8 (16.5)	47.3 (17.5)	48.2 (17.8)	-	
NEW WHEAT	13.8 (7.5)	20.0 (11.0)	26.0 (13.4)	34.8 (14.0)	38.9 (15.5)	41.9 (16.2)	45.3 (17.0)	- -	- -	- -	- -
BARLEY	10.0 (6.2)	15.8 (9.5)	20.3 (11.5)	26.2 (12.6)	30.3 (13.8)	32.7 (14.4)	33.7 (14.7)	- -	- -	- -	- -
RAPE SEED	-	-	-	-	-	-	-	-	-	-	-
OATS	7.0 (5.5)	10.6 (8.5)	13.8 (10.5)	19.0 (11.5)	22.4 (12.0)	24.6 (12.8)	26.0 (13.3)	- -	- -	- -	- -
VETCHES	14.35 (8.7)	23.05 (13.5)	32.1 (17.0)	41.6 (21.0)	- -	- -	- -	- -	- -	- -	- -
SPLIT PEAS	15.6 (8.0)	21.0 (11.0)	30.0 (14.1)	38.1 (14.9)	42.4 (16.0)	45.3 (17.4)	46.8 (17.5)	47.5 (17.9)	48.2 (18.5)	- -	- -
PEAS	12.9 (12.0)	21.7 (18.5)	24.4 I (20.5)	- -	- -	- -	- -	- -	- -	- -	- -
SMALL PELLETS	-	-	-	-	-	-	-	-	-	-	-
BIG PELLETS	9.36 (9.0)	17.1 (13.5)	22.1 (17.9)	25.0 (19.0)	-	-	-	-	-	-	-
SOY BEANS	13.0 (10.0)	21.4 (16.5)	28.1 (20.7)	- -	- -	- -	- -	- -	- -	- -	- -
WHITE MILLET SEED	15.8 (4.8)	21.0 (6.7)	31.4 (8.0)	34.7 (8.9)	37.3 (9.4)	39.7 (9.9)	41.6 (10.1)	43.5 (10.6)	44.7 (10.9)	45.0 (11.0)	- -

In brackets: Air flow rate (SCFM) at maximum pressure drop.

I L=7"

Table 19

PRESSURE DROP AT THE SPOUTING POINT IN A 6 INCH DIAMETER SPLIT COLUMN.

Pressure drop (pounds per square foot - per foot)

PACKINGS	L=4"	L=6"	L=8"	L=10"	L=12"	L=14"	L=16"	L=18"	L=20"	L=22"	L=24"	L=26"	L=28"
OLD WHEAT	6.87 (7.65)	11.8 (11.6)	14.0 (13.6)	16.0 (15.1)	18.46 (16.6)	19.4 (17.8)	22.23 (19.1)	24.28 (20.25)	26.2 (21.1)	27.8 (22.0)	28.2 (23.5)	29.9 (24.0)	31.87 (24.8)
NEW WHEAT	6.35 (8.0)	10.15 (12.0)	13.0 (14.5)	15.1 (15.5)	17.68 (17.5)	19.16 (18.2)	20.79 (19.4)	- -	- -	- -	- -	- -	- -
BARLEY	4.20 (7.4)	6.5 (10.5)	7.8 (13.5)	9.7 (14.5)	11.50 (16.4)	13.0 (18.0)	13.6 (18.7)	15.50 (20.5)	- -	- -	- -	- -	- -
RAPE SEED	6.45 (5.4)	10.65 (8.0)	13.11 (9.1)	14.72 (10.1)	16.20 (11.0)	16.95 (11.5)	18.06 (12.2)	19.59 (12.6)	21.16 (12.9)	21.61 (13.6)	- -	- -	- -
OATS	2.61 (6.2)	4.26 (9.0)	5.44 (11.0)	6.55 (12.2)	6.60 (13.0)	7.5 (13.8)	8.4 (15.5)	- -	- -	- -	- -	- -	- -
VETCHES	6.6 (9.9)	11.65 (15.6)	14.45 (19.2)	19.66 (23.4)	- -	- -	- -	- -	- -	- -	- -	- -	- -
SPLIT PEAS	7.17 (8.7)	10.5 (12.2)	12.87 (15.1)	17.66 (18.3)	20.80 (20.5)	22.77 (22.1)	24.96 (23.5)	26.7 (24.5)	- -	- -	- -	- -	- -
PEAS	6.51 (15.2)	10.25 (22.0)	12.0^{I} (25.1)	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
SMALL PELLETS	4.68 (7.3)	5.7^{II} (8.7)	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
BIG PELLETS	4.7 (10.4)	6.9 (14.3)	9.66 (18.8)	11.0 (20.7)	- -	- -	- -	- -	- -	- -	- -	- -	- -
SOY BEANS	5.3 (12.7)	8.84 (19.5)	12.1 (24.5)	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
WHITE MILLET SEED	8.36 (5.0)	13.31 (7.0)	16.0 (8.2)	19.0 (9.0)	21.58 (9.7)	23.54 (10.2)	24.74 (10.9)	26.0 (11.1)	28.64 (11.9)	29.64 (12.3)	30.55 (12.9)	31.0 (13.3)	- -

^{I} L=7" ; ^{II} L=5"

In brackets: Air flow rate (SCFM) at spouting.

Table 20

PRESSURE DROP INTERCEPTS AT REYNOLDS NUMBERS 90 AND 120 FOR MAXIMUM PRESSURE DROP AND PRESSURE DROP AT SPOUTING, RESPECTIVELY.

Pressure drop (pounds per square foot per foot).

PACKINGS	6" column $\left(\frac{\Delta P_M}{L \lambda^2}\right)_{40}$	6" column $\left(\frac{\Delta P_S}{L \lambda^{1.75}}\right)_{40}$	6" split column $\left(\frac{\Delta P_S}{L \lambda^{1.75}}\right)_{40}$
OLD WHEAT	18.8	7.3	8.6
NEW WHEAT	17.0	6.0	7.8
BARLEY	16.3	5.2	6.9
RAPE SEED	52.5	25.8	25.7
OATS	19.9	5.8	7.5
VETCHES	12.2	3.7	4.6
SPLIT PEAS	12.5	3.5	4.4
PEAS	5.2	-	2.0
SMALL PELLETS	17.4	-	-
BIG PELLETS	7.2	2.3	2.7
SOY BEANS	4.4	1.4	1.5
WHITE MILLET SEED	46.0	28.6	34.4

Derivation of Equation 18 (10)

It is convenient to begin with an analogy of flow through empty pipes

For pipe flow:

$$\frac{\Delta p}{L} = \frac{\rho v^2}{g_c d_c} \; f\left(\frac{d_c \; v}{\mu}\right)^{n-2} = \frac{\rho v^2}{g_c d_c} \; K'\left(\frac{d_c \; v \rho}{\mu}\right)^{n-2}$$

$$\frac{\Delta p}{L} = \frac{K'}{g_c} \; \frac{\mu^{2-n}}{\rho^{1-n}} \; v^n \; d_c^{\,n-3} \qquad \text{(I)}$$

Let the velocity of the fluid through the pores be given by:

$$\frac{v}{k_\delta \, \delta} \qquad \text{(II)}$$

where v is the average velocity of the fluid approaching the bed; k_δ, the proportion of effective voids in the bed, and δ is the porosity ratio, expressed as volume of voids per unit volume of packed tube.

Assuming that the dimensions of the voids are of the same order of magnitude as the particle diameter, then $D_p = 4r$, where r is a modified hydraulic radius of the interstices. By definition, let

$$r = \frac{\text{effective volume of the packing interstices}}{\left(\begin{array}{c}\text{effective surface of}\\ \text{particles}\end{array}\right)\left(\begin{array}{c}\text{particle shape}\\ \text{factor}\end{array}\right)}$$

$$r = \frac{k_\delta \, v_p \, \delta}{(1-\delta) \; k_a \lambda S} \qquad \text{(III)}$$

k_a, is the proportion of the effective area of the packing. Substituting (II) and (III) into (I) one obtains;

$$\frac{\Delta P}{L} = \frac{K'}{g_c} \frac{\mu^{2-n}}{\rho_f^{1-n}} \left(\frac{v}{k_\delta \delta}\right)^n \left(\frac{k_\delta}{k_a} \frac{\delta}{(1-\delta)} \frac{v_p}{\lambda S}\right)^{n-3} \qquad \text{(IV)}$$

Rearranging and substituting S/v_p by $6/D_p$ (the expression for spheres), and also $\rho_f v$ by G, Equation (4) becomes:

$$\frac{\Delta P}{L} = \frac{K}{g_c} \left(\frac{D_p G}{\mu}\right)^n \frac{\mu^2}{\rho_f} \frac{\lambda^{3-n}}{D_p^3} \frac{(1-\delta)^{3-n}}{\delta^3} \qquad \text{(V) or (18)}$$

The exponent n in Equation V can have any value, ranging from n=1 for completely laminar flow to n=2 for the most turbulent flow.