AERODYNAMIC CHARACTERISTICS OF GRAIN IN A RECTANGULAR SPOUTED BED DRYER

by

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ABSTRACT

The aerodynamic characteristics of four grains in a rectangular cross section spouted bed dryer were investigated in this report.

Bed depth and moisture content were varied for each grain and the effects on the characteristic pressure drop - airflow curves, and pressure drop required for spouting were noted. Both high bed depth and moisture content were observed to increase hysteresis in the pressure drop - superficial velocity curves of all grains. The characteristics of corn and wheat beds seemed the least affected by these changes.

The power requirement for the apparatus used was relatively high. However, since drying rates for spouting versus static grain were found to be 40 to 50% higher, it is felt that with proper inlet and dryer design, the overall energy efficiency of this dryer could become at least comparable to that obtained with cylindrical spouted bed dryers.

ACKNOWLEDGEMENTS

The author wishes to express her sincere thanks to Professor Raghavan for his patience and advice throughout the conduction of this experiment.

The entire staff of the mechanical engineering undergraduate laboratory is to be commended for their cooperation and help during set up and running of this test.

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NOMENCLATURE

D_c - Column diameter

D_i - Inlet orifice diameter

d_p - Particle diameter

d_v - Diameter of a sphere of same volume as particle

g - Gravitational acceleration

H - Grain bed height

H_m - Maximum spoutable height

ΔP - Pressure drop across the grain bed

ΔP_m - Maximum pressure drop prior to onset of spouting

ΔP_{mf} - Pressure drop at minimum fluidization condition

ΔP_{ms} - Pressure drop at minimum spouting condition

ΔP_s - Pressure drop at spouting condition

Re_m - Reynolds number at the maximum of U_{ms}

U - Superficial velocity

U_m - Superficial velocity at point of maximum pressure drop

U_{ms} - Minimum spouting velocity

U_t - Terminal fall velocity

v - Velocity in supply pipe at position of pitot static tube

$\dot{V}$ - Volumetric flow in supply pipe at position of pitot static tube (m^3/s)

φ - Angle of internal friction

ε_{mf} - Voidage at minimum fluidization

$\lambda, \phi_s, \psi, \bar{\psi}$	-	Particle shape factors
μ	-	Fluid viscosity
ρ_b	-	Solids bulk density
ρ_f	-	Fluid density
ρ_p, ρ_s	-	Particle density

CHAPTER 1 - INTRODUCTION

INTRODUCTION

As the trend continues towards increasing the efficiency of agricultural operations, grain drying is becoming an operation of industrial magnitude. It is estimated that on a worldwide basis between the years 1980 and 1981 approximately 94.5 million metric tons of water were removed from drying coarse grains (Anon., F.A.O. Prod. Yearbook, 1980/1981).

Presently a variety of static bed or mechanically recirculated grain dryers exist on the market. Most are capable of drying sufficiently large quantities of grain at a time, however, even portable models are often large and cumbersome to set up and dismantle. High capital cost and non-uniformity of drying are other disadvantages of this type of dryer.

In 1955 Gishler and Mathur published a paper on the possible application of a "spouted bed" dryer, as they called it, for the drying of coarse particles including agricultural materials. Ease of transferring solids to and from vessels, uniformity of conditions within the grain bed, high heat and mass transfer rates, compact size and low capital cost were some of the positive aspects that prompted the investigation of this dryer.

Through the years the spouted bed dryer has been used in industry for coating, blending, cooling and granulation of various chemical products. It has not, however, been used in the agricultural industry simply because present models are too small in size*.

The subject of this report, the rectangular spouted bed dryer, is essentially a vertical column of rectangular cross section into which air enters through a long slot. The dryer's capacity may be increased by extending its longest rectangular dimension making it a potential candidate for "scale up" to become the first high capacity spouted bed dryer.

* The largest dryers are between 2 and 4 feet in diameter by 7 to 8 feet high cylinders.

CHAPTER II - OBJECTIVES

OBJECTIVES

The purpose of this report was to study the aerodynamic characteristics of the rectangular dryer. More specifically, it was the author's intention to investigate the effect of varying bed depth and grain moisture content on the airflow required for spouting and the differential pressure across the grain bed.

It was also desired to compare the drying rate for the static bed condition to that obtained for the same grain subjected to spouted bed drying.

The final objective was to compare the findings of this report, where possible, to available information on cylindrical spouted bed dryers.

CHAPTER III - EXPERIMENTAL PROCEDURE AND APPARATUS

EXPERIMENTAL PROCEDURE

This experiment consisted of three sections; each of the parts being carried out for corn, wheat, oats and barley. For the first part, testing was carried out for grain depths varying from approximately 11.5 cm to 23.5 cm. For each depth, the airflow was varied from very low values through those required for spouting to those at which aggregative fluidization began to occur. Pressure drop - velocity readings were taken at various times during the run. In each case the airflow required to initiate and to maintain spouting were noted as closely as possible.

The second portion of the test was conducted in exactly the same manner as the first, except that the variable was grain moisture content.

Curves of pressure drop (ΔP) versus superficial velocity (U), bed depth (H) and moisture content were plotted. Airflow required for spouting was plotted versus moisture content. A calibration curve of ΔP versus U was plotted for the empty dryer so that the pressure drop across the screen (which prevents grain in the dryer column from falling into the inlet manifold) could be subtracted from the total differential pressure across the grain and screen.

For the final part of this experiment the moisture loss of corn and wheat whose initial moisture contents were

32.3% and 22.8% wet basis respectively, were measured during 45 minutes of drying in both the spouting and static conditions. No heat supply was provided, however friction from the blower blades heated the air to approximately 32°C.

APPARATUS

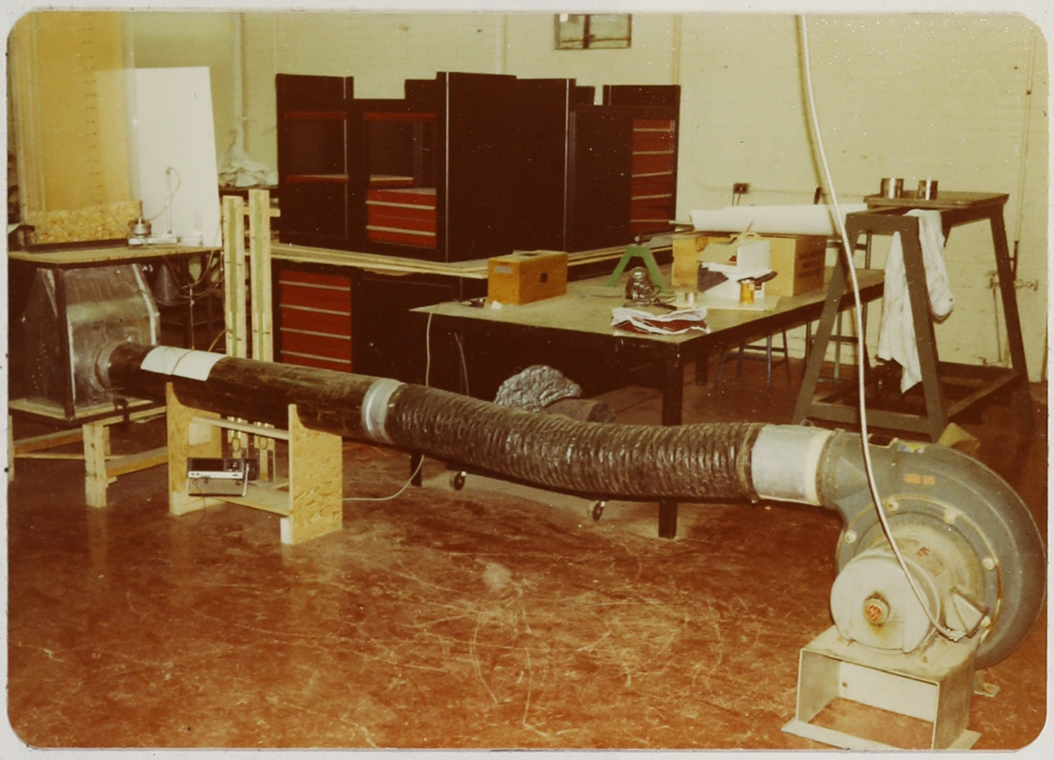
The apparatus used for this experiment is illustrated in Figure 1a. A five horsepower impeller - type blower was used to force air through 20.32 cm (8 inch) diameter ducting to an inlet manifold which redirected it through a slot running the width of the dryer column.

As shown in Figure 1b, a screen was placed on the outlet of the blower, and a piece of honeycomb in the cast iron pipe, in order to provide the streamlined flow necessary for velocity measurement.

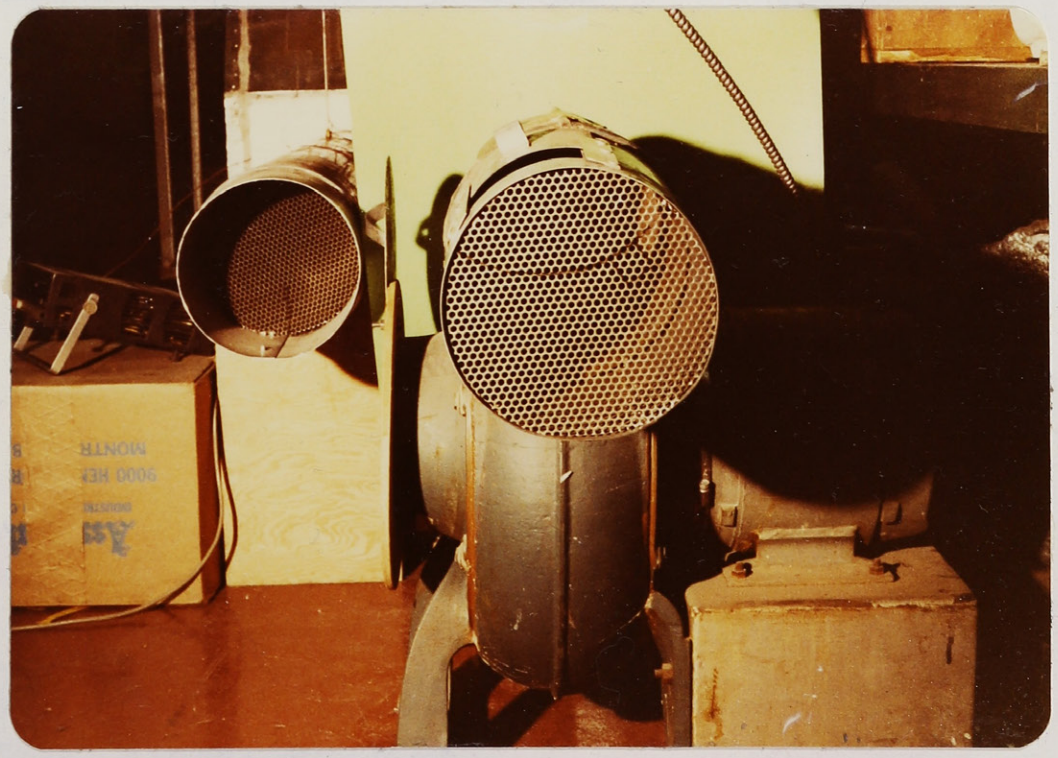
Velocity, temperature and static pressure measurements were taken in the cast iron pipe using a pitot static tube and manometer, thermocouple and digital meter, and water filled manometer respectively. Referring to Figure 1c the position of measurement is indicated by the two pieces of paper on the iron pipe.

Differential pressure across the bed was measured directly with the use of a water filled manometer. One side of the manometer was connected to a static pressure tap near the screen-covered air inlet, and the other, to one of the taps on the face of the dryer. Bed depth was measured from the air inlet to the grain bed surface. Airflow was varied by opening or closing the orifice restrictor and bleed valve shown in Figure 1d.

Figures 1e and 1f show a small depth of corn spouting, and poorly fluidized in that order.

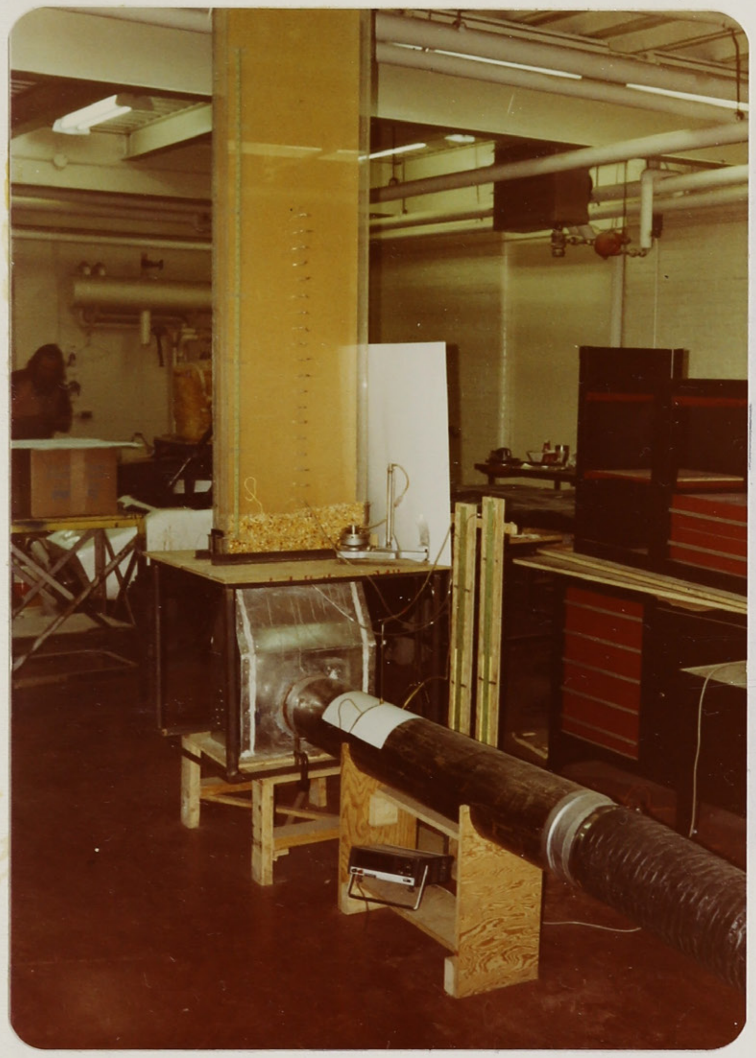


a) Overall view of apparatus used.



b) Screen and honeycomb used to provide streamlined airflow.

Figure 1. Experimental apparatus.



c) Positions of velocity and pressure measurements.

d) Orifice restrictor and bleed valve.

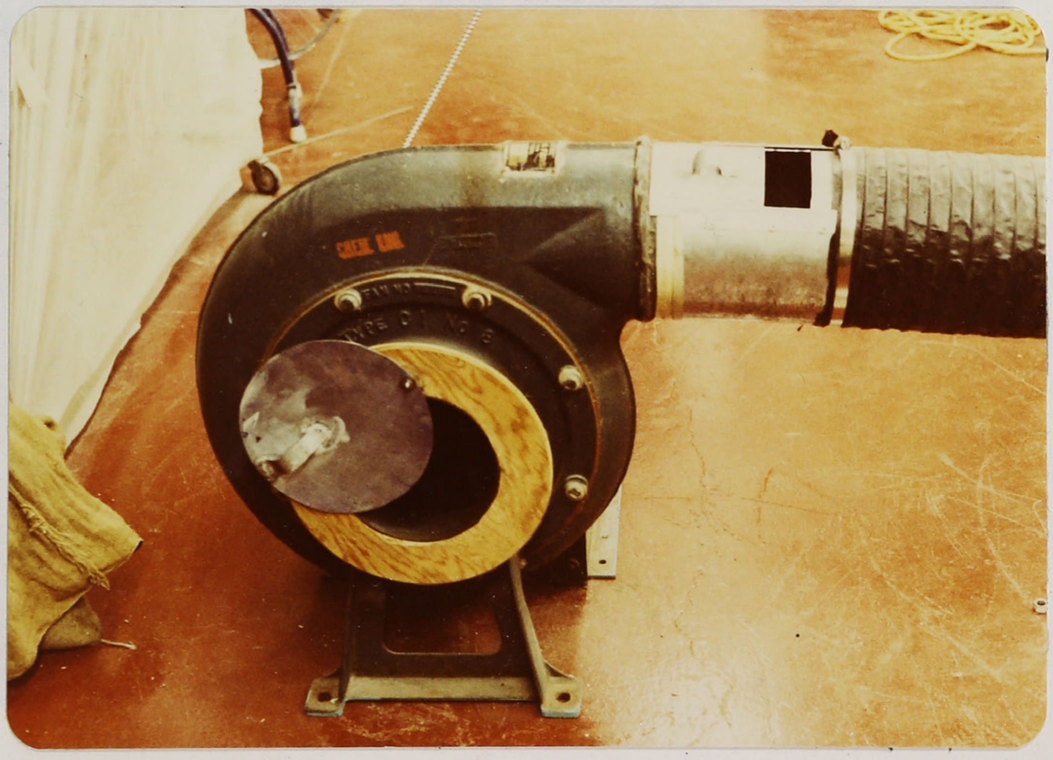


Figure 1. continued

e) Spouting corn.

f) Fluidized corn.

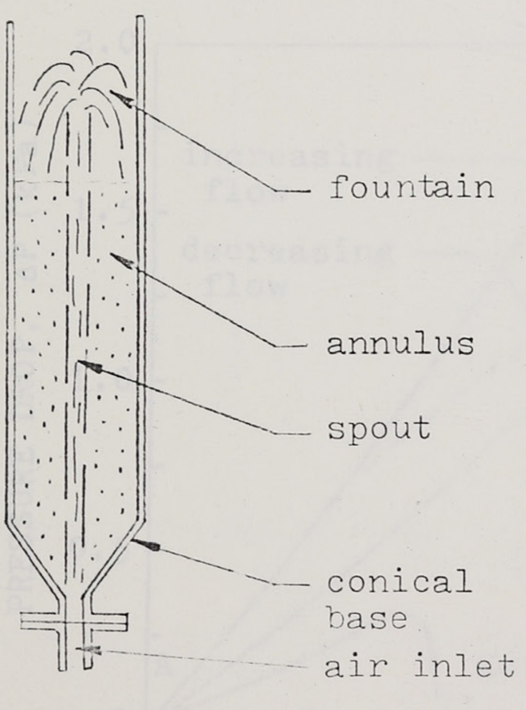
Figure 1. continued

CHAPTER IV - THEORY AND LITERATURE REVIEW

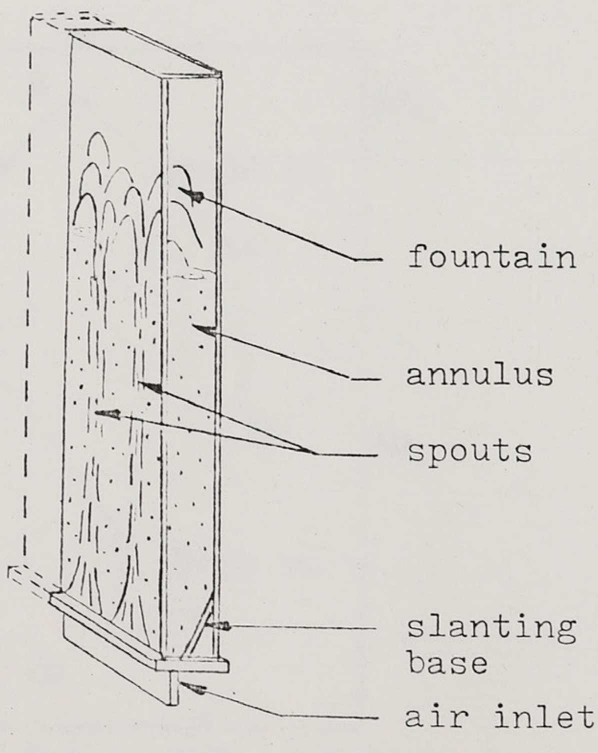
THEORY

Perhaps, before delving into the findings of this and other reports, it would be best to review the general principles associated with the spouting bed dryer.

The spouted bed dryer is somewhat of a compromise between a fluid and a static bed model. Existing types are usually cylindrical columns which have cone-shaped bottoms. A jet of air enters at the dryer base and blows up through the column making the grain "spout" in the form of a fountain, as shown in Figure 2.



a) Cylindrical or circular column spouted bed dryer



b) Rectangular spouted bed dryer showing possible extension of size.

Figure 2. Schematics of a circular and a rectangular spouted bed dryer.

Since the residence time of any one kernel of grain in the hot air jet is fairly low, substantially higher drying temperatures than found in conventional agricultural models may be used. Higher drying temperatures combined with increased gas to solid contact area provide for large convective heat transfer coefficients. Hence, faster drying times are achieved without the mechanical or heat damage sometimes encountered in conventional recirculating and batch dryers.

The actual mechanism of spouting may be better understood by referring to the typical pressure drop - airflow curves obtained by Madonna et al (Mathur and Epstein, 1974) for a 15.2 cm diameter half section circular column shown in Figure 3.

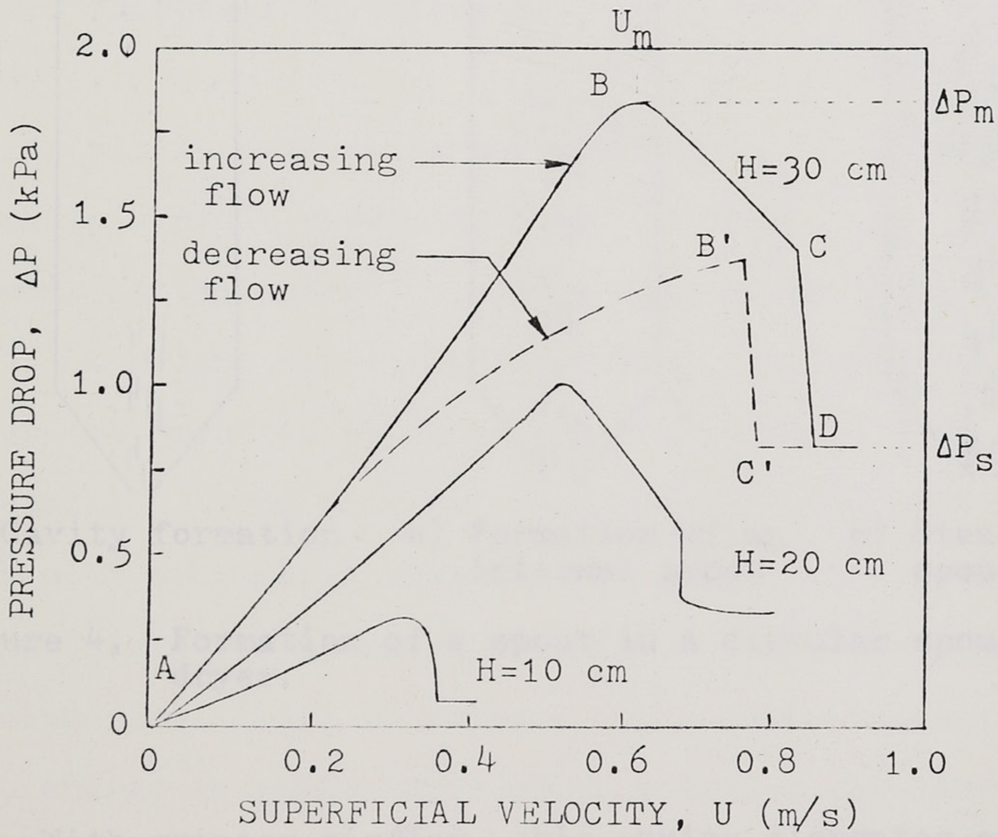
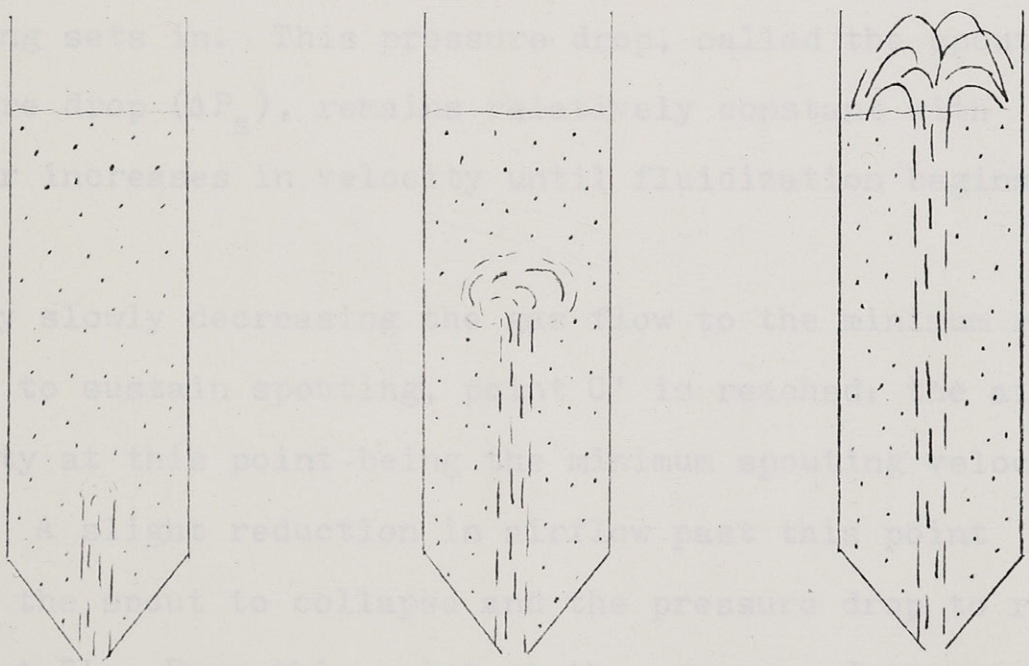


Figure 3. Typical Pressure Drop versus velocity curves obtained by Madonna et al. for a 15.2 cm diameter half section circular spouted bed dryer.

The curves labelled ABCD and DC'B'A represent pressure drops across the grain bed for increasing and decreasing airflows in that order. At first the gas simply passes up through the grain without disturbing any of the particles; the pressure drop increasing with airflow. Then, in the immediate vicinity of the spout, the particles are pushed back to form a small cavity whose wall is compacted. This offers greater resistance to airflow, causing the pressure to rise further, as illustrated below.



a) Cavity formation b) Formation of an internal spout c) Steady spouting

Figure 4. Formation of a spout in a circular spouted bed dryer.

With greater airflow, this cavity elongates and the formation of an internal spout occurs. However, because the upper wall of this spout consists of a layer of closely packed kernels, the pressure rises further until point B is reached. Past this point at which the maximum pressure drop (ΔP_m) across the bed is achieved, the height of the relatively hollow internal spout becomes quite large in comparison with the packed solids above the spout. Hence, the pressure decreases along BC. Past point C, which is called the point of incipient spouting, the internal spout breaks the surface. Due to the fact that the solids concentration immediately above the spout is markedly decreased, the pressure drop decreases to point D and steady spouting sets in. This pressure drop, called the spouting pressure drop (ΔP_s), remains relatively constant with further increases in velocity until fluidization begins to occur.

By slowly decreasing the gas flow to the minimum required to sustain spouting, point C' is reached; the air velocity at this point being the minimum spouting velocity (U_{ms}). A slight reduction in airflow past this point causes the spout to collapse and the pressure drop to rise to point B'. From this point on the pressure drop merely falls with decreasing airflow. It should be noted that the reverse curve for pressure drop falls below that for increasing flow. This is because for a given increasing airflow, energy is being expended to overcome the forces due to friction and initial bed packing. Whereas, for decreasing flows, these forces have already been overcome and air channels through the grain bed have been established making pressure drops lower.

The maximum bed depth (H_m) of a given material that may be spouted in a given dryer depends on the column and air inlet sizes. Grain beds of depth higher than H_m change from the static to fluidized state since the superficial velocity required to maintain spouting is greater than minimum fluidization velocity.

LITERATURE REVIEW

Various correlations have been derived which relate bed depth, inlet orifice size, column diameter, particle size to the airflow, pressure drop required for spouting and maximum spoutable depth. Although some work has been done by Mitev and Volkov et al. on rectangular dryers in the Soviet Union (Mathur and Epstein, 1974), work in North America has concentrated on circular cylindrical vessels. Hence, these correlations are applicable to cylindrical dryers, and presenting a detailed review of existing mathematical relations in this section would be extraneous to the subject matter of this paper.

Instead, a few key relations will be presented to give the reader a general idea of the interdependence of the above mentioned variables*. This way the reader will hopefully have a better idea of the general "state of the art" of spouted drying and thus have a better appreciation for the results of this report.

For the prediction of minimum spouting velocity in circular spouting beds the Mathur and Gishler correlation below, has proved valid over a wide range of variables (Mathur and Epstein, 1974).

* A more complete summary of relevant correlations may be found in Appendix B.

$$U_{ms} = (d_p / D_c)(D_i / D_c)^{1/3}(2gH(\rho_s - \rho_f) / \rho_f)^{1/2} \quad . . (1)$$

The relation does not appear to apply for column diameters much larger than 61 cm, since Peterson carried out a test on a 91.4 cm (3 ft) diameter by 119 cm (approximately 4 ft) deep bed of wheat and found the value of U_{ms} to be nearly double that predicted by the Mathur and Gishler equation (Mathur and Epstein, 1974).

More recently Littman and Morgan (1982) found that U_{ms} did not always vary as $H^{\frac{1}{2}}$ as suggested by equation (1). Hence, they presented a new general correlation for U_{ms} based on the pressure drop at minimum spouting condition and its derivative with respect to bed height. Apparently the relation matches a wide range of experimental data to 11.6% on average.

A number of correlations have been proposed for the prediction of maximum spoutable depth including those of Becker (1961), and Malek and Lu (1965).

Becker:

$$\left[\frac{H_m}{d_v}\right]\left[\frac{d_v}{D_c}\right]^{1.76}\left[\frac{12.2\ D_i}{D_c}\right]^{1.6\ \exp(-0.0072\ Re_m)}\left[22 + \frac{2600}{Re_m}\right]\psi^{2/3}\ Re_m^{\ 1/3} = 42 \quad . . . . (2)$$

where ψ is a shape factor (1.0 for spheres, 0.62 and 0.76 for wheat, 0.35 for flax seed etc.) and d_v is the diameter of a sphere of same volume as particle.

Malek and Lu:

$$\left[\frac{H_m}{D_c}\right] = 0.105 \left[\frac{D_c}{d_p}\right]^{0.75} \left[\frac{D_c}{D_i}\right]^{0.4} \left[\lambda^2 / \rho_s^{1.2}\right] \quad . . . (3)$$

where λ is a shape factor (1.0 for millet, sand, and timothy seed, 1.65 for gravel) and ρ_s is in megagrams per cubic meter.

Mathur and Epstein (1974) concluded that the Malek and Lu equation was the only equation supported by a sufficiently wide range of variables to be of practical interest. However, they found Becker's method to be the most reliable when tested against a wide range of experimental data covering different materials, column diameters, and air inlet sizes.

Correlations for peak and spouting pressure drop are difficult to compare due to the fact that the location of the upstream pressure tap used in measuring differential pressure across the bed varied depending on the experimenter. This would have considerable effect on the observed value of ΔP_m due to the temporary pressure drop immediately downstream of an orifice plate. Nevertheless, appendix B contains Manurung's relations for ΔP_s and ΔP_m. Malek and Lu (1965) stated that the maximum pressure drop approximately equals the weight of the bed regardless of the size of the inlet orifice used, provided that the value of H/D_c is not greater than unity. However, a check against the data of other workers indicates that this is not generally valid

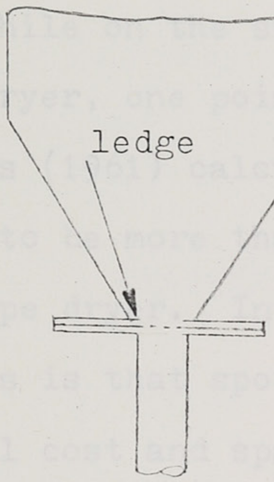
(Mathur and Epstein, 1974).

The general effect of major variables was investigated experimentally by Mathur and Gishler (1955) using 9, 13.5, 20.25 and 27 cm (4, 6, 9 and 12 inch) diameter columns. They found bed depth to vary linearly with minimum spouting velocity. A couple of interesting results of this study indicated that deeper beds could be spouted with smaller inlet sizes, and that larger diameter columns permitted higher spoutable depths and required less airflow to spout. Obviously, however, there exists a limiting column diameter for which the latter observation no longer holds true and the airflow required for spouting increases again.

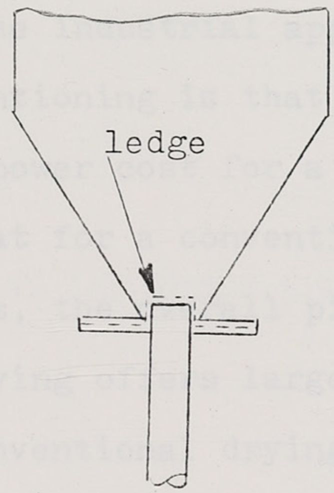
Other parameters such as inlet design and cone angle have been shown to affect the "spoutability" of a bed. Various inlet designs shown in Figure 5 such as a constricting orifice, converging protruding nozzle, protruding straight pipe, and truncated conical plug insert have been used to obtain higher spoutable depths.

The optimum cone angle for most materials in a cylindrical column was suggested by Mathur and Epstein (1974) to be in the region of 40°. Although the optimum slant angle for a rectangular dryer might be entirely different, note that the angle used in this experiment was 60°; a substantially higher value.

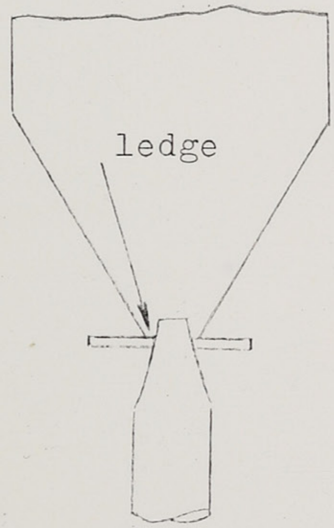
Regarding the scaling up of the spouted bed dryer for industrial application, Nemeth et al. (1982) worked on



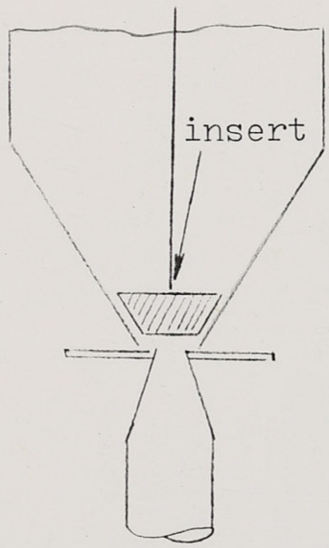
a) Constricting orifice



b) Straight inlet pipe, protruding



c) Converging nozzle, protruding



d) Truncated conical plug insert

Figure 5. Various inlet designs used to improve spoutability of a circular spouted bed dryer.

determining the limits of invariance of the flow correlations presently serving as the basis upon which dryers are dimensioned.

While on the subject of the industrial application of this dryer, one point worth mentioning is that Becker and Sallans (1961) calculated the power cost for a spouted bed dryer to be more than twice that for a conventional moving bed type dryer. In other words, the overall picture that emerges is that spouted bed drying offers large savings in capital cost and space over conventional drying methods at no additional total cost*.

*Due to recent fuel price increases, it is not known whether the overall costs for conventional and spouted bed dryers are still comparable.

CHAPTER V - RESULTS AND DISCUSSION

RESULTS AND DISCUSSION

When the graphs of ΔP vs U for each grain were compared, most were found to have the shape shown in Figure 6.

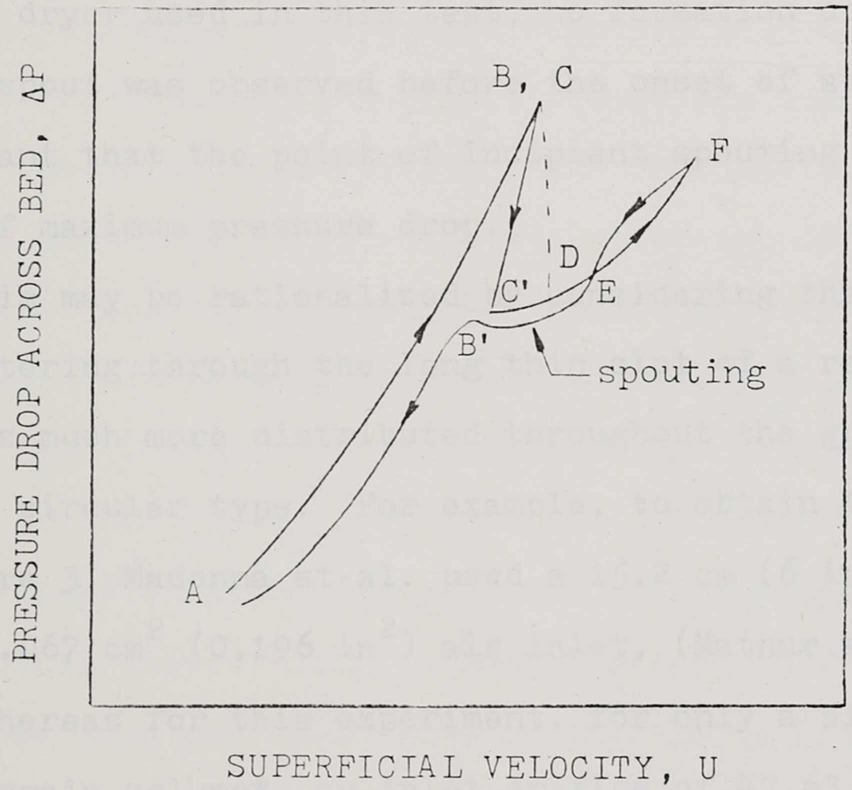


Figure 6. Typical pressure drop versus velocity graph for a rectangular spouted bed dryer.

The fact that this curve is fundamentally different from that shown in Figure 3 may be explained by differences in experimental procedure and inherent behaviour of the dryer.

First of all, each of the runs for this experiment monitored pressure drops for airflows varying from the static condition into fluidization. Most researchers in the past stopped increasing the airflow in the "spouting" region shown in Figure 6. Hence, the entire section of the curve to the right of point E is missing for their results.

Another fundamental difference is that for the rectangular dryer used in this test, no formation of an internal spout was observed before the onset of spouting. This meant that the point of incipient spouting was the point of maximum pressure drop.

This may be rationalized by considering that the airflow entering through the long thin slot of a rectangular dryer is much more distributed throughout the grain than for the circular type. For example, to obtain the results of Figure 3, Madonna et al. used a 15.2 cm (6 in) column and a 5.067 cm^2 (0.196 in^2) air inlet, (Mathur and Epstein, 1974) whereas for this experiment, for only a slightly higher grain volume*, an inlet orifice of 47.63 cm^2 (7.38 in^2) was used. Since a much greater volume of grain is supported above each square unit of inlet orifice for the rectangular model, the airflow supplied to initiate

*The volume contained in a unit height of a 19.6 cm (7.7 in) circular column is approximately equal to that contained in a unit depth of the rectangular model used in this experiment.

spouting seems to be utilized to set a great proportion of the grain bed in motion rather than to form a localized internal spout from a small volume of grain.

Yet another factor contributing to the discrepancy between curves is the fact that unfortunately a velocity measurement was not taken immediately after spouting occurred. Instead, when spouting occurred, the velocity was lowered to the minimum spouting velocity, and a pressure measurement was taken. The velocity was than increased, and pressure and velocity readings were taken through spouting to fluidization and back again. Point E of Figure 6 is the point at which the spouting pattern gave way to poor quality fluidization characteristic of that obtained with coarse particles. The dotted line between points C and D shows the curve that might have been obtained had the "velocity after spouting" been measured. Note the similarity to the circular column graph.

Another observable difference between this curve and that of Madonna and co-workers is that no marked elevation of pressure occurred immediately after the transition between the spouting and static bed (point B' on figures 3 and 6). It is possible that there exists a pressure increase for a very small range of velocities lower than U_{ms} and that these were simply overshot by making too coarse an airflow adjustment during the transition.

However, other factors may come into play. For example, the greater airflow distribution in the rectangular dryer and small bed depths used in this experiment may have prompted air channels formed during spouting to remain open, even after the collapse of the spout. This would keep the pressure drop low.

Reducing airflow past point B' generally resulted in pressure drops somewhat less than those for the increasing flows as found for the circular dryer.

Figure 7 is a summary of the various shapes of the pressure drop - velocity graphs obtained for each grain along with curves showing the effect of high moisture and high depth. It may be seen that for all cases, the high depth and moisture content plots are characterized by a greater amount of hysteresis between the upper and lower curves. This result supports the theory that air channels formed during the transition from a spouting to a static bed, remain open after spouting ceases.

Pronounced hysteresis was observed in the lower portions of the high depth curves of oats and barley probably due to the above mentioned reason. No such effect was observed for the remaining two grains. Since the moisture tests were done with relatively low grain depths, the high moisture plots tend to show less lower curve hysteresis than those for high depth. The curve shapes of corn and wheat seem to be least affected by changes in moisture content and bed depth.

Spouting pressure drop was found to vary, as is shown in Figure 8 with bed height. When a graph of log (ΔP)

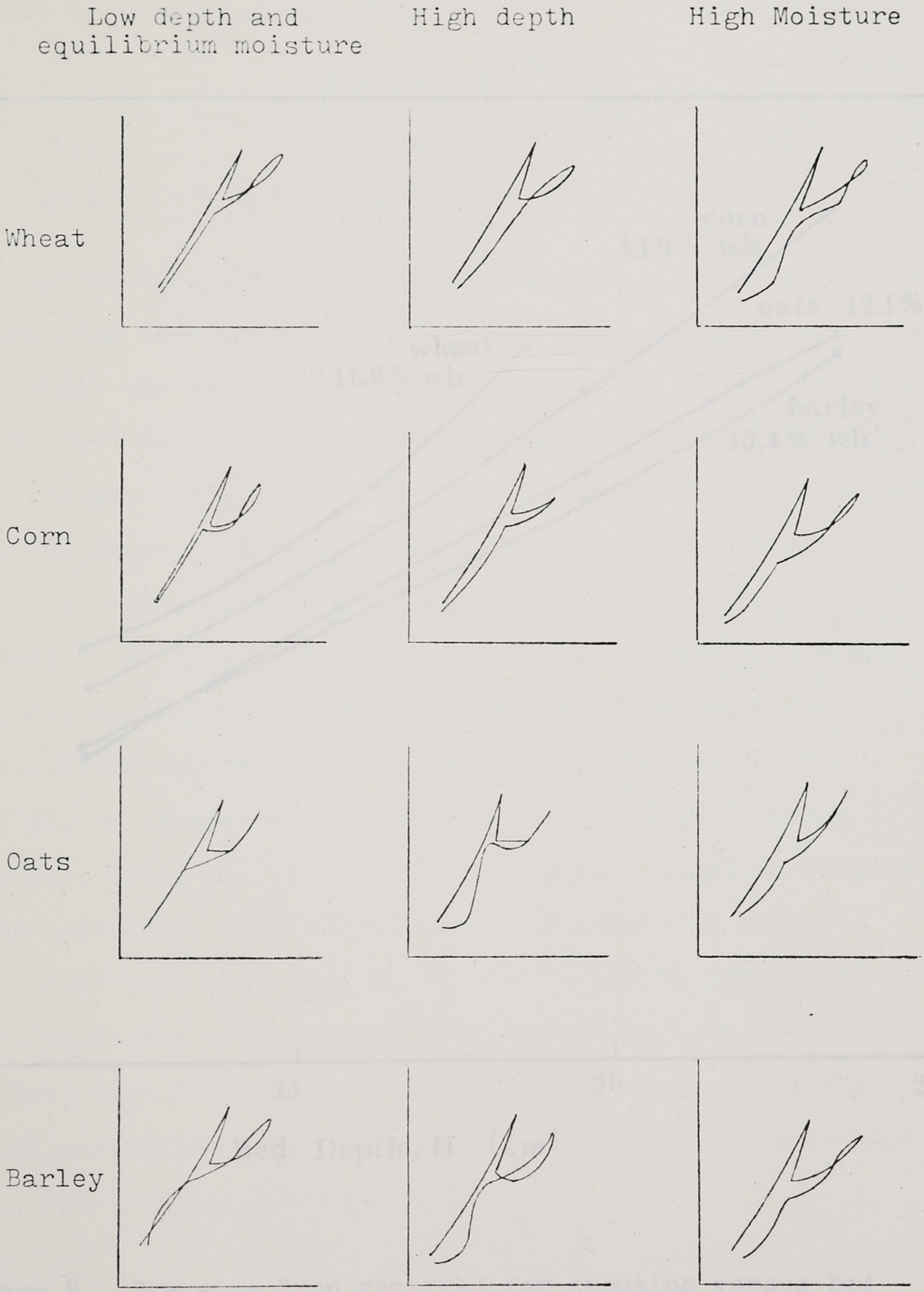


Figure 7. Typical pressure drop versus superficial velocity graphs for four grains at varying moisture contents and bed depths.

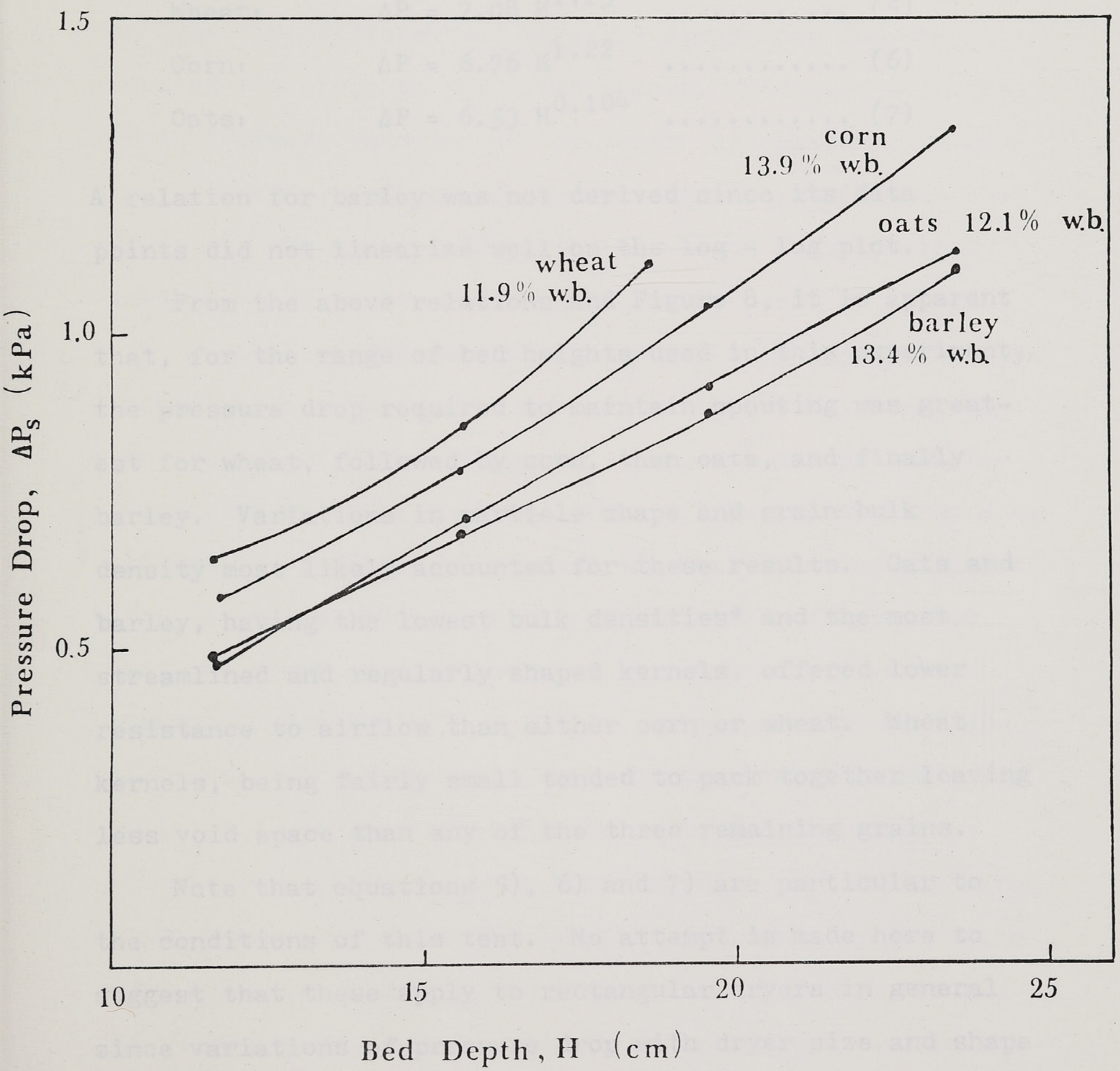


Figure 8. Pressure drop required for spouting versus bed height for four grains.

versus log (H) was plotted for each grain the following empirical relations were obtained:

Wheat: $\Delta P = 7.08\ H^{1.13}$ .... (5)

Corn: $\Delta P = 6.76\ H^{1.22}$ .... (6)

Oats: $\Delta P = 6.53\ H^{0.104}$ .... (7)

A relation for barley was not derived since its data points did not linearize well on the log - log plot.

From the above relations and Figure 8, it is apparent that, for the range of bed heights used in this experiment, the pressure drop required to maintain spouting was greatest for wheat, followed by corn, then oats, and finally barley. Variations in particle shape and grain bulk density most likely accounted for these results. Oats and barley, having the lowest bulk densities* and the most streamlined and regularly shaped kernels, offered lower resistance to airflow than either corn or wheat. Wheat kernels, being fairly small tended to pack together leaving less void space than any of the three remaining grains.

Note that equations 5), 6) and 7) are particular to the conditions of this test. No attempt is made here to suggest that these apply to rectangular dryers in general since variations of pressure drop with dryer size and shape have not been taken into account.

*Densities of wheat, corn, oats and barley were found to be 753, 680, 591 and 571 kg/m^3 respectively.

Before continuing it might be well to mention that all pressure drops presented in this report include the contribution of the inlet screen. The lower pressure tap used in measuring differential pressure across the bed was located too close to the inlet screen. Hence, due to the venturi effect (suction at the lower tap) extremely high and erroneous readings of pressure were obtained when the dryer was run empty. Thus, the ΔP versus U calibration curve for the inlet screen could not be used.

Results of the moisture tests for this experiment were inconclusive. The spouting velocity versus moisture content curves of Figure 9 appear to show no set pattern for increasing moisture content. This may be explained by consideration of Figure 10 which shows that spouting pressure drop (ΔP_s) remains approximately the same through a 10% (wet basis) or greater increase in moisture content. Apparently for the 4.34×10^3 cm^3 volume used in this experiment, increasing grain water content by 15 to 20% wet basis, did not increase the bulk grain weight enough to affect the airflow required for spouting. The drying rates shown below indicate that, for all conditions equal, using unheated air a spouting bed of grain dries between 40 and 50% faster than a static one. Although this figure is already impressive, it, most likely, will be higher for heated air spouted bed dryers since extremely high drying temperatures may be used.

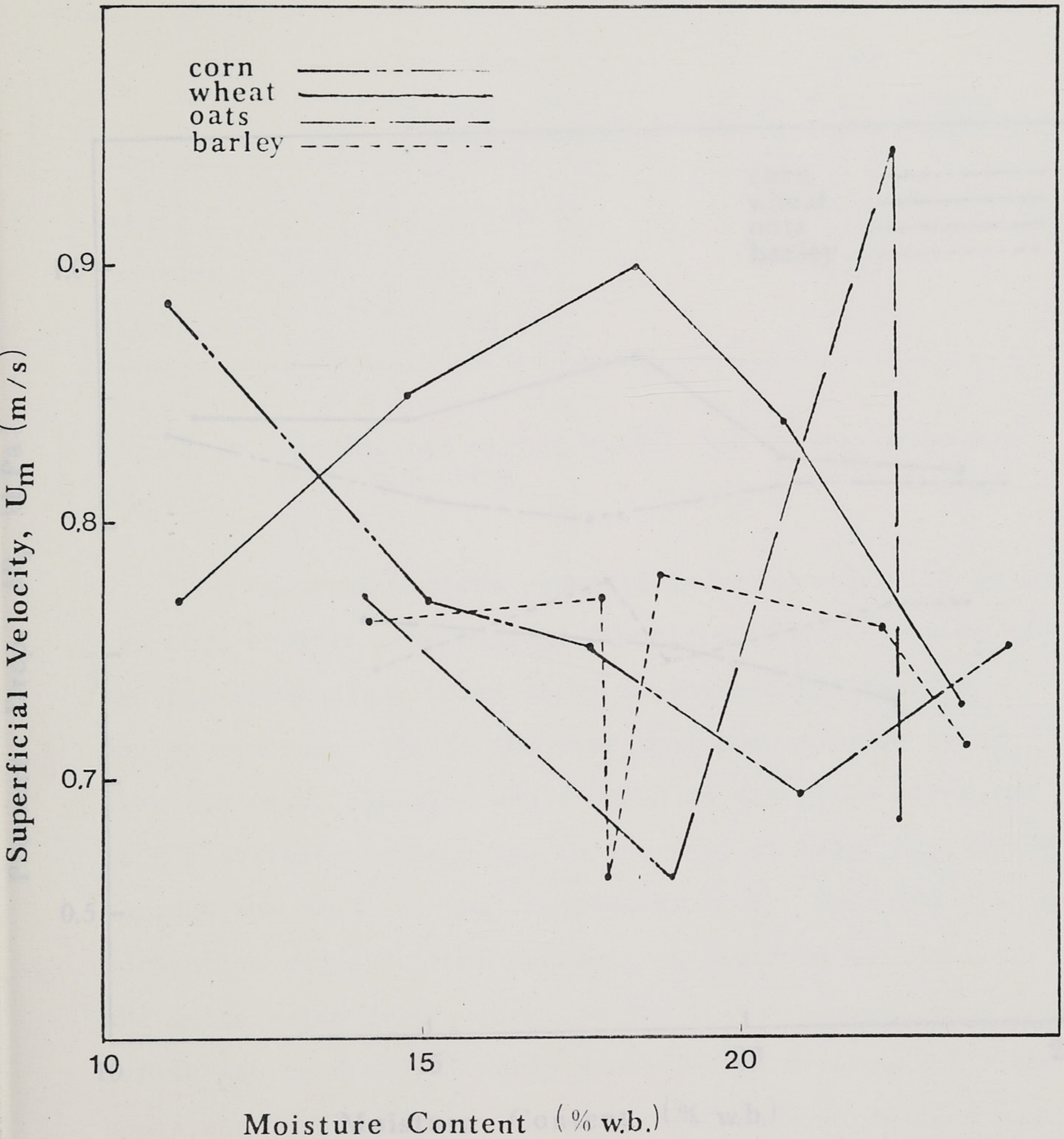


Figure 9. Superficial velocity needed to initiate spouting versus grain moisture content for four grains.

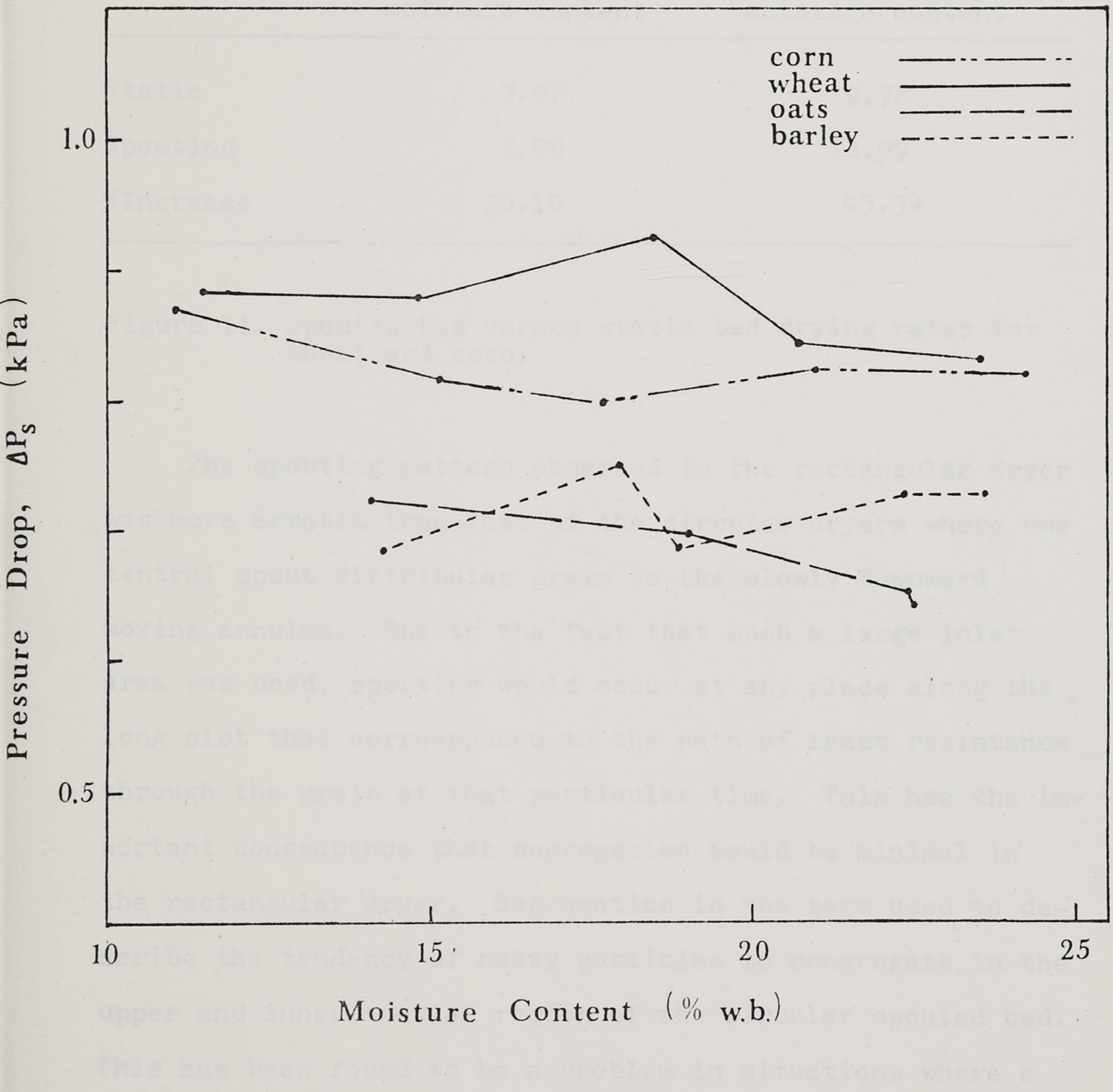


Figure 10. Pressure drop required for spouting versus moisture content for four grains.

DRYING RATES (pts./hr.)

	Wheat 22.8% w.b. initial moisture content	Corn 32.3% w.b. initial moisture content
Static	3.97	9.76
Spouting	5.96	13.99
%Increase	50.10	43.34

Figure 11. Spouted bed versus static bed drying rates for wheat and corn.

The spouting pattern observed in the rectangular dryer was more erratic than that of the circular dryers where one central spout distributes grain to the slowly downward moving annulus. Due to the fact that such a large inlet area was used, spouting would occur at any place along the long slot that corresponded to the path of least resistance through the grain at that particular time. This has the important consequence that segregation would be minimal in the rectangular dryer. Segregation is the term used to describe the tendency of heavy particles to congregate in the upper and inner annular region of the circular spouted bed. This has been found to be a problem in situations where a steady state drying operation is desired.

CHAPTER VI - SUMMARY AND CONCLUSIONS

SUMMARY AND CONCLUSIONS

In summary, two of the major differences between the graphs obtained in this experiment and those of other researchers are as follows. Firstly, since no formation of an internal spout was observed just prior to spouting, spouting was initiated at the point of maximum pressure drop. Secondly, the pressure drop across the grain bed following the collapse of the spout was always found to be lower than spouting pressure drop.

Increases in bed depth and grain moisture curve shifted the decreasing flow curve of the ΔP versus U graphs to the right. The graphs for high grain depths showed the greatest amount of hysteresis in the lower pressure and velocity region. The curve shapes of corn and wheat seemed to be least affected by changes in bed depth and moisture content. For a given height of grain the pressure drop across a bed of wheat was the highest, followed by corn, oats and barley. Raising moisture content did not appear to affect the airflow required for spouting for a bed depth of 15.62 cm. Natural air drying rates were 40 to 50% higher for the spouted bed than the static bed.

In comparison to the circular spouted bed dryer the rectangular dryer has the advantage of not causing segregation of heavy particles in the inner and upper annulus region. However, its main limitation is a high inlet area to column area ratio which means that the airflow must be able to support a great proportion of the bed before spouting initiates. An improvement might be obtained by redesigning the air inlet so that the flow is somewhat nozzled.

Another possibility would be to compartmentalize the airflow before it reaches the inlet dryer orifice by using a series of slats in the inlet manifold. This would eliminate the lateral airflows occurring under high pressure drop conditions where the supplied airflow sometimes hits the dryer screen, and is merely redirected sideways and forced back into the supply pipe.

Yet another alternative might be a design tried out in the Soviet Union where the air inlet is such that the airstream enters at an angle from the vertical. This shifts some of the grain bed weight off the air jet.

Lowering the slant angle from the 60^{o} value used in this experiment and increasing the shorter rectangular dimension of the dryer column might also aid the bed weight distribution.

If higher operating costs are not to outweigh the advantages of low capital cost and fast drying time, much work must be done on the rectangular dryer to optimize dryer shape and provide smooth nozzled inlet orifice that will supply a concentrated jet of air.

Once these obstacles are overcome, however, the author sees no reason why this dryer could not be implemented for agricultural use since it has the definite advantages of being more compact and less cumbersome to set up than present models.

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RECOMMENDATIONS

The first recommendation to anyone carrying out further work on this subject is to pay close attention to the points made about slant angle and air inlet orifice design made in the summary and conclusions section.

Secondly, it is best to limit the scope of variables to be investigated and attempt to attain meaningful results for those tested. For example, when obtaining pressure drop versus velocity characteristics for a given grain bed it is best to take as many as 30 readings, especially concentrating on the region near spouting.

Superficial velocity measurement should be done directly in the dryer column if some means of not obstructing the spouting pattern or clogging the measurement device can be devised.

If an AC blower of constant capacity is to be used such as the one used for this investigation, a better set up than an orifice restrictor and bleed valve for airflow variation would be the combination of a gate and bleed valve. A funnel shaped nozzle could then be placed on the inlet orifice of the blower. This would aid the problem encountered in this experiment of air backing up due to the sharp pressure transition, and blowing out around the periphery of the blower inlet orifice.

Lastly, when measuring the differential static pressure drop across the grain bed, the lower static tap should not be placed too near the inlet screen for reasons discussed previously.

APPENDIX A - SAMPLE GRAPHS AND METHOD OF CALCULATION

SAMPLE PRESSURE DROP VERSUS SUPERFICIAL VELOCITY GRAPHS:

Presented here are three sample plots of pressure drop versus superficial velocity. Comparing the three curves one may confirm the afore-mentioned effects of high moisture and high bed depth.

The log (ΔP_s) versus log (H) plot was included as a check for the reader. The remaining data has been summarized in the results and discussion section and need not be included here.

The key below will help the reader to interpret the following graphs.

KEY:

1 - Maximum flow and pressure drop for which the grain bed remains static.

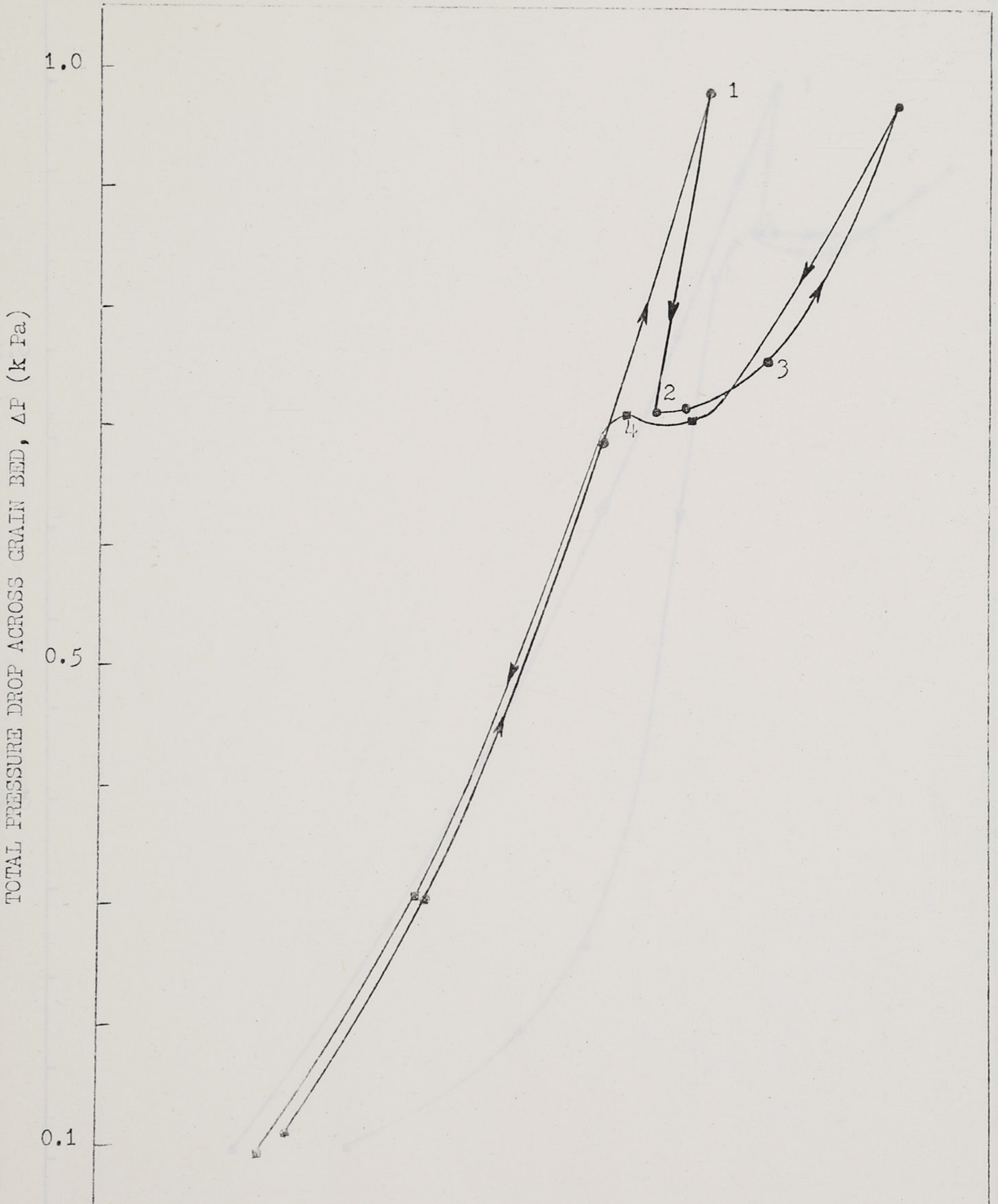
2 - The minimum pressure and velocity required to maintain spouting.

3 - Transition point from spouting to aggregative fluidization.

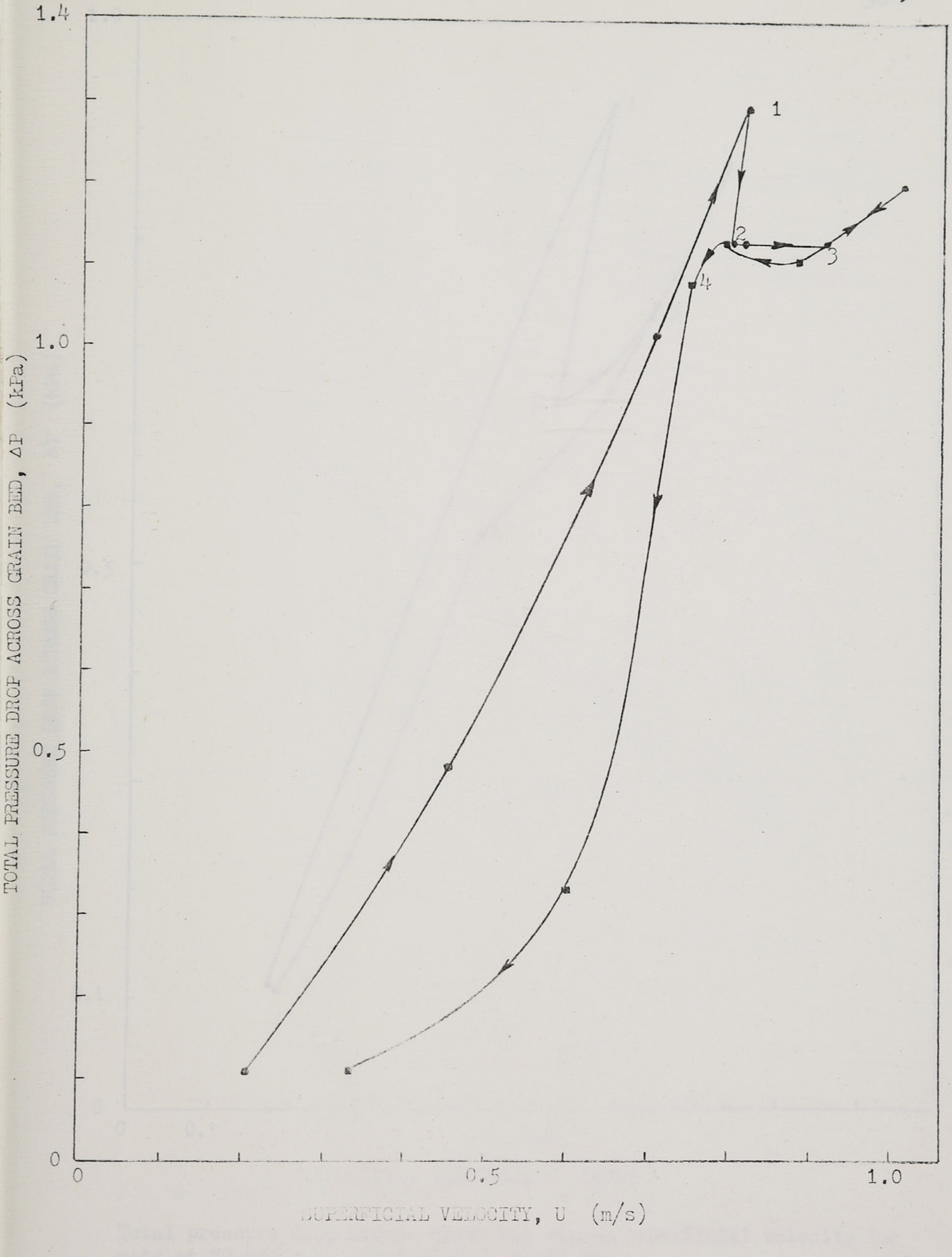
4 - The point at which collapse of the spout occurs.

● - Points plotted for increasing flow.

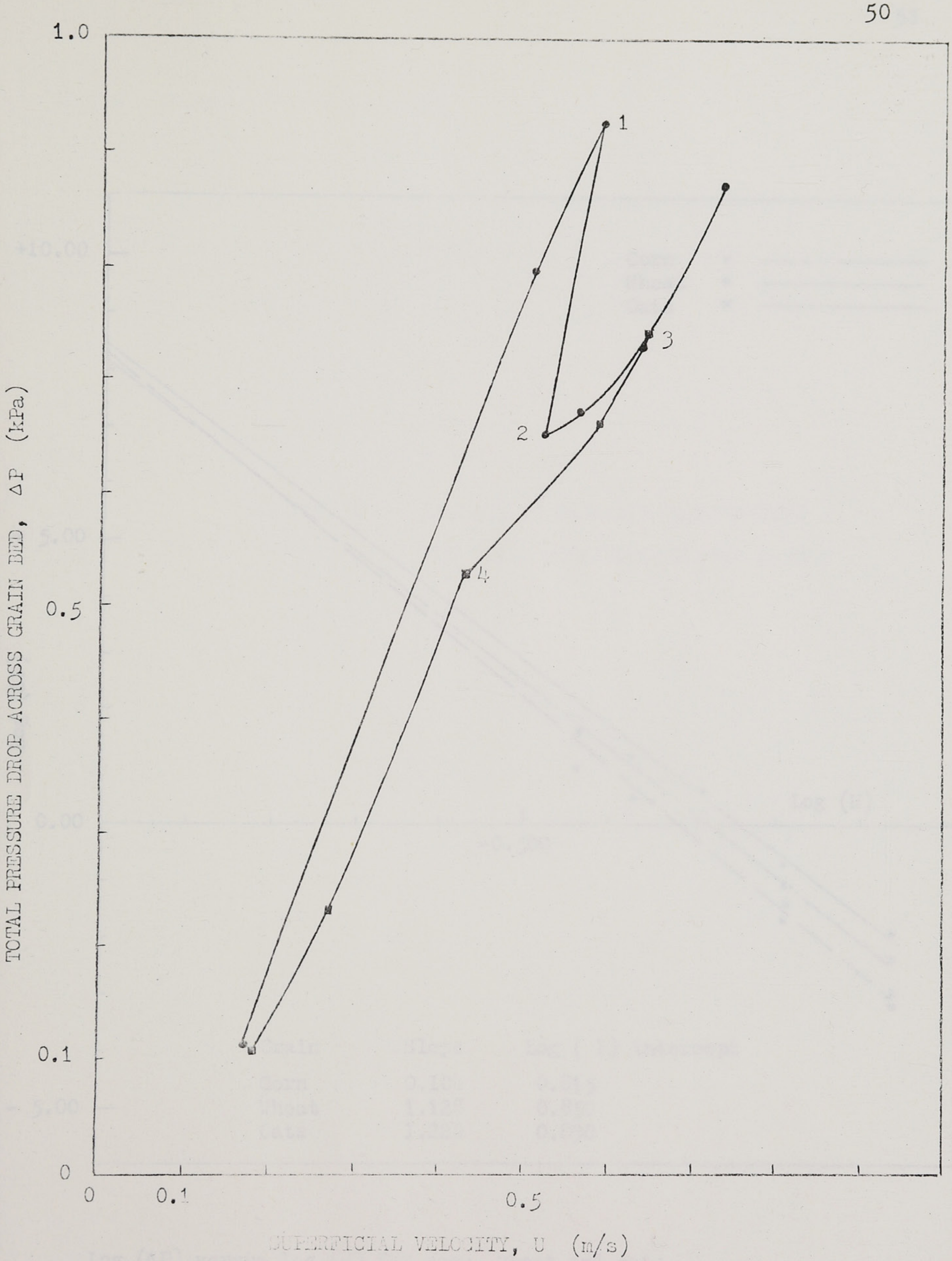
■ - Points plotted for decreasing flow.



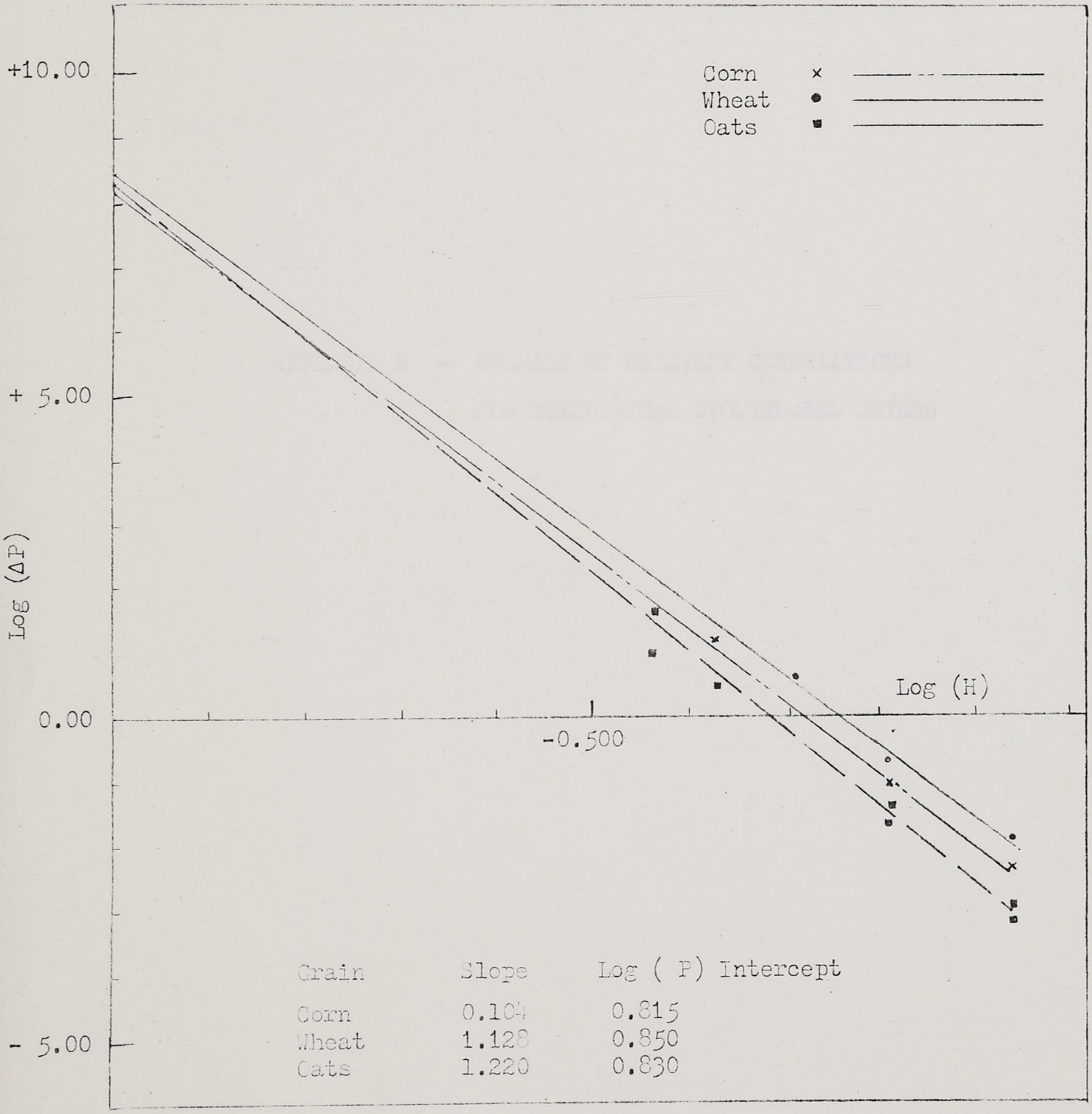
Total pressure drop across the grain bed versus superficial velocity for oats at 12.10% w.b. (bed depth: 15.62 cm)



Total pressure drop across the grain bed versus superficial velocity for oats at 12.10% w.b. (bed depth: 23.62 cm).



Total pressure drop across grain bed versus superficial velocity for oats at 22.45% w.b. (bed depth: 15.62 cm).



Grain	Slope	Log (P) Intercept
Corn	0.104	0.815
Wheat	1.128	0.850
Oats	1.220	0.830

Log (ΔP) versus Log (H) for corn, wheat and oats

APPENDIX B - SUMMARY OF RELEVANT CORRELATIONS FOR CYLINDRICAL SPOUTED BED DRYERS

SUMMARY OF RELEVANT CORRELATIONS:

In this section the reader will find the correlations suggested by various researchers, the bed geometry and the materials for which they were developed.

METHOD OF CALCULATION:

Velocity was calculated using the following relations:

$$v = \sqrt{2g\, h_{al}\left(\frac{S_o}{S_{air}} - 1\right)}$$

where: v = the air velocity at the position of the pitot tube

g = 9.806 m/s^2

h_{al} = the velocity head read off the alcohol containing manometer

S_o = specific gravity of alcohol at standard temperature and pressure.

S_{air} = specific gravity of air at standard temperature and pressure.

Volumetric flow in the pipe at the position of the pitot static tube was calculated by multiplying "v" by the cross-sectional area of the pipe which was $3.2429 \times 10^{-2}\ m^2$.

$$\dot{V} = (3.2429 \times 10^{-2})v$$

Superficial velocity could then be obtained by dividing $\dot{V}$ by the cross-sectional area of the dryer column which was $2.779 \times 10^{-2}\ m^2$.

$$U = 1.1672\ v$$

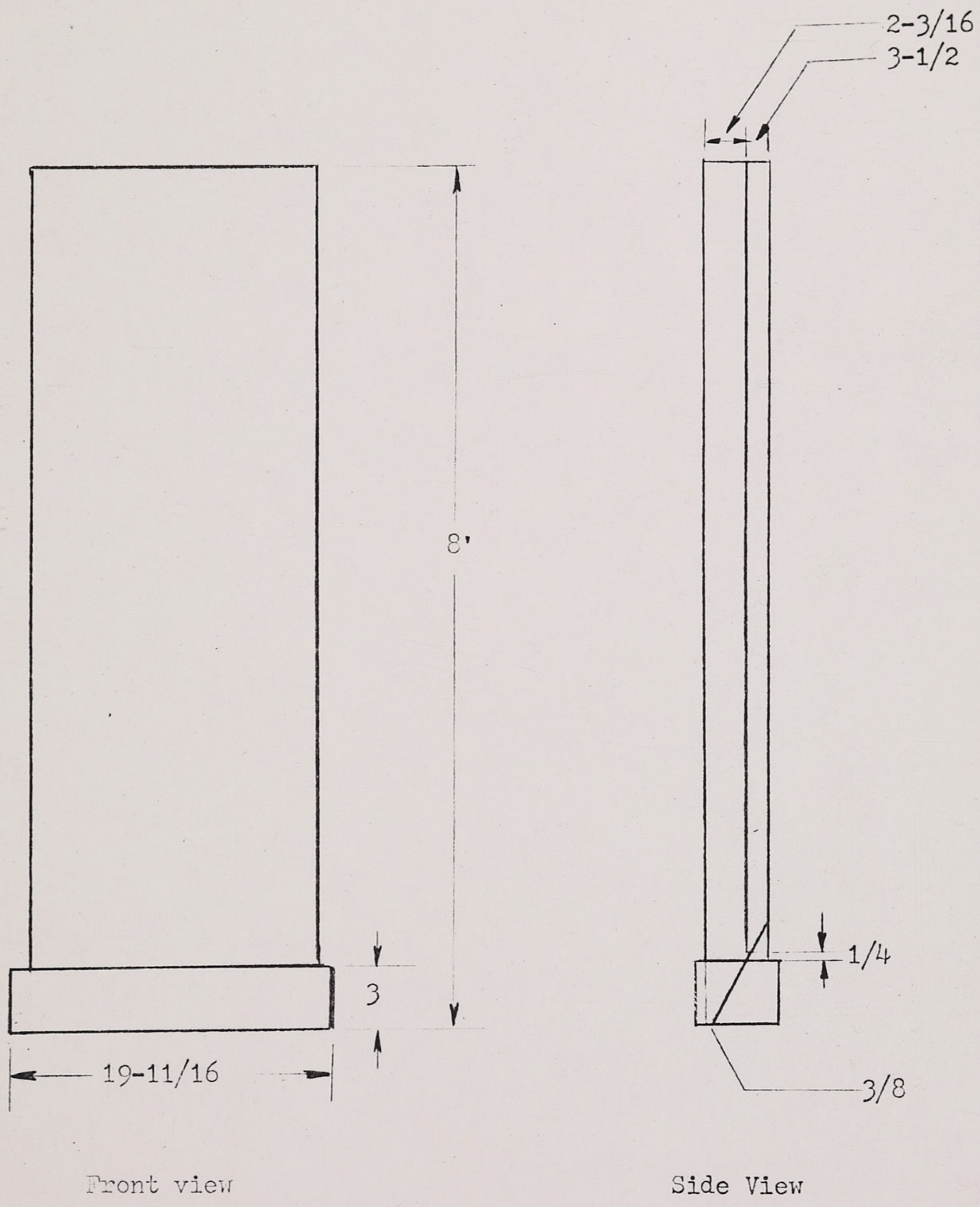
Researcher	Correlation and Remarks	Bed Geometry	Solids Used
Malek and Lu (1965)	$H_m = 0.105\left[\frac{D_c}{d_p}\right]^{0.75}\left[\frac{D_c}{D_i}\right]^{0.4}\frac{\lambda^2}{\rho_s^{1.2}}$ Predicted and measured values differ by ± 11%.	D_c = 10 - 23 cm Different orifice sizes	λ = 1.0 - 1.65 d_p = 0.8 - 3.7 mm ρ_s = 0.91 - 2.66 mg/m^3
Reddy et al. (Mathur and Epstein 1974)	$H_m = 11.6\ d_v^{1.26}\ D_i^{-0.33}\rho_s^{-0.2}$ For Re 70 $H_m = 20.4\ d_v^{-0.57} D_i^{-0.125}\ \rho_s^{-0.2}$ For Re 70 H_m, d_v, and D_i in inches, ρ_s in lbs per cubic foot.	Only 15 cm	Several materials of mixed size in the range 0.25 - 3.3 mm.
Becker (1961)	$U_{ms} = U_m\left[1 + s\ \ln\left(\frac{H}{H_m}\right)\right]$ $s = 0.0071\left(\frac{D_i}{D_c}\right)Re_m^{0.295}\psi^{2/3}$ $\left[\frac{H_m}{d_v}\right]\left[\frac{d_v}{D_c}\right]\left[12.2\ \frac{D_i}{D_c}\right]^{1.6\ \exp(-0.0072\ Re_m)}\left[\frac{2600}{Re_m} + 22\right]\psi^{2/3}\ Re_m^{1/3} = 42$ Good for $D_c > 0.61$ m, but for $D_c < 0.61$ Mathur and Gishler equation gives better results.	$\frac{H}{D_c} > 1$ $\frac{D_i}{D_c} < .1$	Re_m of 10 - 100

Researcher	Correlation and Remarks	Bed Geometry	Solids Used
Mathur and Gishler (1955)	$U_{ms} = \left[\frac{d_p}{D_c}\right]\left[\frac{D_i}{D_c}\right]^{1/3}\left[\frac{2gH(\rho_s - \rho_f)}{\rho_f}\right]^{1/2}$ Air and water are the two spouting fluids used. Good for column diameters up to 0.61 m.	D_c = 0.076 - 0.305 m	Large number of different, closely sized particles.
Littman and Morgan (1982)	$U_{ms} = -\frac{f_1}{2f_2\,U_{mf}} + \sqrt{\left(\frac{f_1}{2f_2\,U_{mf}}\right)^2 + \left(1 + \frac{f_1}{f_2\,U_{mf}}\right)C_p}$ $f_1 = 150(1 - \varepsilon_{mf})^2 \mu / \varepsilon_{mf}^{3} (\phi_s\, d_p)^2$ $f_2 = 1.75(1 - \varepsilon_{mf})\left[\rho_f / \varepsilon_{mf}^{3}\right] \phi_s\, d_p$ $C_p = 1 - Y - \frac{H}{D_c} \cdot X_1^{2} \frac{[2Y + (X-2) + (X-0.2) - (3.24/\theta)]}{[2Y + 2(X-0.2) - 1.8 + (3.24/\theta)]}$ $X = 1/[1 + (H/D_c)]$ $Y = 1 - (\Delta P_{ms} / \Delta P_{mf})$ $\theta = 7.18\left[A_{\phi_s} - (D_i / D_c)\right] + 1.07$ $A = \rho_f / (\rho_p - \rho_f)(U_{mf}\, U_t / g\, D_i)$		

Researcher	Correlation and Remarks	Bed Geometry	Solids Used
	$A_{\phi_s} = A(5\phi_s^3 - 7.57\phi_s^2 + 4.09\phi_s - 5.16)$ Fits a large amount of literature data to 11.6 % on average.		
Manurung (1964)	$-\frac{P_m}{H\rho_b g} = \left[\frac{6.8}{\tan\gamma}\left(\frac{D_i}{D_c}\right) + 0.80\right] - 34.4\frac{d_p}{H}$ Where $\tan\gamma$ is the coefficient of internal friction (1.25 for rape seed to 3.2 for coal). d_p was taken as the reciprocal mean dia. Good for $H/D_c > 1$	15 cm diameter 60° cones	Crushed coal, plastic particles, rape seed, millet. $d_p = 1 - 4$ mm $\rho_s = 0.92 - 1.43$ Mg/m^3
	$-\frac{P_s}{H\rho_b g} = \frac{1}{1 + \left[0.81(\tan\gamma)^{1.5}/\bar{\psi}^2\right]\left[D_c d_p / D_i^2\right]^{0.78}\left[D_c / H\right]}$ Predicted values are up to 30 % higher than those observed for large diameters (30.5 cm and 61 cm wheat).		Same data base as the first relation.

APPENDIX C - DRYER COLUMN DIMENSIONS

DRYER COLUMN DIMENSIONS:



* All dimensions are in inches unless otherwise specified