Analysis of Static Pressures for Cross-Flow Air Circulation in Cylindrical Grain Bins

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Bulletin No. B-645

March, 1966

Contents

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Cross-flow air systems seem potentially suitable for drying or aerating grain stored in tall, upright, clyindrical bins. The shorter air circulation path reduces air resistance compared to vertical circulation from bottom to top. As a result, blowers that operate against lower pressures can be used in cross-flow systems. The capital and operating costs may be reduced. During prolonged storage, cross-flow systems can be used with low air circulation for grain cooling and aeration.

The objective of this experiment was to develop a prediction equation for cross-flow air circulation through cylindrical bins of wheat, or physically similar grains. A prediction equation thus obtained could then be used to design or predict performance of cross-flow ventilation systems similar to those investigated in this experiment.

Figure 1 shows a prototype arrangement for a cross-flow drying or aeration system. Figure 2 shows the three air flow arrangements which were studied.

Experimental Prediction Equation

An experimentally-derived prediction equation was obtained based on results from experiments with three model systems. The design and conduct of the experiments and analysis of the data were based on similitude theory. The general approach was to identify the pertinent quantities which characterized the system and then organize them into dimensionless parameters, referred to as Π terms. Then, experiments were conducted in which each of the independent parameters was varied, one at a time, while the response of the dependent parameter was ob-

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Research reported herein was done under Oklahoma Station project 679.

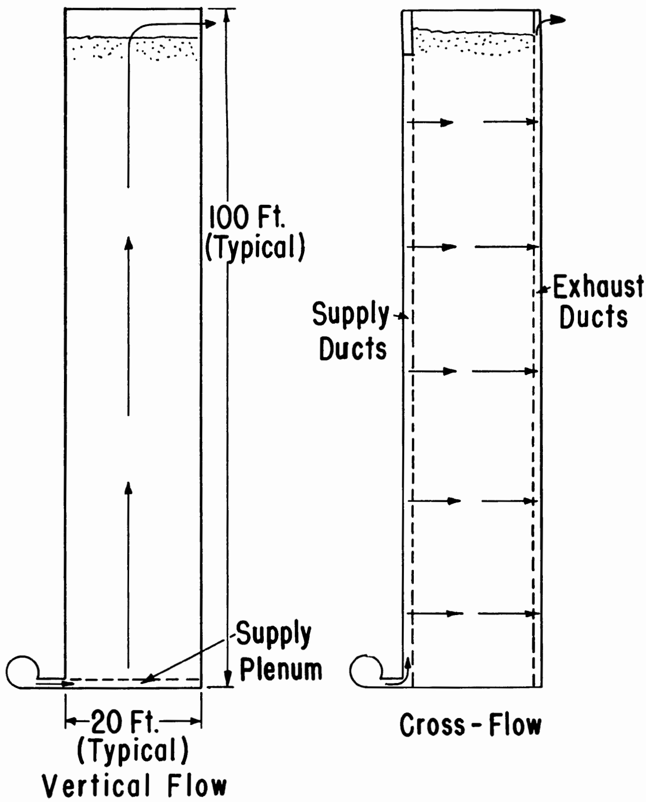


Figure 1 — Typical configurations of vertical flow and cross-flow drying or aerating systems in deep cylindrical bins.

served. Each experiment produced a component equation. Finally, the component equations were combined mathematically to obtain a final prediction equation that related the dependent parameter to all of the independent parameters.

Knowledge of the basic mechanics of fluid flow through packings, such as wheat in a tall cylindrical bin, was used to identify the pertinent quantities. These are listed in Table 1. The dimensional system used in Table 1 includes force(F), mass(M), length(L), and time(T). The inertial effects in the fluid flow system are indicated by including Newton's second law coefficient as one of the pertinent quantities. In Table 1, N is the total number of ducts, 2, 4, or 6, with the duct inlet and exhaust arrangements shown in Figure 2.

No.	Symbol	Description	Units	Dimensional Symbol
1	N	Total Number Of Ducts (cf. Fig. 2)	——	Dimensionless
2	α	Particle Shape Index	——	Dimensionless
3	ν	Particle Surface Roughness Index	——	Dimensionless
4	d	Particle Characteristic Dimension	Ft.	L
5	D	Cylinder Diameter	Ft.	L
6	ρ	Fluid Density	$Lb._M$/cu. Ft.	ML^{-3}
7	μ	Fluid Viscosity	($Lb._F$/Sq.Ft.)x Sec.	$FL^{-2}T$
8	Q	Fluid Circulation Rate	Cu.Ft. Fluid/Cu. Ft. Packing x Sec.	T^{-1}
9	P	Fluid Static Pressure Drop Through Packing Between Inlet And Outlet Ducts.	$Lb._F$/Sq.Ft.	FL^{-2}
10	N_e	Newton's 2nd Law Coefficient, $\frac{1}{32.2}$	$Lb._F/(Lb._M$ x Ft./Sec.^{2})	$FM^{-1}L^{-1}T^2$

Table 1 — Quantities pertinent to cross-flow fluid (air) circulation through cylindrical bins of wheat with spaced ducts.

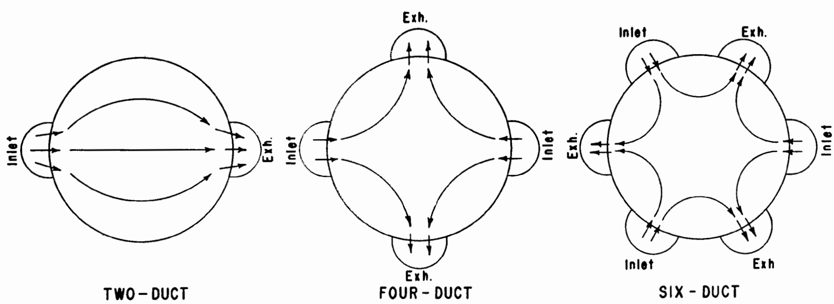


Figure 2 — Cross-flow duct arrangements and schematic flow paths.

These quantities were organized into six terms as listed in Table 2. These are dimensionless and independent. Next, based on the hypothesis that the quantities listed in Table 1 are adequate to characterize the system, equation 1 can be written to indicate that some mathematical function exists relating the dependent term to the other five independent terms. For a specific packing material such as wheat, terms 5 and 6 are essentially constant. Therefore equation 2 is valid for the present study. Substituting the definitions of the terms from Table 2 gives equation 3.

In Table 2, term 1 is an index of the ratio of static pressure forces to inertial forces developed in fluid (air) flow through the packing. (Note that the product of the fluid circulation rate, Q, and cylinder diameter, D, is an index of fluid velocity through the packing.) Term 2,

No.	Symbol	Definition	Description
1	π_1	$\frac{P}{Q^2 D^2 \rho N_e}$	Index Of Ratio Of Fluid Static Pressure Forces To Fluid Inertial Forces
2	π_2	$\frac{d}{D}$	Index Of Ratio Of Particle Size To Fluid Flow Path Length
3	π_3	N	Total Number Of Ducts (cf. Fig. 2)
4	π_4	$\frac{Q D d \rho N_e}{\mu}$	Index Of Ratio Of Fluid Inertial Forces To Fluid Viscous Forces (Reynolds No.)
5	π_5	α	Particle Shape Index
6	π_6	ν	Particle Surface Roughness Index

Table 2 — Dimensionless terms for analysis of cross-flow fluid circulation through cylindrical bins of wheat.

Equation 1

$$\pi_1 = f_1(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6)$$

Equation 2

$$\pi_1 = f_2(\pi_2, \pi_3, \pi_4)$$

Equation 3

$$\frac{P}{Q^2 D^2 \rho N_e} = f_2\left(\frac{d}{D}, N, \frac{Q D d \rho N_e}{\mu}\right)$$

the ratio of particle or wheat kernel size to bin diameter, may be regarded as an index of the ratio of the cross-section size of an interstitial flow path through the packing to flow path length. Term 4 is a form of Reynold's number, an index of the ratio of fluid inertial forces to viscous forces. At very low Reynold's numbers, only viscous forces affect the flow, and inertial forces are insignificant. Then pressure drop "P" varies directly and linearly with fluid flow velocity through the packing.

The function relating term 1 to the other three parameters was evaluated by controlled experiments over a range of air flow rates from approximately 0.02 to 0.50 cu. ft. per second per cu. ft. of grain, and for three cross-flow configurations, two-duct, four-duct, and six-duct. More detailed information on the experimental equipment and methods has been given by Day and Nelson (1964).

The experimental data were analyzed mathematically to produce equation 4. It can be used to predict static pressure drop in fluid (air) circulation across cylindrical beds of grain with any of the three cross-flow duct arrangements illustrated in Figure 2, and for values of terms Π_2, Π_3, and Π_4 covered in the experiments.

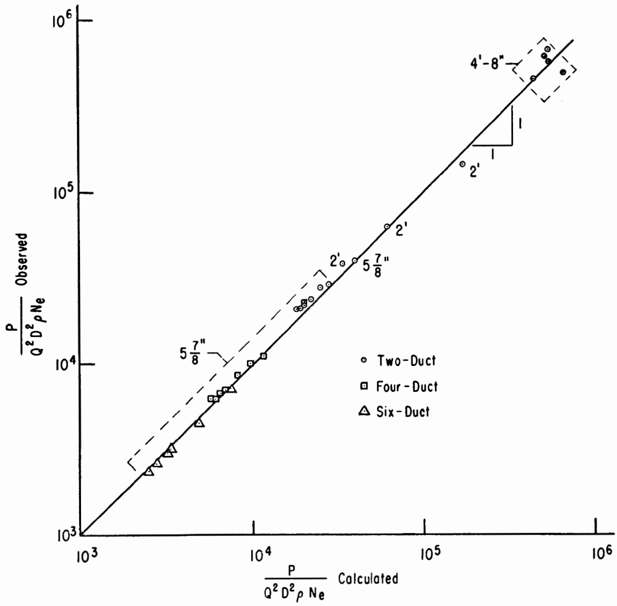
Equation 4

$$\frac{P}{Q^2 D^2 \rho N_e} = 6.767 \times 10^{-3} \left(\frac{d}{D}\right)^{-1.349} (N)^{-1.410} \left(\frac{QDd\rho N_e}{\mu}\right)^{-0.744}$$

It should be noted that term 4, Reynold's number, appears in equation 4 with exponent (—0.744). The absolute value of the exponent is an index of the relative influence of inertial and viscous effects in the flow. At exponent absolute values of unity (1.00), the flow is known to be incluenced by viscous effects only. At exponent absolute values much less, than unity, the flow is influenced mainly by inertial forces; and viscous forces are relatively insignificant. As has been pointed out by Rose (1950), the resistance coefficient of a single spherical particle in a fluid stream varies as Reynold's number with an exponent (—1.00) when Reynold's number is less than approximately 10. At Reynolds numbers between 10 and 100, the value of the exponent begins to decrease. At Reynolds numbers larger than about 1000, the exponent is practically zero. The resistance becomes independent of Reynolds number and is influenced by inertial effects only.

It appears that flow in the present experiments was governed partly by viscous and partly by inertial effects, because the absolute value of the exponent which best fits the data is 0.744. The numerical values of the Reynolds number as defined in Table II were in the range 4.25 to 14.0 (approximately). The Reynolds number exponent in equation 4 is consistent with the Reynolds number values that prevailed. It should be noted that as defined in the present study, Reynolds number is based on a nominal velocity, calculated as flow per unit volume of packing multiple by packing diameter. The mean flow velocity is doubtless greater, because the flow paths diverge from the inlet to the mid-point of the flow path, then converge to the exhaust.

Figure 3 shows a graph of the precision with which the observed values of the pressure drop parameter, Π term 1, agree with those calculated by prediction equation 4. The notation accompanying the plotted points, 5-7/8″, 2′, and 4′-8″, indicates the diameter of the model bins used in the experiments.



$$\frac{P}{Q^2 D^2 \rho N_e} = 6.767 \times 10^3 \left(\frac{d}{D}\right)^{-1.349} (N)^{-1.410} \left(\frac{Q D d \rho N_e}{\mu}\right)^{-0.744}$$

Figure 3 — Precision of prediction equation for static pressure drop in cross-flow circulation.

Analog Studies

Flow of a fluid such as air across a cylindrical bin of wheat or other granular packing can be simulated by electrical current in a sheet of conducting paper cut to a cross-sectional shape geometrically similar to the cross-section configuration of the bin or container of the packing through which fluid flow occurs. Conductive paint to form terminals is applied to tabs at the edges of the sheet to correspond with the inlet and outlet ducts in the prototype. A potentiometer probe is used to define lines of constant potential when current is flowing through the analog. A more complete description of equipment and procedures has been given by Hamilton (1964). These constant potential lines are analogous to lines of constant pressure in the cross-flow system. A typical plot is shown in Figure 4(a).

Flow paths are defined with a second conducting sheet of the same cross-sectional shape and size, but with terminals corresponding to the bin perimeter portions between the inlet and outlet ducts. The flow path lines will be orthogonal to the equipotential lines. A map of the flow path lines, Figure 4(b) in the cross-flow system obtained with the electrical analog can be used for qualitative analysis of cross-flow circulation. Where the flow paths are wide, air velocity is low, and drying or cooling rate may be reduced.

The flow path lines and equal pressure lines are not completely symmetrical in Figure 4, especially for the innermost lines. This lack of symmetry occurred because the conducting paper for the analog had slight directional variations in electrical resistance. Ideally, the analog paper should have the same electrical resistance in all directions.

An electrical analog can be used also for quantitative estimates of flow rate and corresponding static pressure drop through a packing.

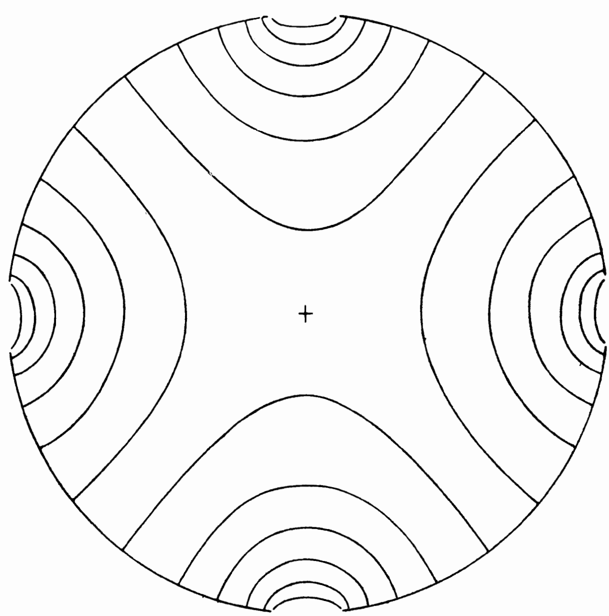
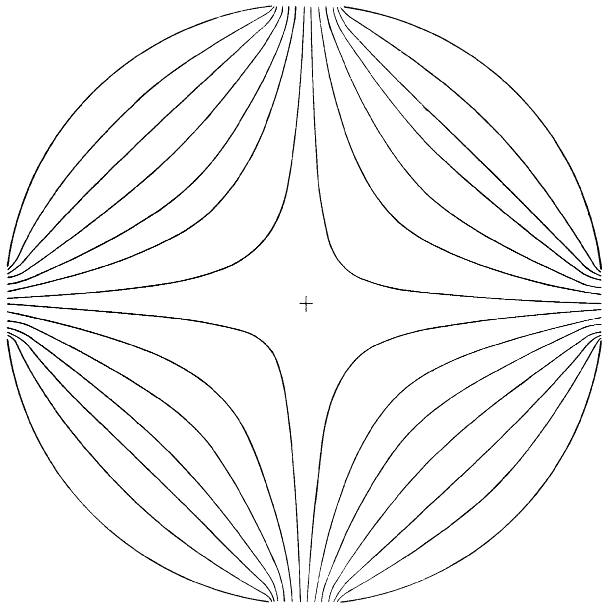
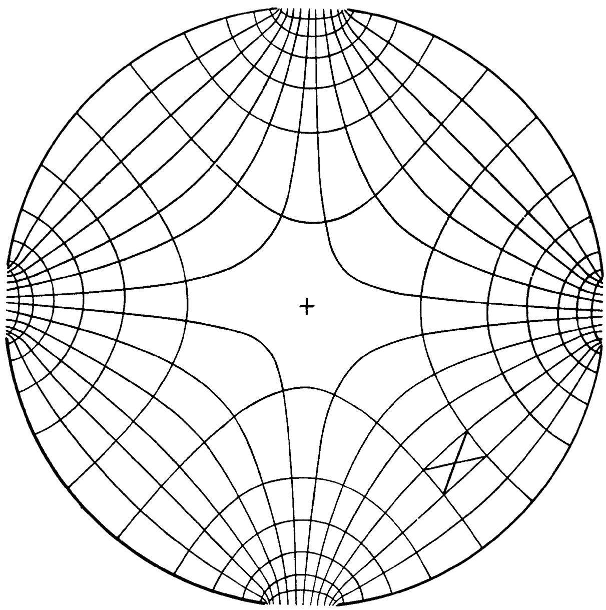


Figure 4 — Constant static pressure lines and air flow path lines in a 4-duct cross-flow system predicted with an electrical analog. (a) Constant static pressure lines



4(b) Flow path lines



4(c) Complete flow net

One method utilizes a flow net, such as Figure 4(c), obtained by superimposing equipotential and flow path lines. If the resistance, r, of the packing material to fluid circulation through the packing is known, the static pressure drop due to flow through a grid segment, such as the one marked with an "X" in Figure 4(c), can be computed assuming uniform flow intensity. The flow intensity will be the flow rate per path divided by the path cross-section. The flow per path will be the total flow from an inlet divided by the number of paths from the inlet. The total pressure drop between inlet and outlet will be the pressure drop across such a segment as "X" in Figure 4(c) times the number of segments between the inlet and outlet along a given flow path.

A second method is based on measurement of electrical current flow through the analog. The electrical resistance "R" of the conductive paper and a resistance coefficient "r" for the material of the packing must be known. Equation 5 gives a relationship for predicting static pressure drop in the cross-flow air circulation system from voltage and current measurements on the analog conducting sheet.

Equation 5

$$P = \frac{\pi D^2}{4} \times Q \times \frac{V}{I} \times \frac{r}{R}$$

Where:

P = Fluid Air Static Pressure Drop, As Defined, Table I.

π = 3.14····

D = Cylindrical Bin Diameter, Ft.

Q = Fluid Circulation Rate, As Defined, Table I.

V = Electrical Potential Across Conducting Sheet Analog, Volts, Between (+) And (-) Terminals.

I = Total Current Through Conducting Sheet Analog, Amps.

r = Packing (Grain) Resistance To Air Flow, [(Lb.$_F$ Static Pressure Drop/Sq.Ft.)/Ft.] /(cfs/Sq.Ft.)
Note: (cfs/Sq.Ft.) Is Flow Intensity Through Cross-Section Normal To Direction Of Flow.

R = Electrical Resistance Of Conducting Sheet Analog, (Volts/Ft.)/(Amp./Ft.), Or Ohms/"Square".

In the present study, an analysis was made to compare quantitative predictions from an electrical analog using equation 5 with predictions by equation 4. The resistance of the analog conducting paper has been determined as 1175 ohms per square by measurements on a square sample. The unit resistance of wheat used in the model experiments was based on data in reference 4, approximately 7.0. Figure 5 shows the predicted static pressure drop, H′, inches of water static pressure drop across the packing, as a function of fluid circulation rate, Q′, in cu. ft. per min. per cu. ft. of grain, through the packing in a 4-duct cross-flow system. The solid lines, one each for cylinder diameters of 40 ft., 20 ft., 10 ft., and 5 ft., are predicted by equation 4, developed from analysis of experimental data. The broken lines are for predicted values using equation 5 and results with the conducting paper electrical analog for grain resistances of 7.0 and 9.0, respectively.

It appears that the electrical analog gives usable results, but the range of agreement of the analog prediction with experiment-based predictions by equation 4 is limited. The limitation occurs because the analog is based on the condition that pressure drop varies directly and linearly with Q, (viscous effects only) but in the experiment-based prediction equation 4, pressure drop varies directly with Q raised to the exponent 1.256. To obtain usable results with an electrical analog, the resistance "r" of the grain to use in equation 5 has to be adjusted for the mean flow rate that will occur in the prototype. Higher flow rates will produce a higher resistance "r". For important studies, it would appear desirable to check the results from the analog by a few

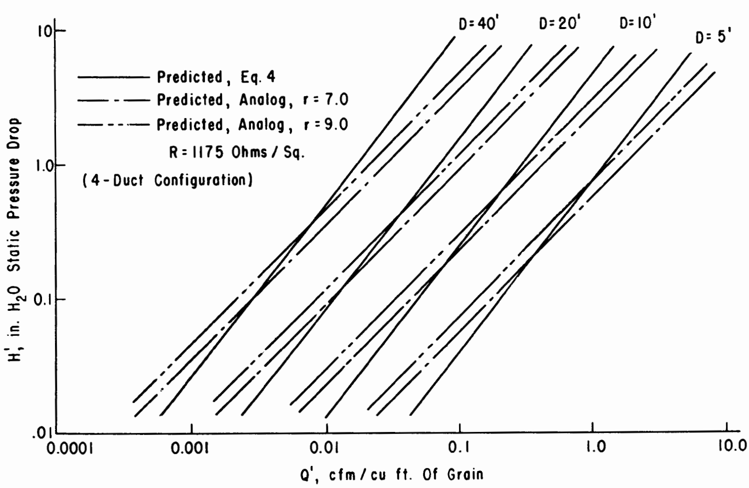


Figure 5 — Comparison of static pressure drop in a cross-flow system predicted by experimentally-derived equation 4 and by electrical analog.

experiments with a prototype pilot model. It should be noted that very low flow rates in a prototype system would exhibit linear variation of resistance with flow rate, and the electrical analog would be a true analog.

Summary and Conclusions

Experiments were conducted using models of three bin sizes to develop a prediction equation for cross-flow air circulation through cylindrical bins of wheat. The prediction equation obtained can be used in designing and predicting the performance of cross-flow, spaced-duct systems of the arrangements shown in Figure 2, and for values of the independent parameters covered in the experiments.

An analog simulation study was made using an electrically conducting sheet. It was shown that the analog gives useful results, compared to the experimentally-derived prediction equation, over a restricted range of air circulation rate. The restriction occurs because flow through the actual grain was governed partly by viscous and partly by inertial forces; but for compatibility with the electrical analog, only viscous effects should exist.

References

1. Day, D. L. and G. L. Nelson. Drying effects of air circulation on wheat stored in deep cylindrical bins. Okla. Ag. Exp. Bull. T-106. Jan. 1964.

2. Rose, H. E. Fluid flow through beds of granular material, in: some aspects of fluid flow. Conference by the Institute of Physics, London, at Leamington Spa. Oct. 25-28, 1950. pp. 136-163. Edward Arnold and Co.

3. Hamilton, Harvey E. Application of an electrical analog to predict cross-flow aeration characteristics in grain drying systems. Unpublished report. Jan. 17, 1964. Agricultural Engineering Department, Oklahoma State University.

4. ASAE Data. ASAE D272. Resistance to air flow through grains and storage components. Agricultural Engineers Yearbook. p. 272. 1965. American Society of Agricultural Engineers, St. Joseph, Michigan.