EVALUATION OF GRAIN AIRFLOW RESISTANCE CHARACTERISTICS AND AIR DELIVERY SYSTEMS

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Field and laboratory tests were conducted on fans and air distribution systems used for moving unheated air through grain. Performance characteristics of more than 100 fans were determined, and several multiple fan configurations were also tested. Four fan transitions and numerous perforated flooring materials were tested to determine their resistance to airflow. The airflow resistance of wheat, barley, sunflowers, canola, corn and flax was determined in typical farm grain bins. The resistance of partially perforated floors and the effect of grain spreaders was investigated. A hopper bottom bin aeration system was designed and tested.

INTRODUCTION

The possibilities of drying grains and oilseeds in storage, using ambient air, generated a high level of interest among prairie grain farmers in the late 1970s and early 1980s. The costs of fossil fuels were rising sharply and "natural air drying" as it is commonly known appeared to offer possibilities of reducing energy costs for grain drying. The inconvenience and extra handling involved in heated air grain drying also made natural air drying appear more attactive in comparison. Natural air drying also allowed a farmer to do some grain drying on a small scale with a relatively small investment. Numerous inquiries from farmers and equipment suppliers indicated a strong need for information on all aspects of natural air drying. Airflow requirements were available for corn and wheat from a computer simulation study done by Fraser and Muir (1981), but there was no reliable information on the actual airflow resistance of grains and oilseeds in farm grain bins, the performance of commonly available aeration fans, the effects of different perforated flooring types and configurations or design requirements for four transitions. Only very limited information was available on the effects of grain spreaders. Some operational and design information for natural air drying of corn was found in various U.S. extension publications, but its applicability to Canadian crops and weather conditions was not known. Shedd (1953), Chang et al. (1980, 1982), Lawton (1965), Osborne (1961) and Foster and Stephens (1976, 1978) conducted numerous laboratory tests on the airflow resistance of small batches of grains and oilseeds but the applicability of these values for farm design situations was not known. Boyce and Davies (1965) conducted tests on pressure requirements for duct systems with varying percentages of open areas, but no data were obtained to compare these results with the pressure requirements for fully perforated floors. Spencer (1969) developed a mathematical model to obtain estimates of the pressure drops for on-floor duct drying systems.

TABLE I. AVERAGE FAN OUTPUTS

	Motor power (kW)						
	0.56	0.75	1.1−1.5	2.2−3.0	3.7−5.2	5.2−6.7	7.8
	Diameter (mm)						
	305	355	455	455	610	610	610
Type: Axial Flow Pressure (Pa)	*Air flow at indicated static pressure (L/s)*						
125	880	1230	2180	2740	5040	5060	6270
250	420	910	1900	2550	4600	4760	5920
375	260	640	1570	2260	4380	4380	5500
500	140	470	1230	1900	4020	3990	5050
625		320	900	1480	3600	3570	4440
750		140	620	1140	3140	3140	3730
875		70	390	900	2610	2690	3000
1000			210	710	2140	2250	2400
1125			50	520	1730	1830	1890
1250				350	1350	1440	1500
1375				220	1010	1100	1110
1500				90	680	800	730
1625					510	580	290
1750					220	370	
1875					90	220	
2000						40	
Sample size	6	6	7	14	6	4	2

	Motor power (kW)				
	2.2	3.7	5.6	7.5	11.2
Type: Centrifugal 3450 rev/min Pressure (Pa)	*Air flow at indicated static pressure (L/s)*				
250	1540	1870	2420	2870	4140
500	1450	1770	2320	2770	3970
750	1350	1690	2220	2680	3840
1000	1240	1590	2120	2560	3730
1250	1120	1500	2000	2450	3580
1500	970	1390	1880	2350	3430
1750	720	1280	1750	2240	3290
2000	550	1110	1620	2120	3130
2250	310	860	1490	1980	2950
2500	80	330	1350	1830	2780
2750		100	1080	1580	2570
3000			840	1330	2290
3250			590	1050	1890
3500			260	670	1060
Sample size	6	7	5	3	2

An overview of the complete Manitoba

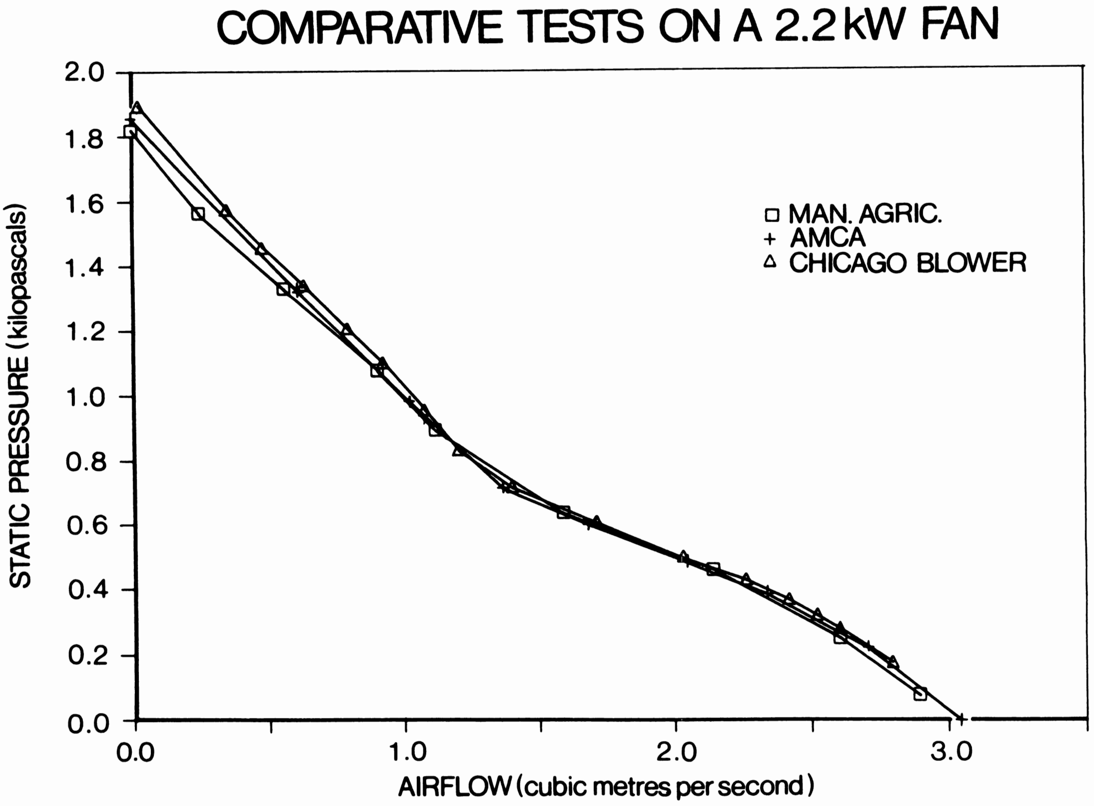


Figure 1. Comparison of test results on an axial fan obtained by three different laboratory tests.

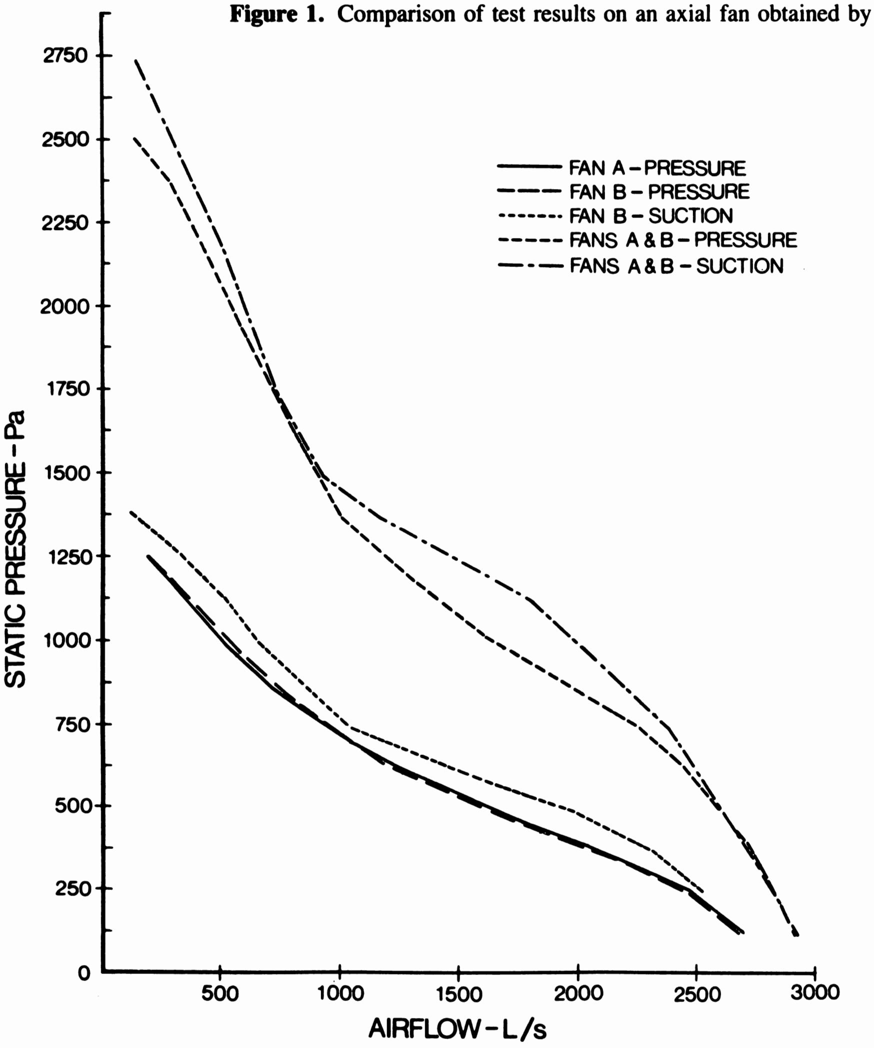


Figure 2. Inlet and outlet tests on two axial fans individually and in series.

Agriculture extension program related to grain aeration and natural air drying was presented by Friesen (1981). This paper concentrates on the field and laboratory measurements and analysis, and does not include the dissemination of information obtained, nor the computer analysis done by Fraser and Muir (1981) to predict the minimum required airflow rates.

Field and laboratory measurements were made to determine the system characteristics and performance of air delivery and distribution components and to obtain field data on the actual airflow characteristics of grains, oilseeds and pulse crops grown in Manitoba. The information obtained is used to design aeration and natural air-drying systems, select components, and provide operational and management counsel.

METHODS

Controlled tests on aeration fans were conducted in the laboratory, using the procedures outlined in AMCA Standard 210-74 (Fig. 7, Air Movement and Control Association (AMCA 1975)). These tests were initiated by Metzger et al. (1980) and continued by Manitoba Agriculture staff. In total, about 140 individual tests were conducted. Fans were obtained from manufacturers, dealers and farmers. The selection of makes and models was based on farmer interest, avail-

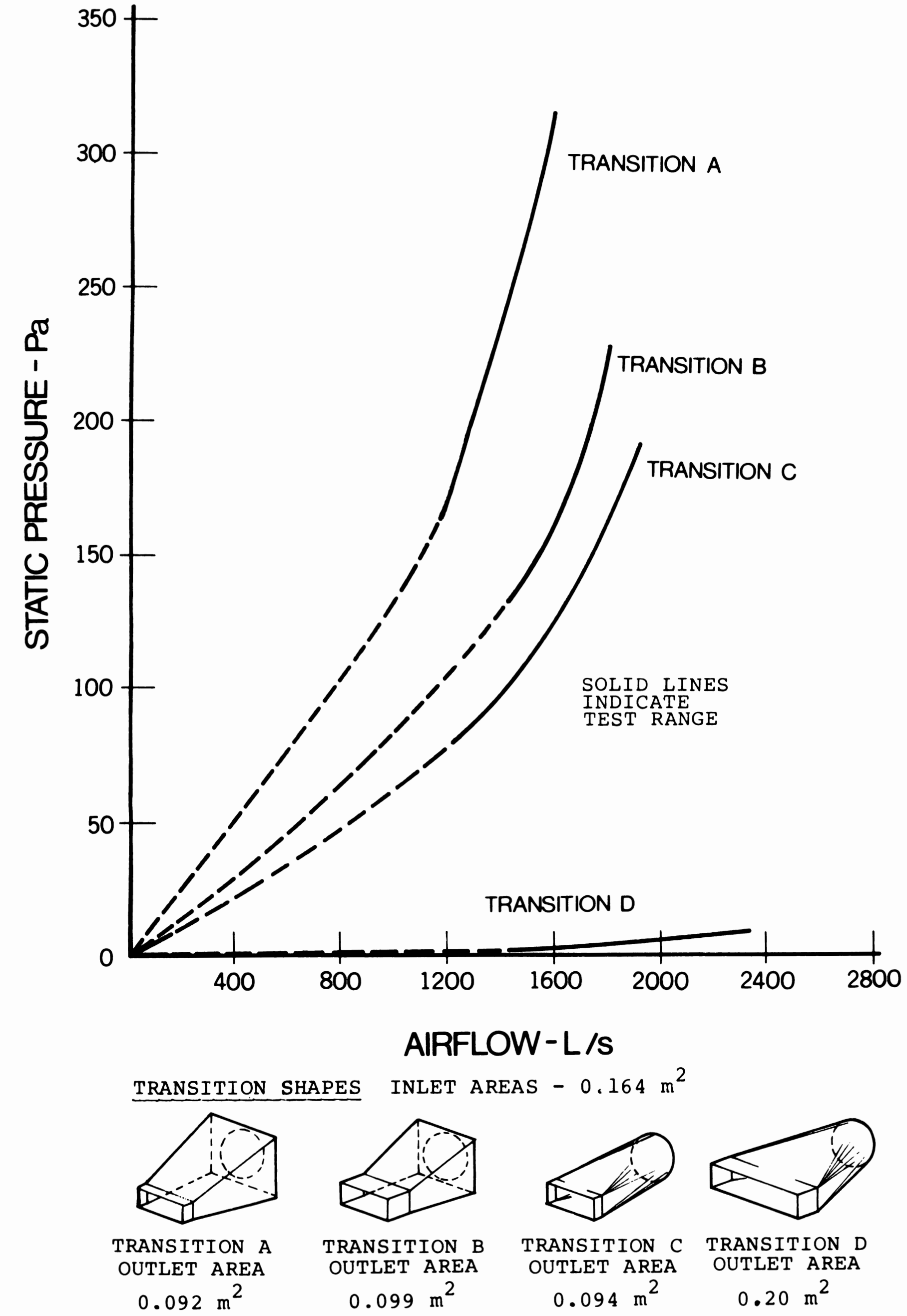


Figure 3. Pressure losses through four different fan transitions.

ability in Manitoba, and in some cases the desires of manufacturers to have a new model or prototype tested. All fans were tested on the pressure side, with inlet screens in place, and without any changes or adjustments. In several instances duplicate tests were performed on different fans of the same make and model and, in a few cases, tests were repeated on the same fan on two different dates. An additional check was made by comparing the results of several tests with those obtained on the same fans at the Chicago Blower Canada test laboratory, and in one case with the AMCA lab in Chicago, Ill. Some auxiliary tests were made on two fans in series (both in suction and pressure) and a single fan in suction.

Several transition shapes were also tested in the laboratory. These were tested by attaching the transition to the discharge end of the outlet duct and varying the airflow by means of a throttling device attached to the transition outlet.

Field tests to determine the airflow resistance of various crops were conducted in farmers' grain bins throughout Manitoba. A wide variety of situations was encountered including different crop varieties, foreign materials (weed seeds, chaff, etc.), grain depths, bin diameters, etc. Wherever possible, grain bins were fitted with pressure taps before harvest to simplify the pressure measurements and to allow the placing of pressure pickups both above and below the perforated floors. For the first 4 yr (1979–1982) the farmers' fans were used to provide the airflow for the tests. This provided only one test point per setup. In 1983 a 3.75-kW centrifugal fan with adjustable shutters was obtained for the field tests. This allowed several (usually three) different airflows to be checked for each setup. A total of 214 tests were conducted on wheat, barley, sunflowers, rapeseed (canola), corn, flax, rye, peas and lentils. The airflow test method used was similar to the inlet duct setup shown in AMCA, Fig. 16 (1975) except that no straightening vanes were used. The fans were all positioned to force air into the bin and up through the grain. The bins were sealed around the base, auger ports, doors, etc. to prevent air losses and the top filler holes, entrance doors, etc. were opened to minimize air outlet restrictions. Wherever possible the grain surface was levelled for the tests.

A series of tests was performed to determine the effect of partially perforated floors on the pressure loss through the grain. Two identical 5.8-m-diameter bins with fully perforated floors were used for the tests. Airflow-pressure tests were conducted on the first bin which contained 150 m^3 of wheat. The second bin was fitted with a plastic sheet which covered about 50% of the floor area, and the wheat from the first bin was then transferred into the second bin. The same procedure was repeated with about 70 and 85% of the bin floors covered with plastic. The exposed perforated floor area was a rectangle at the center of the bin with the longest dimension being 3.63 m in each instance. Airflow-pressure tests were conducted after each transfer.

Two sets of field tests were conducted on grain bins using two fans in series. Tests were conducted with the following arrangements:

- two fans pushing air up through the grain
- a single fan pushing air up through the grain
- a single fan drawing air down through the grain
- one fan pushing air up through the grain and the other fan drawing air up through the grain.

Field tests on two hopper bottom bin aeration systems were conducted to determine the airflow distribution patterns produced. One system was designed by the first author and the other system was a commercial prototype.

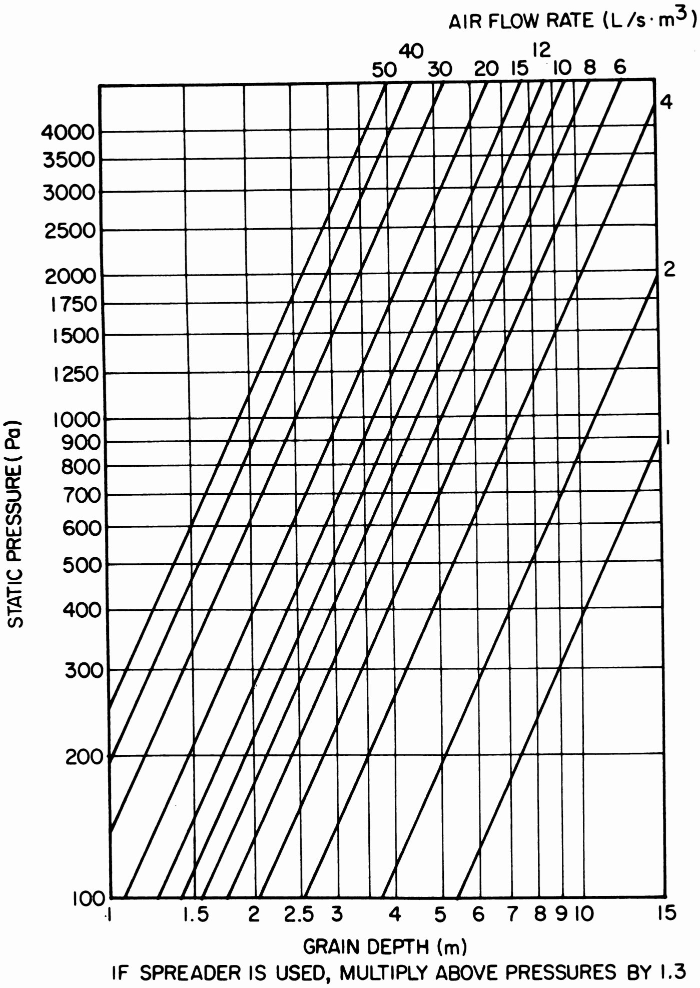


Figure 4. Airflow resistance for wheat on a fully perforated floor.

TABLE II. FIELD TEST DATA AND ANALYSIS (FULLY PERFORATED FLOORS)

Crop	No. of tests	*x* factor† $\bar{x}$	*x* factor† σ	*x* factor† $\bar{x} + 1.5\sigma$	*y* factor†	Range of air velocities tested ($L \cdot s^{-1} \cdot m^{-2}$)
Wheat	30	2.16	0.30	2.6	1.17	13–88
Barley	25	2.05 <50‡	0.42	2.7	1.10	18–91
		0.81 >50‡	0.17	1.07	1.34	
Sunflowers	18	0.89	0.11	1.05	1.29	27–115
Rapeseed	14	6.50	1.01	8.0	1.05	12–77
Corn	7	0.46	0.07	0.56	1.35	14–55
Flax	5	15.7	0.89	17.0	1.06	9–37

†$Pa/m = x(L \cdot s^{-1} \cdot m^{-2})^y$.
‡Air velocity in $L \cdot s^{-1} \cdot m^{-2}$

RESULTS

The results of the laboratory fan tests are shown in Table I, as an average of the fans of each size and type. Not enough tubular centrifugal fans and low-speed centrifugal fans were tested to determine representative performance data. A comparison of the test results obtained by Manitoba Agriculture, AMCA (Chicago) and Chicago Blower Canada Ltd., (Winnipeg) on a 2.2-kW axial fan is shown in Fig. 1. The performance of 91 individual makes and models is given in the publication *Fan test results* by Huminicky and Friesen (1983).

Tests on two axial fans in series produced the results shown in Fig. 2. The small differences in output between the pressure and suction modes were attributed to differences in inlet and outlet conditions in the test setup. Details of the tests are contained in a report by Huminicki (1982).

The airflow resistance of four transitions is shown in Fig. 3. The solid lines indicate the test range, and the dashed lines are extrapolations. The outlet area of the transition had the greatest effect on the pressure loss produced. Transition D had an outlet area twice as great as the other transitions and an insignificant pressure loss over the airflow range tested. Transition shape also had an effect, with the smoother lines and absence of abrupt enlargements in transition C producing a lower pressure loss than transitions A or B. The loss in transition A is about 5.4 h_v, in B it is about 3.0 h_v, in C about 2.3 h_v and in D about 0.055 h_v, based on the air inlet velocity.

The ISO Standard 4174 (1980) suggests that airflow resistance equations for laboratory samples of grain should be of the form $A = xB + yB^2$. However, field tests to determine the airflow resistance of various crops on fully perforated floors confirmed that, in general, the pressure loss equation for farm grain storages is of the form

$$A = x(B)^y \quad (1)$$

as was previously indicated by Boyce and Davies (1965) and Matthies and Petersen (1974), where *A* is the pressure drop in pascals per metre (Pa/m) of grain depth, *B* is the airflow (L/s) divided by the perforated floor area (m²) and *x*, *y* are experimentally obtained coefficients.

The coefficients for various crops were determined to be as follows:

$$\text{Wheat, } Pa/m = 2.6\,(L \cdot s^{-1} \cdot m^{-2})^{1.17} \quad (2)$$

$$\text{Barley, } Pa/m = 2.7\,(L \cdot s^{-1} \cdot m^{-2})^{1.10} \quad \text{if } L \cdot s^{-1} \cdot m^{-2} \leq 50 \quad (3)$$

$$Pa/m = 1.07\,(L \cdot s^{-1} \cdot m^{-2})^{1.34} \quad \text{if } L \cdot s^{-1} \cdot m^{-2} > 50 \quad (4)$$

$$\text{Sunflowers, } Pa/m = 1.05\,(L \cdot s^{-1} \cdot m^{-2})^{1.29} \quad (5)$$

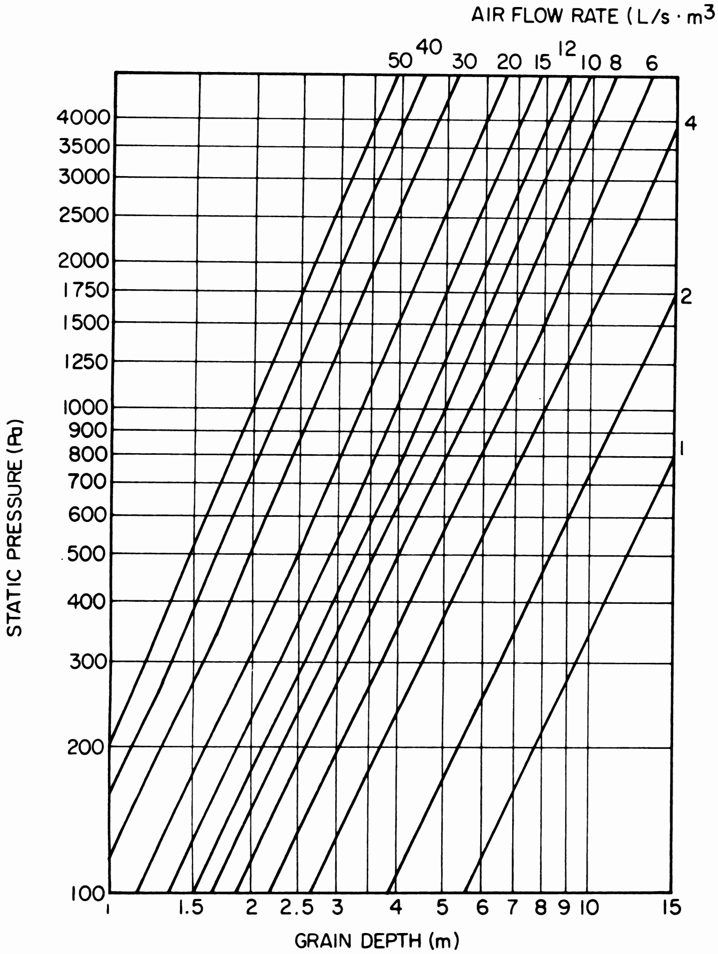
$$\text{Corn, } Pa/m = 0.56\,(L \cdot s^{-1} \cdot m^{-2})^{1.35} \quad (6)$$

$$\text{Flax, } Pa/m = 17.0\,(L \cdot s^{-1} \cdot m^{-2})^{1.06} \quad (7)$$

$$\text{Argentine rapeseed, } Pa/m = 8.0\,(L \cdot s^{-1} \cdot m^{-2})^{1.05} \quad (8)$$

Figures 4 to 9 are derived from the above equations. The number of tests, the mean values and standard deviations for each crop are given in Table II.

The equations are based on the average resistance plus 1.5 standard deviations. It would be expected, therefore, that 90% of all samples would have a pressure requirement equal to or less than that predicted by these equations. Conversely, 10% of all samples would be expected to have pressure requirements higher than those predicted. Insufficient data were obtained on peas, lentils and rye to make a reliable prediction on these crops. Full details



IF SPREADER IS USED, MULTIPLY ABOVE PRESSURES BY 1.5

Figure 5. Airflow resistance for barley on a fully perforated floor.

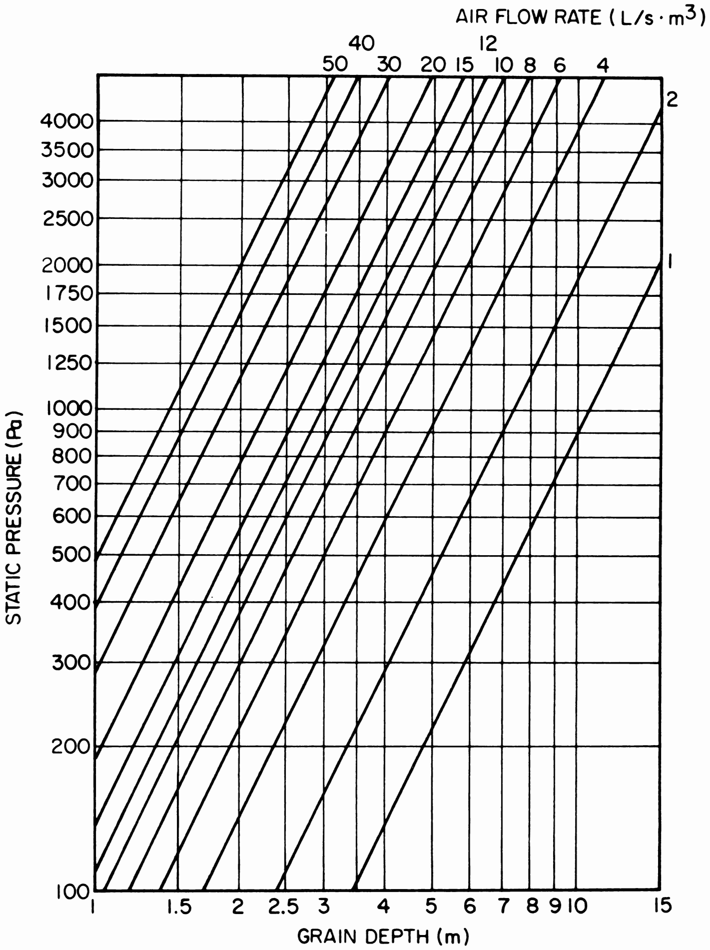


Figure 6. Airflow resistance for Argentine rapeseed on a fully perforated floor.

of the individual field tests are given in Manitoba Agriculture internal reports by Friesen (1979, 1982a, 1983a) and Huminicki (1980b, 1981).

The mean resistance for wheat obtained in these field tests falls between the loose and packed fill values obtained by Shedd (1953), the value for barley is close to Shedd's packed fill value, and the values for corn and flax are substantially higher than Shedd's packed fill values. The values obtained for rapeseed are very close to those reported by Moysey (1973), but are somewhat higher than those reported by Lawton (1965). The values for sunflowers are substantially higher than those reported by Moysey (1973). The factors for wheat and barley produce values very close to those suggested by Matthies and Petersen (1974).

The effects of partially perforated floors, flooring types, and grain spreaders were also investigated. Grain spreaders are not commonly used in Manitoba, so only limited data could be collected. Reference was made to other tests conducted in the U.S. by Chang et al. (1980, 1982) and Stephens and Foster (1976, 1978) and together with the information obtained in Manitoba, the spreader factors shown in Table III were determined for use in system design.

Equations 2–8 are multiplied by the spreader factors to produce a design pressure loss per metre of grain depth for bins with spreaders.

A total of 55 tests was conducted to determine pressure losses through perforated floors. Two types of flooring are used in Manitoba. They are commonly referred to as cereal flooring and rapeseed flooring, depending on the size of the perforations in the screen. Tests on cereal flooring showed pressure drops of 40 Pa or less for air velocities up to 225 $L \cdot s^{-1} \cdot m^{-2}$ With rapeseed flooring, pressure drops were 50 Pa or less with air velocities up to 75 $L \cdot s^{-1} \cdot m^{-2}$, and up to 100 Pa at velocities of 110–125 $L \cdot s^{-1} \cdot m^{-2}$. For design purposes, pressure losses through perforated flooring can therefore be ignored for velocities up to 225 $L \cdot s^{-1} \cdot m^{-2}$ for cereal flooring and up to 75 $L \cdot s^{-1} \cdot m^{-2}$ for rapeseed flooring. Lampman and Hukill (1968) measured pressure drops of about 30 Pa with wheat on perforated sheet metal with holes 5 mm in diameter, and 15 Pa with holes 2.5 mm in diameter, with a 10% solidity ratio and an apparent air velocity of 225 $L \cdot s^{-1} \cdot m^{-2}$.

TABLE III. SPREADER FACTORS USED IN SYSTEM DESIGN

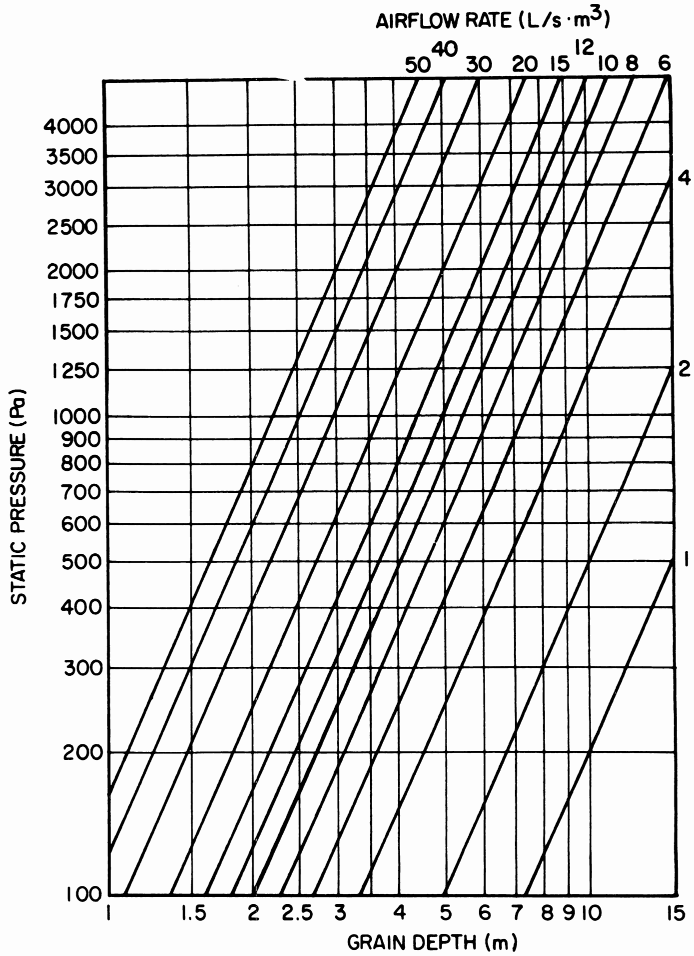
Crop	Spreader factor
Wheat	1.3
Barley	1.5
Corn <5% f.m.†	1.5
>5% f.m.	2.0
Sunflowers	1.5

†Fine material, passes through a 4.8-mm-diameter round-hole screen.

If the bin floor is not totally perforated, the air velocity through the grain near the perforated section of the floor is greater than it is through the grain near the top of the pile. In comparison to the same airflow through a fully perforated floor, the pressure loss through the grain is greater in a partially perforated floor bin because of the greater air velocity. The results of a series of tests on the effects of partially perforated floors using two bins of wheat are shown in Fig. 10. The partial floor factor as determined by these tests is given by the following equation:

$$K = (\mathrm{L\cdot s^{-1}\cdot m^{-2}} - 100)\ 0.00065 + \frac{6.31 - \ln(\%\text{ of floor covered by perforated flooring})}{2.38} \qquad (9)$$

where K is the multiplying factor to be applied to Eqs. 2–8 or Figs. 4–9, and $\mathrm{L\cdot s^{-1}\cdot m^{-2}}$ is the airflow divided by the area of perforated flooring. (Note, this equation is to be used only for floors with 50% or less of the floor area covered by perforated flooring. When $\mathrm{L\cdot s^{-1}\cdot m^{-2}}$ is less than 100, it should be set equal to 100.)



IF SPREADER IS USED, MULTIPLY ABOVE PRESSURES BY 1.5

Figure 7. Airflow resistance for sunflowers on a fully perforated floor.

Williamson (1965), using a small test bin of wheat with a 1:1 depth to width ratio, determined comparative pressure drops using a number of different duct shapes, sizes and spacings. With an air escape area equal to 32.4% of the total floor area, and an air velocity of 100 $\mathrm{L\cdot s^{-1}\cdot m^{-2}}$, the K factor obtained was equal to that obtained in our tests (i.e., 1.32). At lower air velocities Williamson's factors were higher than ours, and with 15.1% air escape area, his factors were lower than ours. He noted that the airflow was uniform across the bin by the time the air reached the upper half of the bin, even with a single central supply duct.

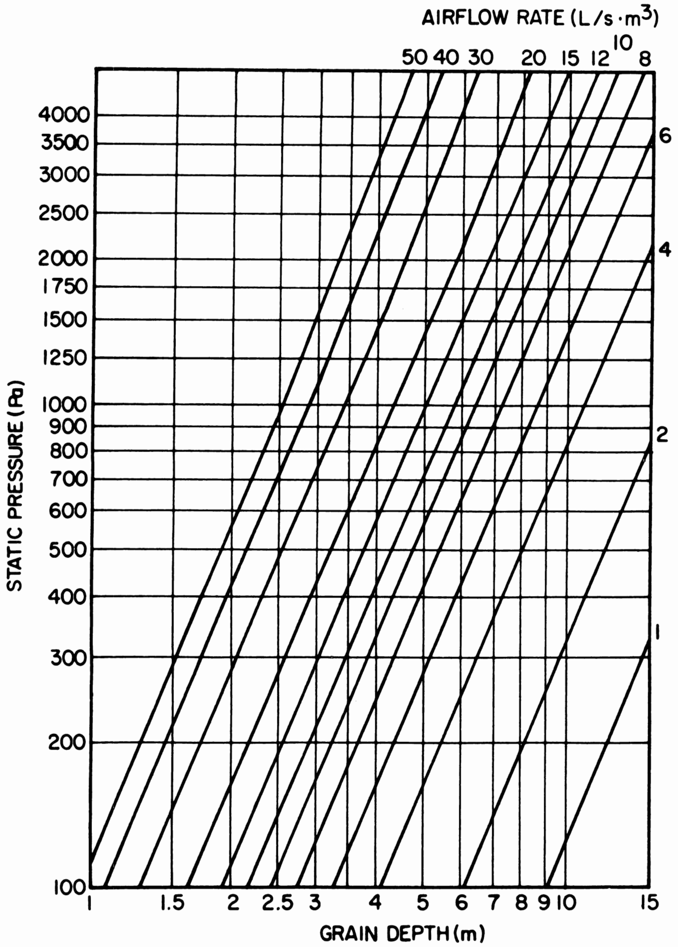
Boyce and Davies (1965) conducted tests with various ducts in a small bin of barley with a depth to width ratio of 1:2. The K factors they obtained were within 10% of ours for air escape areas between 13 and 33% of the total floor area, with air velocities of 20–80 $\mathrm{L\cdot s^{-1}\cdot m^{-2}}$. They also determined that the airflow was uniform by the time it reached the grain surface, when using a single central supply duct.

Barrowman and Boyce (1966) ran tests on a bin of barley with a depth to width ratio of 2:1 and a central supply duct. They obtained a K factor about 30% lower than ours with an air velocity of 105 $\mathrm{L\cdot s^{-1}\cdot m^{-2}}$, and air escape areas of 11–33% of total floor area. This difference is primarily due to the difference in depth to width ratios. They found that by the time the air reached 1/4 of the bin depth, the airflow was essentially uniform. The top 3/4 of the bin was therefore only marginally affected by the duct outlet area. It appears reasonable then that the K factor would be less for a bin with a 2:1 depth to width ratio than one with a 1:1 ratio.

It is recommended that Eq. 9 should be used only for bins with a depth to width ratio near 1:1. It is expected that for ratios less than 1:1 the factors would be lower. An analysis of test results on 44 bins with partially perforated floors and depth to width ratios between 0.4 and 1.5 confirms a definite tendency in this direction. Further work is continuing to determine the depths at which parallel airflow begins in bins with various duct and partially perforated floor configurations. Additional pressure loss tests with other grains and oilseeds on partially perforated floors and various depth to width ratios would also be desirable.

The airflows produced by using two axial fans in series on a bin of grain were also investigated. Airflows were measured with both fans located at the base of the bin forcing air up through the grain, and also with one fan mounted on the bin roof and the other at the base. The airflows obtained were compared to that provided by a single fan. Tests were conducted in a bin of barley and a bin of rapeseed. In both cases the airflow was increased by 40–45% by using two fans in series as compared to using a single fan. Mounting one fan on the roof provided no increase in airflow as compared to having both fans in series at the base of the bin. Details on the series fan tests are contained in reports by Huminicki (1980a, 1982).

The temperature patterns produced by the hopper bottom bin aeration system designed by the first author are shown in Fig. 11. The bin was completely filled with sunflower seed and air was forced through at a rate of about 12 $\mathrm{L\cdot s^{-1}\cdot m^{-3}}$. Since the grain at the top was last to cool, it was easy for the operator to check for completion of cooling. Easy cleanout, simple construction and an out-of-the-way fan location were additional features of this system. Complete details are contained in a report by Friesen (1982b). A prototype commercial aeration system was also tested for airflow distribution. This system has a concentric perforated area extending 2/3 of the way up the hopper, with the air entering through the unloading port. A concentric air distribution



IF SPREADER IS USED, MULTIPLY ABOVE PRESSURES BY 2.0

Figure 8. Airflow resistance for corn on a fully perforated floor.

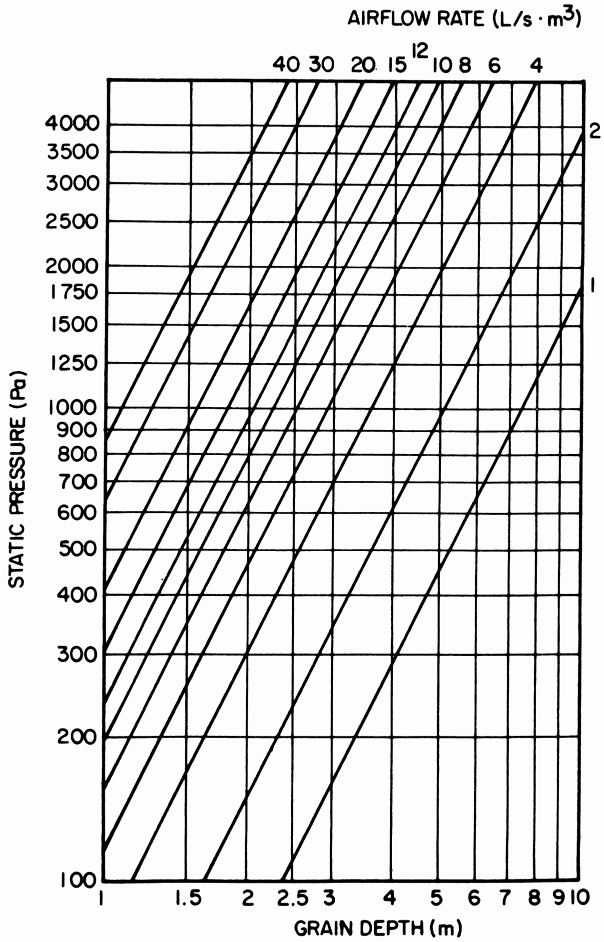


Figure 9. Airflow resistance for flax on a fully perforated floor.

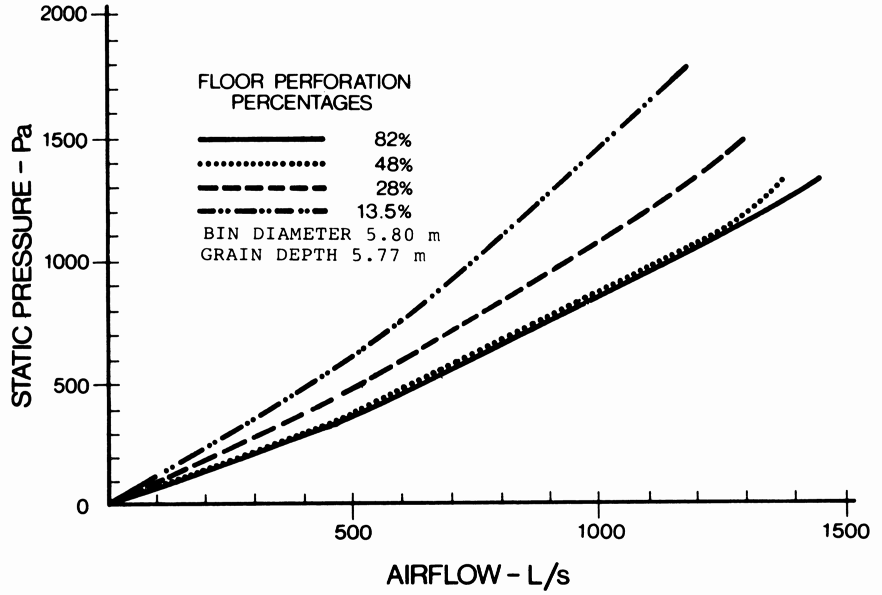


Figure 10. Pressure losses through a bin of wheat with various percentages of perforated floor area.

pattern was observed, with the center section receiving a slightly lower airflow rate than the edges, due to the differences in grain depth. Details are given in a report by Friesen (1983b).

SUMMARY

(1) Laboratory tests were conducted to determine the performance of more than 100 different axial, centrifugal and tubular centrifugal fans ranging from 0.25 kW to 11.2 kW in motor power.

(2) Field and laboratory tests were conducted to determine the performance of axial fans in series, both in pressure and suction.

(3) Field and laboratory tests were conducted to determine the airflow resistance of fan transitions and perforated flooring materials.

(4) Field tests were conducted to determine the airflow resistance for wheat, barley, sunflowers, canola (rapeseed), corn and flax, on fully perforated floors.

(5) Field tests were conducted to determine the effects of grain spreaders and partially perforated floors on the airflow resistance of various crops.

(6) Field tests were conducted to determine the airflow patterns produced in

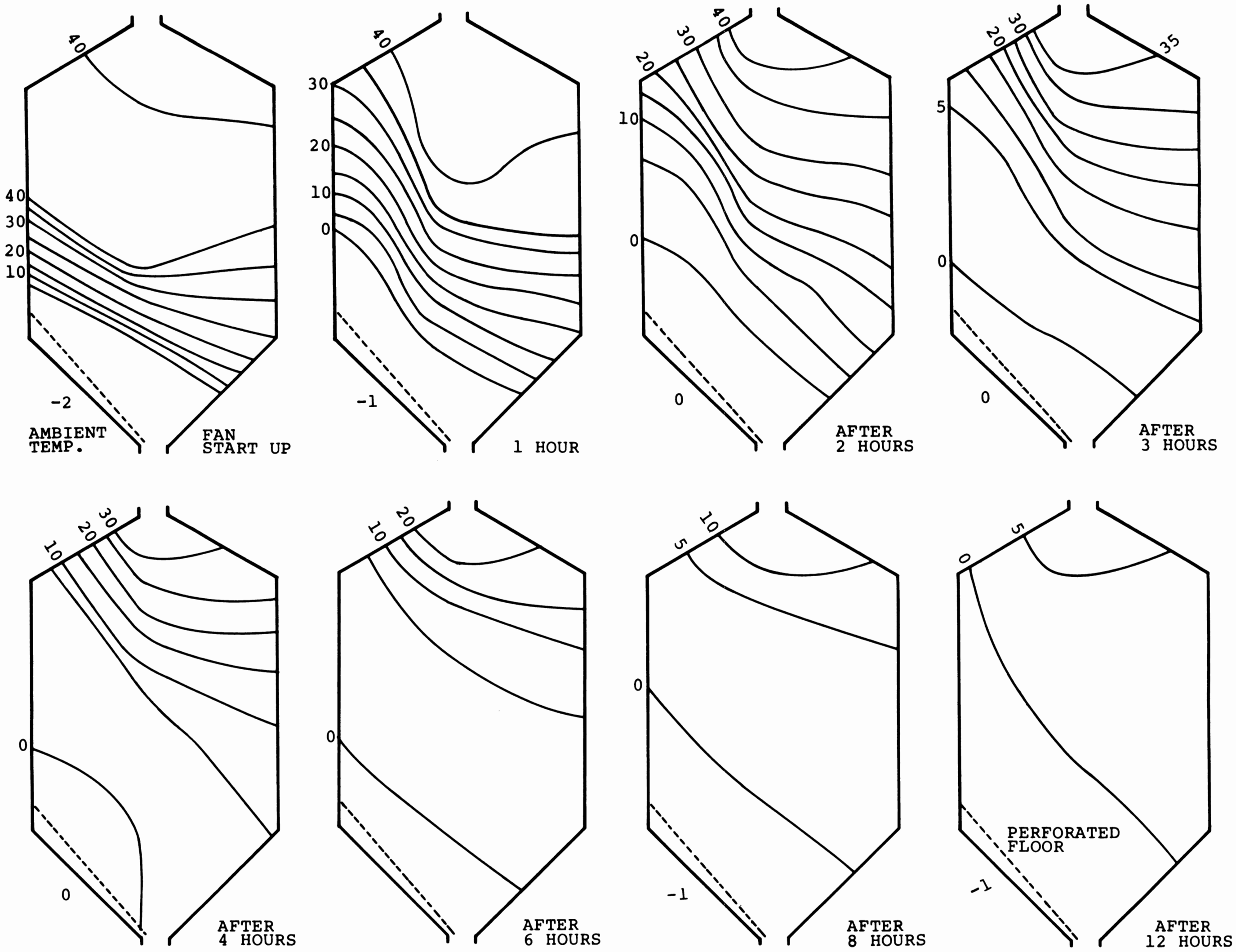


Figure 11. Temperature patterns in a hopper bottom bin (temperatures in °C).

hopper bottom bins with two different aeration systems.

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