EFFECT OF FINE MATERIAL ON STATIC PRESSURE DURING GRAIN DRYING

By

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INTRODUCTION

Air is used in grain conditioning systems to perform many functions. In a grain drying operation the air carries heat into the system to evaporate moisture and then carries the evaporated water out of the system. Sometimes air is used to carry moisture into the system for the purpose of rewetting the product.

When air is forced through a layer of grain, resistance to the flow, the so-called pressure drop, develops as a result of the energy lost through friction and turbulence. The resistance is overcome either by providing a pressure build-up on the air entrance side of the grain mass, or by providing a vacuum on the air exit side. The pressure drop for airflow through any product depends on: airflow rate, type of grain, depth of grain, moisture content, packing factor and grain condition (broken and fine material).

Grain drying is an energy intensive operation that will be increasingly affected by high fuel cost. To design drying and storage facilities requires a careful analysis of systems. Many factors influence the choice of equipment, but drying cost, performance, and capital costs are major factors in the decision. Because many systems and combinations of equipment are available, a systematic procedure for comparing optimized drying cost is needed to help select the facilities best suited to needs.

Determination of grain resistance to airflow is fundamental in the design of drying and aeration systems. In order to select a fan capable of overcoming the resistance offered by drying or aeration systems, one has to know how much resistance will be developed in a particular bed of grain. The most common approach in estimating pressure drop through grain is to use experimental curves relating airflow and pressure drop (Ahmed et al., 1982).

Foster (1970) investigated the airflow resistance of a mixture of fines and clean corn. As the percent fines in the mixture increased, the resistance pressure increased, reaching a maximum pressure drop approximately double that for clean corn. Haque et al.(1978) examined the effect of percent fine material in shelled corn at 12% moisture content on airflow resistance. They noted that a bed of corn with fine material had a higher resistance to airflow than did a mass of whole kernels. Concentration of fine material can result in a wide variation in resistance to airflow within a grain bed. If foreign materials are smaller than grain, resistance to airflow is increased; if foreign materials are larger than the grain, resistance to airflow is reduced (Shedd, 1953).

Non-uniform distribution of fines in bulk grain occurs when bins are filled (Stephens and Foster, 1976) and this non-uniformity contributes to non-uniform distribution of the air used for aeration and drying. Packing is not as important a variable as the method of filling and amount of fine material on the static pressure. Unfortunately, adequate data relating airflow resistance to the amount of fine material in corn being dried are not available. In order to provide useful information about aeration and drying processes it is very important to know the characteristics of airflow within grain beds witn different percentages of fine material and moisture content.

REVIEW OF LITERATURE

Data on airflow-static pressure relationships have been published in graphical form in the American Society of Agricultural Engineers' Yearbook (1980). These curves, now known as Shedd's curves, are widely used and were adopted as American Society of Agricultural Engineers (ASAE) technical data. The use of these experimental curves provides a definite convenience, but the accuracy of the pressure drop predictions may be poor because of insufficient consideration of the effects of variations due to some important factors, such as void space, fine material and product moisture content. Shedd (1951) observed changes in pressure drop of over 60 % at the same airflow rate when the filling method was changed. Shedd's curves are for a loose fill condition which was obtained by pouring grain into a funnel, the outlet of which was held just above the surface of the grain in the bin.

Stephens and Foster (1976) studied the effect of bin filling method on the segregation and distribution of fines and broken kernels. They concluded that non-uniform distribution of fines in bulk grain led to non-uniform distribution of air used for aeration and/or drying. They also reported that airflow resistance through corn in a deep-filled bin was found to be 20 to 40 % higher than reported by Shedd (1953) and 100 to 300 % greater for a bin filled with a mechanical spreader. Lawton (1965) noted that resistance to airflow, depended on the type of seed and to a great extent on the degree of packing and the presence of contaminants (fine material).

Thompson and Isaacs (1967) reported that a high grain test weight or bulk density denoted a low percentage of void space. The reduction in void space associated with the grain as it is dried probably accounts for the increased static pressure required to move a given quantity of air through the dry corn. They found that the porosity (percent of void or air space) of bulk lots of shelled corn was influenced by differences in variety, kernel moisture content, amount of fine material, method of harvesting, and method of drying. The porosity of a bed of shelled corn increased with an increase in kernel moisture content.

Brooker et al. (1974) indicated that the pressure drop for airflow through any product depended on the airflow rate; the surface and shape characteristics of the product; the number, size and configuration of the voids; the variability of particle size; and the depth of the product.

Several studies have involved attempts to fit equations to experimental curves relating airflow and pressure drop. Henderson (1943) used the equation,

$$V = k\ (\Delta P)^{c} \qquad (1)$$

Where:

V = Airflow rate in cfm/ft^2

ΔP = Static pressure drop/foot of depth (in. of water)

k and c = constants

Shedd (1953) also fitted his data to Equation (1). He stated that a particular set of constants, k and c, only gave good prediction over a narrow range of airflow rates. This equation assumes a straight line relationship between static pressure and airflow rate on a log-log plot.

Hukill and Ives (1955) proposed the following equation for Shedd's data:

$$P = \frac{aV^2}{\ln(1+bV)} \qquad (2)$$

Where: a and b are constants depending on the product. This equation, by proper selection of the constants, a and b, expressed the relationship between velocity and pressure drop with good accuracy throughout the range of velocities reported.

Haque et al. (1978) modified Equation (2) and made it applicable for corn containing fines as follows:

$$P = c_1 V + c_2 V^2 + c_3 (fm) \qquad (3)$$

Where:

fm = fine material percent, expressed as a decimal

c_1, c_2, c_3 = constants

Equation (3) is applicable for an airflow range of 15-75 cfm/ft^2 . While Hukill and Ives' equation was based on a lower range of airflows (2-40 cfm/ft^2), Equation (3) can be applied to higher airflow rates.

Bern (1973) developed the following equation to relate pressure drop to airflow rate through a bed of corn.

$$P = A_n V^2 + B_n V + C_n \tag{4}$$

where:

A_n, B_n, C_n = grain characteristic coefficients

Bern stated that the accuracy of Equation (4) for pressure drop prediction was likely to be poor at low airflow rates.

Ahmed et al. (1982) using corn, wheat and sorghum with 12 to 23 % moisture content (w.b.) found that the static pressure drop decreased with an increase in moisture content for the same level of airflow. They also reported that the effects of particle size, shape and surface characteristics on static pressure drop seemed more pronounced than the effect of void fraction. For this reason, wheat exhibited a much greater pressure drop than corn, even though void fractions for both commodities are almost the same. They reported that the following equation adequately described the relationship between static pressure drop and airflow rate with good accuracy throughout the range of velocities tested:

$$P = AV + BV^2 - C(MC)V \tag{5}$$

Where:

MC = moisture content, % (w.b.)

A, B, and C = constants depending on the products

Chung et al. (1983) reported the follwing equation for describing the static pressure through grain sorghum in terms of airflow rate, moisture content and percentage of fines:

$$SP = AV + BV^2 - C(MC) + D(FM)V \tag{6}$$

Where:

SP = Pressure drop per meter depth of grain, pascal/m.

V = Air velocity, m/s

MC = moisture content, % (w.b.)

FM = fine material, %

A, B, C, and D = constants depending on the product

They reported that the equation adequately described the relationship between static pressure, air velocity, grain moisture content and fine and broken kernels.

Gonzaga, L. (1985) examined the effects of moisture content and fine materials on static pressure through rough rice at various airflow rates. He obtained the following equation:

$$SP = a\ (AF) + b(AF)^2 - c\ (MC)(AF) - d\ (FM)(AF) \qquad (7)$$

Where:

SP = static pressure drop per meter of grain, pascal/m

AF = air velocity, m/s

MC = grain moisture content, % (w.b.)

FM = foreign material, %

a, b, c, and d = constants

He reported that the equation adequately described the relationship between static pressure, air velocity, grain moisture content and fine and broken kernels.

Ergun (1952) developed the following equation by theoretical analysis:

$$P_0 = \frac{150 - (1 - C)^2 LuV}{C^3 d^2 g} + \frac{1.75\ (1 - C) LpV^2}{C^3 dg} \qquad (8)$$

Where:

P = pressure drop, inches of water per foot

C = void fraction (dimensionless decimal on volume bases)

u = fluid viscosity, $lb/sec/ft^2$

p = fluid density, lb/ft^3

d = equivalent particle diameter, ft

g = acceleration due to gravity, ft/sec^2

V = velocity, ft/sec

L = bed depth, ft

This equation reflects all the independent variables on which the pressure depends. Bakker-Arkema et al.(1969) and Patterson et al. (1971) extended Ergun's equation to cover agricultural products such as cherry pits, shelled corn and navy bean. Matthies and Petersen (1974) developed a similar equation for different agricultural grains. Application of these types of theoretical equations is extremely difficult and as such Matthies and Petersen (1974) suggested the use of a simpler equation.

Calderwood (1973) reported that moisture content of rough rice caused variation in airflow resistance in seed, but he did not specify what kind of effect the moisture had on the airflow resistance.

Brown (1962) studied the variation in bulk density of wheat, barley and oats in relation to moisture content. He found that bulk density decreased at higher moisture content.

Chung and Converse (1971) studied the changes in physical properties of corn and wheat caused by both adsorption and desorption of moisture. Their results agreed with the findings of Thompson and Isaacs (1967). They reported more void space in wheat than corn at the same bulk density, due mainly to the higher true density of wheat.

OBJECTIVES

The objectives of this investigation were:

1. To determine the effect of fine material and broken kernels, moisture content and packing factor in corn on airflow resistance during drying of shelled corn by natural air.
2. To develop mathematical models that would describe the effects of fine material and moisture content and/or the effect of packing factor on airflow resistance through a corn bed.
3. To examine the effect of fine material in corn on the natural air drying rate of shelled corn.

MATERIALS AND METHODS

The static pressure changes through shelled corn, initially at about 20 % moisture content (w.b.), with different levels of fine material were examined as corn was being dried by natural air with different airflow rates. Also examined were the drying rates of corn with different levels of fine material.

Yellow dent corn, harvested in 1986 was used for the experiments. Four levels of fine material (0, 2, 4 and 6 %) were investigated. Each level of fine material was tested with three different airflow rates (1.0, 1.5 and 2.0 cfm/bu).

Table 1. Experimental design

FACTORS	LEVELS			
	1	2	3	4
Fines (%)	0	2	4	6
Airflow rate cfm/bu	1.0	1.5	2.0	-

Initial moisture content: 20 - 21 %

Fig. 1 shows a schematic diagram of the experimental system and equipment. The test column was constructed from

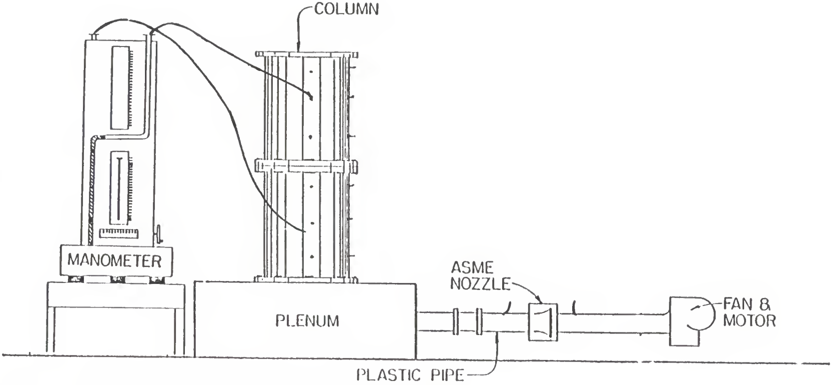

Fig. 1. Schematic Diagram for the Experimental Set-up

2.753 mm mild steel sheet rolled into a 29.90 cm diameter by 30.50 cm long section. Sections were connected by flanges to increase or decrease the depth of the bed as, and when, necessary. The volume of the test bin was 51,720 cu cm. The floor of the test bin was constructed of perforated sheet metal with 2.00 mm diameter holes, totaling 14 % of the entire area.

Five mm diameter and 50 mm long copper tube pressure taps were welded to the test column wall at 15.25 cm intervals, beginning approximately 7.6 cm above the bed floor. The taps protruded inside the column to make sure that air became static at the tap. Cooper tubes, 1.5 cm diameter and 2.0 cm long were welded to the side of the test column opposite the pressure taps at 15.25 cm intervals, beginning approximately 7.6 cm above the floor bed. These tubes were for taking corn samples to measure the moisture content. The plenum chamber consisted of a 91.4 by 91.4 by 30.5 cm rectangular box, made of 2.753 mm mild steel sheet.

Airflow to the drying test column was measured using a 25.4 mm throat diameter ASME nozzle and a micro-manometer capable of measuring up to 254 mm of water with a minimum reading of 0.00254 mm of water.

The ASME flow nozzle was placed between the blower and the plenum chamber within a 50.0 mm diameter plastic pipe. Air was supplied by a fan equipped with a 1/2 HP variable speed motor.

Natural air at room condition (average 50 % r.h. and 25^{0} C) was used throughout this experiment.

Corn from the 1986 crop was obtained through the Manhattan Milling Co. The entire lot of corn to be used in the experiments was cleaned using an M2B Clipper seed cleaner. All fine material and broken kernels which passed through a 4.76 mm (12/64 in.) diameter round-hole sieve were collected and retained for later use.

High moisture content corn (20-21 % m.c.) was not available at the time the experiments were conducted. Moisture content of lots of corn were adjusted as follows for test purposes:

1. Two bushels of cleaned corn at approximately 14 % m.c. was placed in a drum mixer and the desired amount of fine material added to the cleaned corn. Fine material was defined as that having passed through a 4.76 mm (12/64 in.) diameter-hole sieve.

2. Water to increase the moisture content of the corn and fine material mixture to 17-18 % m.c. was added as the drum was rotated.

3. After mixing for 30 minutes the corn was trasferred to 30 gal. garbage cans, covered and allowed to temper for 24 hrs.

4. Interim moisture content of the tempered corn was determined using the Motomco 919 Moisture Tester. The amount of water needed to bring the corn to 20 % m.c. was calculted and added to the corn as indicated in 2 and 3.

5. Final moisture content of the tempered corn was determined using an oven method for whole kernel at 103 C for 72 hours (Hall, 1980) prior to placing the corn in the drying test column.

Lots of corn were similarly tempered for each of the drying test replicates.

The drying test column was filled by a loose fill method described by Shedd (1953). Grain was poured into a funnel, the outlet of which was held just above the grain surface. The funnel was gradually raised as the filling progressed. The depth of the test column of corn was 73.7 cm.

The section of corn used for static pressure measurement consisted of a 61 cm portion with the first measurement taken 7.6 cm above the bottom of the test unit.

After filling the drying test column with corn having the desired percentage of fines and moisture content the blower was turned on, and the desired airflow was set.

Pressure differential across the ASME nozzle was read from the micro-manometer for calculating the airflow volume rate. Then the static pressure drop across the 61.6 cm measured section of grain bed was read by the same micro-manometer after properly closing the ASME nozzle taps. This procedure was repeated for all 24 beds of corn, i.e. for two replicates of each combination of four levels of fines and three airflow rates.

Samples were taken out at four different places along the column every 12 hours until the corn was about 12% m.c. These samples were used to measure moisture content changes and to measure the true density by the toluene displacement method. As the moisture content decreased, the bed height of corn also decreased. The bulk density was calculated using the difference in bed height of corn.

A packing factor, the fraction of volume occupied by solids (grain kernels, fine material, etc.), was calculated by the ratio of bulk density to true density for all samples. The packing factor is a value which jointly reflects the effects of moisture content, fine material and bulk density.

RESULTS AND DISCUSSION

Average packing factor values for two replications for various levels of moisture content, fine material and air flow rate were determined (Tables 2 through 4). Average values of static pressure for two replication were determined (Tables 5 through 7) for various levels of moisture content, fine material and airflow rate. The rates of drying for different levels of fine material, airflow rate and moisture ratio are presented in Tables 7 through 10.

Average packing factors for four levels of fine material were plotted against moisture content at each of three airflow rates (Figures 2 through 4). As corn was dried from approximately 20 % to 12 % m.c. the packing factor increased with decreased moisture content at each of the four levels of fines. This pattern was observed at each of the three airflow rates used. Ahmed (1982) reported the same moisture content relationship, however, he calculated the void space in a corn mass as it dried and showed that the void space decreased as moisture content decreased. He referred to this as "packing factor". Packing factor also increased as the percentage of fines was increased from 0 to 6 % at a given airflow rate. This increase in packing factor occurred because fine materials filled void spaces and increased the percentage of solid material within the grain bed. There appeared to be a tendency for packing factor to decrease as airflow rate was increased.

A model was selected to predict the effects of moisture content, airflow rate and fine material on packing factor using the Standard Stepwise Procedure (SAS, 1984/86). Two models were obtained:

I. $PF = a(MC) + b(FM) - c(MC)(FM)$ $R^2 = 0.987$

II. $PF = a(AF) - b(AF)^2 + c(MC) + d(FM)$ $R^2 = 0.996$

Where:

PF = packing factor, in decimal

MC = moisture content, % (w.b.)

FM = fine material, %

AF = air velocity, m/s

a, b, c and d = constants (see Table 14)

The percentage of total variation around the mean was higher in Model II indicating this model fit the data best.

Average static pressure for four levels of fine material were plotted against moisture content at each of three airflow rates (Figures 5 through 7). Maximum average static pressure drop across the column of corn occurred at 12 % m.c. with 6 % fine material at 2 cfm/bu. Minimum average static pressure drop occurred at 20 % m.c. with 0 %

fine material at 1 cfm/bu. At a given airflow rate, average static pressure drop increased as percent fine material was increased and decreased as moisture content increased. As airflow rates increased, average static pressure drop increased at all moisture contents and percentage of fines.

The results of this investigation showed that moisture content, fine materials and packing factor are important parameters that should be considered in designing grain aeration and drying systems.

The Standard Stepwise Procedure (SAS 1984/86) was used to select a model that would predict the effects of airflow rate, packing factor, moisture content and fine material on static pressure. The following two models were obtained;

III. $SP = - a(AF) - b(AF)^2 + c(AF)(PF)$ $\qquad R^2 = 0.993$

IV. $SP = a(AF) - b(AF)^2 - c(AF)(MC) + d(AF)(FM)$ $\qquad R^2 = 0.990$

Where:

SP = static pressure drop, Pascal/m

AF = air velocity, m/s

MC = moisture content, % (w.b.)

FM = fine material, %

a, b, c, and d = constants (see Table 14)

Equation III fit the data best. However, it should be noted that Equation IV is in the same form as those obtained by Chung et al. (1983) for grain sorghum and Gonzaga (1985) for rough rice.

Average packing factor for the four levels of fine material were plotted against average static pressure drops at three air flow rates. (Figures 8 through 10). Static pressure drop increased with increased packing factor and with increased levels of fine material at a given airflow rate. Static pressure drops also increased as airflow rates were increased. Increases in static pressure were almost linear as packing factor increased for the four levels of fine material and three airflow rates (Figures 8-10).

The bulk density increases as corn is drying and the packing factor increases with an increase in bulk density. Therefore, the static pressure will increase as grain dries (or moisture content decreases).

Table 2. Average Packing Factor of Shelled Corn as Affected by Moisture Content at 1.0 cfm/bu.

Moisture Content % (w.b.)	Packing Factor (in decimal)	Fine Material (%)
12.0	0.614	0
14.0	0.609	0
16.0	0.602	0
18.0	0.597	0
20.0	0.592	0
12.0	0.627	2
14.0	0.612	2
16.0	0.605	2
18.0	0.598	2
20.0	0.597	2
12.0	0.628	4
14.0	0.620	4
16.0	0.611	4
18.0	0.608	4
20.0	0.605	4
12.0	0.629	6
14.0	0.621	6
16.0	0.617	6
18.0	0.611	6
20.0	0.608	6

Table 3. Average Packing Factor of Shelled Corn as Affected by Moisture Content at 1.5 cfm/bu.

Moisture Content (% w.b.)	Packing Factor (in decimal)	Fine Material (%)
12.0	0.617	0
14.0	0.604	0
16.0	0.600	0
18.0	0.597	0
20.0	0.591	0
12.0	0.619	2
14.0	0.605	2
16.0	0.601	2
18.0	0.599	2
20.0	0.597	2
12.0	0.622	4
14.0	0.610	4
16.0	0.607	4
18.0	0.605	4
20.0	0.600	4
12.0	0.625	6
14.0	0.612	6
16.0	0.609	6
18.0	0.607	6
20.0	0.606	6

Table 4. Average Packing Factor of Shelled Corn As Affected by Moisture Content at 2.0 cfm/bu.

Moisture Content % (w.b.)	Packing Factor (in decimal)	Fine Material (%)
12.0	0.608	0
14.0	0.598	0
16.0	0.597	0
18.0	0.595	0
20.0	0.591	0
12.0	0.617	2
14.0	0.604	2
16.0	0.598	2
18.0	0.597	2
20.0	0.596	2
12.0	0.620	4
14.0	0.607	4
16.0	0.606	4
18.0	0.604	4
20.0	0.603	4
12.0	0.625	6
14.0	0.614	6
16.0	0.608	6
18.0	0.606	6
20.0	0.605	6

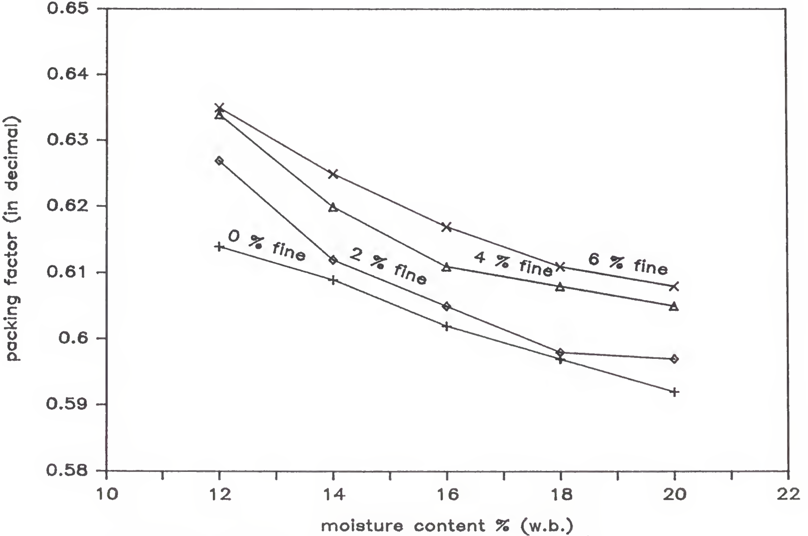

Fig. 2. Packing Factor vs. Moisture Content at 1.0 cfm/bu

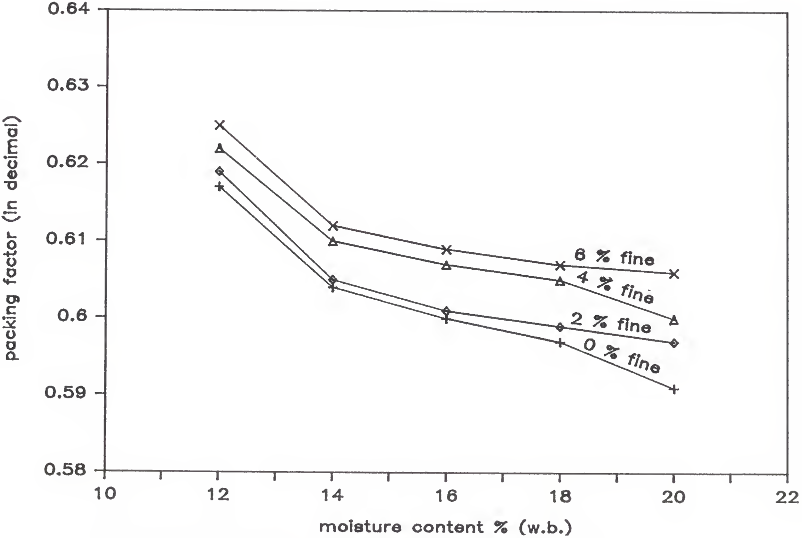

Fig. 3. Packing Factor vs. Moisture Content at 1.5 cfm/bu

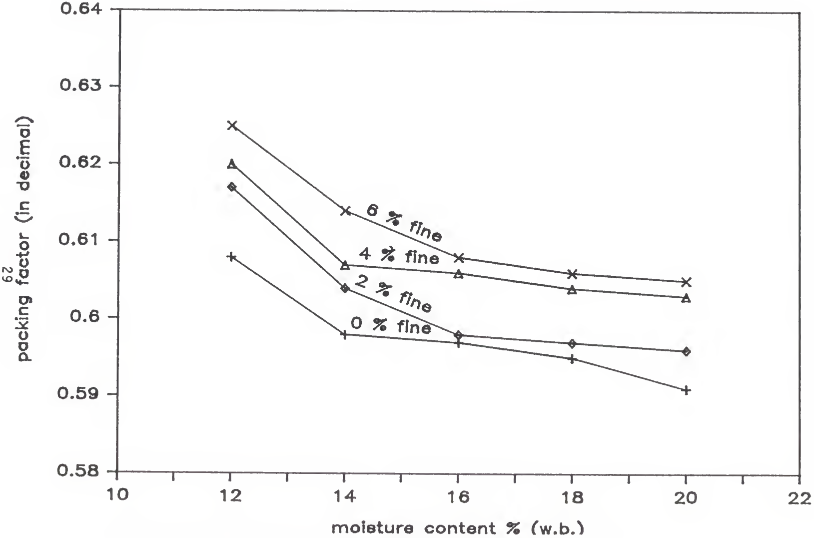

Fig. 4. Packing Factor vs. Moisture Content at 2.0 cfm/bu

Table 5. Average Static Pressure Drop For Shelled Corn At 1.0 cfm/bu.

Moisture Content (% w.b.)	Static Pressure Drop (Pascal/m)	Fine Material (%)
12.0	49.80	0
14.0	43.26	0
16.0	37.55	0
18.0	31.84	0
20.0	28.57	0
12.0	51.43	2
14.0	45.72	2
16.0	40.00	2
18.0	35.92	2
20.0	33.47	2
12.0	53.88	4
14.0	47.35	4
16.0	42.45	4
18.0	38.37	4
20.0	35.92	4
12.0	57.96	6
14.0	49.80	6
16.0	44.09	6
18.0	41.64	6
20.0	40.82	6

Table 6. Average Static Pressure Drop For Shelled Corn At 1.5 cfm/bu.

Moisture Content (% w.b.)	Static Pressure Drop (Pascal/m)	Fine Material (%)
12.0	54.70	0
14.0	47.35	0
16.0	40.82	0
18.0	36.37	0
20.0	34.20	0
12.0	56.52	2
14.0	51.08	2
16.0	46.54	2
18.0	43.27	2
20.0	42.45	2
12.0	60.33	4
14.0	52.62	4
16.0	48.98	4
18.0	45.72	4
20.0	44.90	4
12.0	65.96	6
14.0	55.52	6
16.0	51.98	6
18.0	48.17	6
20.0	47.35	6

Table 7. Average Static Pressure Drop For Shelled Corn At 2.0 cfm/bu.

Moisture Content % (w.b.)	Static Pressure Drop (Pascal/m)	Fine Material (%)
12.0	66.13	0
14.0	62.86	0
16.0	59.59	0
18.0	57.96	0
20.0	55.15	0
12.0	69.39	2
14.0	65.50	2
16.0	62.05	2
18.0	61.23	2
20.0	57.41	2
12.0	71.03	4
14.0	66.95	4
16.0	64.31	4
18.0	63.50	4
20.0	59.68	4
12.0	88.17	6
14.0	80.00	6
16.0	76.74	6
18.0	73.48	6
20.0	71.03	6

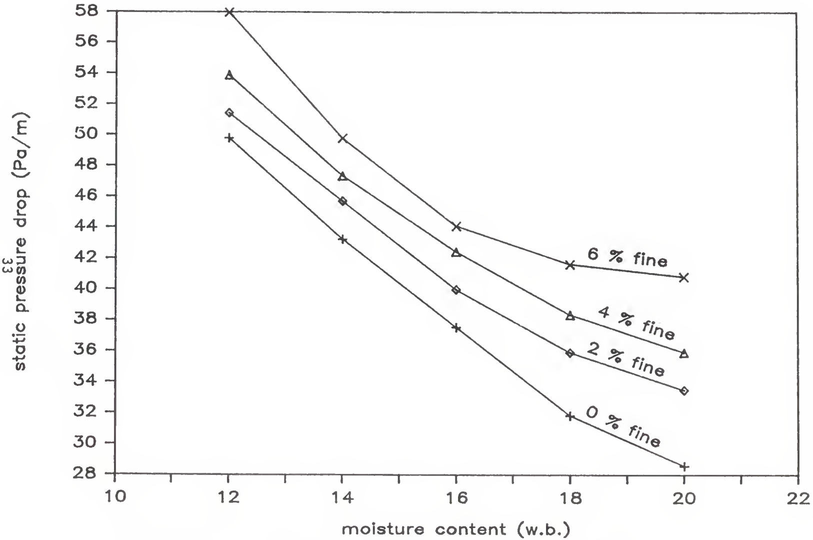

Fig. 5. Static Pressure vs. Moisture Content at 1.0 cfm/bu

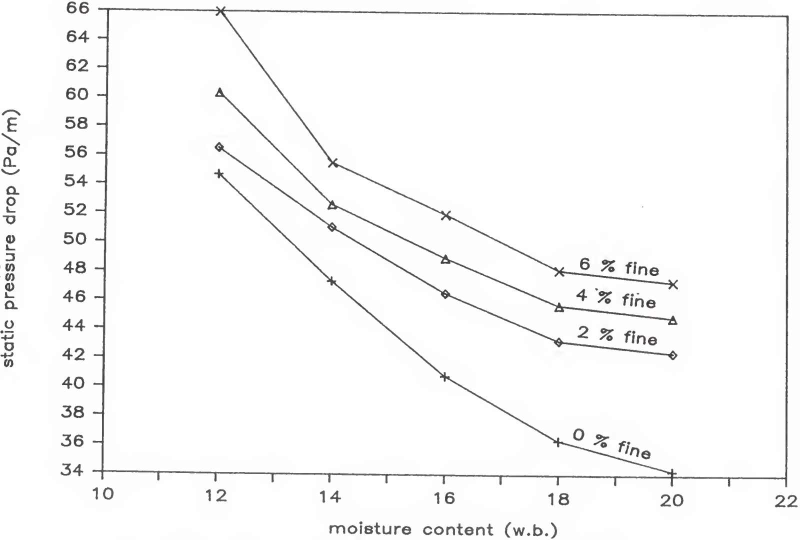

Fig. 6. Static Pressure vs. Moisture Content at 1.5 cfm/bu

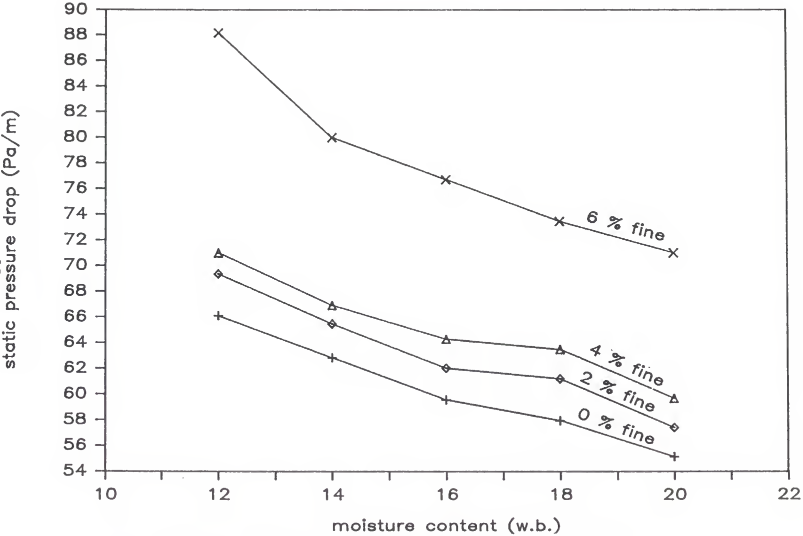

Fig. 7. Static Pressure vs. Moisture Content at 2.0 cfm/bu

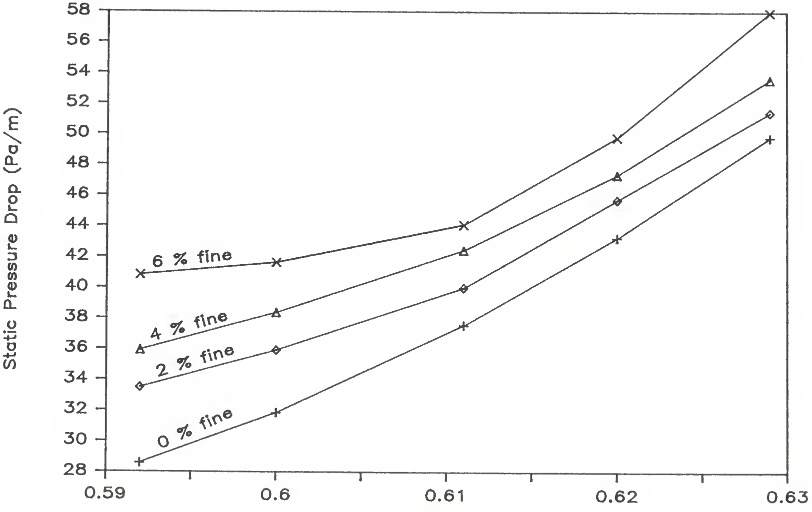

Fig. 8. Static Pressure vs. Packing Factor at 1.0 cfm/bu

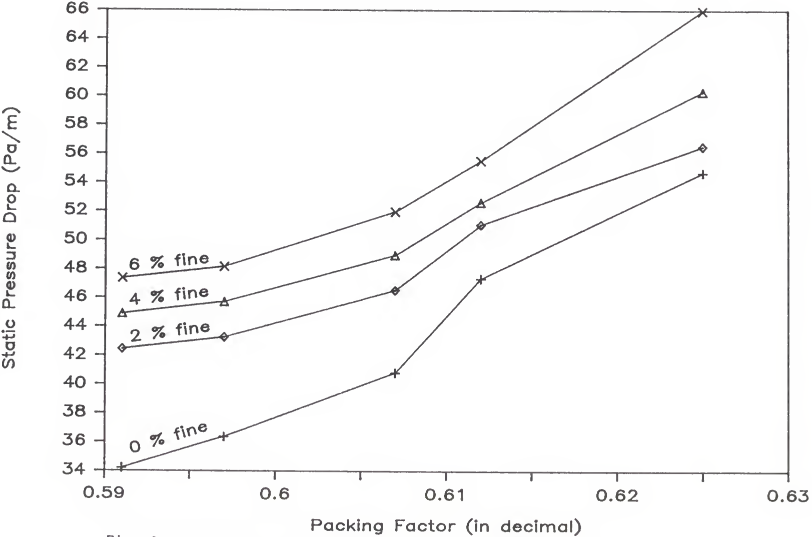

Fig. 9. Static Pressure vs. Packing Factor at 1.5 cfm/bu

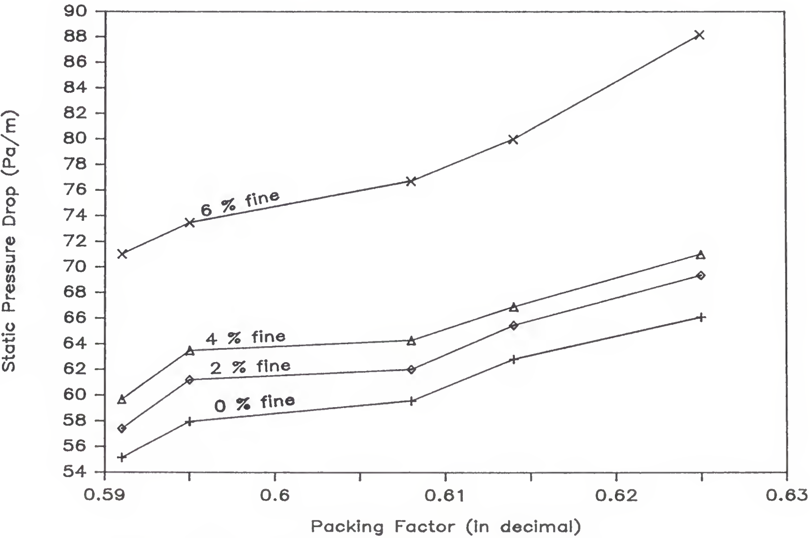

Fig. 10. Static Pressure vs. Packing Factor at 2.0 cfm/bu

Moisture ratios (MR) were calculated at 0, 12, 24 and 36 hours intervals at each airflow rate (1.0, 1.5 and 2.0) for each level of fine material (Tables 8-11). Moisture ratios indicate the fraction of the original moisture remaining to be removed to reach equilibrium. When moisture ratios were plotted against time, a drying rate curve was developed. At any given time, moisture ratios decreased with increased airflow rates. This indicated that rates of drying increase with increased airflow rates. As percent fine material was increased, moisture ratios increased indicating that as fine material increased rates of drying decreased. Drying rate curves obtained by plotting moisture ratio (MR) versus time are presented in Figures 11-14.

The purpose of using moisture ratio (MR) rather than moisture content(m.c.) in developing the rate of drying curvesin Figures 11-14, was to allow the prediction of drying times under various equilibrium moisture content conditions, (i e under various temperature and relative humidity conditions.) and different beginning moisture contents.

The Standard Stepwise Procedure (SAS 1984/86) was used to select a model to predict the effects of time and airflow rates on moisture ratio. The following model was obtained:

V. $MR = a(T) + b(AF) + c(T)(AF)$ $R^2 = 0.917$

Where:

MR = moisture ratio = $\dfrac{M - M_e}{M_o - M_e}$

M = average moisture content (d.b.) at a given drying time

M_e = equilibrium moisture content (d.b.) at the inlet drying air condition

M_o = initial moisture content at drying time = 0

T = drying time, hours

AF = air velocity, m/s

a, b, and c = constants (see Table 14)

The percentages of fine material were plotted against drying times for reducing corn at 20 % to 14 % m.c. (w.b.) with different airflow rates (Figure 15). It can be seen that the drying time increased with the fine material but increased with airflow rates.

During the drying process fine materials have a very important role. As fine materials increase in the mass of grain the drying time also increases. The increased time can increase costs. Cleaning grain to remove fine material can have many benefits, not only in the drying process, but also in storage, tranportation, handling and marketing.

Table 8. Moisture Ratio vs Time for Shelled Cornat 0 % Fine Material with Three Airflow Rates.

Time (hrs)	Airflow Rate (cfm/bu) 1.0	1.5	2.0
0	1.000	1.000	1.000
12	0.549	0.489	0.382
24	0.345	0.283	0.187
36	0.139	0.080	0.039

Table 9. Moisture Ratio vs Time for Shelled Corn at 2 % Fine Material with Three Airflow Rates.

Time (hrs)	Airflow Rate (cfm/bu) 1.0	1.5	2.0
0	1.000	1.000	1.000
12	0.680	0.618	0.533
24	0.478	0.347	0.282
36	0.243	0.136	0.089

Table 10. Moisture Ratio vs Time for Shelled Corn at 4 % Fine Material with Three Airflow Rates.

	Airflow rate (cfm/bu)		
Time (hrs)	1.0	1.5	2.0
0	1.000	1.000	1.000
12	0.766	0.638	0.590
24	0.510	0.394	0.396
36	0.288	0.182	0.165

Table 11. Moisture Ratio vs Time for Shelled Corn at 6 % Fine Material with Three Airflow Rates.

	Airflow rate (cfm/bu)		
Time (hrs)	1.0	1.5	2.0
0	1.000	1.000	1.000
12	0.779	0.717	0.653
24	0.547	0.505	0.435
36	0.356	0.292	0.217

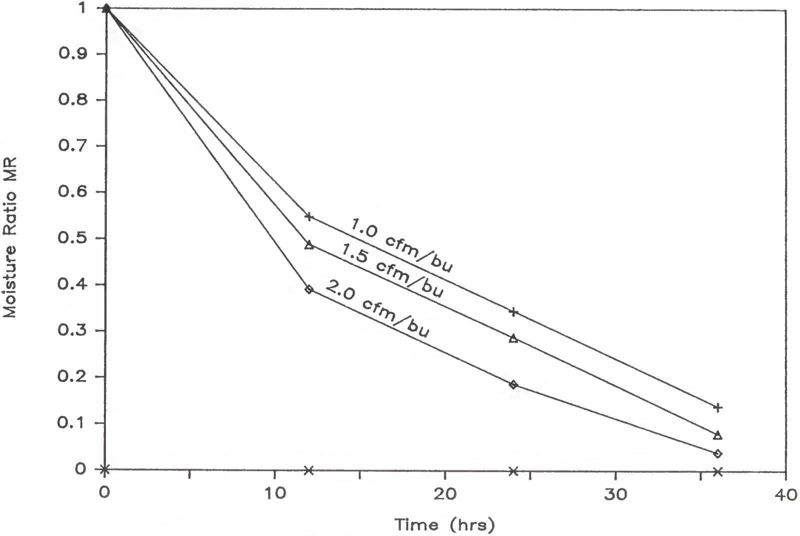

Fig. 11. Rate of Drying at 0 % fine

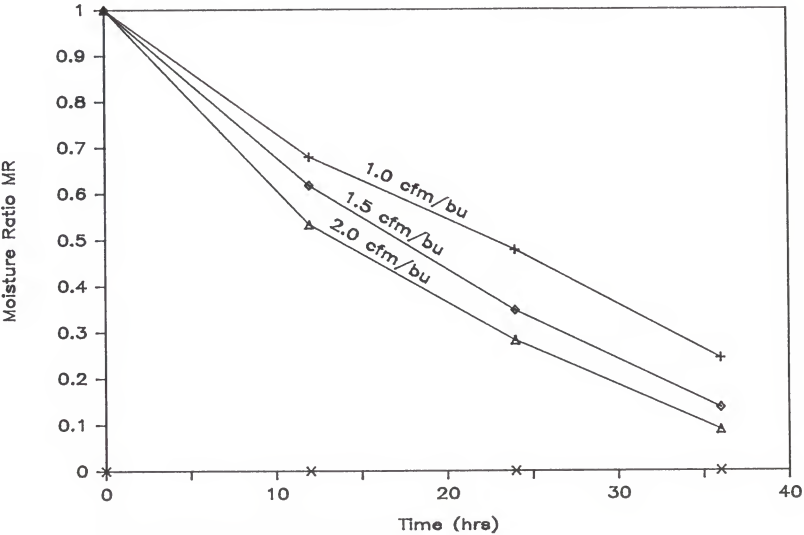

Fig. 12. Rate of Drying at 2 % fine

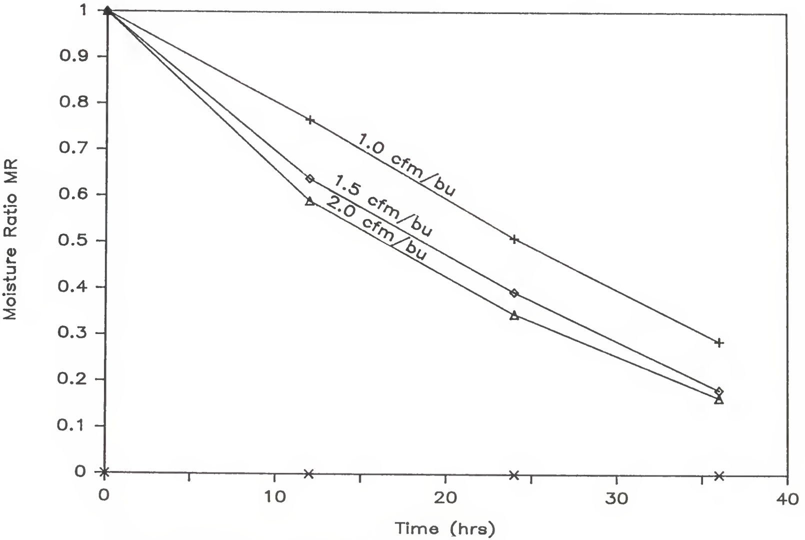

Fig. 13. Rate of Drying at 4 % fine

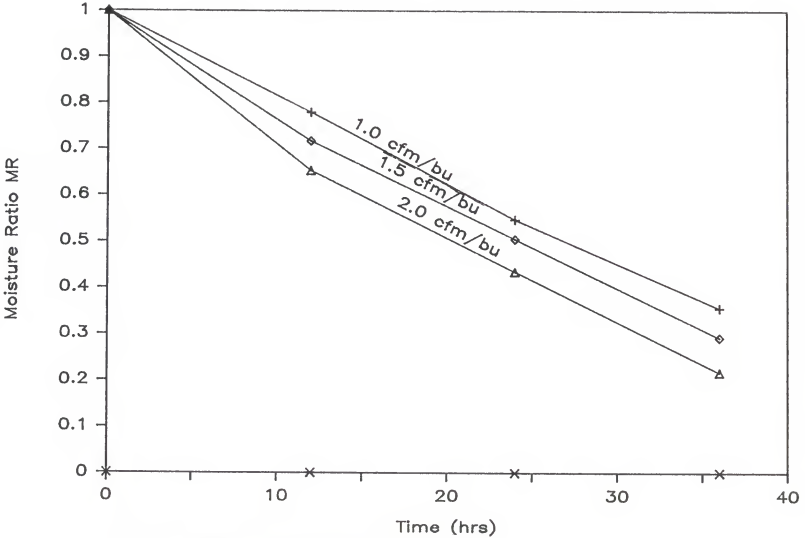

Fig. 14. Rate of Drying at 6 % fine

Table 12. Drying Time from 20 % to 14 % Moisture Content (w.b.) vs. % FineMaterialat Different Airflow Rates.

Airflow Rate (cfm/bu)	Fine Material (%)	Drying Time (hrs)	Drying time Increase %
1.0	0	28	0
1.0	2	32	14.28
1.0	4	36	28.57
1.0	6	40	42.85
1.5	0	23	0
1.5	2	27	17.39
1.5	4	31	34.78
1.5	6	36	56.52
2.0	0	18	0
2.0	2	23	27.78
2.0	4	28	55.56
2.0	6	33	83.34

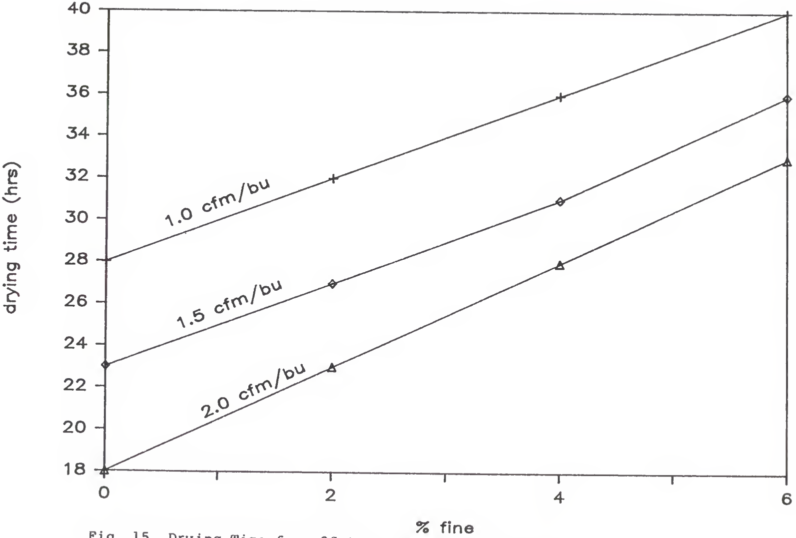

Fig. 15. Drying Time from 20 % to 14 % moisture content (w.b.) vs % fine at three airflow rates

Clean grain means less time in the drying process with increased drying capacity.

To analyse the data statistically, all combinations of airflow rate and fine material had to be compared at same moisture content. The static pressure drops were interpolated at fixed moisture content.

The independent variables were air velocity, moisture content, and fine material. The dependent variables were static pressure drop, packing factor and moisture ratio. Analysis of variance and multiple regression analyses were performed using the SAS statistical computer package.

The following statistical model was used in analyzing the data:

$$X_{ijk} = u + A_i + M_j + F_k + (A*M)_{ij} + (M*F)_{jk} + C_{ijk} \qquad \text{(VI)}$$

Where:

X_{ijk} = observed value (static pressure, packing factor, moisture ratio)

u = overall mean

A_i = average effect for the i treatment of air velocity

Table 13. Analysis of Variance for Static Pressure Drop for All Treatment Combination.

Source of Variation	Degrees of Freedom	Sum. of Squ.	F-Value	Lev. of Signif.	Dec.
Fine Material	3	2151.36	798.14	0.0001	Rej.
Airflow	2	13487.14	7505.47	0.0001	"
Moisture Content	4	3301.30	918.57	0.0001	"
FM * AF	6	388.56	72.08	0.0001	"
FM * MC	12	52.34	4.85	0.0001	"
AF * MC	8	201.61	28.05	0.0001	"
FM * AF*MC	24	139.35	6.46	0.0001	"

The desicion is based on the null hypothesis that the group means for each effect are equal.

M_j = average effect for the j treatment of moisture content

F_k =average effect for the k treatment of fine material

All others terms are interaction of the main effects

C_{ijk} = the random error of static pressure, packing factor and moisture ratio

The analysis of variance indicated that all main factors and their interactions significantly affected the static pressure, with airflow rate having the most significant effect followed by moisture content and fine material (Table 13).

The following is a summary of models selected that would predict the effects of moisture content, air velocity and fine material:

I. $PF = a(MC) + b(FM) - c(MC)(FM)$

II. $PF = a(AF) - (AF)^2 + c(MC) + d(FM)$

III. $SP = - a(AF) - b(AF)^2 + c\ (AF)(PF)$

IV. $SP = a(AF) - b(AF)^2 - c(AF)(MC) + d\ (AF)(FM)$

V. $MR = (T) + b(AF) + c(T)(AF)$

Where:

PF = packing factor, in decimal

SP = static pressure drop, Pascal/m

MR = moisture ratio

AF = air velocity, m/s

MC = moisture content, % (w.b.)

FM = fine material, %

T = time, (hrs)

a, b, c and d = constants (see Table 14)

Table 14. The Values of the Constants Estimated for Mathematical Models Obtained.

Equations	Constants				R^2
	a	b	c	d	
I.	0.0364	0.1399	0.0083	-	0.987
II.	0.8199	0.2695	0.0011	0.0035	0.996
III.	257.287	3.683	490.784	-	0.992
IV.	57.756	6.036	1.040	1.239	0.990
V.	0.0195	0.5870	0.026	-	0.917

CONCLUSIONS

Within the range of moisture contents, fine materials and airflow rates used the following conclusions were drawn from this study:

1. Packing factor increased with decreasing moisture content and/or airflow rate and increased with increased fine material.

2. Static pressure increased with increased fine material and/or airflow rate and decreased with decreased moisture content.

3. Drying time increased with increased fine material.

4. The statistical models:

   I. $PF = a(MC) + b(FM) - c(MC)(FM)$ $R^2 = 0.987$

   II. $PF = a(AF) - b(AF)^2 + c + d(FM)$ $R^2 = 0.996$

   III. $SP = - a(AF) - b(AF)^2 + c(AF)(PF)$ $R^2 = 0.993$

   IV. $SP = a(AF) - b(AF)^2 - c(AF)(MC) + d(AF)(FM)$ $R^2 = 0.990$

   V. $MR = a(T) + b(AF) + c(T)(AF)$ $R^2 = 0.917$

   adequately describethe relationships between static pressure, packing factor, moisture ratio, airflow rate, grain moisture content, time and fine material.

5. The results of this study are expected to help designers of natural air drying systems, by providing an accurate description of the static pressure drop and packing factor behavior as affected by moisture content, airflow rate and fine material.

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EFFECT OF FINE MATERIAL ON STATIC PRESSURE DURING GRAIN DRYING

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submitted in partial fulfillment of the
requirements for the degree

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ABSTRACT

Determination of grain resistance to airflow is fundamental in the design of drying and aeration systems. The objectives of this investigation were: (1) To determine the effect of fine material, moisture content and packing factor in corn on airflow resistance during natural air drying ; (2) to develop models that would predict the effect of moisture content, fine material and packing factor on airflow resistance; and (3) to examine the effect of fine materialon the natural air drying rate of shelled corn.

Yellow dent corn with four levels of fine material (0, 2, 4, 6 %) were dried from 20 to 12 % moisture content using natural air at three different airflow rates (1.0, 1.5, 2.0 cfm/bu). Every 12 hours during drying, pressure drop in the bed of corn was measured using a micromanometer; samples were taken for moisture measurement; and a packing factor relating bulk density to true density of the corn was calculated.

Functional relationships between packing factor, fine material and moisture content were established and R2 values for these relationships were greater than 0.92. Packing factor increased with fine material and decreased with moisture content and was directly related to static pressure

drop and drying time. As fine material was decreased, drying time decreased.