7-1988

An Aeration Duct Design Model for Flat Grain Storage

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ABSTRACT

TRADITIONALLY most grain is stored in circular type bins which provide a convenient means for handling and management. With the excess grain production and government loan programs of the past few years, some producers have used rectangular structures and covered piles to complement their round storages. The recommended management practices used with round bins are still required in those alternative storages and may be more critical in obtaining a quality end product.

One such recommended practice used with round bins is aeration. This practice is used to maintain a uniform temperature in the grain mass, preventing condensation and "hot" spots from occurring in the bins. For grain stored in piles and rectangular structures, aeration is generally conducted using above floor or flush mounted duct systems. The design of these systems is dependent on several factors including the configuration of the grain mass, the design airflow rate and grain volume and duct spacing criteria that will provide a relatively uniform distribution of air throughout the grain mass. The objective of this paper is to present a computer model that will determine duct sizes and duct spacing for aeration of rectangular storages based on system design requirements specified by the user. The model will be developed for use on the personal computer and should provide a useful design tool for extension engineers.

MODEL DEVELOPMENT

Aeration of stored grains in flat storages is a more difficult design problem than in the typical round bins. Each situation is unique and requires individual analysis by the extension engineer. However, there are several general criteria that are used in duct spacing and design for most flat storage systems. The purpose of the computer model was to incorporate these criteria into a design tool that would assist the engineer in the analysis of individual situations. A discussion of these criteria and their inclusion in the model follows:

Building Geometry

The program considers only structures with rectangular geometry. The user specifies the width and length of the building along with the grain height at the side wall and that of the peak. If these two heights are specified equal then the program assumes a uniform storage depth. In most design situations the grain peak will run lengthwise of the building, but this direction may be specified at the discretion of the user. An angle of repose for the grain peak is determined from the input peak and wall heights and checked against the maximum value for the specified grain type. If the calculated value is larger than the maximum, the user may reinitialize the input variables. The grain volume for a peaked storage (Fig. 1) is determined from the input dimensions assuming a rectangular box for a base, a triangular section on top with the two upper end sections combining to form a pyramid (Fig. 1). The length of the end sections forming the pyramid is determined from the input dimensions and the maximum angle of repose of the specified grain.

Duct Spacing

Ducts may be spaced along either building dimension at the discretion of the user. For level storages or in situations where ducts may be placed across the grain peak, the duct spacing and number are determined by dividing the appropriate building dimension by the maximum grain height. For peaked storages with ducts placed in the same direction as the peak, the model positions ducts so that the longest air path served by the duct is not more than 1.5 times the shortest air path (USDA, 1960, Fig. 2). Initially when determining the appropriate number of ducts, the model uses the computed angle of repose to determine a minimum ratio of the grain height at the side wall to building width (HSW) such that the USDA criteria is satisfied. This HSW ratio is calculated for each of ten duct

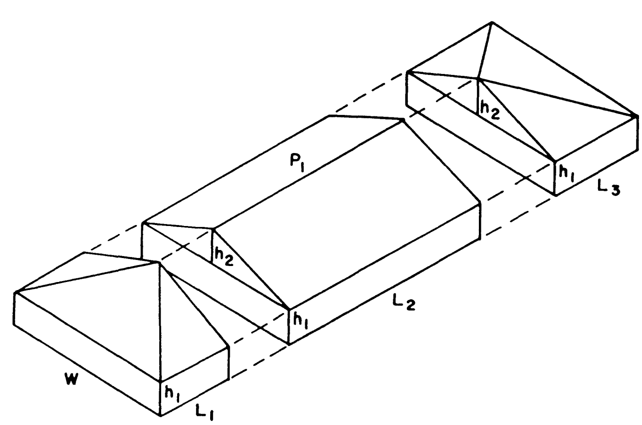

Fig. 1—The geometric volumes used to represent a peaked grain mass in a rectangular storage (Brook, 1983).

Article was submitted for publication in April, 1988; reviewed and approved for publication by the Food and Process Engineering Institute of ASAE in July, 1988. Presented as ASAE Paper No. 87-6546.

This work is published with the approval of the Director of the Kentucky Experiment Station and designated as Paper No. 87-2-264.

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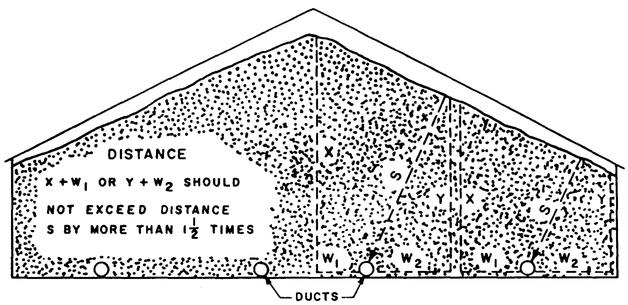

S IS SHORTEST AIR PATH TO DUCT
X IS GREATEST GRAIN DEPTH SERVED BY ONE DUCT
Y IS LEAST GRAIN DEPTH SERVED BY ONE DUCT
W_1 AND W_2 ARE HORIZONTAL DISTANCES TO DUCTS

Fig. 2—Spacing configuration for lengthwise ducts in a peak loaded flat storage.

combinations. The required number of ducts is determined when the user specified grain wall height to width ratio is greater than the corresponding HSW value determined by the model for a given duct combination.

Table 1 gives the minimum HSW ratios for each of the ten duct combinations with an angle of repose of 25 deg. If, for example, an existing building had a side wall grain height of 3.05 m (10 ft) and a width of 12.2 m (40 ft) for this angle of repose, the model would select a three duct combination using the actual HSW ratio of 0.25. If the side wall grain height is reduced to 1.83 m (6 ft) for the same building width then a four duct combination would be required. The ducts are then spaced accordingly using the duct configuration determined by the required number. The duct spacing is used to determine the grain volume served by the duct and the average grain height above the duct. Odd duct combinations feature a center duct and even combinations are offset from the center similar to Fig. 2.

Duct Size

The required airflow that each duct must carry is determined from the grain volume to be aerated by the duct and the design airflow rate specified by the user. One recommendation is to choose the duct diameter such that the maximum air velocity in the duct is no more than 457.2 m/min (1500 fpm), (Hellevang, 1984). The reason for keeping the air velocity near this value is to maintain uniform airflow within the duct and provide an even air distribution in the grain mass.

TABLE 1. MINIMUM GRAIN HEIGHT AT THE SIDE WALL TO BUILDING WIDTH RATIOS (HSW) FOR EACH OF 10 DUCT COMBINATIONS AND AN ANGLE OF REPOSE OF 25 deg

Duct number	Minimum HSW Ratio*
1	0.5092
2	0.3733
3	0.1704
4	0.1422
5	0.0819
6	0.0709
7	0.0444
8	0.0391
9	0.0255
10	0.0226

* These ratios were calculated using a spacing constant such that the longest air path is not more than 1.5 times the shortest air path (USDA, 1960).

Another factor that affects the selection of duct diameter is the type of system operation. The model allows the user to specify the use of a positive (fan on pressure) or negative (fan on suction) operation. Shove and Hukill (1963) presented the following differential equation for predicting the static pressure in a perforated duct with uniform airflow:

$$\frac{dh}{dx} = -K \frac{d}{dx} \left(\frac{V^2}{2g} \right) \pm \frac{fV^2}{D\ 2g}$$

h = static pressure head
K = velocity head constant
V = air velocity in duct
D = hydraulic diameter
g = acceleration of gravity
f = friction factor

This equation shows that for a negative system (combining flow) the static pressure change associated with the friction term is additive to that associated with the velocity head. In a positive system (dividing flow) a static pressure regain is often experienced, where the pressure change due to velocity tends to offset that associated with the friction loss. Table 2 shows the pressure loss calculated from the equation of Shove and Hukill for an 0.457 m (18 in.) diameter round metal duct using both positive and negative aeration for representative duct lengths. These values show much higher pressure drops for the negative type system as both velocity and length increase. Inspection of the table also shows the pressure drops for a positive system at 762 m/min (2500 fpm) to be generally less than those of a negative system with the recommended velocity of 457.2 m/min (1500 fpm). This demonstrates the characteristic static pressure regain experienced in positive pressure systems. For this reason, the higher velocity was chosen as the model design value for positive systems with the recommended value being retained for negative system design.

Once the initial duct diameter is established from the required airflow and maximum system velocity, a further check is performed on the average exit velocity of the air from the duct into the grain. Brook (1979) recommends

TABLE 2. PRESSURE DROP (Pa) IN 0.457 m (18 in.) ROUND METAL DUCT FOR VARIOUS DUCT LENGTHS AND AIR VELOCITIES

Duct length, m (ft)	System* pressure	Air velocity, m/min (fpm) 457.2 (1500)	609.6 (2000)	762.0 (2500)	914.4 (3000)
15.2 (50)	(+)	33.1	58.7	91.8	132.1
	(−)	78.9	140.3	219.2	315.8
22.9 (75)	(+)	23.4	41.6	64.7	93.3
	(−)	98.3	157.5	246.4	354.6
30.5 (100)	(+)	13.7	6.0	37.8	54.5
	(−)	98.3	174.9	273.2	393.4
38.1 (125)	(+)	4.0	7.0	10.7	15.7
	(−)	108.0	192.1	300.3	432.5
45.7 (150)	(+)	5.7	10.5	16.2	23.4
	(−)	117.7	209.5	327.2	471.3

* Positive sign refers to a system with fan on pressure; negative sign refers to a system with fan on suction. Pressure drops are based on the equations of Shove and Hukill (1963) using a friction factor = 0.05 and a K value of 1.7 for a positive pressure system and 1.5 for a negative system.

The pressure drops shown assume uniform air intake or discharge along the length of the duct.

that the maximum air velocity leaving the duct should be no larger than 7.62 m/min (25 fpm) to avoid large pressure drops. The model uses this value as a check and continues to increase the duct diameter until there is sufficient surface area to allow a velocity less than the maximum. If the largest duct diameter is incurred before a satisfactory velocity value is found the model will complete the design and print a message noting the excess value.

Once the final diameter is selected the velocity is determined for each individual duct and the pressure drop is calculated using the equations of Shove and Hukill. Ducts are assumed to have a 1.52 m (5 ft) permanent section at the fan and run lengthwise of the appropriate building dimension stopping short of the wall by a length equal to that of the permanent section.

Grain Types

The model currently includes the following grain type for evaluation: wheat, corn, soybeans, barley, oats and sunflower. Maximum angles of repose for these grains were taken from Richey et al. (1961). Pressures losses for each grain are calculated using the airflow resistance equation and grain constants from the ASAE standard D272.1 (ASAE, 1987). For level storages the pressure drop is computed from the equation using the user specified design airflow rate and the grain height. For peaked storages, the procedure remains the same except

TABLE 3. INPUT SPECIFICATIONS AND DUCT LOCATION INFORMATION FOR LEVEL GRAIN MASS (ENGLISH UNITS)

Input Specifications

Building length: 70 ft.	Building width = 30 ft.
Wall grain height = 8.0 ft.	Peak grain height = 8.0 ft.
Grain type = Wheat	Angle of repose = 0.0 deg
Aeration system = Negative	Design airflow = 0.2 cfm/bu
Peak direction = Level Mass	Duct direction = Lengthwise
Grain volume = 13,440 bu	Design ducts = 4 round metal

Duct Information

Duct No.	Grain volume, bu	Duct* spacing, ft	Duct† length, ft	Duct diameter, in.	Air velocity, fpm	Air volume, cfm	Exit velocity, fpm	Pressure‡ loss in H_2O
1	3331.6	3.8	65.0	10.0	1221.7	666.3	5.3	0.364
2	3331.6	11.3	65.0	10.0	1221.7	666.3	5.3	0.364
3	3331.6	18.8	65.0	10.0	1221.7	666.3	5.3	0.364
4	3331.6	26.3	65.0	10.0	1221.7	666.3	5.3	0.364

* Duct spacing is from building wall.
† Duct length includes 5 ft permanent section.
‡ Pressure loss shown is the loss in the duct and that in the grain with 1.5 packing factor and does not account for entrance or transition losses.

TABLE 4. INPUT SPECIFICATIONS AND DUCT LOCATION INFORMATION FOR LEVEL GRAIN MASS (METRIC UNITS)

Input Specifications

Building length: 21.3 m	Building width = 9.14 m
Wall grain height = 2.44 m	Peak grain height = 2.44 m
Grain type = Wheat	Angle of repose = 0.0 deg
Aeration system = Negative	Design airflow = 0.223 m^3/t
Peak direction = Level Mass	Duct direction = Lengthwise
Grain volume = 473.6 m^3	Design ducts = 4 round metal

Duct Information

Duct No.	Grain volume, m^3	Duct* spacing, m	Duct† length, m	Duct diameter, cm	Air velocity, m/min	Air volume, m^3/min	Exit velocity, m/min	Pressure‡ loss Pa
1	117.4	1.16	19.8	25.4	372.4	18.87	1.62	90.6
2	117.4	3.44	19.8	25.4	372.4	18.87	1.62	90.6
3	117.4	5.73	19.8	25.4	372.4	18.87	1.62	90.6
4	117.4	8.02	19.8	25.4	372.4	18.87	1.62	90.6

* Duct spacing is from building wall.
† Duct length includes 1.52 m permanent section.
‡ Pressure loss shown is the loss in the duct and that in the grain with 1.5 packing factor and does not account for entrance or transition losses.

TABLE 5. INPUT SPECIFICATIONS AND DUCT LOCATION INFORMATION FOR A PEAKED GRAIN MASS WITH POSITIVE AERATION (ENGLISH UNITS)

Input Specifications

Building length: 100 ft.	Building width = 40 ft
Wall grain height = 10 ft	Peak grain height = 20 ft
Grain type = Corn	Angle of repose = 26.6 deg
Aeration system = Positive	Design airflow = 0.2 cfm/bu
Peak direction = Lengthwise	Duct direction = Lengthwise
Grain volume = 45906 bu	Design ducts = 3 round metal

Duct Information

Duct No.	Grain volume, bu	Duct* spacing, ft	Duct† length, ft	Duct diameter, in.	Air velocity, fpm	Air volume, cfm	Exit velocity, fpm	Pressure‡ loss in H_20
1	5723.6	4.8	95.0	10.0	2098.8	1144.7	6.1	0.296
2	34137.7	20.0	95.0	24.0	2173.3	6827.5	15.1	0.743
3	5723.6	35.2	95.0	10.0	2098.8	1144.7	6.1	0.296

* Duct spacing is from building wall.
† Duct length includes 5 ft permanent section.
‡ Pressure loss shown is the loss in the duct and that in the grain with 1.5 packing factor and does not account for entrance or transition losses.

TABLE 6. INPUT SPECIFICATIONS AND DUCT LOCATION INFORMATION FOR A PEAKED GRAIN MASS WITH POSITIVE AERATION (METRIC UNITS)

Input Specifications

Building length: 30.48 m	Building width = 12.2 m
Wall grain height = 3.05 m	Peak grain height = 6.1 m
Grain type = Corn	Angle of repose = 26.6 deg
Aeration system = Positive	Design airflow = 0.223 m^3/t
Peak direction = Lengthwise	Duct direction = Lengthwise
Grain volume = 1617.7 m^3	Design ducts = 3 round metal

Duct Information

Duct No.	Grain volume, m^3	Duct* spacing, m	Duct† length, m	Duct diameter, cm	Air velocity, m/min	Air volume, m^3/min	Exit velocity, m/min	Pressure‡ loss Pa
1	201.7	1.46	29.0	25.4	639.7	32.4	1.86	73.6
2	1203.0	6.10	29.0	61.0	662.4	193.4	4.60	184.9
3	201.7	10.73	29.0	25.4	639.7	32.4	1.82	76.6

* Duct spacing is from building wall.
† Duct length includes 1.52 m permanent section.
‡ Pressure loss shown is the loss in the duct and that in the grain with 1.5 packing factor and does not account for entrance or transition losses.

that the grain height is an average value for the width of grain served by the duct. The standard packing factor value of 1.5 is used to increase these pressure losses which are then added to the duct losses to reflect the total pressure for the grain and the duct.

Duct Types

The model considers three duct types: round metal, half-round metal and round plastic. If the user does not wish to specify type, the model will default to round metal for a given design. The available diameters range from 0.15 m to 0.91 m (6 in. - 36 in.) for the metal ducts and inside diameters of 0.20 m to 0.61 m (8 in. - 24 in.) for the plastic type. For the round, on-floor ducts the surface area available for aeration is assumed to be 80% of the total to account for the portion of the duct in contact with the floor (Brook, 1979). Friction factors used in Shove's equation were established at 0.05 for metal ducts and 0.14 for plastic. The value for plastic was arrived at using static pressure versus velocity data for a 0.381 m (15 in.) non-perforated corrugated tubing (Hancor, 1986).

MODEL OUTPUT AND DISCUSSION

Tables 3 to 8 show input specifications and output information in both English and Metric units for two examples using the computer model. The first example (Tables 3 to 4) is for a level mass of wheat in a rectangular structure with the ducts running lengthwise of the building. The four ducts are uniformly spaced at a distance somewhat less than the overall grain height.

TABLE 7. INPUT SPECIFICATIONS AND DUCT LOCATION INFORMATION FOR A PEAKED GRAIN MASS WITH NEGATIVE AERATION (ENGLISH UNITS)

Input Specifications

Building length: 100 ft	Building width = 40 ft
Wall grain height = 10 ft	Peak grain height = 20 ft
Grain type = Corn	Angle of repose = 26.6 deg
Aeration system = Negative	Design airflow = 0.2 cfm/bu
Peak direction = Lengthwise	Duct direction = Lengthwise
Grain volume = 45906 bu	Design ducts = 3 round metal

Duct Information

Duct No.	Grain volume, bu	Duct* spacing, ft	Duct† length, ft	Duct diameter, in.	Air velocity, fpm	Air volume, cfm	Exit velocity, fpm	Pressure‡ loss in H_20
1	5705.3	4.8	95.0	12	1452.9	1141.1	5.0	0.601
2	34003.4	20.0	95.0	30	1385.4	6800.7	12.0	0.784
3	5705.3	35.2	95.0	12	1452.9	1141.1	5.0	0.601

* Duct spacing is from building wall.
† Duct length includes 5 ft permanent section.
‡ Pressure loss shown is the loss in the duct and that in the grain with 1.5 packing factor and does not account for entrance or transition losses.

TABLE 8. INPUT SPECIFICATIONS AND DUCT LOCATION INFORMATION FOR A PEAKED GRAIN MASS WITH NEGATIVE AERATION (METRIC UNITS)

Input Specifications

Building length: 30.48 m	Building width = 12.2 m
Wall grain height = 3.05 m	Peak grain height = 6.1 m
Grain type = Corn	Angle of repose = 26.6 deg
Aeration system = Negative	Design airflow = 0.223 m^3/m-t
Peak direction = Lengthwise	Duct direction = Lengthwise
Grain volume = 1617.7 m^3	Design ducts = 3 round metal

Duct Information

Duct No.	Grain volume, m^3	Duct* spacing, m	Duct† length, m	Duct diameter, cm	Air velocity, m/min	Air volume, m^3/min	Exit velocity, m/min	Pressure‡ loss Pa
1	201.0	1.46	29.0	30.5	442.8	32.3	1.52	149.6
2	1198.2	6.10	29.0	76.2	422.3	192.6	3.66	195.1
3	201.0	10.73	29.0	30.5	442.8	32.3	1.52	149.6

* Duct spacing is from building wall.
† Duct length includes 1.52 m permanent section.
‡ Pressure loss shown is the loss in the duct and that in the grain with 1.5 packing factor and does not account for entrance or transition losses.

Each duct aerates the same amount of grain in this example so they were uniformly designed with equal diameters and airflows. The selected duct diameters are such that air velocity through the duct is less than design velocity of 457.2 m/min (1500 fpm) for a negative pressure system and the average exit velocity is well below the recommended value discussed earlier. The pressure loss shown for each duct is that from the grain (1.5 packing factor) and that lost in the duct. No allowances have been made for entrance or transition losses and any additional pressure drop used to compensate for these values is left to the discretion of the design engineer.

A second example comprised of two parts is shown for a peaked mass of corn with the ducts and peak extending lengthwise of the structure. The angle of repose for this example is 26.6 deg and the model selected a three duct design to aerate the grain mass. Tables (5 to 6) show model results using a positive aeration system while Tables 7 to 8 show the same configuration with a negative flow system. The ducts are positioned the same in both examples with the center duct aerating approximately 73% of the total grain mass thus requiring a much larger duct than those offset on either side. The required duct length provided sufficient surface area such that the average exit velocity was less than the design maximum of 7.62 m/min (25 fpm). This example shows the advantage of a positive versus negative aeration system. The negative system requires larger duct sizes and lower air velocities, yet the pressure drop that the fan must overcome is larger than that of the positive example. No attempt has been made to calculate the fan power from the information in Table 3 to 8. It was decided that matching the fan based on the pressure drop and air volume through the duct would be more appropriate than selection in terms of a power value.

SUMMARY

A duct location and design program has been developed for aeration of grains in flat rectangular structures. The program results are based on the latest design considerations and the system constraints. Once an initial design is completed for a structure, program options are provided to allow changes in duct number or size, duct type or design airflow. This provides the user with additional flexibility in analysis of a given situation. The program is written in Fortran and developed for use on an IBM personal computer or compatible with sufficient memory. For availability please contact the authors at the Agricultural Engineering Department at the University of Kentucky.

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