KP1-1

Development of a new low-energy environmentally compatible grain and seed drying and storage technology

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Abstract

Airflow rates in conventional bolted steel silos are limited by vertical depth and seed characteristics to low aeration airflow. New technology horizontal, cross-flow air movement where air paths radiate from a center vertical aerator to perforated sidewall plenums allow airflow rates capable of in-silo grain drying without high temperature heat. Jayas and Muir (1991) and Jayas and Mann (1994) found horizontal airflow resistance through elongated kernels (maize, wheat, sunflower, etc.) was 40-50 % lower than the same vertical airflow through the grain.

Combining a center vertical perforated aerator pipe to provide cross-flow aeration with controlled sidewall exhaust outlets in sealed silos can allow drying of partially filled silos and continuation of drying while the silo is being filled. Controlling airflow rates through sidewall and roof exhaust vent air-valve openings allows wetter grain layers to be dried while partially or completely dried grain receives reduced airflow or no airflow. The addition of low burner heat to drying air with modulating controls allows for seed drying day and night without germination damage.

In-silo dryers with hopper bottoms allow rapid dry-grain transfer to storage bins for efficient, economical drying of food and feed grains and seeds. Farmers can reduce losses by earlier harvest with in-silo drying and storage. This technology should allow development of retrofit kits to convert existing steel storage silos into efficient in-silo dryers.

Key words: Low-energy, drying grain, stored grain.

Background of in-silo grain drying technology

Conventional in-silo grain dryers – vertical airflow

Moist grain must be dried to prevent storage mould and spoilage. Traditionally, grain drying takes place outside storage silos as separate drying equipment. Grain drying typically involves burning high volumes of fossil fuel to heat drying air, causing rapid grain moisture release. Heating drying air increases its moisture holding capacity by raising air temperature while lowering its relative humidity (RH). For every 11.1 ºC (20F) increase in drying air temperature, the air RH is reduced by half. Air at 20 ºC, 90 % RH heated to 31.1 ºC is 45 % RH.

Early on-farm drying was done in steel walled silos or bins using vertical movement of air forced under fan pressure into an air chamber (plenum) under a perforated steel grain floor (false floor). Pressurized air forced through the floor perforations heated grain and absorbed grain moisture before exhausting to atmosphere through roof vents. When drying air absorbs all

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the moisture it can hold, it slowly continues warming the remaining moist grain. The level in the grain where drying air stops absorbing moisture is the "leading edge of the drying zone" or the "drying front". If grain depth is shallow, or the air velocity is high enough that it is still absorbing moisture when it passed through the grain surface, then entire grain depth is in the drying zone.

High temperature grain drying - 60-90 ºC (140-195 F) - causes multiple stress cracks of the pericarp (seed coat). When seed or kernel temperature exceed about 40-42 ºC (104-107.6 F), seed or kernel germination begins to decrease. Full in-silo drying is limited by the extreme static air pressures required to move drying air through deep grain. If high volumes of ambient or slightly heated air (up to 40-42 ºC) can be forced through full silos of grain with relatively low electrical power, in-silo drying is ecologically and environmentally viable.

Proper natural air drying preserves grain at the highest quality levels.

Since the mid-1940's grain drying systems have been incorporated in bolted steel storage silos or bins. In-silo drying required grain spreaders or levelers in the top of silos, and full perforated drying floors (false floors) which form an air distribution chamber above concrete silo bases, Figure 1. A high capacity pressure fan blows ambient air through a gas burner or heater. Heated air is forced upward through a thick (1.5-2 m) layer of grain, ideally of uniform depth, but often uneven, variable depth.

Because of uneven airflows and air pressures

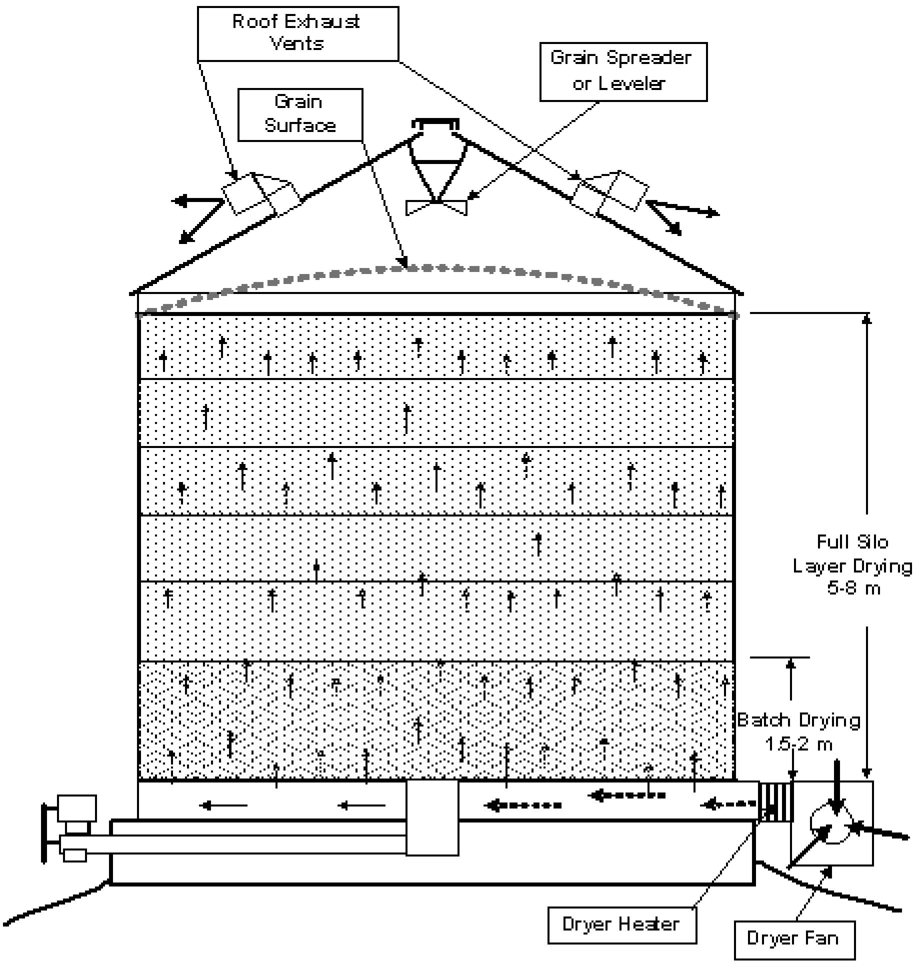

Figure 1. Schematic side view of in-silo batch drying system, showing batch-in-bin and in-bin layer drying.

from one side of the silo base to the other, airflow up through the grain is often not uniformly distributed. Uneven depth grain due to non-level filling causes variable airflow and non-uniform drying.

Layer In-Silo Grain Dryers

Early systems for in-bin or in-silo drying of grain were called "In-Bin Layer Drying", Figure 1. These in-silo dryers developed in the U.S. in the late 1940's required grain levelers to add uniform layers of fresh grain to dried grain layers. The first layer of grain was typically about 1-2 m (3-6 feet) deep, as shown at the bottom of the silo in Figure 1. Successive layers were usually about 1 m deep.

As grain layers increased the grain depth to a total of 4-6 meters, airflow (and thus drying) rates slowed dramatically. As grain depth increased, the drying air temperature had to be reduced to minimize over-drying of bottom grain layers. Layer in-bin drying was very slow; the bottom 2-3 m of grain was often over-dried. To maximize drying during harvest, farmers usually had several in-silo layer dryers operating at the same time.

Batch-In-Silo Grain Dryers

In-silo grain dryers are vertical airflow, cross-flow batch driers. To improve performance and reduce the over-drying problem of in-layer silo dryers, in-silo dryers needed an unload system so they could unload a 1-2 m batch layer fast. In the mid-1950's, agricultural engineering researchers at Purdue University (Lafayette, Indiana) developed the "bin-sweep unload auger" which could clean out 95-98 % of each batch of dried grain. They gave this *"sweep unloader"* technology to the U.S. grain industry. Combined with grain levelers or spreaders, the *sweep unloader* allowed bin-dryers to dry several times faster than the same dryer used for "in-layer drying". Batch drying minimized over-drying of grain, as farmers or elevator grain managers dried to a ***blended average*** for storage or marketing the grain.

One or more "batch-in-bin" dryers were combined with several steel storage silos and a central grain handling system to form efficient farm or country elevator grain centers. These in-bin or in-silo dryers allowed farmers to spread a 1-1.5 m (3-5 ft.) deep layer of freshly harvested, medium to high moisture grain fairly uniformly, dry and cool, then transfer the grain from the bin-dryer efficiently and effectively into storage silos. Farmers could load, dry, cool and transfer about one 1.5 m batch of grain per day. During harvest, one batch-in-bin dryer could typically dry and transfer as much grain as 5 to 7 in-bin layer dryers of the same diameter, with less heat damage.

Development of horizontal airflow in-silo grain dryers

Conventional cross-flow aeration in deep silos

Cross-flow aeration research in high depth-to-diameter ratio (3:1 to 6:1) silos at Oklahoma State University (Day and Nelson, 1962) in the early 1960's demonstrated that moving the same volume of air horizontally from ducts on one side of a silo to the opposite side required much less power and static pressure compared to the same airflow rates moved vertically. Much higher air volumes could be moved horizontally across a silo, than when using the same fan power to force the air through the full grain depth vertically.

Navarro et al., (2002) discuss cross-flow and horizontal air-flow aeration technology development in detail. The authors notes that when using two-duct cross-flow aeration, airflow path lengths vary widely from the shortest to longest air paths. Air path distance along the wall is about 75 % longer than the air moving straight across the center.

Researchers tested a 4-duct cross-flow aeration model (ducts spaced uniformly around the inside of the silo walls), with two options. Option 1 supplied pressure on two adjacent ducts, A and B, with exhaust through ducts C and D. Option 2 applied pressure to opposite ducts A and C, with exhaust through ducts B and D. Although four-duct cross-flow aeration shortened air path lengths, where the longest air path around the silo wall is 55 % of the shortest, direct path between ducts, “dead-air zones” formed in the center of silos made these aeration methods unacceptable.

Navarro et al., (2002) describes a new 4-duct method of cross-flow aeration which eliminates the dead air zone by using one inlet duct with three outlet ducts, alternating air inlets between duct A and duct C, with the fan on each duct operating 50 % of the time. Ducts B and D are dedicated exhaust ducts, while ducts A and D operate as exhaust ducts 50 % of the time.

Another major problem with conventional cross-flow aeration is that silos have to be full. Grain has to cover the tops of vertical ducts attached to the silo walls. The silo roof has to be sealed so that all air from the pressure duct(s) is forced to exit through the exhaust duct(s). Unless a method is developed to close off or seal the perforated ducts to a point below the grain surface, the aeration system can not be used in partially filled silos. Surface grain does not receive good aeration, as some air short circuits through surface grain. Grain in the top center of the silo is not aerated well.

Even though the two-fan, four-duct system can provide excellent airflow rates, until additional technology to close the air ducts above the grain level during partial filling, the aeration system can only work satisfactorily when the silo is full. Even then it is difficult to recommend this system because of the many times when silos are not completely filled, thus grain in need of aeration could not be cooled.

New in-silo cross-flow grain aeration and drying technology

Day and Nelson (1964) discussed cross-flow drying of grain, but early cross-flow systems were not suitable for drying. New technology aeration and drying involving high air-flow delivery with low static pressure and low fan power which can operate efficiently at variable silo fill levels (once grain fill exceeded 30 to 40 % of the silo), will be highly beneficial to worldwide grain systems for in-silo grain drying. This technology will be valuable for aerating grain in storage silos, and can allow much higher airflows suitable for low cost, efficient in-silo grain drying, providing relatively fast drying below critical moisture levels. For safe storage, interstitial air equilibrium relative humidity (ERH) must be below 70 % RH.

ERH 70 % is a critical value which defines safe upper storage limits of most biological products. Microbial activity is restricted (most molds will not germinate) on biological products when water activity is below 70 % ERH. Both product temperature and product moisture is used to determine ERH levels for biological products. When product levels are reduced below 70 % ERH, most microbes are dormant.

For in-silo drying, a primary design goal is to operate the airflow system continuously from relatively low fill levels until the silo is full. This allows the start of fast grain moisture reduction through drying and cooling early in harvest when fresh, moist grain is transferred into the silo. Fast early drying of moist grain can reduce moisture content of freshly harvested grain steadily toward a safe environmental condition, while harvest and silo loading continues.

It is desirable to have a flexible in-silo drying system which will allow selective conditioning of grain in different vertical sections of the silo. As grain moisture in the lower part of the silo is reduced, and higher moisture grain is added, airflow can be increased on the wetter grain while reducing airflow to partially dried grain, especially after lower grain levels drop close to or below 70 % ERH. Typically, 70 % ERH moisture contents at temperatures of 16 ºC and 32 ºC for wheat range from 13.9 % to 13.0 %. At those same temperatures, maize grain moistures range from 14.1 % to 11.6 %, while sorghum moisture contents vary from 14.1 % to 13.5 %. Between 15 ºC to 35 ºC, soybeans moisture contents range from 12.4 to 11.7 % (ASAE Standards, 1993).

Valuable research, which further clarifies horizontal airflow conditions, was conducted during the early 1990's by D.S. Jayas and associates at the University of Manitoba (Jayas and Muir, 1991; Jayas and Mann, 1994). These researchers discovered that horizontal airflow through elongated seeds and kernels, such as maize (corn), wheat, sunflowers, barley, rice, edible beans, etc., has much less airflow resistance than the same vertical distance and airflow rates. Long kernels tend to orient with their long axis more consistently in a horizontal direction, so air void spaces are more open in horizontal than vertical directions. They discovered that frictional airflow resistance was reduced by 40 % to 50 % using horizontal airflow paths that were the same length vertical air flow paths. So, only 50 to 60 % as much power is required to aerate long grain or seeds with horizontal airflow. When aerating relatively spherical seeds, such as soybeans, sorghum (milo), millet, etc. the fan power requirements were essentially the same for vertical vs horizontal airflow.

This airflow data contributes much to the economy and efficiency of cross-flow (horizontal) aeration and drying technology. To be conservative, when aerating or drying long kernel grains and seeds, the equivalent length air path is considered to be 40 % shorter than vertical air path lengths.

In the summer of 2003, while working with grain scientists in Ukraine on a moist grain storage project, I developed the technology described above for a new method of high capacity, low pressure, low power cross-flow air movement with the capability to deliver horizontal air flow to selected levels of the grain mass inside a silo.

New silo-centered cross-flow aeration and drying technology

This original new technology involves a bolted steel silo fitted with a perforated center aerator tube extending from base to near roof eave level, perforated curved wall panels spaced away from the outer wall to form a shallow air plenum space along the outer silo wall, and air exhaust vent openings through the outer wall at spaced levels, such that each vent is controllable at each level to selectively proportion the amount of air passing through each selected level of grain. One or more adjustable vents mounted in the roof allow control of airflow through surface grain, Figure 2.

The perforated inner wall air plenum ring sections have a sloped top section which attaches to the wall and a formed or bolted angle at the bottom of the panel for structural rigidity. These rings sections are braced from the outer wall to withstand bulk grain forces. Panels have short separations from plenum sections above and below for selective air flow control, Figure 2, so that the amount of opening of the exhaust vents at each level controls the percentage of total fan airflow which would pass through the cylinder of grain in that section. One or more roof vents would allow air to pass through the surface grain if the top of the vertical aerator tube is immersed in the grain. This causes airflow near the grain surface to flow diagonally — approximately

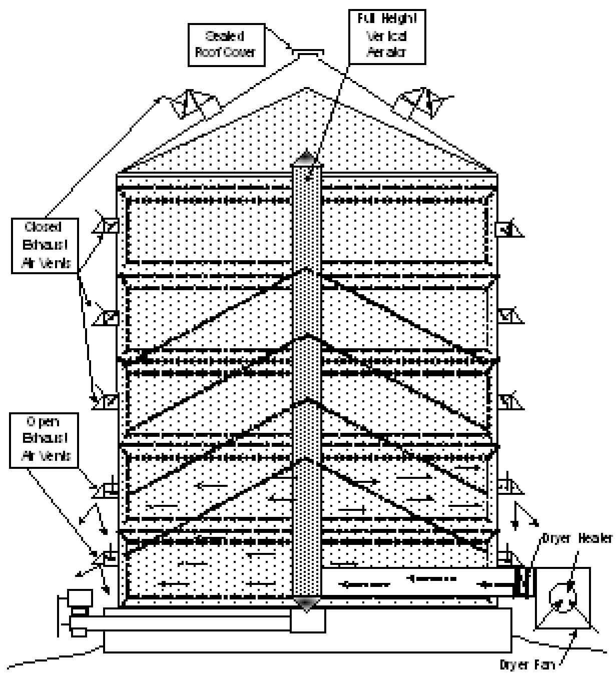

Figure 2. Schematic side view of original in-silo cross-flow drying system illustrating sidewall plenums with external sidewall discharge air vents with control valves.

perpendicular to the grain slope, compared to primarily horizontal airflow in most sections more than one meter from the surface.

To facilitate maximum use of the in-silo dryer for batch drying with high airflow rate and low temperature supplemental heat drying, primary drying is done to lower the grain moisture to about 75-80 % ERH, (1.5-3 % above 70 % ERH levels). Then the grain is cooled and transferred to storage silos which would have cross-flow aeration to continue slowly reducing grain moisture to about 65 % ERH. Storage silos with aeration systems, with smaller vertical perforated aerator pipes and proportionately smaller plenum and venting components, could have flat bottom floors for economy of storage costs. Hopper-bottom drying silos are used for complete rapid cleanout of each batch of dried grain.

Alternative cross-flow in-silo dryer configuration

An alternative configuration of this in-silo dryer technology is shown in Figure 3. This version of silo has a full wall height inner perforated cylinder which will be the primary structural containment for the grain mass. With a smooth, full height inner perforated wall, less vertical grain loading is transferred to the outer sidewall, compared to corrugated steel walls in direct contact with the grain bulk. The outer silo wall can now be smooth (non-corrugated) steel sheeting, rolled to the curvature of the silo-dryer outer diameter. This sheeting may be slightly lighter gauge metal than normal corrugated steel grain storage silos sidewalls

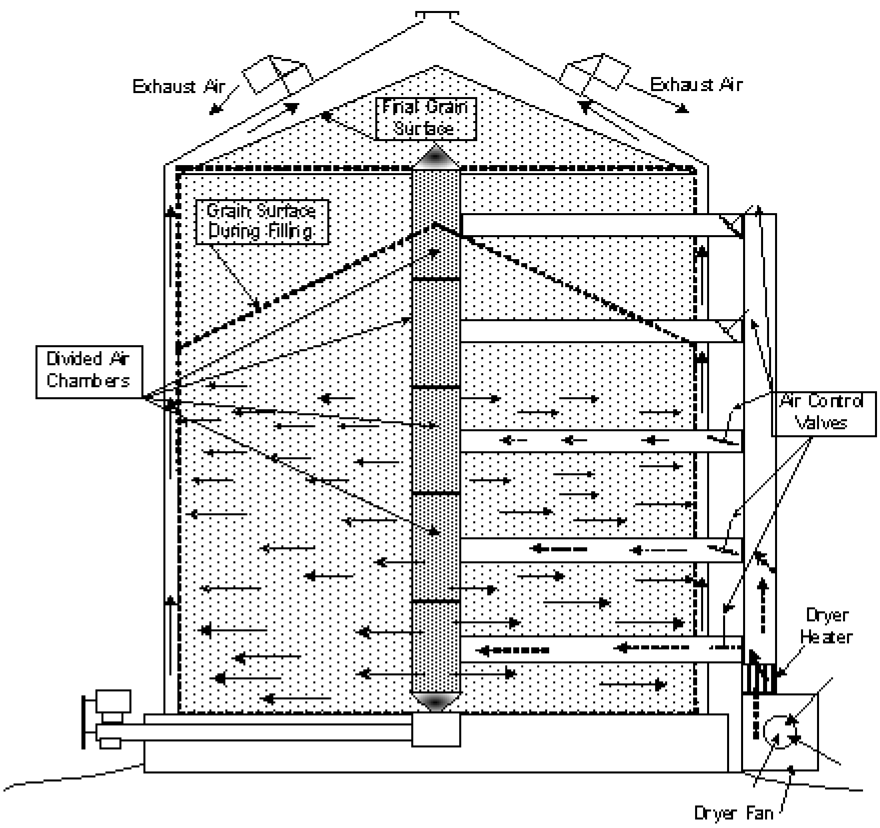

Figure 3. Schematic side view of alternate in-silo cross-flow drying system illustrating sidewall plenum cylinder with separate air delivery tubes to separate air chambers in the vertical aerator. Each supply pipe to a vertical aerator section has an air control valve for drying of selected layers of moist grain.

as the vertical grain load is not directly carried by these sidewall members. Full sidewall height U or Z shaped spacers between outer wall and inner cylinder, combined with the perforated inner wall cylinder to provide primary structural strength to handle the vertical component of grain shearing forces on silo walls. Rolling corrugated steel is an expensive structural process, so by reducing the need for corrugated steel on the exterior of silos can partially offset cost of the inner perforated cylinder and vertical wall spacer column braces.

Sidewall and roof exhaust vents each comprise an adjustable air valve so air volume can be proportionally controlled at each level of the dryer. Thus, as grain fills the silo and passes the first row of exhaust ports, drying can begin, and continue at selected vertical sections of the silo.

The full height center vertical aerator tube distributes drying air radially, directly to the outer perforated wall plenums. As air “fans out” from the vertical aerator pipe, the air velocity gradually slows, providing increased cooling or drying time in the outer grain.

Example: If the inner perforated cylinder plenum walls are 10 meters diameter, and the vertical aerator is 1 meter diameter, horizontal air paths are (10 -1)/2 = 4.5 m long. In a conventional 10 m diameter silo, with 20 m sidewalls, air paths will be 3 to 4 times as long.

Discussion of vertical versus cross-flow aeration power and static pressures

Table 1 compares air volumes and power between vertical and horizontal airflows in an 8 m dia x 20 m sidewall height silo aerating 5 types of grain and oil seeds. Five aeration airflow rates were checked comparing conventional vertical aeration with cross-flow aeration. Using the same fan power for horizontal as vertical airflow, cross-flow systems moves 4 to 9 times as much air volume with only 20 to 35 % as much static pressure. It is clearly apparent that air systems on elongated seeds (maize, wheat and sunflowers) developed higher airflow rates with cross-flow systems than the two spherical type seeds. These ratios are directly related to the vertical aeration grain depth compared to horizontal distance from the vertical aerator tube wall to the perforated sidewall.

When considering horizontal cross-flow aeration or drying in a specific grain volume at a selected fan power level, airflows will be higher and static pressures lower through smaller diameter, deeper silos than for the same grain volume in shorter, wider silos.

Table 2 compares power and static pressure requirements for vertical vs horizontal (cross-flow) air movement for several sizes of silos, comparing three high volume long kernel grains and oil seeds (maize, wheat and sunflowers) and two round kernel grains or seeds (soybeans and sorghum) using the same airflow rates.

The important point is that relatively high airflow rates can be developed with low static pressures in large, upright bulk storage units. With proper design, it is economically feasible to conduct major drying efforts in large bulk dryers which can be easily unloaded and reloaded for relatively high-volume low-energy drying. The final column in both tables lists the H/V Ratio. This is a ratio comparing horizontal airflow to vertical airflow, using the same fan power on both silos to compute the date for that line of the table.

These data in Tables 1 and 2 were developed using the ***FANS*** program developed by Dr. Bill Wilcke, Professor of Agricultural Engineering, University of Minnesota, St. Paul, MN, and Dr. Dirk Maier, Professor of Agricultural Engineering, Purdue University, Lafaytette, IN.

This cross-flow in-silo drying and aeration technology has the potential for use in retrofitting existing steel silos to this more efficient airflow design.

Table 1. Comparison of Five Vertical to Horizontal Airflows[1]. Using Vertical Silo Fan Power Settings in Horizontal Silos in an 8 m x 20 m, 800 ton Silo.

	Vertical Airflow			Horizontal Airflow			
Grain Type	Airflow Rate $m^3/m/m^3$	Static Press g/cm^2	KW	Airflow Rate $m^3/m/m^3$	Static Press g/cm^2	KW	H/V Ratio
Maize	0.08	9	3.6	0.42	1.6	3.6	5.2
	0.16	20	16.1	1.16	2.7	16.1	7.2
	0.24	34	41.4	1.93	4.2	41.4	8.0
	0.32	52	82.8	2.70	6.0	82.8	8.4
	0.40	71	143.0	3.46	8.2	143.0	8.6
Wheat	0.08	25	10.3	0.60	3.3	10.3	7.5
	0.16	54	43.8	1.34	6.4	43.8	8.4
	0.24	87	105.9	2.09	10.0	105.9	8.7
	0.32	124	201.4	2.82	14.0	201.4	8.8
	0.40	165	334.6	3.57	18.5	334.6	8.9
Sunflower (oil)	0.08	12	5.0	0.50	2.0	5.0	6.2
	0.16	28	22.5	1.24	3.6	22.5	7.8
	0.24	47	57.2	2.02	5.7	57.2	8.4
	0.32	70	113.4	2.76	8.1	113.4	8.6
	0.40	96	194.9	3.51	11.0	194.9	8.8
Soybean	0.08	7.5	3.0	0.37	1.6	3.0	4.6
	0.16	16	12.6	1.07	2.3	12.6	6.7
	0.24	26	30.9	1.83	3.3	30.9	7.6
	0.32	37	59.7	2.60	4.6	59.7	8.1
	0.40	50	100.7	3.36	5.9	100.7	8.4
Sorghum	0.08	25	10.1	0.60	3.3	10.1	7.5
	0.16	53	42.8	1.33	6.3	42.8	8.3
	0.24	84	102.8	2.08	9.8	102.8	8.7
	0.32	120	194.6	2.82	13.6	194.6	8.8
	0.40	159	322.0	3.56	17.8	322.0	8.9

[1] NOTE: Data developed using FANS computer program, developed by Dr. W. Wilcke, Univ. of Minnesota; Dr. D. Maier, Purdue Univ.

Table 2. Comparison of vertical to horizontal airflows*. Using vertical silo fan power settings in horizontal silos for a range of silo sizes.

Silo Size	Vertical Airflow			Horizontal Airflow			
(dia x ht, meters)	Airflow Rate	Static Press	KW	Airflow Rate	Static Press	KW	H/V Ratio
Grain	$m^3/m/m^3$	g/cm^2		$m^3/m/m^3$	g/cm^2		
Maize							
10 x 15	0.08	5.2	2.4	0.25	1.6	2.4	3.1
10 x 20	0.08	8.8	5.6	0.38	1.8	5.6	4.8
15 x 20	0.08	8.8	12.6	0.30	2.4	12.6	3.8
15 x 25	0.08	13.6	24.1	0.38	2.8	24.1	4.8
20 x 25	0.08	13.6	42.9	0.31	3.5	42.9	3.9
20 x 30	0.08	20.3	77.1	0.38	4.2	77.1	4.8
Wheat							
10 x 15	0.08	14.2	6.7	0.35	3.1	6.7	4.4
10 x 20	0.08	25.4	16.1	0.50	4.0	16.1	6.2
15 x 20	0.08	25.4	36.1	0.34	6.0	36.1	4.2
15 x 25	0.08	39.4	69.7	0.42	7.4	69.7	5.2
20 x 25	0.08	39.4	123.9	0.34	9.1	123.9	4.2
20 x 30	0.08	58.1	221.0	0.42	10.9	221.0	5.2
Sunflowers (oil)							
10 x 15	0.08	5.2	2.4	0.26	1.6	2.4	3.2
10 x 20	0.08	8.8	5.6	0.38	1.8	5.6	4.8
15 x 20	0.08	8.8	12.6	0.29	2.5	12.6	3.6
15 x 25	0.08	13.6	24.1	0.37	2.9	24.1	4.6
20 x 25	0.08	13.6	42.9	0.31	3.5	42.9	3.9
20 x 30	0.08	20.3	77.2	0.38	4.2	77.2	4.8
Soybeans							
10 x 15	0.08	4.5	2.1	0.18	1.9	2.1	2.2
10 x 20	0.08	7.5	4.7	0.26	2.2	4.7	3.2
15 x 20	0.08	7.5	10.6	0.19	3.2	10.6	2.4
15 x 25	0.08	11.2	19.8	0.24	3.8	19.8	3.0
20 x 25	0.08	11.2	35.3	0.20	4.5	35.3	2.5
20 x 30	0.08	16.3	62.1	0.24	5.3	62.1	3.0
Sorghum							
10 x 15	0.08	13.9	6.6	0.23	4.7	6.6	2.9
10 x 20	0.08	24.9	15.8	0.32	6.1	15.8	4.0
15 x 20	0.08	24.9	35.5	0.21	9.5	35.5	2.6
15 x 25	0.08	38.6	68.2	0.26	11.8	68.2	3.2
20 x 25	0.08	38.6	121.3	0.21	14.1	121.3	2.6
20 x 30	0.08	56.8	216.0	0.26	17.5	216.0	3.2

[1] NOTE: Data developed using FANS computer program, developed by Dr. W. Wilcke, Univ. of Minnesota; Dr. D. Maier, Purdue Univ.

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