Final REPORT

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Palmer

NEW INSIGHTS INTO NATURAL AIR GRAIN DRYING

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Final Report
New Insights into Natural Air Grain Drying

Summary

This research project started over a decade ago in 2007. At the time there was no formative practice as to how an aeration fan should be controlled; but, there was a vague notion that there must be a better, more effective, more efficient method to control the fans rather than just running them continuously and hoping for the best. Eventually the grain would dry; but at what cost? What was happening in that grain bin when the fan was running continuously? What ambient conditions yielded the best drying? Were there times when drying was not occurring? This research project had many questions to answer; but, the overall objective was to find a control strategy that would efficiently dry the grain. It would then be safe for storage and ready to sell.

A method was devised to measure the amount of drying by measuring the absolute humidity of the air entering and leaving the bin. The absolute humidity is the amount of water in the air and it is a function of temperature and relative humidity. The difference in absolute humidity of the air flowing in and out of the bin in one hour renders the amount of water removed from the grain. This method of measuring drying, was instrumental in the subsequent research to measure and observe *drying* in real time.

A daily pattern of drying was discovered called the **diurnal drying cycle** and it clearly showed that the most drying occurred at night and the least during the day. This was controversial; yet undeniably the case. The cold dry night air is warmed by the grain as it flows through the bin absorbing moisture from the grain.

The hourly drying graphs demonstrated a strong correlation between drying and cooling of the grain. It was observed that: "*Cooling is Drying*" or "*Drying results in Cooling*". This became the basis for a fan control strategy. If cooling the grain resulted in drying; then it would be logical to only run the fan when cooling occurs. To cool the grain, one requires air that is colder than the grain. Consequently, the following control strategy was established: *Only run the fan if the outside air temperature is less than the grain temperature.* It is called **Differential Temperature Control** and it is the best control for keeping the grain cold. This controller was built and tested. The duty cycle of the run-time of the fan started at approximately 50% but, quickly dropped to 20% or less as the grain cooled.

During the course of this research, the original objective of just getting the grain dry, was questioned. It was believed that if you only got the grain dry, everything would be fine; the grain would have no spoilage. However, it was learned that the grain was deteriorating from the moment it was harvested. Fraser and Muir (1981) [7,14] were able to measure the amount of spoilage and revealed that spoilage was a function of grain temperature and moisture content. The best grain storage, that resulted in the least spoilage, would have the grain dry and cold. Even if grain is dry, it can still be spoiling. To essentially stop spoilage, one must have the grain both dry and cool. The original objective of: *drying the grain*, needed to be reconsidered. To condition the grain for the best storage, with the least spoilage, one would have to include, cooling the grain. The revised objective, for the best grain storage, with the least spoilage must include the grain temperature: keep the grain as cold as possible.

When the grain is cold, it possesses little heat energy to expel and evaporate more of its moisture. Even if grain is loaded into the bin at a high temperature, one should expect only modest drying with moisture content reduction of a couple of percentage points. The grain will need to be re-energized to expel more moisture. Night drying only worked while the grain had some heat in it; once cold, there was no more drying.   Being cold the grain was safe from spoilage, even though it might be tough.

If the paramount objective of the farmer was to dry the grain, then the fan should run whenever a drying condition exists. Drying conditions exist when the absolute humidity of the air leaving the bin is greater than the absolute humidity of the air entering the bin through the fan. By measuring the absolute humidity of the air entering and leaving the bin; it would be possible to determine drying conditions and when to turn the fan on. It is called **Absolute Humidity Control** and it is the best control strategy for optimum drying: *only run the fan if the absolute humidity of the air leaving the bin is greater than the absolute humidity of the air entering the bin*. This controller was built and tested. The duty cycle of the run-time of the fan was initially about 50% but it quickly dropped to 20% or less as the grain cooled and dried.

The calculations to determine the absolute humidity are rather onerous. To determine drying conditions by hand with a calculator is complicated and tedious. A calculator was designed and installed on www.planetcalc.com to do the difficult calculations. One simply inputs the grain temperature, its moisture content, and the temperature of the outside air. The calculator returns the threshold Relative Humidity, RHthres. If the outside relative humidity is below this threshold, one has drying conditions. This calculator can be ported to a cell phone and used anywhere there is cell service.

The calculator has another purpose; it can be used to determine if condensation would form under the roof of the bin. Conditions for condensation exist if the calculated threshold relative humidity is greater than 100%. It would not be advisable to run the fan under these conditions as condensed moisture would literally be raining down onto the grain.

It has been noticed by many that the bottom of the bin dries first and often over-dries by the time the top dries. Why? The air at the bottom of the bin is slightly warmer from compression. The compression was enough to support 5 or 6 inches of water, which resulted in warming the air by a few degrees. The warmer air has more capacity to hold water, and thus dries the bottom more. If one uses a bigger fan, one will get more compression, more of a temperature difference from top to bottom and more over drying the bottom. Using a bigger fan with more compression can be counter productive in over-drying the bottom. The best flow was found to be about 0.4 CFM/bu.

Overall the project has been successful. Two control strategies have been developed, one for best storage and one for best drying. And a better understanding of what is happening in the bin has been found and made available to farmers. The control strategies are being used by farmers. One farmer is using the absolute humidity controller for aeration on his 48,000 bushel bin. Another farmer is using the control strategy to keep bagged grain from spoiling in a sea-cargo-container as it is being shipped to its destination.

Much of the understanding of what is happening with Natural Aeration Drying (NAD) has been incremental and has been a collaborative effort.   A blog was started to record this journey and now this analysis and understanding has been recorded in detail. Much of it has resulted from the analysis of the data, but a significant amount has been the result of farmers asking probing questions, which when worked out revealed the theory and gave a better understanding of the dynamics of aeration.

There has been one common parameter throughout all aspects of this research, and that is grain temperature. Grain temperature is the dominant parameter in determining absolute humidity as well as securing the grain from spoilage. On the one hand, hot grain is good because heat energy is required to push moisture out of the grain, but on the other hand, it is hot grain that spoils. We want to get that heat energy into the grain for drying; but once hot, we want to cool it immediately to mitigate the spoilage. It is a paradigm shift – we always thought that dry grain was paramount, and perhaps this would be the case if there was no control over temperature. With NAD aeration, the temperature of the grain can be controlled; the grain can be cooled in a matter of hours and thus cool grain becomes more of an important ideal than dry grain.

This research project, has more than met its objectives. Controllers have been designed and tested, the theory has corroborated the observation, and many bonus findings have been discovered, such as the cause of condensation on the roof, the calculator, and the reason the bottom dries first.

Introduction

A farmer has a large investment in producing a bin of grain [8]. Large input costs, of seed fertilizer, pesticides, herbicides and large capital costs of machinery and land are required to produce this grain. Bulk grain stored in bins is an ecosystem in which living organisms (e.g. bacteria, insects, mites, fungi, and moulds) exist in a dynamic environment of changing temperature, humidity and oxygen levels. Certain conditions, especially high temperature and humidity, are ideal for growth of these spoilage organisms and should be curtailed for both economic and health reasons [4]. Concerns are being raised about the contamination of cereal-derived staples and other commodities like beer with the toxic fungal metabolite Ochratoxin A [13]. It has been reported that in sub-Saharan Africa, up to 40% of the food produced spoils before reaching the consumer because of poor storage conditions [18]. Cereal grain loss due to spoilage and respiration is on average 4.5% with an additional 1 to 3% loss by insects [3].

In the Canadian Prairies, harvested grain often gets added to bins at higher grain moisture contents than what is safely recommended, due to the unpredictability of the weather, and due to the requirement of harvesting the crop in a timely manner to maintain quality. Thus, a common practice is the use of fans to cool and/or dry the grain to avoid spoilage [14].

Grain is produced under natural conditions and is subject to microbiological contamination and infection (Abdullah et al., 2000). Grain starts to deteriorate from the time of harvest due to interactions between the physical and biological variables within the environment (Mason et al., 1997). Cereal grains just after being harvested contain microbial contamination coming from several sources, such as dust, water, ill plants, insects, fertilisers and animal feces. Grain deterioration is also a result of respiration of the grain itself and of the accompanying microorganisms. The production of carbon dioxide, water and heat is associated with respiration, (Steele et al., 1969). A freshly harvested bin of grain is living, breathing, and, contaminated with spoilage agents. To make things worse it is often tough (high moisture content) and it has started to spoil. In storage it will continue to spoil, it will only decrease in quality. The objective of good storage would be to curtail this spoilage and to preserve the quality of the freshly harvested grain.

Objective

The overall objective of this project was to find a better way to control aeration fans, to only turn them on when necessary and yet, to provide for safe grain storage. The fan controller should be:

- Efficient, saving power -- fan on only when necessary (if drying, fan on, if not drying, fan off)
- Safe, conditioning the grain for minimal spoilage
  - Cool grain
  - Dry grain

The original strategy was to develop a controller that would only run the fan when the ambient air conditions resulted in drying the grain. After learning about the conditions that are required for safe grain; the strategy changed somewhat to develop a controller that would only run the fan when the grain was cooled, to make it as safe as possible, with the least spoilage.

Vapour Pressure

There is a battle going on with the grain and the air concerning drying. Both have vapour pressure, with the air trying to push water into the grain, and the grain trying to expel and evaporate its moisture into the air. Air vapour pressure is a function of moisture content and temperature [2]; but, the dominant factor is temperature, as shown in Figure 1. Likewise, for grain, its vapour pressure is a function of moisture content, type of grain, and temperature; and again, the largest contributor is the temperature of the grain.

When air vapor pressure is greater than grain vapor pressure, water enters the grain and *wetting* occurs. When grain vapor pressure is greater than the air vapor pressure, water evaporates from the grain into the air and there is *drying*. When the vapor pressure of the grain and air are equal, there is neither wetting or drying; there is a steady state of equilibrium that establishes the basis for Equilibrium Moisture Content equations (EMC). [1]
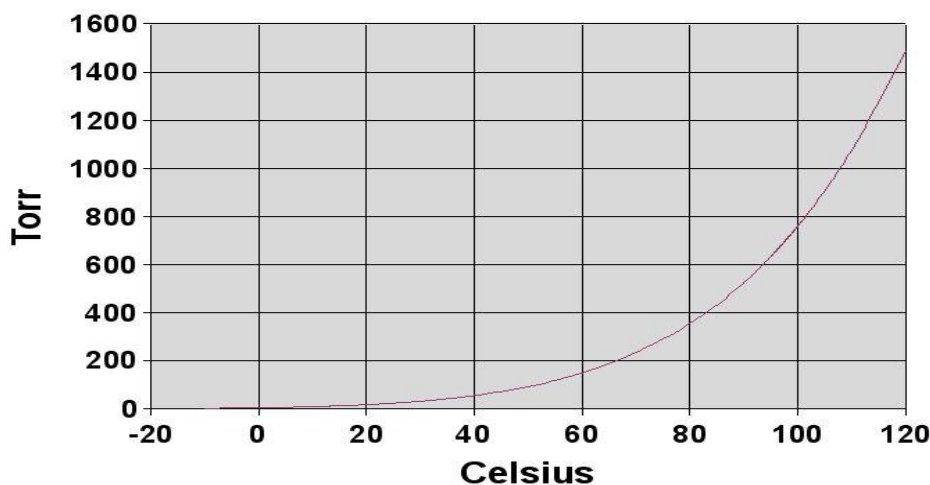

Figure 1. Vapour Pressure as a Function of Temperature

The Black Box Approach

One could consider the bin to be a black box. It is not known exactly what goes on inside, but if one observes and measures what goes in and what comes out, it would be possible to determine the net effect.   If one measures the amount of water going in, and out of the bin, the difference would indicate the amount of drying taking place as is shown in Figure 2. The absolute humidity is the amount of water in the air. An example is shown in Figure 3.
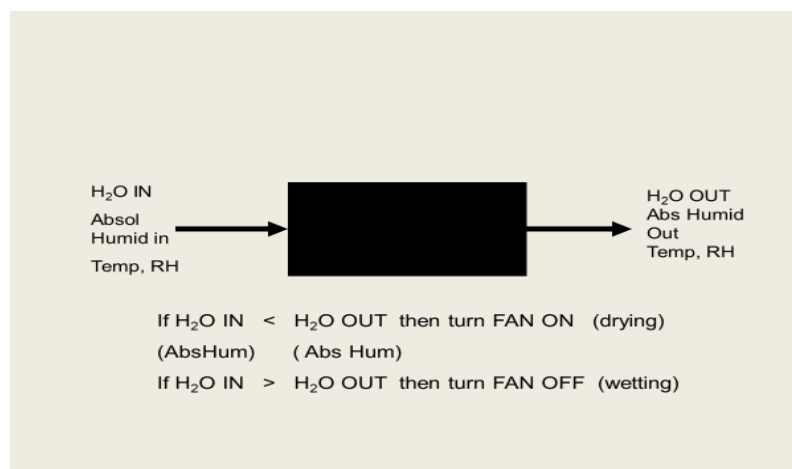

H_2O IN
Absol
Humid in
Temp, RH

H_2O OUT
Abs Humid
Out
Temp, RH

If H_2O IN < H_2O OUT then turn FAN ON (drying)
(AbsHum)   (Abs Hum)

If H_2O IN > H_2O OUT then turn FAN OFF (wetting)

Figure 2. Black Box approach to Drying

H_2O **25 gr/m³**

Air goes in through the fan, passes through the grain, and exits the bin

Amount of Air In = Amount of Air Out

For every cubic meter of air that goes in, there is a cubic meter that exits at the top.

Air holds water, **Absolute Humidity** grams per cubic meter (m³)

Example: Air entering has an Absolute Humidity of **20 gr/m³** and exits the bin with an Absolute Humidity of **25 gr/m³**

Therefore for every cubic meter of air that passes through the bin, **5 grams of** water are being removed. We are drying.

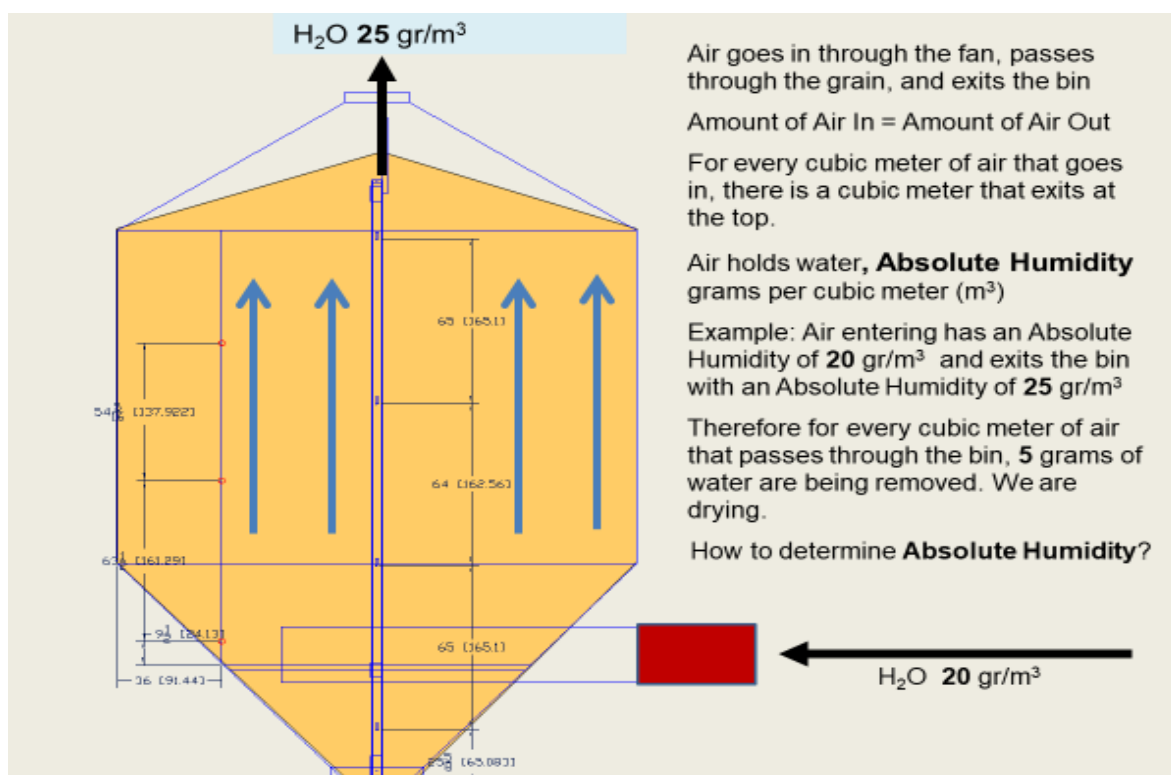How to determine **Absolute Humidity**?

H_2O **20 gr/m³**

Figure 3. An example of the amount of water leaving and entering the bin
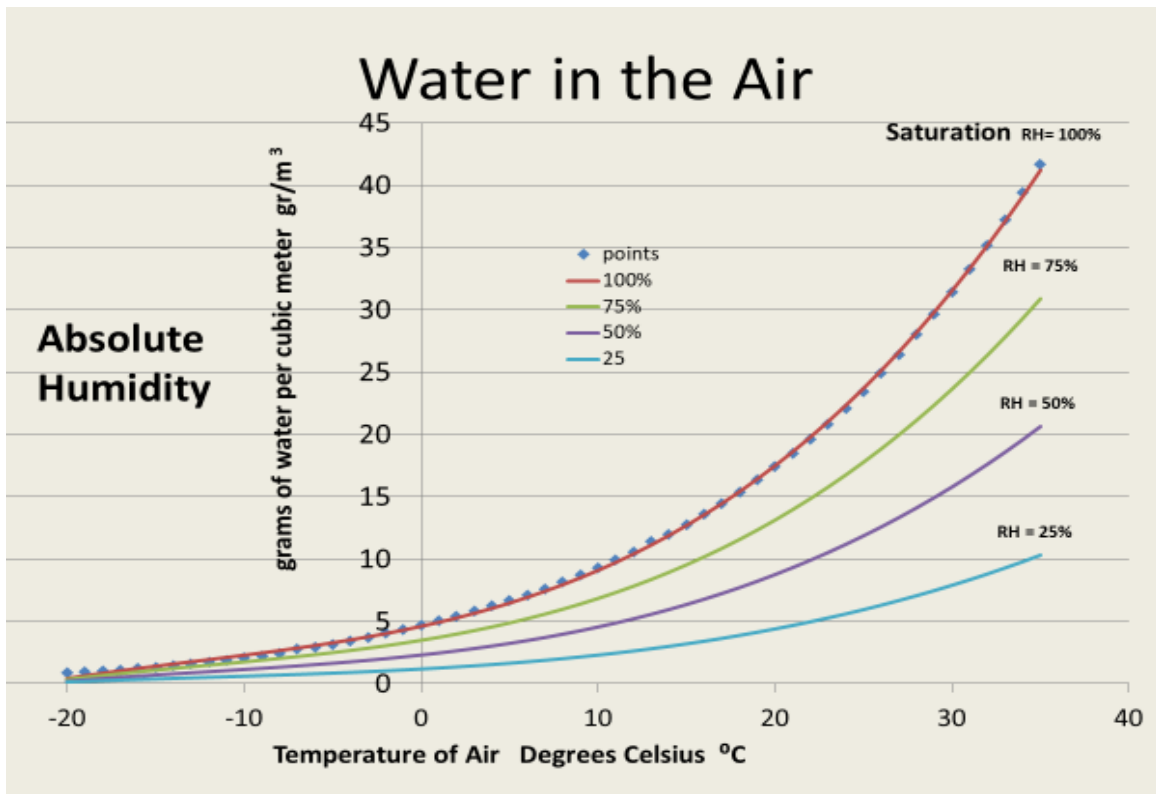
Psychrometric Chart

Figure 4. Absolute Humidity as a Function of Temperature and Relative Humidity

The absolute humidity, or the amount of water in the air, can be determined from a psychrometric chart as shown in Figure 4. Absolute humidity is a function of temperature and relative humidity [2].

The amount of water in the air is calculated using the following psychrometric formula:

$$W = W_S \times RH/100 \tag{1}$$
$$W_S = 0.000289T^3 + 0.010873T^2 + 0.311043T + 4.617135 \tag{2}$$

W (grams/m³) is the mass of water in one cubic meter of air, W_S (grams/m³) is the maximum mass of water that saturated air can hold at a specific temperature (T), expressed in ^{0}C, and relative humidity (RH) expressed as a percentage (%).

There are many ways to determine the Absolute Humidity:
1. Use the graph from Figure 4
2. Use the equation above, Eq.(1)
3. Use the online Web calculator found at: www.planetcalc.com/2167/

Consider the following problem: Air is entering a grain bin through the fan at a temperature (T) of 26°C and a relative humidity (RH) of 80%. The air is leaving the bin through the roof with a temperature of 32°C and a RH of 74%. The fan is pushing the air through the bin at 3,000 cubic feet per minute (CFM). Are we drying or wetting? How much?

The measurements made on the air entering and leaving the bin are all that is necessary to determine the amount of drying that is taking place. Using equation 1, the absolute humidity of the air entering and leaving is calculated; it is 20 gr/m³ and 25 gr/m³ respectively. For every cubic meter of air that goes through the bin, there are 5 grams of water removed. There are 35.31 cubic feet in a cubic meter, so there are 85 m³/min or 5098 m³/hr. x 5 gram/m³ = 25,488 gr/hr or 25.488 kg/hr., which is 56.17 lbs of water removed every hour. Yes, indeed the grain is being dried. Figure 5 shows this example on a psychometric chart.
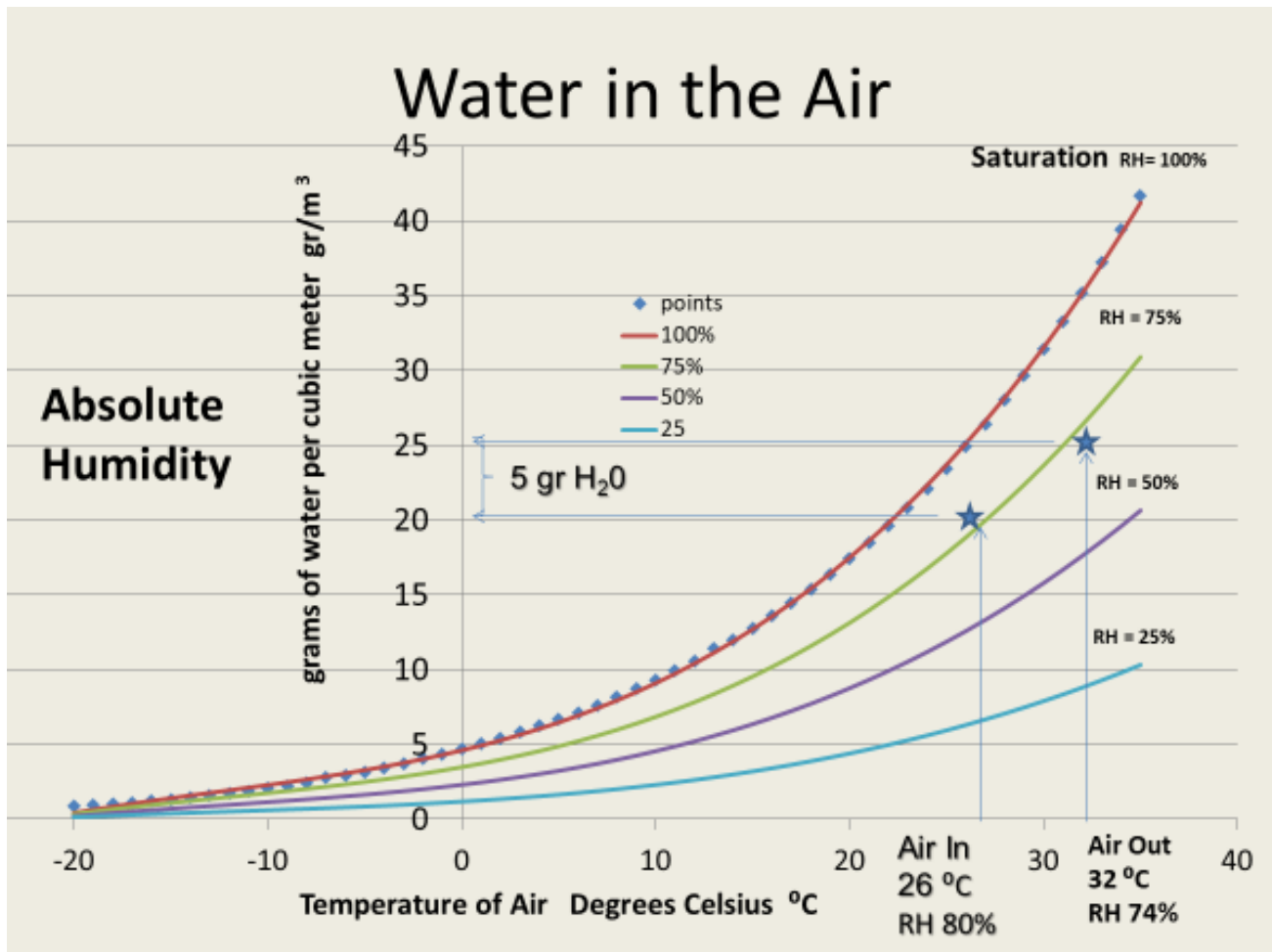

Figure 5. The difference in absolute humidity is the amount of drying

With the ability to measure the amount of water removed per hour; it is possible to measure the amount of drying hour after hour. Figure 6 plots the hourly drying for a bin of peas in 2009 with the fan on continuously. There are a few interesting things to observe: the drying goes negative, with significant wetting occurring; and there is a definite cyclic pattern occurring over a 24-hour period.

Many of these hourly drying graphs were observed, trial after trial, year after year; each with this distinctive cyclic pattern. Nineteen of these graphs were compiled to yield an average cycle, which is commonly called the **diurnal drying cycle** as shown in Figure 7.
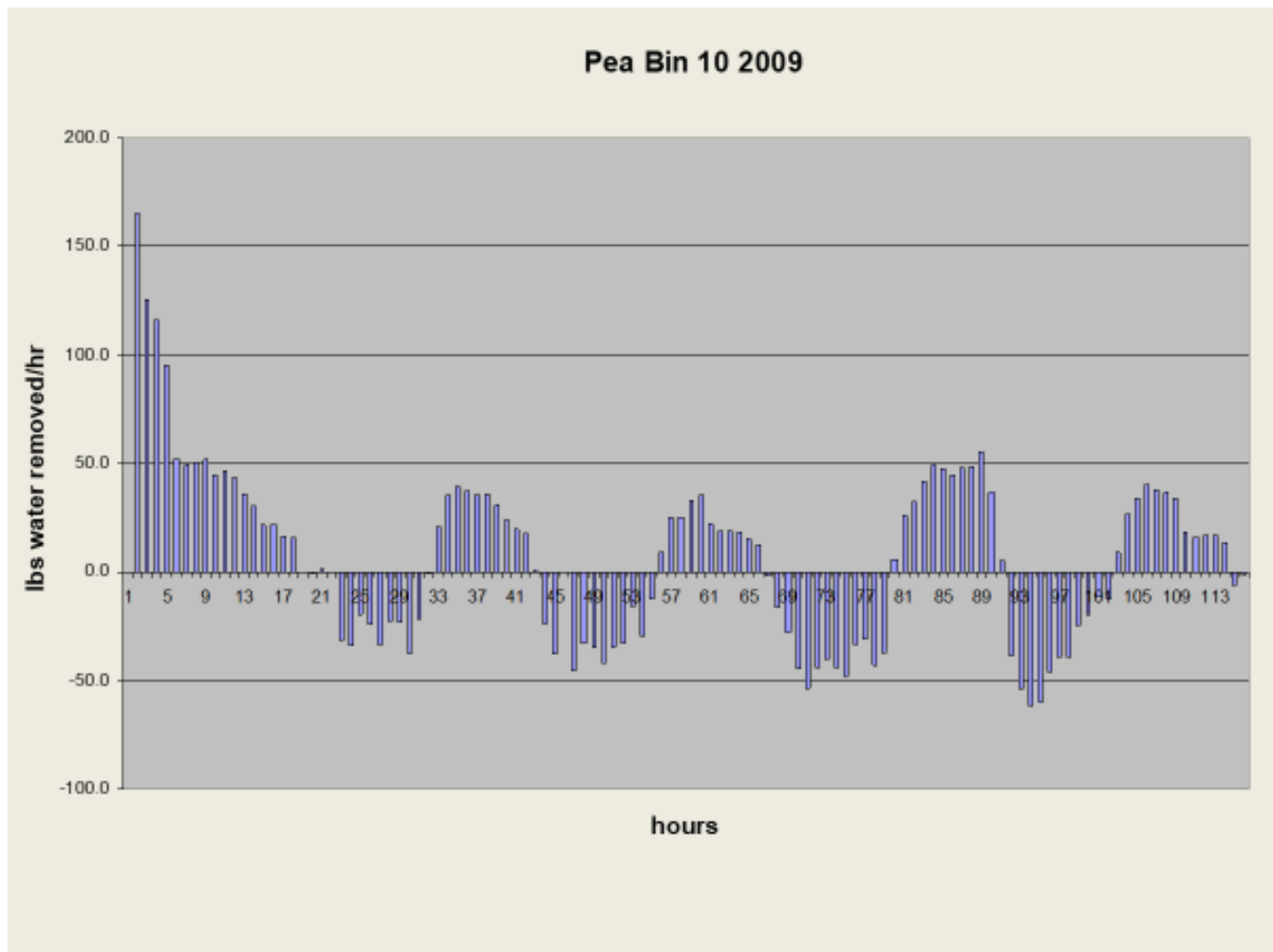

Figure 6. Hourly drying of peas in 2009

The diurnal drying cycle was not the result of a theoretical or predicted model, it was formulated from actual measured results; it was empirical. It was also unexpected -- drying occurred at night, circa 2 AM; whereas the most wetting occurred during the hottest part of the day, circa 2 PM. How could this be? It was commonly believed that you needed heat to dry the grain, and it would only be logical that the best drying would occur during the hottest part of the day.

To answer this question, one would go back to the psychrometric chart. At night the air is cold, and it holds very little water; but, as it hits the relatively warmer grain, it warms up and is then capable of holding much more water and so it absorbs moisture from the grain and drying occurs. During the day the outside air maybe hot, but it is also carrying a large amount of water. When the fan forces the hot air onto the relatively cool grain, the air cools around it. It no longer can carry the water and it condenses on the grain, wetting it down.
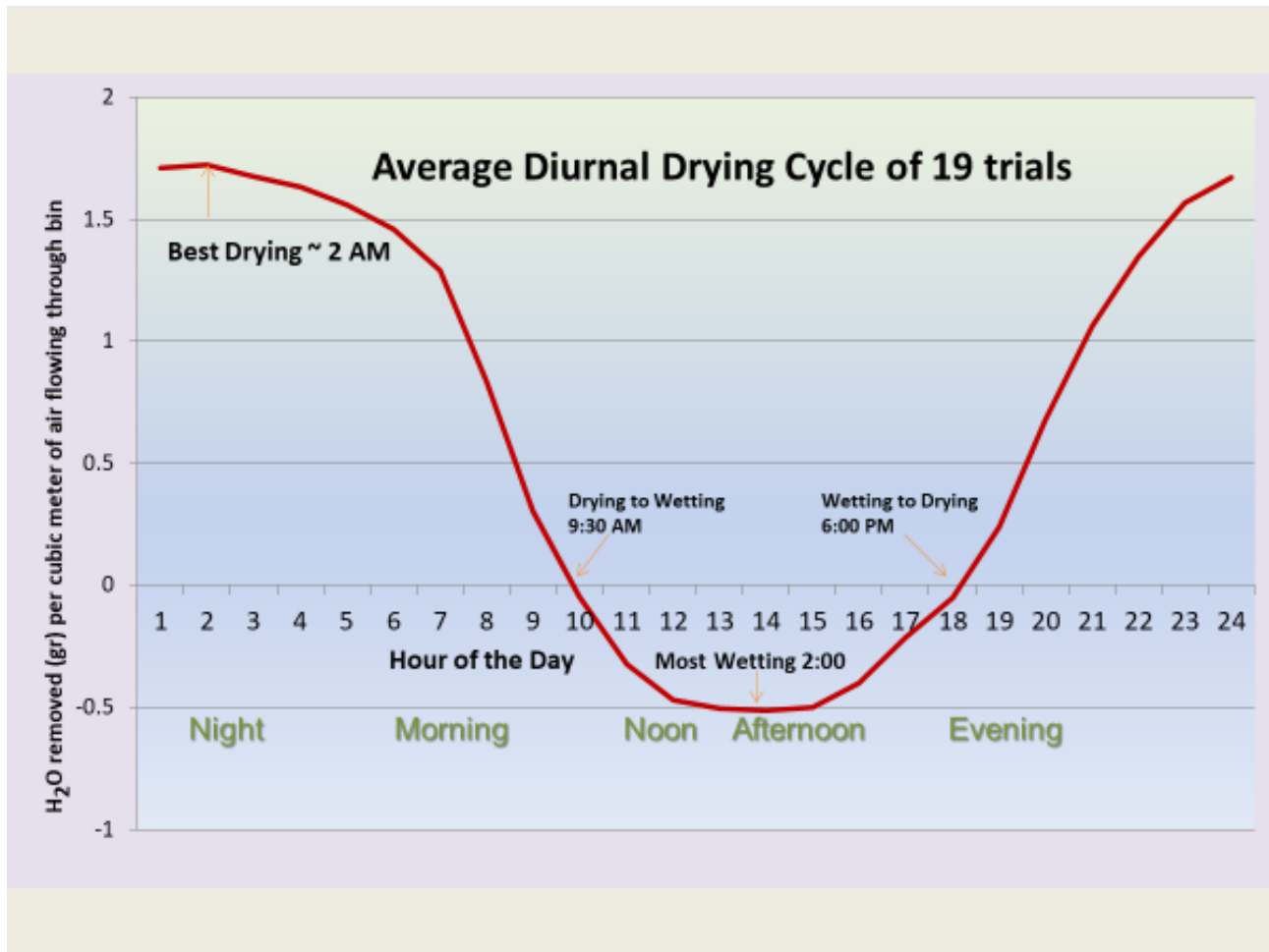

Figure 7. The diurnal drying cycle

The discovery of the diurnal drying cycle led to a recommendation for night drying. Turn your fans off during the day and on during the night. The yard light rule was established:

> **Yard Light Rule** (2010)
>
> On at night, you are bright,
>
> On during the day, you will pay

The Yard Light Rule control is very simple; it requires no sensors, no calculations or knowledge of the grain type, RH or grain temperature. However, this may have been a little too simple; this rule works only when the grain is relatively warm. When the grain cools to a temperature matching the night temperature, no more drying occurs. The rule only works for the first few days. More information is needed. The temperature of the grain and the temperature of the outside air must be known. It turns out that the difference in temperature of the grain and the air is the most important determinant for drying.

Cooling is Drying

Further investigations using the hourly drying charts led to another interesting discovery. There was a very strong relationship to grain cooling and grain drying as shown in Figure 8.
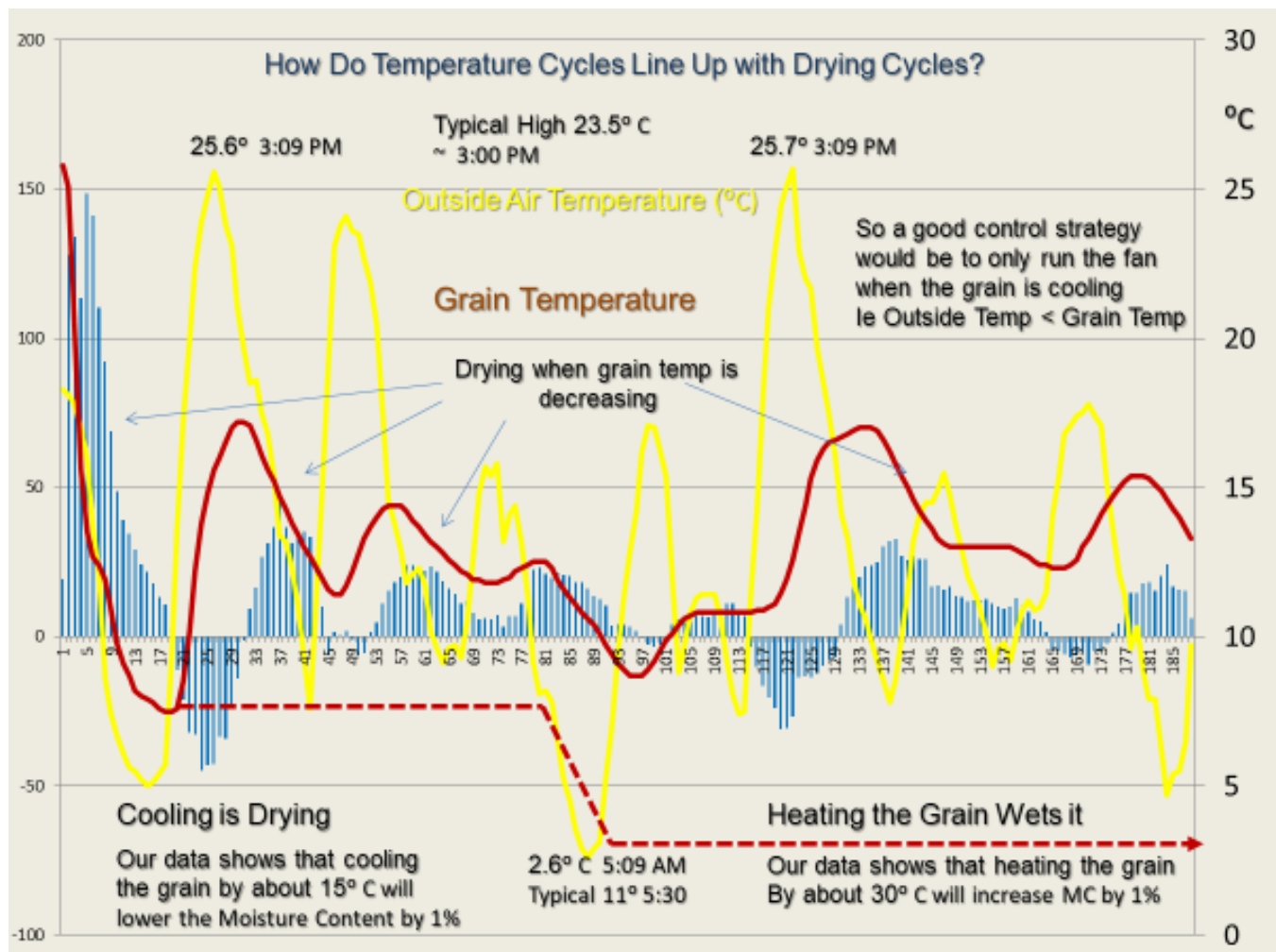

Figure 8. The relationship of grain cooling and grain drying: Cooling is Drying

In measuring the amount of cooling and the amount of drying of many trials, the relationship was quantified:

<div style="border: 1px solid; padding: 10px; text-align: center;">

FOR EVERY 15° C THAT THE GRAIN IS COOLED,
THE MOISTURE CONTENT IS REDUCED BY ONE PERCENTAGE POINT

</div>

The cooling-drying relationship became the basis for the control of the fan. If drying occurs with cooling; and the only means to cool grain would be with air that is colder than the grain; then one would only turn the fan on if cooling would result:

Turn the fan on if the outside air temperature is less than the temperature of the grain.

This strategy requires a minimum of sensors – only the temperature of the grain. Furthermore, this strategy could be further enhanced to preclude wetting by additionally restricting fan operation when the outside air has a relative humidity that is less than 85% [F].

The differential temperature control strategy would result in the coldest grain, but would it be the best for drying? No, the best drying strategy would be to only run the fan when there are drying conditions or when the absolute humidity of the air coming out of the bin is greater than going in. When the fan is running, RH and T sensors placed near the exit, can be used to calculate the absolute humidity of the exhaust air. But, when the fan is not running; how can the RH and T of the potential exhaust air be measured? Figure 9 shows the placement of these sensors.

When the fan is not running the potential, exhaust air will be at the same temperature as the grain. A temperature sensor buried in the grain can be used. The RH of the potential exhaust air can be obtained by measuring the RH directly or by using Equilibrium Moisture Content (EMC) equations in which the RH is a function of T and the Moisture Content (MC) of the grain [1].

Moisture cables have sensors that measure both the T and RH and they use EMC equations to yield the moisture content of the grain. They use the equations such that the MC is a function of T and RH.

What if you don't have moisture cables? And, you only know the temperature of the grain by probing or maybe you have temperature cables. The temperature of the exhaust air, when the fan does start will be the temperature of the air, now surrounding the grain. We have the temperature, but we need the RH of the exhaust air as well. How can it be determined? Use EMC equations; the RH is a function of the temperature and moisture content of the grain.
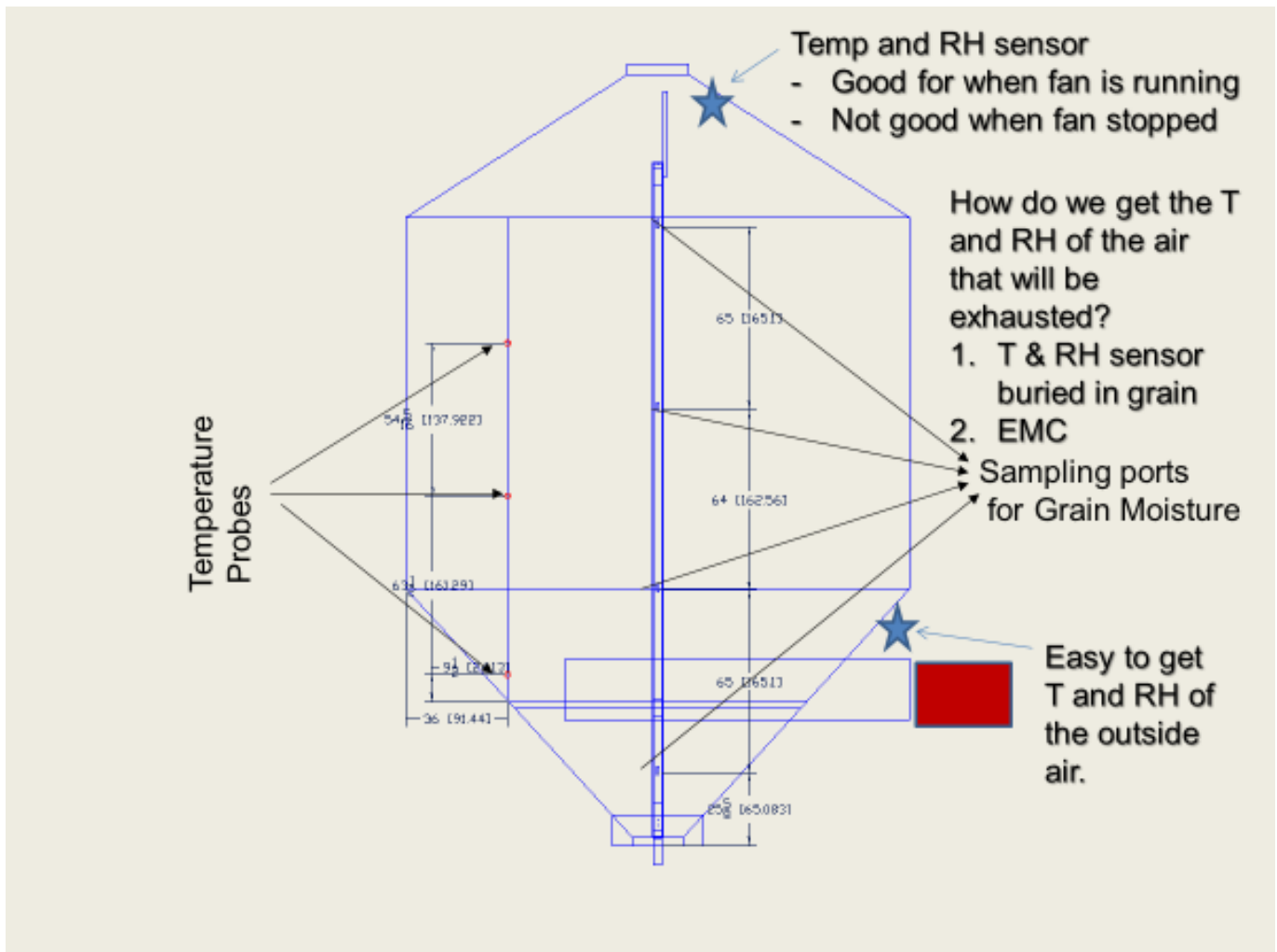
Figure 9. Temperature (T) and Relative Humidity (RH) sensors used to calculate Absolute Humidity

Equilibrium Moisture Content (EMC)

To establish EMC equations, researchers did some empirical work. They put grain in a sealed container at a given MC and T. They waited several hours until equilibrium was reached in terms of temperature and vapor pressure and then measured the RH. This was done many times, for varying temperatures and moisture content and they established equations that showed how the RH was a function of T and MC. There are many researchers that have done this, Henderson, Chung, Pfost; each with a slightly different set of equations. These are the EMC equations that have been published, and peer reviewed [1].

The relationship of parameters of EMC equations can be transposed such that MC is a function of T and RH. Moisture cables measure the T and RH of the air surrounding the grain to yield MC. This is only valid if the grain is in equilibrium with its surrounding air; that is in terms of temperature and vapor pressure. It was thought that this might take hours. It was learned that equilibrium in a grain bin could be reached in a few minutes.

To use EMC equations:

1. Find the RH of the air inside the bin using the EMC equation: RH is a function of T and MC.

2. Calculate the saturation absolute humidity for air that is the same T as the grain.

3. Find the absolute humidity of the air inside the bin by multiplying: 1. x 2.

4. Calculate the saturation absolute humidity of the outside air at its T

5. Determine the threshold relative humidity of the outside air, RH_{thres}, by dividing 3. by 4. If the outside air has a RH that is less than RH_{thres}; drying conditions exist.

Fortunately, all this math is done with the grain drying calculator. Simply enter the MC of the grain, its T, and the outside temperature. The calculator will calculate the threshold RH for a number of grains using the steps above. Find the grain in question, and its threshold RH. If the outside air has an RH that is lower than this, the outside air is in a condition to dry your grain.

The Grain Drying Calculator

The grain drying calculator[H] uses EMC equations to get the RH of the air in the bin, and it incorporates this with the temperature of the grain to determine the absolute humidity of the exhaust air. It then calculates the value of the relative humidity of the outside air that would yield the same absolute humidity. This is referred to as the Threshold Relative Humidity (RH_{thres}). Figure 10 shows how three parameters are entered: Grain Moisture Content, Grain Temperature and Outside Air Temperature and when 'Calculate' is pressed, the RH_{thres} is given for a number of grains.

The Grain Calculator is based on finding the relative humidity of the outside air that will produce an absolute humidity for the outside air that is equal to the absolute humidity of air surrounding the grain in the bin. If the outside air has a RH that is less than RH_{thres}, then the absolute humidity of the outside air would be less than the absolute humidity of the air in the bin. This would constitute a drying condition. Likewise, if the RH is greater than RH_{thres}, this would indicate a wetting condition.

In theory, this is the best that can be done to determine a condition for drying. The only error, would be the accuracy in measuring T and RH as well as the accuracy of the EMC equation.

The calculator can be used to determine the RH_{thres} for varying outside air temperatures. Consider canola at 12% MC and 20° C. The EMC equation for this canola reveals that it will equalize to the air around it with a RH of 81.4% which has an absolute humidity of about 14 gr/m^3. If air is blown into the canola with an absolute humidity of less than 14 gr/m^3, drying will occur. If the absolute humidity is greater than 14 gr/m^3, wetting will occur. The calculator can be used to calculate the RH_{thres} for a range of temperatures. The RH_{thres} is shown in Figure 11 for temperatures ranging from 10° C to 30° C. One can see that the RH_{thres} remains close to 80% as is shown by the thick blue graph.

Figure 10. The Grain Drying Calculator: Inputs Grain T and MC, Air T, providing RHthres
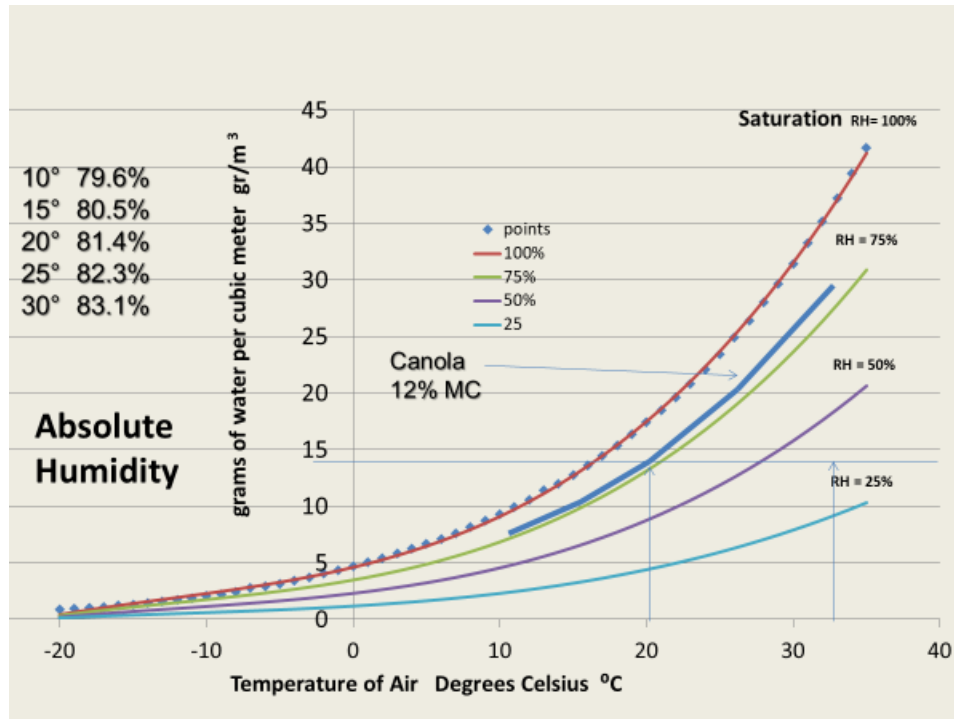
Figure 11. Calculating RH$_{thres}$ over a range of temperature

Safe Days to Spoilage

Being able to measure the deterioration of grain under various storage conditions would help farmers to manage the storage conditions to prevent further quality loss (Kaleta et al., 2013, Kakunakaran et al., 2001) [20]. It is generally accepted that 5-15 % of the total weight of all cereals, oilseeds, and pulses is lost after harvest (Padin et al., 2002). Improved storage conditions would allow a 10 – 20 % increase in the supply of food available to people (Christiansen and Kaufmann, 1969). Grain quality is critical in today's grain trade because of more stringent food-safety demands and an increase in market competition, therefore to avoid spoilage of grain during storage it is necessary to determine the safe grain storage time.

Safe storage time is the period of exposure of a product at a moisture content (MC) and temperature (T), below which crop deterioration may occur and beyond which the crop may be impaired. Determination of safe grain storage time is an answer to the following question: how long can grain of a particular moisture content and temperature be stored without the risk of the quality deterioration. To measure safe storage time, three methods have been suggested: carbon dioxide (CO_2) production and dry matter loss, appearance of visible moulds, and germination capacity. The latter is the most regarded due to it being the most objective and measurable. Fraser and Muir (1981) [7,14] developed a set of regression equations for predicting allowable storage times for wheat, and for canola.

$$\log t = 6.234 - 0.2118\ MW - 0.0527\ T \quad (wheat) \tag{3}$$

$$\log t = 6.224 - 0.302\ MW - 0.069\ T \quad (canola) \tag{4}$$

where the number of safe days, *t*, is the number of days that the grain can be stored at a moisture content, *MW*(in % w. b) , and temperature, *T (*°C)*,* before the germination capacity drops by 5 %.

   Figure 12 shows a table of safe days for wheat, using equation (3). The pink box shows the wheat at 18% MC and 30° C. Wheat under this condition has 5 to 8 days before it spoils to 95% germination. There are several ways to increase the safe days to over 100 (dotted green line). Conventional thinking would be to dry it down to 14% MC; but, drying will take many days, if not weeks. Cooling the wheat will increase the number of safe days; and, it can be achieved much quicker – in a matter of hours. Cooling will also do some drying. Cooling the wheat from 30 to 15° C will reduce the MC to about 17%. Within a matter of hours, this wheat could be cooled, to increase its safe days to over 100.
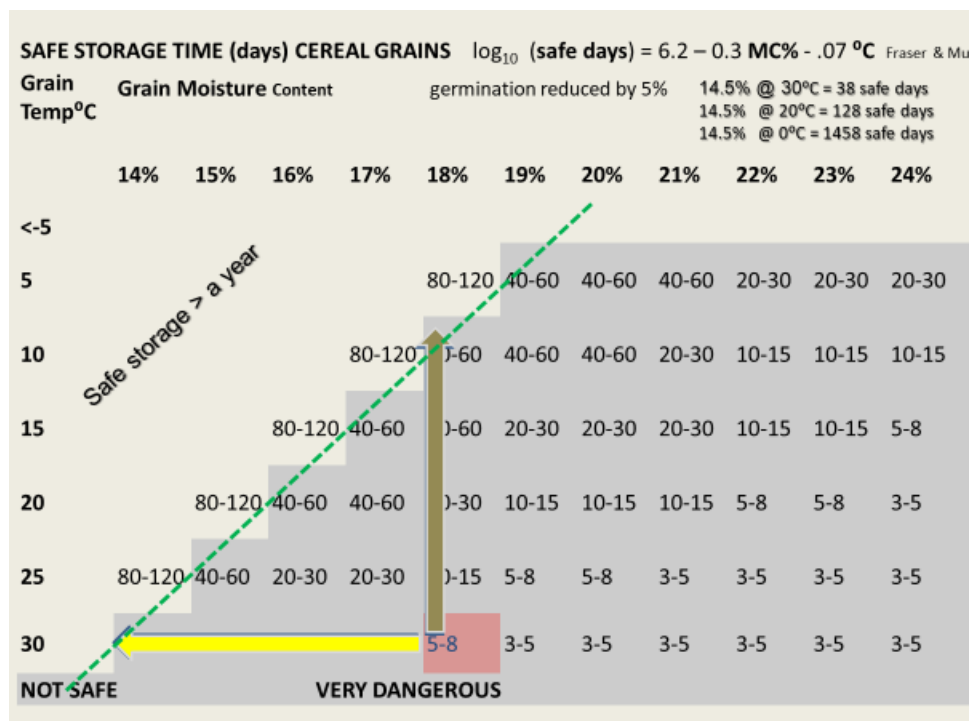

Figure 12. Safe Days to Spoilage as a function of Temperature and Moisture Content

   To calculate grain spoilage or deterioration under dynamic or changing conditions, Arinze et al. (1993) defined **spoilage index** (SI), and it is expressed in percentage as:

$$SI = 100 \ \Sigma \ (1/\text{safe days}) \tag{5}$$

   For example, consider grain in storage under conditions which indicate six safe days. After three days the SI is: 100 x (1/6 + 1/6 + 1/6) = 50. Or we could say the grain has deteriorated to the half-way point of 95% germination capacity.   After six days of storage, the SI would be 100, deterioration has occurred in which the germination has been reduced to 95%.

   It will be seen that on the first day of fan operation, that conditions change rapidly, and the SI can be refined to reflect this by integrating on an hourly basis rather than a daily basis. The safe day

calculation is done hourly with current temperatures and moisture contents. The spoilage index, as a percentage, is an accumulation of the hourly deteriorations:

$$SI = 100/24 \ \Sigma \ (1/\text{safe days}) \hspace{4cm} (6)$$

Condensation

For many years, farmers have noticed a crust forming on the top layer of grain. It is probably the result of condensation. It occurs when the grain is warm, and the outside air is cold. Cold air is forced into the bin and is warmed by the grain. It now has the capacity to hold more water, so it satisfies its thirst for water by absorbing moisture from the grain as it passes through. As it reaches the top of the bin, it hits a cold roof and it instantly cools. It becomes saturated – no longer being able to hold the water as it cools. The water condenses on the roof and rains down onto the grain below. The wet grain forms the crust.

Consider the following example: flax is harvested dry, 8% MC; but it is warm at 28⁰ C. Nothing is done for a month, but eventually the farmer decides to cool it down, by using night drying [C]: yard light rule. Nights are getting cooler and going down to 8⁰ C. The next morning there is lots of condensation on the inside roof. Did drying at night add water? Or, where did the water come from? The flax was dry!

Inputting values into the grain calculator, 8%, 28° C, 8° C ,yields a RHthres of 186% for flax. What's going on here? How can an RH be greater than 100% ? The calculator is telling us that condensation will occur if RHthres is greater than 100%.   The more it is greater than 100%, the greater the condensation.
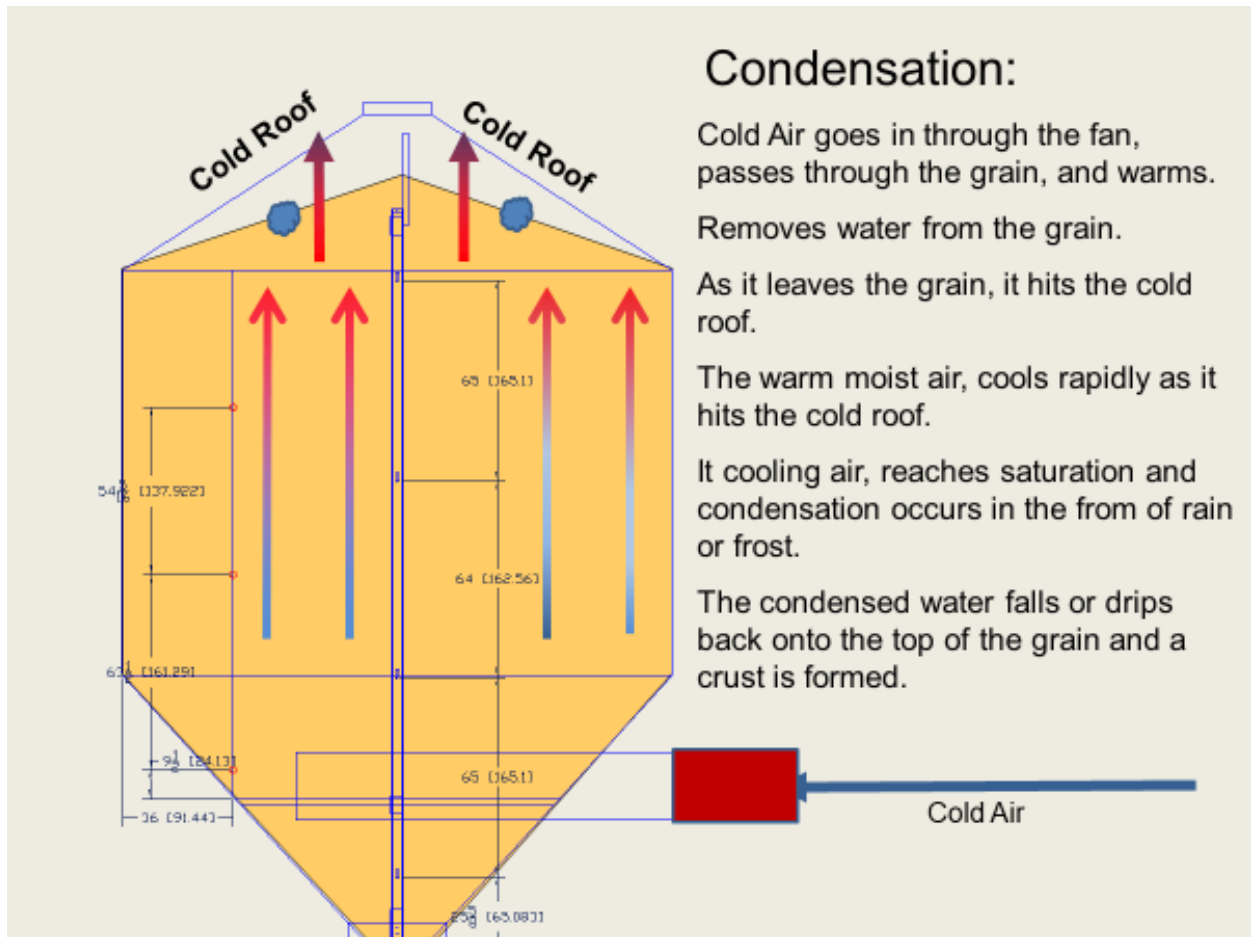
Condensation:

Cold Air goes in through the fan, passes through the grain, and warms.

Removes water from the grain.

As it leaves the grain, it hits the cold roof.

The warm moist air, cools rapidly as it hits the cold roof.

It cooling air, reaches saturation and condensation occurs in the from of rain or frost.

The condensed water falls or drips back onto the top of the grain and a crust is formed.

Figure 13. Condensation Forming on the Roof

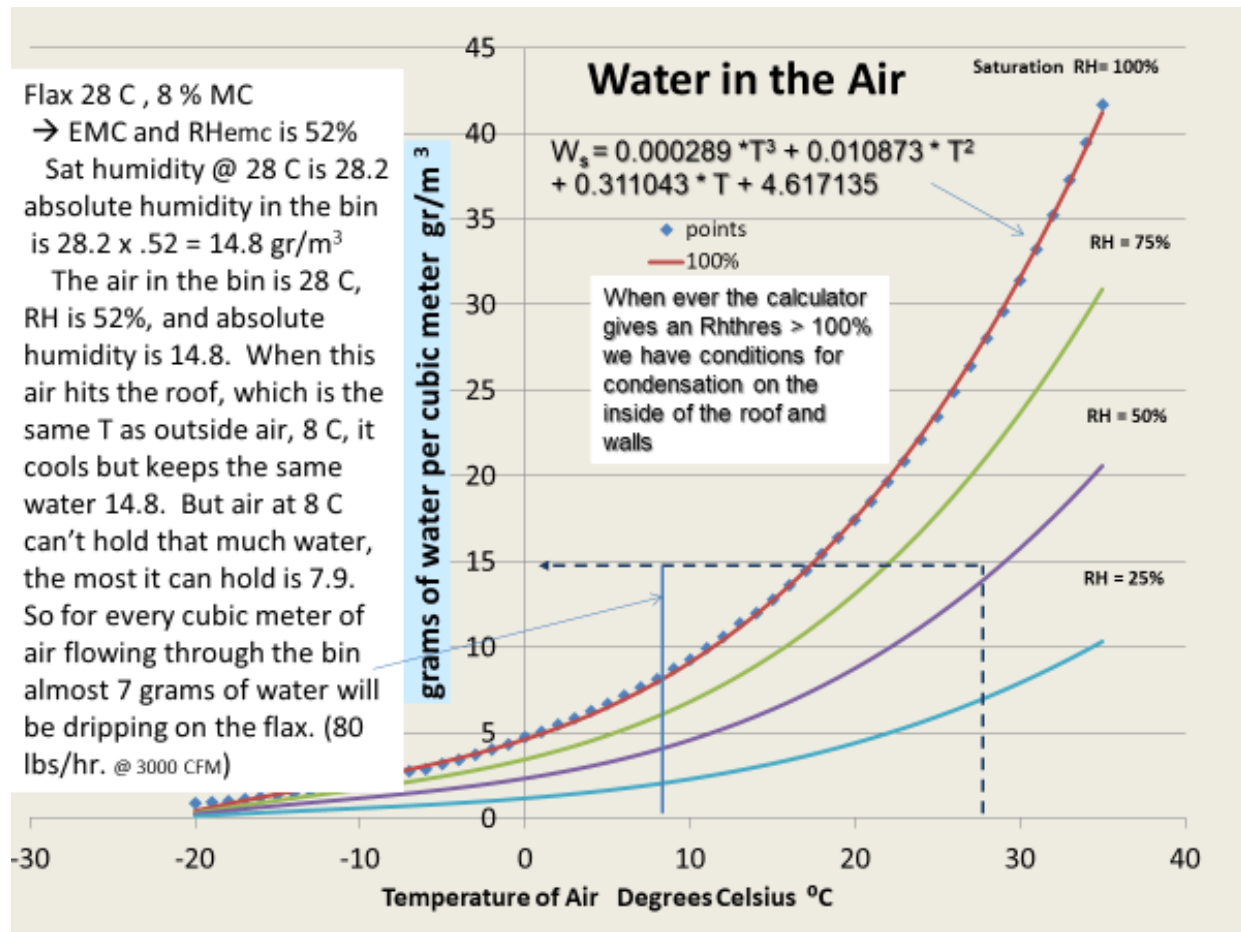This condensation can be explained using the psychrometric chart as shown in Figure 14.

Figure 14. Condensation explained with the psychrometric chart

A farmer can not be expected to use a psychrometric chart to determine conditions for condensation. A simple guide or rule-of-thumb can be used to estimate these conditions:

Rule of Thumb:
- **If the gain is warmer than the outside air by more than 5 or 6 degrees C there will be condensation.**
- **If the calculator gives a RHthres of 100% or more, you will get condensation.**

Bottom Dries First

Why does the grain at the bottom of the bin dry first? Every farmer knows this; but why? For an ideal gas there is a relationship between pressure, volume and temperature: (Shortley & Williams pp 342) [24].

$$PV = nRT \qquad (7)$$

P in N/m^2
V in m^3
n in kmol
R in J/kmol*K°
T in K°

Pressure is proportional to temperature; if the pressure increases, the temperature increases accordingly. The aeration fan increases the pressure of the air at the bottom of the bin enough to support a column of water in a manometer by five or six inches, this in turn immediately increases the air temperature by a few degrees. The psychrometric chart, Figure 4, shows the increase in water carrying capacity with an increase in temperature. This warmer air absorbs the moisture from the grain at the bottom; and, as the air rises in the bin it decompresses and cools, no longer being able to carry as much water, and so it dumps its water onto the upper layers of grain.

This is more fully explained in the blog at www.grain-aeration.com "Air Flow: How Much? Making a Case for Lower Rates" [D]. This article makes a case for smaller fans, with less compression to mitigate the top/bottom drying discrepancy.

Winter Warming by Conduction

Dry canola was monitored in 2200 bushel bins to determine the warming of the grain throughout the winter and into the summer. The aeration fans were off, so the warming logically came from the heat transfer through the walls and roof. Figure 15 shows that the grain warmed about 18° C, over a duration of 125 days or approximately one degree per week. The grain temperature lagged the mean ambient temperature by a few degrees.

This is interesting in that if the grain is cooled, or even deeply frozen with aeration in the dead of winter; the grain can be safely stored without any intervention until well into July. Perhaps, starting in August, the aeration control strategy could be applied to keep the grain as cold as possible until it is well frozen again in the following winter. Long term, safe storage of grain is possible with very little spoilage.

If the grain was somewhat tough, this long-term storage method will remove the water. As the grain is heated in the spring, it is acquiring this energy without being wetted down. The bin is an implicit solar collector.   In the fall when the temperature of the grain is cooled, there would be some drying that takes place since we know that cooling with aeration is drying.
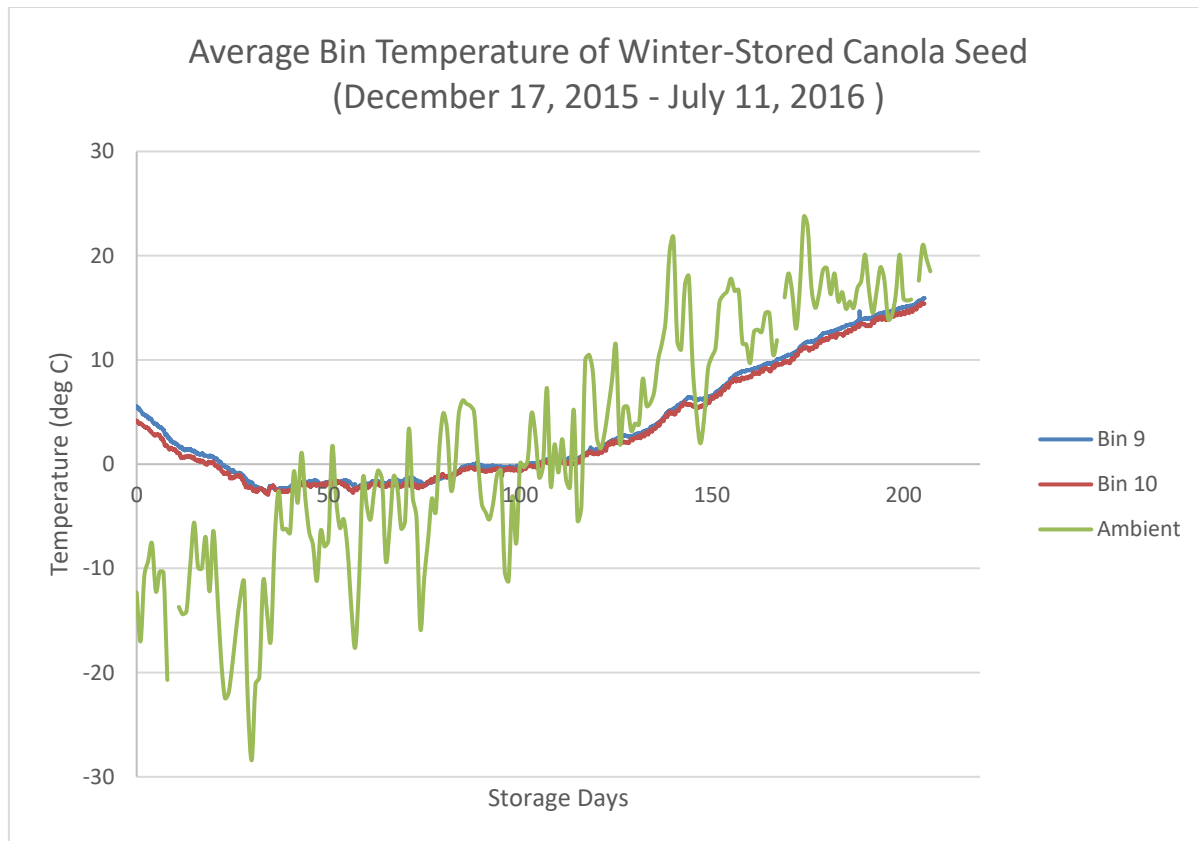
Figure 15. Warming-up of Grain by Heat Transfer through the walls and roof of the bin

First 24 Hours is Critical

In observing the hourly drying graphs from trials done from 2007 to 2014; it was noticed that there was a tremendous amount of drying in the first few hours that the fan was turned on. The first 24 hours were considered and averaged for 33 trials. The averaged results are shown in Table 1.

First 24 Hours	Start	End	Difference
Grain Temp ° C	26.2	14.6	11.6
Moisture Content %	17.65	16.77	0.88
Safe Days	6	32	26

Table 1. The First 24 Hours of Fan Operation

In the first 24 hours of fan operation the grain was cooled 11.6° C, and the Moisture Content reduced by close to one percent. The cooling drying ratio was 11.6/0.88 = 13.18°C/%MC, which is reasonably close to our rule of thumb of 15°C per %MC. The first day of operation gives us cooler, dryer grain and increases the security of the grain with the number of safe days increasing by 26. At the start the grain would spoil in about a week, and with only one day of operation the grain was conditioned to be safe for over a month. The first day of operation is critical, and It is recommended that the aeration fan be turned on immediately and run for at least one day to cool the grain down. This would apply, no matter what control strategy one would have for the fan.

Fan Control Strategies

There are many strategies that a farmer can use to control his aeration fan. The strategy chosen will depend on what sensors the bin is equipped with and the objective efficiency and convenience desired. We will start with a very simple control strategy and work our way to sophisticated, optimum controllers.

1. **Continuous**
    This is the contemporary method of controlling the fan – turn the fan on and leave it on continuously until we think the grain is dry. One would turn the fan off if it is raining, but otherwise just let it run.   The advantages of this method are with its simplicity and low cost. There are no sensors, no measurements, no calculations and no attention needed. However, the disadvantages are many; consider the diurnal cycle of Figure 3, the grain is cycled through drying and wetting, heating and cooling. Every time it is heated and wetted, it spoils a little bit. And there is a good percentage of the time when the operation of the fan is wetting the grain. This is a waste of energy in spinning our fans needlessly; but, more importantly we are going through cycles of unsafe storage. At the very least, if one is still insisting on using this method, one should start the fan immediately upon filling the bin to cool the grain – even if it is dry. When the time comes to eventually shut the fan off; it should be done in the morning after a cold night, so the grain will be cool. Do not shut it off after a hot day, leaving the grain warm.

2. **Night Drying**
    Upon studying the diurnal drying cycle, it becomes clear that running the fans at night would be a better option than running them continuously. But it only works in drying the grain; if the outside air is colder than the grain. Then there is no more drying. We can improve this system somewhat by reducing the hours of operation at night as the grain gets cooler; perhaps using only the coldest part of the night:
    a) the first day run the fan from the time of filling the bin until 9 AM the next morning. The next evening start the fan at 8 PM and run it until 8 AM the next morning; the next night from 9 PM until 7 AM, then 10 PM until 6 AM, etc.
    b) only run the fan on the coldest nights,
    c) only run the fan when the air temperature is lower than the grain T. This is somewhat more demanding as it requires knowledge of the grain temperature.

    This method has the advantage of not requiring any in-bin sensors. It does, however, require more attention and is not convenient to manage. It does save energy and more importantly it conditions the grain to be much safer with less spoilage. The biggest disadvantage is the attention that is required to oversee this method, turning the fan on at night and off during the day. This could be automated with a simple timer or a yard light solar cell switch. The night drying method might be better than the continuous method; but, there are better ways to control the fan.

3. Temperature Differential

The temperature differential control is simple in concept and implementation. It requires a very simple rule to be followed: **Turn the fan on, if: the air T is less than the grain T**. This is a slightly more complicated method, one in which we need to measure the temperature of the outside air and the grain. Turn the fan on if the temperature of the air is cooler than the grain temperature. This can be done manually, or a simple differential temperature controller can be used to automate the process. This is still a relatively simple method, but a temperature sensor is required in the bin to measure the grain temperature. There is no need to know the type of grain, or the moisture content of the grain – only the temperature. This controller Is the best in terms of keeping the grain as cold as possible, and in keeping the grain as safe as possible, with the least spoilage. It is not the optimum controller for drying but it could be improved slightly in that regard by only running the fan if the outside RH is less than 80%.   There would be two conditional checks to run the fan, the grain temperature must be greater than the air temperature, and the outside humidity must be less than 80%. These two conditions could easily be incorporated in an inexpensive controller that does not need knowledge of grain type or moisture content. Even if you do not have first hand knowledge of the grain temperature, it is still possible to automate this process with a simple thermostat. Set the thermostat to what you think the grain temperature is, and the fan will only go on when the air temperature is less than this. There are no complicated equations and no inputs required to be entered manually. It is very convenient, inexpensive and the ultimate in keeping the grain safe. That said, it is not the best controller for doing the most drying.

4. Absolute Humidity

The controller that is best for drying is the absolute humidity controller. It calculates the absolute humidity of the air entering and leaving the bin. If there is more water leaving the bin than entering the bin, then logically there is drying taking place and the conditions are suitable for drying. So, run the fan if these conditions exist.   This is the ultimate for a drying control strategy, theoretically the best.

There are two ways to determine what drying conditions exist; the Grain Calculator can be used with manual control of the fan. Or, an automatic controller can be used with essentially the Grain Calculator built in, such that the fan will be turned on when the absolute humidity of the exhaust air is greater than the absolute humidity of the air entering the fan. This method might be the best drying control strategy; but, it is much, much more complicated with difficult calculations of ugly-looking equations. It also relies on the measurement of RH sensors in the bin, which are not only expensive, they are also somewhat unreliable, prone to failure when they get contaminated with dust. Yes, absolute humidity controllers do work, they have been designed, built and tested; but, considering the complication and expense of this controller, the much simpler Differential Temperature Controller would be the most practical.

Practical Recommendations

These recommendations are a culmination of analysis of the data collected over several years of trial runs, as well as conclusions drawn from stories and issues of discussions with farmers.

1. All steel bins should be equipped with aeration. Grain, coming off the field, warm or even hot, is spoiling – even if it is dry. It is important that the grain be cooled down as much as possible to minimize the spoilage. The bin does not necessarily require a dedicated fan, but it should have the portal and internal screen in order that a mobile or temporary fan can be used to cool the grain to a safe temperature.

2. Every day that a mature crop sits out in the elements waiting to dry is a risk. To mitigate this risk, the grain could be harvested tough, perhaps a moisture content of a point or two above dry. This may reduce the risk of the crop being in the elements by a day or so.

3. We know that with aeration, the bottom of the bin dries first, and typically is over-dried. Therefore, it is recommended that the toughest grain be put on the bottom of the bin. Typically, when harvesting, the grain in the morning is tougher than in the afternoon. One could start the day with a new bin and in the morning the tough grain would be at the bottom, and as the day progresses with drier grain; it could be placed on top.

4. Start the aeration fan immediately; don't even wait for the bin to be full, start the fan as soon as the screen is covered and leave it on, to cool the grain until the next morning. Even if the grain is dry, it still needs to be cooled. The most important, and effective time to use your aeration fan is immediately upon filling the bin.

5. There are many strategies that can be used to control the aeration fan. The Differential Temperature Control Strategy is simple and is the safest strategy, offering the least spoilage. And it is close, to being, the best for drying. One needs only knowledge of the temperature of the grain and this control can be implemented:
   a) Manually: turn the fan on manually whenever the air T is less than the grain T.
   b) Thermostat control: set the thermostat slightly below the temperature of the grain.
   c) Differential Temperature Control: control turns the fan on when the air T < grain T. An embellishment to this control, would be to incorporate the RH < 80% qualifier.

6. To prevent condensation and internal dripping, the fan should be turned on immediately in order that the grain is cooled to the ambient temperature. That is so the grain is never 5 or 6° C warmer than the outside air temperature.

7. Use the Grain Calculator www.planetcalc.com/4959/ to determine when there are drying conditions and conditions for condensation. Drying conditions exist when the RH of the air is less than RH_{thres} – the more the difference the better the drying conditions. Condensation conditions exist when RH_{thres} >100%.

8. Get the grain as cold as possible. Using the suggested control strategies throughout the Fall and into the Winter will result in very cold grain (~-20° C ?). This is good for several reasons: the grain is now extremely safe from spoilage, a little bit of drying will have occurred in dragging the grain temperature down, and some of the pathogens and insects would be destroyed. So, it is recommended that the control of 5. be used until the coldest part of winter, to get the grain as cold as possible.

9. Seal the bin after the coldest part of the winter (January). The fan opening as well as vents should be covered. The top lid should be closed as tightly as possible. The grain in the bin is cold, and we want to keep it that way for as long as possible. Sealing the bin prevents the warm spring breezes from entering the bin, hitting the cold grain, with frost and condensation forming on the grain. It is good to have the grain warmed by conduction – heat transfer through the walls and roof. This adds energy to the grain without wetting it down. The bin has become an implicit solar collector; collecting the sun's energy and putting it into the grain. This warming is about one degree per week. This heat energy can be used to later dry the grain (if it is tough).

10. Grain in long term storage should be kept as cold as possible. The sealed bin from (9.) should be opened and the control of (5.) be applied when the temperature of the grain exceeds the air temperature. This may occur in late summer. The aeration fan control of (5.) would again be applied until the coldest part of winter, at which time the bin would again be sealed, as in (9.).

11. The aeration fan control of (5.), required knowledge of the grain temperature. However, the grain temperature can vary slightly depending on the location of the temperature sensor within the bin. The best place to take the temperature is about half way up the bin, close to the center. If a temperature string is used, one could average several values of sensors in this vicinity; however, one should not use values from sensors that are exposed or too close to the bottom or near walls. A simple, reliable thermistor can be used as a sensor.

12. Take a load of grain from the bottom of the bin. We know that the bottom of the bin dries first; so, when the bottom does dry, take a load of this grain out of the bottom of the bin. This will do several things:
    a) The dry load can be sold or stored in another bin and not get over-dried.
    b) The top peak or cone is flattened or slightly inverted to provide more even air flow.
    c) The resistance of the overall grain body is reduced which increases air flow and it provides for more even top to bottom drying.

13. Supplemental Heat: If supplemental heat is to be used, it should not be used continuously. Use the heat of the day with the supplemental heat to warm the grain. Remove the supplemental heat; and use the cool night air to cool and dry the grain. Repeat this daily routine until the grain is dry.

14. Smaller fans might be considered to mitigate the '*over-drying-the-bottom*' syndrome.

15. Consider, *open-bottom* screens to eliminate the pressure drop through the screen.

Future Work

The emphasis of this research was to find a better control method for aeration fans; and this was done. Some peripheral issues to this research require a more thorough investigation. Such as:

- A smaller fan produces less compression, which in turn results in the top-bottom discrepancy in drying. If a fan is too small, it will not be capable of cooling the grain quick enough to reach a safe condition. What is the optimum fan size (capacity)? What is the optimum CFM/bu.?

- Limited work was done with supplemental heat. Is the daily cycling of heating and cooling the most effective way to dry grain?

- It was recommended that for long term storage, that grain be deeply frozen and then warmed by the spring and summer; yet to be cooled down and frozen in the fall. How safe is this in terms of spoilage? How much drying occurs with each of these annual temperature cycles?

- Measurements were made with a manometer to determine the pressure drop across the screened pipe. A significant pressure-drop occurred across the screen. An open bottomed tube would have no pressure drop with the air being injected directly into the grain. This would increase the capacity and effectiveness of the fan. An open bottom pipe would be self cleaning. Fines collect at the bottom and are a breeding ground for grain pathogens. More work is needed on open bottom air delivery systems for both hopper bottom and flat bottom bins.

- The Grain Calculator has a limited set of grains; not all modern grains have a published set of EMC equations [1]. These could be researched and added to The Grain Calculator.

- The Safe days to spoilage equations that Fraser and Muir produced were for cereals and canola. Accurate equations for safe days could be produced for specific grains such as flax.

- Could the Temperature Differential control be adapted for grain in transit and for storage at its destination? In a shipping container? Ship's cargo hold? Train box car?

- It has been suggested that when the grain bin is being used as a solar collector to heat the grain, that the exhaust air be directed back to the inlet of the fan, making for a closed loop system. No water is entering this system, so the grain could be warmed without wetting it down. This may not be practical with existing steel bins but would be more amenable to shipping containers. How well would this work?

- It has been suggested that if a grain is deeply frozen that insects and grain pathogens such as fusarium will be destroyed. At what cold temperatures are various pathogens killed?

- Grain Bags have become a common means to temporarily store grain. Are there practical ways to implement grain aeration?

- Many grain bins are remotely located, far from the power grid. Can a gen-set be used to power the fan with the heat from the engine being used as supplemental heat? Can the Temperature Differential Control be incorporated?

- Could someone manufacture and commercialize the Temperature Differential Controller with the RH < 80% qualifier? The prototype has been designed and tested; commercialization is required.

Conclusions

There is a diurnal cycle with NAGD. This pattern was consistent and statistically significant. The best drying occurs a couple of hours after midnight and the least drying occurs in the afternoon circa 2:00 PM. Typically there is significant wetting of the grain in the afternoon.

Cooling is drying. There is a very strong correlation: when the grain is being cooled by the air flowing past it, it has been observed that the grain is drying.

A flow of 0.4 CFM/bu. is adequate for aeration – to cool and dry the grain and to mitigate the top/bottom drying discrepancy.

Grain in a sealed bin will warm up in the Spring lagging the mean ambient temperature by a few degrees. A rise of one degree Celsius per week has been observed. This warming is all due to heat transfer through the walls and roof of the bin.

Although the absolute humidity controller is the best for drying; the Temperature Differential Controller is the best to ensure the safest grain storage with the least spoilage.

There is a better way to manage grain storage with aeration.

Acknowledgments

References

[1] American Society of Agricultural Engineering, ASAE D245.4   EMC equations

[2] ASHRAE Handbook 2013   ISBN 978-1-936504-46-6 Psychrometrics

[3] Brooker, D.R., Bakker-Arkema, F.W. and Hall, C.W. 1974. Drying Cereal grains. The AVI Publishing Company Inc. 265 pages.

[4] Canada Grain Commission. 2011. Good grain storage practices at harvest help prevent problems later. Available at http://www.grainscanada.gc.ca/media-medias/press-presse/2010/2010-08-26-eng.htm (accessed 20 January 2011) Canada Grains Commission, Winnipeg.

[5] Canada Grain Commission, Jan **2013.** Cold Weather Controls Grain Insects, Winnipeg, Manitoba

[6] Engineering Tool Box. 2011 Air Humidifying with Steam – Imperial Units**.** Available at: www.engineeringtoolbox.com/air-humidifying-steam-d_261.html

[7] Fraser, B.M. and W.E. Muir, 1980 Airflow Requirements predicted for drying grain with ambient and solar-heated air in Canada. Trans. ASAE (Am. Soc. Agric. Eng.) 24(1):208-210

 [8] Fulton, F. and Sonntag, B. 2010. History of Early Western Canadian Agriculture – Setting the Stage for Conservation Pages 1-14 *in* Lindwall, C.W. and Sonntag, B. (eds) 2010. Landscapes Transformed: The History of Conservation Tillage and Direct Seeding. Knowledge Impact in Society, University of Saskatchewan: Saskatoon, pp219.

[9] Grain Drying Calculator www.planetcalc.com/4959/

[10] Hall, C.W. 1980. Drying and Storage of Agricultural Crops. The AVI Publishing Company Inc.

[12] Halross. 2011. Moisture Meter and Accessories. Available at: http://www.halross.com/English/product-moisture.asp (accessed 20 January 2011) Dimo's Tool & Die / Labtronics, Winnipeg.

[13] Health Canada. 2011. Call for Data on Ochratoxin A. Available at http://www.hc-sc.gc.ca/fn-an/securit/chem-chim/toxin-natur/call-demande-eng.php (accessed 20 January 20 2011;

[14] Metzger, J.F. and W.E. Muir, Aeration of Stored Wheat in the Canadian Prairies, Canadian Agriculture Engineering 1983 Vol 25 No 1 See Fig 5 pp 129 (safe days)

[15] Padbury, G., S. Waltman, J. Caprio, G. Coen, S. McGinn, D. Mortensen, G. Nielsen, and R. Sinclair. 2002. Agroecosystems and Land Resources of the Northern Great Plains. Agron. J. 94: 251–261.

[16] Reliable Controls 2011. Reliable Controllers. (accessed 20 January 2011). http://www.reliablecontrols.com/products/controllers/ Reliable Controls, Victoria

[17] Sharp, J.R. 1982. A review of low Temperature drying simulation models. J. Agric. Engng Res, 27:169-190.

[18] Woomer, P.L. 2004. Approaches to impact-oriented agricultural research. p. 37-50 In B.K. Patel, K. Muir-Leresche, R. Coe and S.D. Hainsworth (ed). The green book: Aguide to effective graduate

research in African Agriculture, environment, and rural development. The African Crop Science Society, Kampala, Uganda.

[19] **AAFC (2001) Agriculture and Agri-Food Canada Publication 1851/**E—Revised (2001) Protection of Farm-Stored Grains, oilseeds and pulses from Insects, Mites and Moulds © Cereal Reseaarch Centre, 195 Dafoe Rd, Winnipeg, Manitoba R3T 2M9

[20] **Khatchatourian, O,A; Vielmo, H.A; Fortolaia, L.A. (2013) Modelling and Simulation of Cross Flow Grain Dryers**, BioSstems Engineering 116 (2013) 335-345

[21] **PAMI (2011) Grain Moisture Measurements Based Control System for Natural Air Drying** – progress report for Agriculture Development Fund ADF #20070171 MIDAS #000641 Project No. A7107

[22] **Sugartech (2014) Psychrometric calculator**: accessed Jan 2014 www.sugartech.co.za/psychro/

[23] **Thompson, T.L. (1967) Predicted Performances and optimal design of convection grain dryers, Ph.D. Thesis**

[24] **Shortley, G. and Williams, D.** *Elements of Physics* 4th Ed. Prentice Hall 1965

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