MANAGING GRAIN STORAGE

New Insight into Natural Aeration Grain Drying

Prairieland Park Hall A Rm #1
503 Ruth St. W.  Saskatoon  SK
Thurs January 14, 2016  10:00 AM

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Content

- Common Practice: Fan on Continuously
- The Set-up 2007, Data Collected
- Objectives
- Vapour Pressure
- Water Balance-In/Out, Diurnal Cycle, Yard Light Rule
- Cooling is Drying → Fan On if: Grain Temp > Air Temp
- Safe Grain, Number of Safe Days, Spoilage Index
- EMC equilibrium moisture content, the calculator
- Dripping, crusting – why? Prevention
- Comparing Fan Control Strategies: Best to Worst
- Review: Points to Take Home
- Future Work → Questions ??
Fan on *continuously*.  
Keep that *drying front* moving.  
Don’t need aeration fans if grain stored “dry”.  
Need heat to dry, so maybe only turn on during the hot days?  
Regarding fans: The bigger the better!  
To dry: 1 CFM/bu. To cool: 0.1 CFM/bu.  
Cold air does not dry grain.  
Turn the fan on when conditions are right.
• Each Sensor’s value was recorded every hour.

• Fans were run continuously.

• Data has been collected every year since 2007.

The Experimental Setup

Sensor measuring T and RH of the air leaving the bin

Sensor measuring T and RH of the air entering the bin

Amount of Air Out = Amount of Air In

Air flow measured with pitot tube in CFM
RH and Temperature Probe On Inside Top of Bin Recording RH and T°.
Sampling ports for Grain Moisture

Temperature Probes
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<th>10-MID LEVEL TEMP</th>
<th>10-HI LEVEL TEMP</th>
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To find out what is going on? When is there drying?

To design a management practice to control the fan:

- Dries Grain to market-dry level standards
- Is efficient – saves power, fan on only when necessary (if drying: fan on -- if not drying: fan off)
- Provides **Safe** Grain Storage – i.e. No spoilage, no loss of grade, no infestation of molds, fungus, toxins (OTA)
  - Cool grain
  - Dry grain
Grain kernel

Water trying to get out
= Vapour Pressure Grain

• % moisture content
• temperature
• type & condition of grain

Air surrounding kernel

Water trying to get in
= Vapour Pressure Air

• temperature
• relative humidity

When grain vapour pressure is greater than the air vapour pressure, water evaporates from the grain into the air and we have DRYING.

When air vapour pressure is greater than grain vapour pressure, water enters the grain and WETTING occurs.

When Vps are equal, → EMC
Air at 20°C can only hold 17 grams water per cubic meter. At 20°C and at a relative humidity (RH) of 50%, the absolute humidity is half of 17 or 8.5 gr/m³.

Water in the Air

Saturation, RH = 100%

Relative Humidity (RH)
- a percentage of Saturation
- AbsHum/Saturation AbsHum

\[ W_s = 0.000289T^3 + 0.010873T^2 + 0.311043T + 4.617135 \]
We have a 2000 bu. Bin with an aeration fan with a flow of 3000 CFM.

The air:
- entering the bin is 15°C @ 55% RH.
  \[ 12.7 \text{ gr.} \times 0.55 = 7 \text{ gr/m}^3 \]
- leaving the bin is 25°C @ 45% RH.
  \[ 23.7 \text{ gr} \times 0.45 = 10.67 \text{ gr/m}^3 \]

Are we drying? Yes \[ 10.67 - 7 = 3.67 \text{ gr/m}^3 \]

How much? \[ 3000 \text{ CFM} = 180,000 \text{ ft}^3/\text{hr.} \]
\[ 180000 / 35.41 \times 3.67 = 18.6 \text{ kg/hr.} \text{ water removed} \]
Water in the Air

\[ W_s = 0.000289T^3 + 0.01087T^2 + 0.311T + 4.6 \]

Temperature of Air  Degrees Celsius  °C

grams of water per cubic meter  gr/m³

Saturation  RH= 100%

RH = 75%

RH = 50%

RH = 25%
Bin 9  Wheat 17% - 13.5%  Start 2:09 PM  
Sept 9  continuous for 190 hrs (8 days)

Switch from drying to wetting at 9:30 AM, -- turn the fan off by 9 in the morning

If we turned the fan on only at night for 3 days, would take 20 + 12 + 12 = 44 hrs with MC to 14.2%

-1.8% so MC = 15.2% by 9 AM
Average Diurnal Drying Cycle of 19 trials

H₂O removed (gr) per cubic meter of air flowing through bin

Best Drying ~ 2 AM

Drying to Wetting 9:30 AM

Wetting to Drying 6:00 PM

Most Wetting 2:00

Night           Morning           Noon           Afternoon           Evening

Hour of the Day
Air is typically holding the most water just after noon, 1:00 PM.

There is a strong correlation between drying and dry air.

Air is typically wet during the day and therefore we get wetting of the grain.

Air is typically dry at night and therefore we typically dry the grain at night.
Yard Light Rule (2010):
On at night, you are bright
On during the day, you will pay.
- Requires no sensors, or calculations, or knowledge of grain type, temp, RH etc.
- Turn off at 9 AM
- Does not account for MC, air T or RH, nor grain T and therefore may not be the best.
How Do Temperature Cycles Line Up with Drying Cycles?

Outside Air Temperature (°C)

Typical High 23.5°C
~ 3:00 PM

25.6° 3:09 PM

25.7° 3:09 PM

Grain Temperature

Drying when grain temp is decreasing

So a good control strategy would be to only run the fan when the grain is cooling
Ie Outside Temp < Grain Temp

Cooling is Drying
Our data shows that cooling the grain by about 15° C will lower the Moisture Content by 1%

2.6° C 5:09 AM
Typical 11° 5:30

Heating the Grain Wets it
Our data shows that heating the grain by about 30° C will increase MC by 1%
Can only make the grain colder by using air that is colder than the grain

Turn the Fan on if:

\[(\text{Air Temperature} + \text{Offset}) < \text{Grain Temperature}\]

This is a simple control strategy: no math, no calculations, and can be automated with simple electronics, but; the MC of the grain, and outside air RH are not accounted for, so again we could question: Is this the best? Can we incorporate the MC and RH?
Safe Days

Number of days until germination capacity is reduced to 95%  (Fraser & Muir 1981)

Safe Days = \(10^{(6.234 - 0.2118 \, MC - 0.0527 \, T)}\)  wheat and cereals

= \(10^{(6.224 - 0.302 \, MC - 0.069 \, T)}\)  canola and oilseeds

The objective for safe storage, is to maximize the number of safe days by lowering the temperature \(T\), and the moisture content, \(MC\). Look at how the number of safe days varies with temperature for ‘dry’ wheat:

- 14.5% @ 30\(^\circ\)C = 38 safe days
- 14.5% @ 20\(^\circ\)C = 128 safe days
- 14.5% @ 0\(^\circ\)C = 1458 safe days

New Definition: Spoilage Index = \(\sum (1/\text{safe days}) \times 100\)

Example, if safe days is six, then after 3 days we will have an accumulated deterioration of:  \((1/6 + 1/6 + 1/6) \times 100 = 50\%\), after 6 days : \((6 \times 1/6) \times 100 = 100\%\) of the way to 95% germination
### SAFE STORAGE TIME (days) CEREAL GRAINS

<table>
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<th>Grain</th>
<th>Grain Moisture Content</th>
<th>Temp °C</th>
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<td></td>
<td>14%</td>
<td>5</td>
</tr>
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<td></td>
<td>15%</td>
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<td>24%</td>
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</table>

- **< -5**: Safe storage > a year
- **5**: 81 safe days
- **10**: cooled to 10°C
- **15**: 80-120
- **20**: 80-120
- **25**: 80-120
- **30**: Not safe

Consider freshly harvested wheat 30°C, MC is 18%, have only 7 safe days if dried to 14.5%. If cooled to 10°C, 81 safe days.
SAFE STORAGE TIME (days) CEREAL GRAINS

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<tr>
<th>Temp °C</th>
<th>Grain Moisture Content (14%)</th>
<th>15%</th>
<th>16%</th>
<th>17%</th>
<th>18%</th>
<th>19%</th>
<th>20%</th>
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NOT SAFE                                    VERY DANGEROUS
## Average of 33 Runs 2007 – 2014

- **First 24 Hours:**
  - Start: 26.2
  - End: 14.6
  - Difference: 11.6

- **Grain Temp  °C**
  - Start: 26.2
  - End: 14.6
  - Difference: 11.6

- **Moist Content %**
  - Start: 17.65
  - End: 16.77
  - Difference: 0.88

- **Safe Days**
  - Start: 13
  - End: 87
  - Difference: 74

- **Cooling/Drying**
  - Start: 11.6/0.88 = 13.18  °C/ %MC
Grain Moisture (%)

Bin 19 Continuous Fan

Grain Moisture (%)

Bin 18  Fan: Tair + 1 < Tgrain

Spoilage Ind 97

Spoilage Ind 56

Fan 134 Hr

$49

Fan 621 Hr

$229

Start Sept 15 2014 7:43

End Oct 16 9:43

Tair = 15.8°C
EMC is the Moisture Content (MC) of a grain after it has been exposed to an environment for a long time.

If one puts barley into a sealed container. The moisture content MC of the barley is 14% and the temperature is 20\(^\circ\) C. We wait a long time – several hours. The RH of the air is measured and it is 63%. It was found that the MC and RH were related and EMC equations were formulated.

\[ MC \sim RH, T \quad \text{or} \quad RH_{emc} \sim MC, T \]

Done by trial & error, slightly different equations, Henderson, Chung, Pfost

Back to our Barley Bin --- rather than measure the RH of the air, we could have used an EMC equation to calculate the RH given the MC and T. And then knowing that the RH is 63% and that saturated air at 20 C can hold 17.5gr/m\(^3\) -- the absolute humidity in the bin is 11 gr/m\(^3\).

Now if we blow in outside air that has an absolute humidity less than 11gr/m\(^3\) the grain will dry.
How to Use EMC to determine drying conditions

1. Find the RH of the air inside the bin using EMC eq. for grain at T and MC or if you have moisture cables, use the RH value directly.
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 RH, $\text{RH}_{\text{thres}}$ by dividing 3. by 4. If the outside air has a RH that is less than $\text{RH}_{\text{thres}}$, we have drying conditions. It is the same as: $\text{AbsHum}_{\text{air}} < \text{AbsHum}_{\text{bin}}$
6. 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 $\text{RH}_{\text{thres}}$ for a number of grains using the steps above. Find the grain in question, and its $\text{RH}_{\text{thres}}$. If the outside air has an RH that is lower than this $\text{RH}_{\text{thres}}$, the air will dry your grain. The bigger the difference, the more the drying.
Barley @ MC 15.5%, 22ºC

Outside Air 19ºC RH 76% -- Is this drying air?

Plug the above into the calculator and it gives: RH_{thres} 82.8% (Ward); the outside air has a RH 76% therefore we have pretty good drying conditions
Barley 22 C, 15.5% MC \rightarrow EMC \rightarrow RH_{emc} is 71%  
* Sat humidity @22C 19.88  
* AbsHum_{bin} is 19.88 \times 0.71 = 14.2 \text{ gr/m}^3 

What RH would the outside air be to have the same humidity of 14.2?  
Sat humidity @ 19 C is 16.4 \text{ gr/m}^3  
RH_{thres} 14.2/16.4 = 86.4% 

Since the actual outside air has a lower RH, 76%, than Rh_{thres}, 86%, we have good drying conditions  
12.5 \text{ gr/m}^3 < 14.2 \text{ gr/m}^3 

When air @ 19C 76% is warmed to 22C, the absolute humidity remains the same, but the RH is reduced to 63% 

Water in the Air  

\[ W_s = 0.000289 \times T^3 + 0.010873 \times T^2 + 0.311043 \times T + 4.617135 \]
Email from farmer near Moose Jaw:

Flax harvested dry 8% MC, but it is warm 28º C
Nothing is done for a month, but then decides to cool it down, by using night drying: yard light rule. Nights are getting cooler and going down to 8ºC. Next morning lots of condensation on the inside roof. Did drying at night add water? Or, where did the water come from? The flax was dry?

Plug numbers into calculator, 8% 28 C 8 C and we get 186% for THthres. What’s going on here? How can an RH be greater than 100% ??
1. Flax 28 °C, 8% MC
2. EMC → RH_{emc} 52%
3. Sat humidity @ 28°C 28.2 absolute humidity in the bin: 28.2 x 0.52 = 14.8 gr/m³
4. The air in the bin is 28° RH is 52%, and absolute humidity is 14.8. When this air hits the roof, which it cools to 8° C but keeps the same water 14.8.
5. But air at 8° can’t hold that much water, the most it can hold is 7.9.
6. For every cubic meter of air flowing through the bin almost 7 grams of water will be dripping on the flax. (80 lbs/hr. @ 3000 CFM)
Control Strategies: The ultimate, the good, the bad and the ugly

**RH on, Water Balance Off** (compare absolute humidity of air in and out)

- This is the **ultimate** controller, but it requires a moisture cable strung from the center roof collar, with the highest RH/T sensor being in the discharge air.
- The lower T/RH sensors would be in the grain. For each of these sensor nodes, the absolute humidity can be calculated and compared to the absolute humidity of the outside air. If the absolute humidity of the outside air is less than the grain air, the fan is activated.
- Once the fan is on, a water balance calculation is done to determine the net amount of water leaving the bin. When the calculation indicates that there is no longer a net flow of water out of the bin, the fan is turned off and in an hour we return to comparing the absolute humidity of outside air, and grain air.
- This strategy depends on the installation of a more expensive moisture cable, it avoids the inaccuracies of the EMC equations, or even the knowledge of the grain type.
- Terminate the process when the average MC of the grain from top to bottom is dry. The grain should still be monitored, and maybe once a month the grain could be cooled to keep it as cold as possible.
EMC Calculator Control

The calculator is used to find the conditions in which drying will occur and thus be used to turn the fan on and off.

Requires the grain’s $T$, $MC$, and type as well as the outside air’s $T$ and $RH$.

It could easily be configured to turn the fan on and off automatically, but it also could be used to control the fan manually. For those that have temperature sensors and are not keen on changing to moisture sensors, this may be the way to go.

The disadvantage with this method is that calculations must be made and that are subject to the inaccuracies of the EMC equations. Also if we have an obscure grain, it may not be listed on the calculator.

The fan should not be turned on if dripping or condensation will occur -- that is if: $RH_{thres} > 100$

The advantage with this method is that moisture cables are not required. The only critical sensor is the temperature of the grain which can be obtained with existing temperature cables, or with a temperature probe. The outside air $T$ and $RH$ can easily be obtained from the weather station.

This control could be improved by adding $RH$ and $T$ in the discharge air to use the Water Balance Method as the criteria to turn the fan off.
**Temp Difference Control: Tair < Tgrain**

- This requires only two simple temperature sensors, one in the grain and the other in the outside air.
- No math or calculations are required, and the comparison can easily be done manually or with very simple electronics.
- This would be a simple technique that could be used for automatic control. It should be started as soon as the bin is filled, and end when the average of the grain is dry, after a cold night.
- It is lacking in that it does not take into account either the MC of the grain or the RH of the outside air. It is not perfect, but it is simple.
- Fine tuning this Method will ensure that no wetting will occur by adding an offset and only turning the fan on if the outside air has an RH < 80% Fan On IFF Tair + 2 < Tgrain and RH < 80% This will ensure no wetting, but it is at the expensive of missing drying opportunities, albeit weak drying opportunities.
- This method keeps the grain as cold as possible and is therefore a very safe method.
Control Strategies: The ultimate, the good, the bad and the ugly

Water Balance, Water In/Out Control

- This requires T and RH sensors on the air entering and leaving the bins.
- It also involves some calculations to determine the net amount of water leaving the bin.
- However the exhaust T and RH sensor are only effective when the air is moving or when the fan is on. When there is no air flow, the fan is off, the sensor are in stagnant air and do not represent the true readings of the exhaust air.
- So this is a great mechanism to determine when to turn the fan off (no or little drying is occurring) but it is useless when in determining when to turn it on. The ultimate controller uses this method to turn the fan off – indeed you really can’t beat it because it does all the averaging etc. and therefore looks at the bin as a whole and can truly shut the fan off when drying ceases – no guess work, no assumptions.
Control Strategies: The ultimate, the good, the bad and the ugly

On at Night

- One requires no sensors, and only a little attention to turn the fan on at night and off by 9 the next morning.
- The fan should be turned on immediately, even while the bin is being filled.
- When the average grain moisture is dry, the process should stop after a cold night of running.
- The grain will warm up slowly by maybe a degree a week, and once a month the grain should be cooled by running the fan on a very cold, dry night.
- This technique does not check for dripping or condensation conditions. It could be automated with a simple timer controlling the fan’s actuator.
Continuous Method

- The absolute worst situation is doing nothing with hot tough grain.
- This requires no attention, no sensors, but has a very high risk for spoilage.
- The number of safe days is small, and the grain is deteriorating quickly.
- It still may work; it may dry the grain, but is very risky with the potential for the most spoilage.
- The next worst thing is to leave the hot tough grain for a week or so before turning it on only during the day. Or, leave it for a week or two, and then turn it on continuously, and finally turn it off after a hot day of running, leaving the grain hot, but somewhat dried.
- It is better to run the fan continuously right from the start, and quitting after a cold night, leaving the grain cold. Leaving the grain hot could be ugly.
Review: What We Learned – Take Home Points

- Best Drying at Night – Diurnal Drying Cycle
- Net Water Out Absolute Humidity Out – Absolute Humidity In
- Cooling is Drying: simple control \( \text{Tair} < \text{Tgrain} \)
- Safe Grain is dry and cool
- EMC can be used to calculate absolute humidity :: control
- Dripping occurs when we don’t cool grain immediately
- Run the fan immediately, get it cool, get it safe
- There is a control management strategy for you:
  - On at night
  - \( \text{Tair} < \text{Tgrain} \)
  - EMC calculator
  - The ultimate: absolute humidity \( \bin_{\text{air}} \) > absolute humidity outside \( \text{air} \)
Possible Future Work

- Bigger bins
- Oil seeds
- Verify ultimate Controller
- Mitigate drying difference top/bottom
- Smaller Fans
- Air Delivery -- Rocket? Side Vents
- Long term storage studies -- years
Email: Ron.Palmer@uregina.ca

IHARF: www.iharf.ca

EMC calculator: http://planetcalc.com/4959/

Absolute Humidity: http://planetcalc.com/2167/

Blog: http://grain-aeration.com/
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