Aeration for grain cooling and drying:
How to use the Psychrometric chart to select suitable air

Philip Burrill, DPI & F

Aeration involves pumping air through a grain bulk using an arrangement of fans, ducts and exhaust vents. The grain can be cooled and / or dried depending on what air is used and how much is pumped through.
Aeration of stored grain with carefully selected air will reduce grain temperatures providing well recognised benefits. These include: allowing early harvested moist grain to be held safely prior to drying; reducing hot spots in storage that lead to mould & insect pest development; and preserving grain quality characteristics such as germination, baking quality and colour.

These notes are designed as a practical guide to using an Aeration Psychrometric Chart. Psychrometrics simply refers to the properties of moist air.

The Psychrometric Chart enables those using aeration equipment to determine the likely results for grain temperatures and moistures when aerating with ambient air at different times of the day or under various climatic conditions. It can help answer questions such as: When should fans be running for grain cooling or drying?; or How much supplementary heating is required when ambient air conditions are not suitable?

Air available for Aeration

The Temperature (T_{dry}) and Relative Humidity (RH) of ambient air is constantly changing.

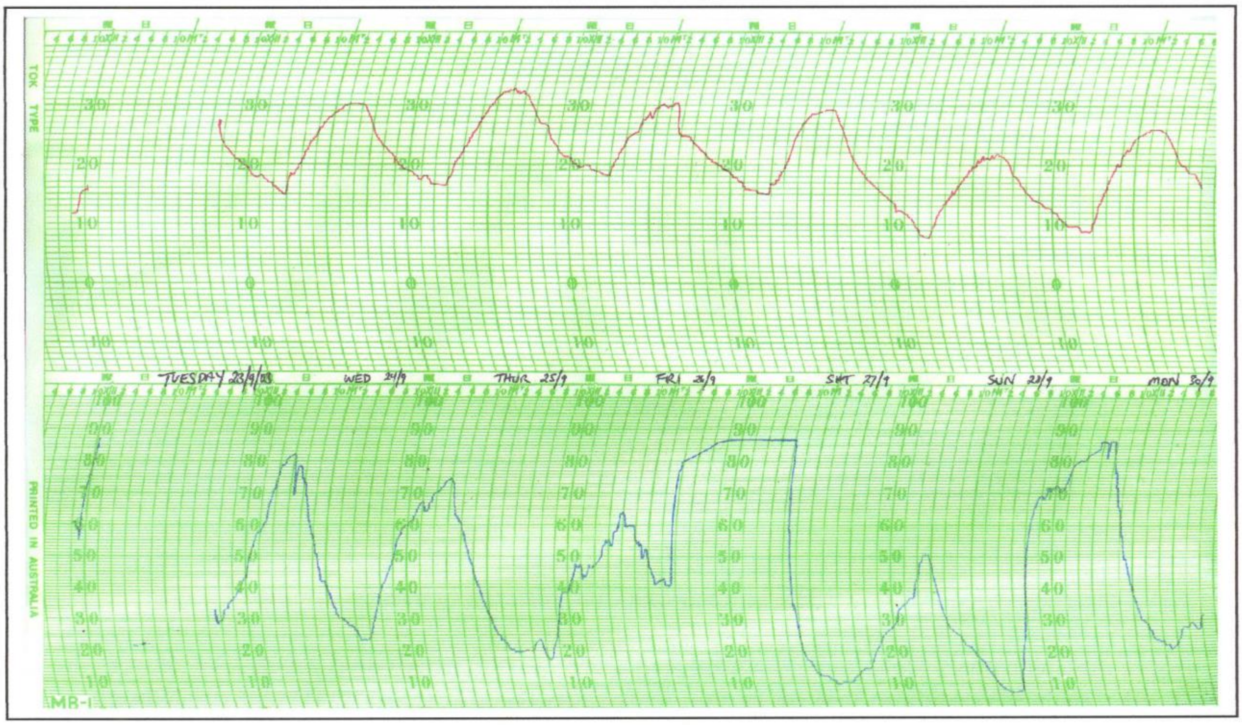

Fig. 1. Typical variations through a week in daily Temperature (top line °C) and Relative Humidity (botton line RH%) of atmospheric (ambient) air recorded in September 2003 at Warwick, Queensland.
Vertical lines with printed numbers 10, 20, 30 etc correspond with midnight.

The chart in Figure 1 shows, temperatures varied from highs of around 30°C at 2pm to minimums at 6am in the morning ranging from 18°C to as low as 8 °C late in the week.

Relative humidity is often at its lowest (20 -30% RH) around the hottest part of the day. At this time of the year in Warwick, humidity increases rapidly in the late afternoon from around 6pm to peak at 75 - 85% RH at the coldest time, around 6am.

On Friday afternoon around 3pm some light rainy conditions produced a temperature drop and rapid RH rise, which remained until clearing Saturday morning.

The following week (not shown) saw overcast, showery conditions, resulting in cooler days and continuous high RH. For the next seven days there was only three days with 3 - 5 hours of relatively dry air (below 50%RH) available. If you had moist grain in storage under these damp conditions, careful use of this air would be advisable. Only enough air would be used to ensure grain temperatures were kept cool until dry air became available.

Fig 2. A range of equipment used to measure temperature and RH.

L – R. Wet & dry bulb thermometer, Sling psychrometer, Tinytag® electronic data logger and Electronic Hygrometer. The Hygrothermograph at the rear produced the chart – Fig 1.

Relative Humidity & Equilibrium Moistures

Relative humidity (RH) tells us how saturated the air is with water vapour at a given temperature.

A common instrument used to calculate RH is the Wet & Dry Bulb Thermometer. This consists of a pair of ordinary thermometers, one having wet cloth over the bulb. (See Fig 2.)

Table 1 shows the maximum quantity of water vapour that air at various temperatures is capable of holding. The actual amount of water vapour in air, often expressed in *grams per cubic metre* (g/m^3) of air (1g = 1ml of water), is called the *absolute humidity* of air.
eg. Air at 20°C that is fully saturated (100%RH) would hold 17.3g/m^3 or 17ml/ m^3.

Quantity of Water Vapour in Saturated Air – 100%RH			
Temperature °C	Water Vapour g/m^3	Temperature °C	Water Vapour g/m^3
0	4.8	20	17.3
10	9.4	25	23.0
15	12.8	30	30.0

(Heading et al. 1972)

Table 1.

For the majority of the time, ambient air is not saturated at 100% RH. For example, using Table 1, if we had air at 25°C and it contained 11.5 g/m^3 of water vapour then its RH is 50%. It is holding only half of the water vapour it is capable of holding at 25°C.

Note how warm air at 30°C is capable of carrying more than twice as much water vapour as cool air at 15°C. This is why under cool or humid conditions it may be helpful to add a small amount of extra heat (eg plus 5°C - 10°C) using a gas / diesel burner to assist aeration drying. It is very important to note however that large volumes of air (usually more than 10 litres of air per second per tonne of grain) are required for aeration drying in silos. There is such a deep bed of grain in a silo that moisture must be quickly moved through and right out of the silo. Adequate exhaust venting at the top of the silo is required to ensure no restrictions to air flow. Low air flow rates can allow moisture to concentrate in grain layers further up the silo with serious consequences.

Cool early morning air is often at a high RH eg. 75 – 90% and therefore close to saturation. When aerating grain with this cool air (eg. 15°C) it can do a valuable job of reducing grain temperature, but is unable to dry moist grain (eg 14 -15% moisture content – “mc”).

Using Equilibrium Moistures found on the Aeration Psychrometric Chart we can predict more reliably the results of aerating grain with air at various temperatures and RH levels.

Equilibrium Moisture Content

When you fill a 100 tonne silo with grain there is a lot of air space between the grains. For 100 tonnes of barley you will need a silo volume of about 130m³. Around 80m³ is taken up with grain and remaining volume of 50m³ is made up of the air space between the individual grains.
With no movement of air in the silo, this entrapped air around the grain will slowly (over a few days) come into equilibrium (balance) with the grain moisture. Fig 3.

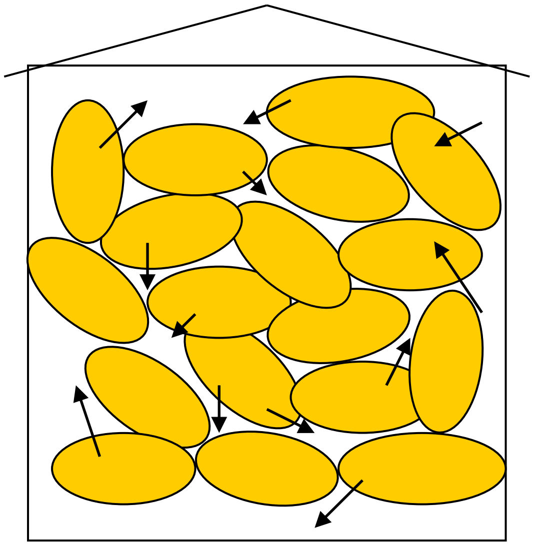

Fig 3. Moisture moves from wet grains into air spaces and also from the air into dry grains.

If, for example, you filled a silo with freshly harvested wheat at a moisture content of 14 % (or even wheat containing a reasonable percentage of green grains) with no aeration, you would find grain temperatures inside the silo can very rapidly rise above 35°C.
While outside air in the mid-afternoon may have quite a low RH (eg 30 – 40%), the air inside the silo mixed with this warm, damp wheat is likely to end up with a high RH around 74%. Under these conditions moulds develop, grain germination levels deteriorate and grain insect pests multiply.
So in this example, in a few days moisture will move out of the 14%mc grain, wetting up the surrounding air to a predicable level of 74% RH. A balance or equilibrium is reached between air and grain inside the silo.
The grain is said to have reached its Equilibrium Moisture Content (EMC) and the air its Equilibrium Relative Humidity (ERH)
Knowing the grain moisture (14%) and grain temperature (35 °C) we can obtain this ERH figure (74% RH) using the Aeration Psychrometric Chart This figure is very useful. We now know if we can aerate the silo with enough ambient air well under 35 °C and 74% RH the grain will be rapidly cooled and also slowly dried.
As water vapour is being drawn out of moist grains with dry air, an evaporative cooling process is underway, thus adding to the cooling effect of aeration.
Using aeration to remove the ‘harvest heat’ and ‘even out’ the grain moisture variations that typically occur between loads of freshly harvested grain is a critical first step in preserving grain quality. Reductions in grain temperatures & humidity, along with uniformity throughout the grain bulk in storage is the desired outcome.

If aeration fans are left running while filling a silo with freshly harvested moist grain you should detect / smell a significant improvement (temperature and humidity) in the air coming out of the top of the silo over a period of several days.

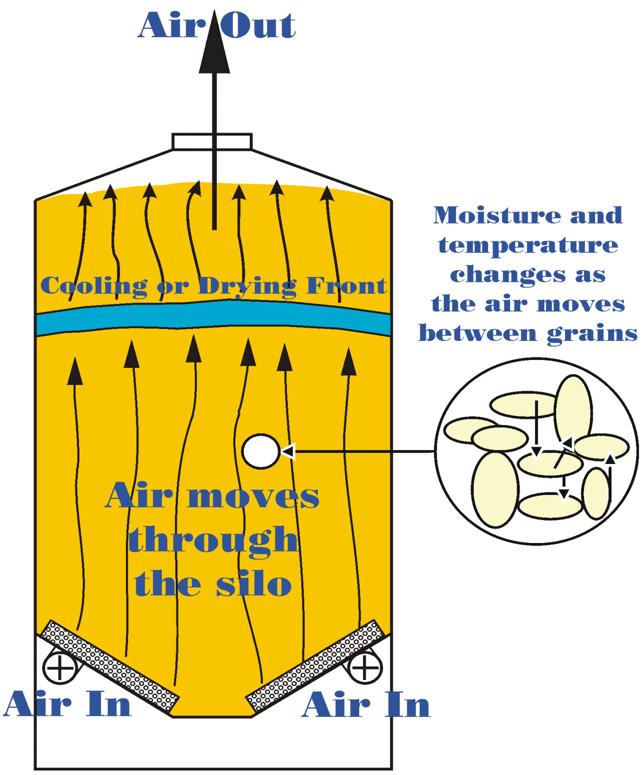

Fig.3 Grain Aeration (C. Newman 2002)

Using the Aeration Psychrometric Chart

We will step through a couple of simple exercises using the Aeration Psychrometric Chart. See attachment 1. Aeration Chart – for wheat.

Step 1 – What's on the Chart.

Although the chart may look complex, it simply looks at air temperatures and the amount of water in the air.
Looking across the bottom horizontal line you will see temperatures range from 0 to 45°C.
On the far right hand side of the chart, the vertical line shows increasing amounts of water held in the air, ranging from zero up to 0.030 kg /kg (30g water vapour / kg of air).

As a basic exercise find 25°C on the bottom line. As you move vertically up this 25°C line you are steadily adding water to the air. Notice that you are crossing a horizontal line marked 0.005 (ie 5g water vapour / kg air).
You will also see on the chart thin curved black lines marked 10%, 20%, 30% etc. These are the Relative Humidity (RH) lines. So as you go vertically up the 25°C line (adding water) you start at 0%RH on the bottom, then over the 10% RH curve, 20%RH curve, all the way to the very top curved line of the chart which is 100% RH (fully saturated air at 25°C).
At the ▲ symbol, the air is 25°C and 70% RH.

Next are the six coloured lines. These are the Isotherms or Equilibrium Moisture Contents (EMC) for wheat. These curves show the balance or moisture equilibrium (EMC & ERH) reached between stored wheat at 9, 10, 11, 12, 13, and 14% mc and the air surrounding this wheat. These moisture equilibria curves have been developed from controlled laboratory tests on wheat.

Looking at the red curve line (12%EMC) we can see that for 12% mc wheat with a grain temperature between 20 and 30°C, the RH of the air surrounding this wheat will be between 50% and 60% RH.
For the same example it could also be said, if wheat was aerated in a silo with large volumes of air at an average temperature of 25°C and a RH around 55%, the wheat should eventually arrive at approx. 12% mc. (Using the chart find the air quality 25°C and 55%RH. This intersects with the red isotherm for 12% mc wheat)
Using our earlier example from page four, wheat with 14% mc (brown line) at 35°C, left sitting in a silo would reach an equilibrium with surrounding air of 74% RH. See symbol: ◘

Step 2 – Using the Chart.

1. Relative Humidity: Using the chart to determine RH, with readings from a wet & dry bulb thermometer.

Your ambient air has a dry bulb reading of 25°C and a wet bulb reading of 21°C.
Find 21°C along the bottom line. Go to the very top - ♣ (100% RH - saturation). Now follow what is called a 'wet bulb temperature line' down to the dry bulb reading of 25°C. You should be at ▲. The RH lines on the chart now tells you your ambient air is at 70% RH.

2. Absolute Humidity: Using the chart to calculate the actual amount of water vapour in a cubic metre of air – gm or ml water vapour / m³ air.
Along the top 100%RH line are Air Density figures (m³/ kg dry air) , 0.86, 0.88 etc.
Using an example from Table 1; Air at 25°C should have 23g water per cubic meter if saturated - 100%RH.
Go to the top of the 25°C line where we are at the 100% RH line (or dew point line). At this point you are a little more than half way between the 0.86 and 0.88 m³/kg air density points. About 0.872 m³/kg. Looking to the far right the amount of water in the air is 0.020 kg / kg of air which is 20g/kg air.
To express this as grams of water per m³ of air: 20g/kg x (1÷ 0.872) = 23.0g/ m³
As another example: air at 25°C and 70% RH 14g/kg x (1÷ 0.864) = 16.2g/ m³

3. Aeration Cooling: How to determine what air is suitable for aerating grain to achieve grain cooling in the silo.

From the earlier example, wheat has been harvested around 14%mc and has heated in the truck and silo to 35°C. Ambient temperature in late November mid afternoon is 30°C with a RH of 30%. To cool this warm grain should I have the aeration fans running in the hot afternoon?

(a) Should fans be on during the day when ambient air is around 30°C and 30% RH ?
(b) Should fans be on during in the early morning with 17°C and 90%RH ?

Note the spot on the chart where the wheat in the silo currently sits 14% mc (brown line) intersects with the 35°C line - ◘ The RH lines indicate a RH around the grain of 74%.

(a) Locate the ambient air point with 30°C and 30% RH ☼. As this is the air you intend to blow through this 14%MC wheat, from ☼ move left, up the sloping 'wet bulb line' to where it hits the brown line of 14% EMC. Now look directly below this point to read off the temperature. Grain will be cooled towards 22 °C even though you are using this 30 °C ambient air. Extra cooling occurs due to blowing drying air (30% RH compared to 74% ERH) through moist grain providing an evaporative cooling effect.

(b) For ambient air of 17°C and 90%RH. Locate this point on the chart ⌂. Note that because this point is above the 14% EMC line (brown) it has a higher RH than the air surrounding the grain (74% RH). So this air will have a tendency to rewet the grain in the silo towards 16 -17% MC, starting with first grain it encounters around the aeration ducting.
As long as there are not too many hours of this high RH air used, this moisture should be removed quickly by air of a lower RH later in the day. However avoid foggy air which is heavily laden with tiny water droplets. Adding water to grain actually slightly heats the grain above the air temperature being used. This is the reverse process of evaporative cooling.

Move down from⌂ along the sloping 'wet bulb line' to meet the 14% EMC line (brown). Look direct below this point to read 20°C. So the cool 17°C morning air is very helpful in reducing the grain temperature from 35°C towards 20°C, but will provide no evaporative cooling effect.

So the cooling actions of ambient air at 30°C, 30%RH and at 17°C, 90%RH on the 14% mc wheat are very similar, driving grain temperatures towards 22°C and 20°C respectively. The low humidity air has the initial benefit of driving off moisture, starting with grain closest to the air distribution ducts in the silo base.

It is worth noting that it is important to have a reliable grain moisture meter and a grain temperature probe to provide grain temperatures and moistures within the silo. A simple wet & dry bulb thermometer will provide the ambient air conditions. Access to weather station information that provides trends in daily temperatures & humidity is very helpful.

4. Aeration Drying: How to check what air is suitable for aerating grain to achieve grain drying in the silo.

You have harvested wheat around 14% mc and grain temperatures in storage are measured at 35°C. Using the chart this gives you 74% RH surrounding the grain.
To dry this grain what air should I be looking to use and what air should I avoid using too much of?

(a) Should fans be on during the day when ambient air is around 30°C and 30% RH ? ☼

(b) Should fans be on during in the early morning with 17°C and 90%RH ? ⌂

Again, first mark the spot on the chart where the wheat in the silo currently sits: 14% mc (brown line) intersects with the 35°C line. ◘

(a) Because this ambient air point ☼ is just below the 9% EMC (yellow line) this air will be trying to dry the 14 % mc grain to less than 9% mc. So while ever you are using ambient air underneath the brown 14% EMC line the grain will steadily dry . If you were using ambient air at 30°C and 65% RH your drying speed would be very much slower (given the same air flow rates) as you are only pulling grain moisture towards the 13% EMC line (blue line)

Changing grain moisture content (drying) inside a silo is a much slower process than changing grain temperatures (cooling). It may require weeks of suitable air at high air flow rates (10-20L/s/tonne) to reduce grain mc. Grain temperature can often be dropped in a matter of hours or days with much lower air flow rates (eg 2 – 3L/s/tonne).

(b) With the much cooler moist ambient air at⌂ the grain around the air duct and further up the silo will be gaining moisture. This point sits above the brown 14% EMC line and therefore would be slowly pulling the grain moisture towards 16 – 17 % mc.

For some, aeration drying may be required on a regular basis. Growers who often harvest high moisture grain or who operate in a region that typically has high RH for much of the year. In this situation supplementary heating (gas / diesel burner) combined with a high capacity air flow system (15 – 20 L/s/tonne) may be an effective option.

Examine the effect of using a gas burner to add 9°C to ambient air of 17°C and 90%RH.

Move horizontally to the right from the ambient air point ⌂ a total of 9°C. You now find you are blowing 26°C and 53%RH air through your grain. At this new location you are drawing your grain towards approx 11.5 % mc rather than 16 –17 % mc by using a small amount of supplementary heating.

If large tonnages of grain required drying on a regular basis over a short time frame then checking on the economics of purchasing a purpose built grain dryer would be advisable. This is often effectively used in conjunction with silo aeration systems both before and after the rapid hot air drying process.

Aeration in Practice

<u>Cooling grain</u>

Numerous aeration fans fitted to storages are operated manually. Due to the pressure of other tasks around harvest time, aeration fans may be left running when they should be off. If fans are left on during foggy conditions or for too many hours of damp (high RH) air, then excessive moisture entering the silo will result in costly grain damage.
Automatic Aeration Cooling Controllers are available. These are designed to select suitable air for cooling grain and thus reduce the risk of fans running at inappropriate times. Sensors used in recent years are also designed to limit the use of high RH air. Basic auto control systems cost around $3000 - $5000 plus electrical wiring costs. One unit can control aeration fans on a number of silos.

A recent trial conducted in southern Queensland showed that a standard aeration cooling fan system (2L/s/t) fitted to 100 tonne capacity silo and utilizing an automatic aeration cooling controller was able to rapidly bring early harvested barley (14 –15 % mc) from initial storage temperatures of 40°C down to temperatures around 20°C. This grain temperature was held within a range of 17°C to 24°C during the warmest months of Nov, Dec, Jan, Feb and March.

If grain temperatures can be held below 20°C, half of the major grain insect pests will cease breeding. If you can pull grain temperatures down to 15°C then virtually all storage pests cease multiplying. For the winter months of June, July, Aug, grain storage temperatures of 10°C to 15°C are quite realistic.
It is worth noting that while achieving storage temperatures under 20°C is very desirable, it is also important to monitor grain moistures and aim for the 11 – 13% mc range for longer term safe storage in cereal grains.

<u>Aeration drying</u>

A common problem seen when attempting to dry moist grain in a silo (or grain containing fair amounts of green grains etc) is the lack of appropriate fan design capacity. Large volumes of air are required at a pressure sufficient to force high air flow rates through the grain stack.
Looking at Fig 3. you will note the “ Cooling or Drying front” illustrated inside the grain bulk. Grain in a silo is often 4.0m – 6.0m deep. This is in stark contrast to a commercial batch or continuous flow hot air grain dryer which works with grain depths around 0.1 - 0.5m.

Take the example of a 110t of sorghum stored at 16-17%mc in a 115t capacity silo with only a standard 2 L/s/t aeration fan (eg 0.37kW motor - fan output capacity approx. 200L / sec.). This low air flow volume can do an excellent job of cooling the grain. However large volumes of low humidity air over an extended period of time are required to safely maintain the gradual process of extracting moisture held inside grain. It is important that this extracted moisture is pushed quickly through the layers of grain above and not left to sit in the upper grain layers in the silo. Otherwise hot, mouldy grain will rapidly develop.
If you combine LOW air flow rates with supplementary heating (ie. gas burner), it is likely to make matters even worse. Without sufficient air volume to shift the moisture front quickly up and out of the silo the result can be very dry grain at the bottom and very wet, hot layers of grain further up the silo.
Seeking specialist advice on equipment requirements for aeration drying is strongly recommended.

Fig 4. A Kotzur® Drying silo is one example of a silo designed for aeration drying. Fitted with a 7.5kW motor & fan combination capable of producing air flow rates of 10 - 20 L / sec /tonne.

Further References

1. White G. (2000) “Grain storage – aeration for cooling or drying”, Queensland Dept. Primary Industries & Fisheries.
2. Newman C. (2002) “Aeration – for preserving grain quality”, West Australian Dept. of Agriculture Farm Note No. 24/2002

Acknowledgement

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Bibliography

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Attachment 1

Aeration Chart

@ 101325.6 pascals

Psychrometric
ASHRAE H'book Fundamentals
SI Edition, Chapter 6, 1993.

Isotherm
ASW wheat
9, 10, 11, 12, 13, 14 %wb
Mod. Chung Pfost correlation
Cassells 2003 53rd ACCC data

J Darby SGRL, Oct 2003.