A NEW LOOK AT AERATION

J.M. Desmarchelier
CSIRO, Division of Entomology
PO Box 1700, ACT 2601, Australia

Abstract

Aeration achieves a wet-bulb temperature (Twb) on commodities in equilibrium with that of the inlet air. Hence, Twb was correlated with: 1) intrinsic rate of increase of insect populations; 2) rates of loss of grain protectants; 3) rates of loss viability. Good 'rule of thumb' correlations were obtained that suggest that the goal of aeration should be redefined in terms of T_{WB}, rather than dry-bulb temperature. This is especially important where seed moisture contents vary. A wet-bulb temperature regime is proposed as the aim of aeration. This regime requires a minimization of the weighted wet-bulb temperature time product.

1. INTRODUCTION

Two types of aeration are used world-wide, including Australia. One, normally called aeration, utilizes a low flow of air, typically 5-20 air changes per hour, with the prime aim of cooling stored commodities without much effect on the moisture content. The other, called near-ambient on-floor drying(Lasseran, 1988), uses larger air flows with the aim of drying wet commodities. This talk is about aeration not near-ambient drying.

Many authors {e.g. (Navarro et al 1973, Foster and Tuite 1982)} cite Burges and Burrell (1964) in saying that the aim of aeration is to achieve a (dry-bulb temperature of 15°C, at which insect reproduction stops.

Thus the goal of aeration is normally defined by (dry-bulb) temperature.

2. Aeration and the Wet-bulb temperature (T_{WB})

However, aeration does not cool grain to the dry-bulb temperature of the inlet air. If the air is drier than the grain, 'over-cooling' occurs, i.e. the grain temperature falls below that of the inlet air, (Lasseran 1988, Wilson 1988). This is due to evaporative cooling. Conversely, aeration with air wetter than the commodity causes 'under-cooling', due to heat of condensation.

These processes of 'under-' and 'over-' cooling were quantitatively analyzed by Sutherland et al, 1971, who showed that the grain, after passage of the temperature front, attained a wet-bulb temperature in equilibrium with that of the inlet air. In Fig. 1, a simplified form of the psychrometric chart relates wet-bulb temperature (T_{WB}) to (dry bulb) temperature, T, and relative humidity (RH). Thus 20% RH and 37°C, 40% RH and 30°C and 60% RH, 26°C all have the same wet-bulb temperature of 20°C,$_{WB}$.

In many countries, including Australia, Pakistan, parts of China and the Middle East, summer grains at time of harvest may have equilibrium relative humidities (e.r.h.) that range from about 20% up to any value that is permitted into storage. The value of 20°C,$_{WB}$, is "typical" for wheat in Australia, with the hot grain (30-40°C dry-bulb) usually being dry (20-40% erh) and the cool grain (20-25°C dry-bulb) usually being near the receival moisture content limit (about 55% erh).

Let us take 2 examples each at 20°C,$_{WB}$, namely 20% erh and 37°C dry-bulb and 60 % erh, 26°C dry-bulb. If grain is aerated with an inlet air wet-bulb temperature of 15°C,$_{WB}$, the wetter grain is cooled to 20°C dry-bulb and the drier grain to 27°C dry-bulb.

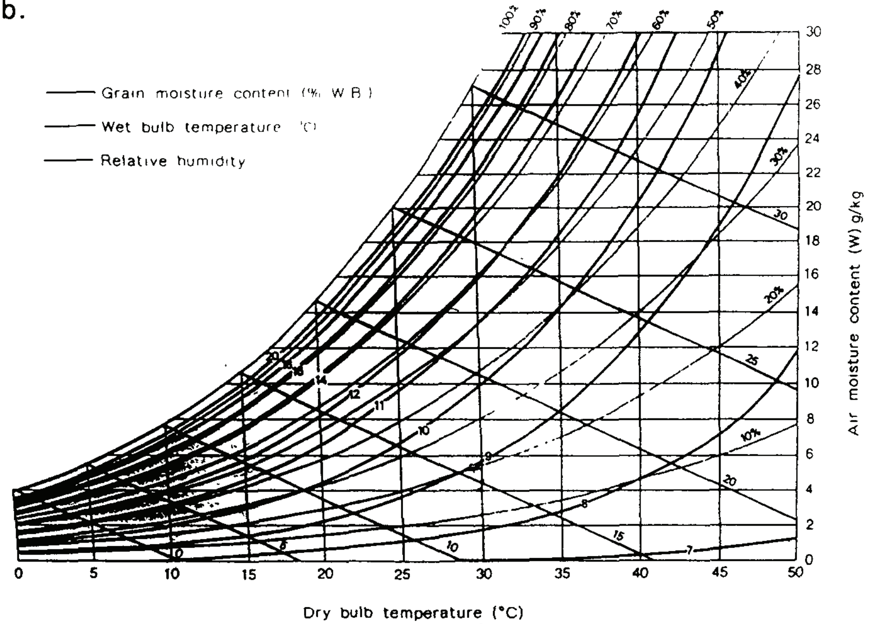

Fig. 1. A simplified form of the psychrometric chart
The vertical lines (0-50°C) record normal (dry-bulb temperature
The curved lines, marked 10-100%, record equilibrium relative humidity and the curved lines labelled 7-20 record moisture content, wet basis.
The sloping lines, 0-30°C, record wet-bulb temperature.
The right hand vertical scale, labelled air moisture content (0-30), records the weight of water (g) per kg of dry air. 1kg of dry air occupies approximately 0.77m^3.

If one accepts a temperature goal for aeration, the logical conclusion is that aeration is unsuitable for, or "useless" on, dry grain. The logic is correct, and the conclusion has been drawn in parts of Australia and, almost certainly, in many parts of the world.

However, is the premise correct? Should the goal of aeration be a temperature goal?

3. Correlations with T_{WB}

There are 2 possible reasons why a temperature goal may be inappropriate for aeration. First, aeration does not control grain temperature, but grain wet-bulb temperature. Second, all processes leading to damage in grain are functions of both T and e.r.h., and not of temperature alone .

Because T_{WB} is also a function of both temperature and e.r.h., it was correlated with 3 parameters, viz rate of increase of insect populations, rate of loss of protectants and rate of loss of viability.

All literature data were analyzed, subject to the following provisoes:

1) only those data were used where rates were determined at constant conditions.

2) correlation between rates and T_{WB} was only used where there were 4 values of rates.

3) values taken at an e.r.h. greater than 80% were ignored, for 2 reasons. The first is that mould growth, which is not constant, may influence such results. The second is that aeration, as distinct from near-ambient drying, is not an appropriate strategy for storage under conditions were mould growth is possible (and certainly not where e.r.h. exceeds 80%).

In the next sections, examples are given that show 'rule of thumb' correlations with Twb.

3.1 Rate of Insect Population growth and T_{WB}

Under fixed conditions, the increase of insect numbers from No to N after time *t* is given by Eq 1.

$$ln(N/No) = r.t. \qquad \text{Eq 1}$$

I therefore correlated the 'intrinsic rate or increase', *r*, with Twb. An example, for *Sitophilus oryzae* (L), is given in Fig 2. Correlations were good, under the conditions described in Eq 2, where $(To)_{WB}$ is the threshold wet-bulb temperature (i.e. that at which $r = o$), and (T_{WB}) max is that value at which *r* reaches its maximum value (i.e. greatest rate of increase of insect populations)

$$r = k(T\text{-}To)_{WB}, \text{ for } (T_{max} > T > To)_{WB} \qquad \text{Eq 2}$$

$$\text{i.e. for} \quad r_{max} > r > 0$$

A further analysis is given in Desmarchelier (1988). In summary, and subject to the limitations discussed by that author, intrinsic rate of increase of insect populations correlates with T_{WB}.

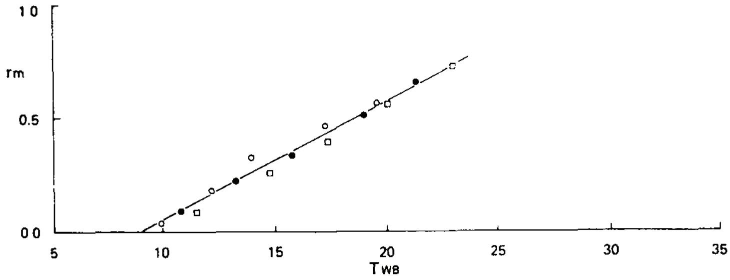

Fig. 2. Relationship between the wet-bulb temperature and the intrinsic rate of increase per week on wheat of *S. oryzae* (data Longstaff and Evans, 1983). ○, 11% moisture content; ●, 12 5% moisture content, □, 14% moisture content

3.2 Loss of Protectants and T_{WB}

Wan and Desmarchelier (1990) analyzed all literature rate constants for loss of protectants with T_{WB}. Under fixed conditions, residues decay from Ro to R after time *t* (Eq 3) and the rate constant, *k*, is related to T_{WB} by Eq 4. An example of the rate of loss of fenitrothion is given in Fig. 3.

$$ln(R/Ro) = -k.t \qquad \text{Eq 3}$$

$$ln\,(k) = A + B\,(T_{WB}) \qquad \text{Eq 4}$$

where A,B are found from regression analysis. Thus loss of protectants also correlates with T_{WB}.

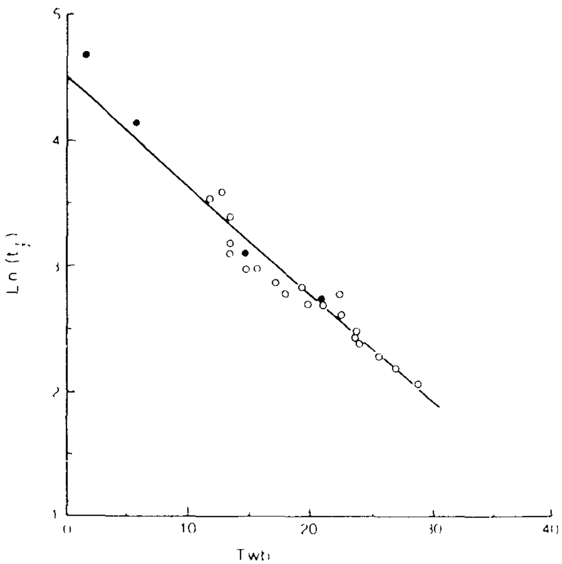

Fig. 3. Relationship between the halflife ($t_{1/2}$) of fenitrothion and the wet-bulb temperature. ● Canadian data o Australian data

3.3 Loss of Viability and T_{WB}

One aim of aeration is to preserve quality. The most studied quality parameter is viability, which is not only often of direct importance, e.g. for malting barley, but is "probably the best direct index of grain soundness" (Pomeranz, 1982).

Under fixed conditions, loss of viability, measured in probits, is proportional to time, where Po and Pv are probit viabilities at time zero and t (Ellis and Roberts 1980, Renard 1982).

$$Po - Pv = kv.t \qquad \text{Eq 5}$$

In older literature (Burges and Burrell 1964), the 't' in Eq 5 is measured and expressed as 'time to 95% viability' $(TV)_{95}$.

In Fig. 4, data from Burges and Burrell 1964, recording 't' values, are plotted against T_{WB}, and the correlation is good. Fig 4 can be represented by Eq. 6 (for conditions where mould growth is not possible).

$$\log\ (TV)_{95} = 2.53 - 0.0539\ T_{WB} \qquad \text{Eq 6}$$

For analysis on very wet grain, Eq 6 is not accurate and the models of Roberts should be used.

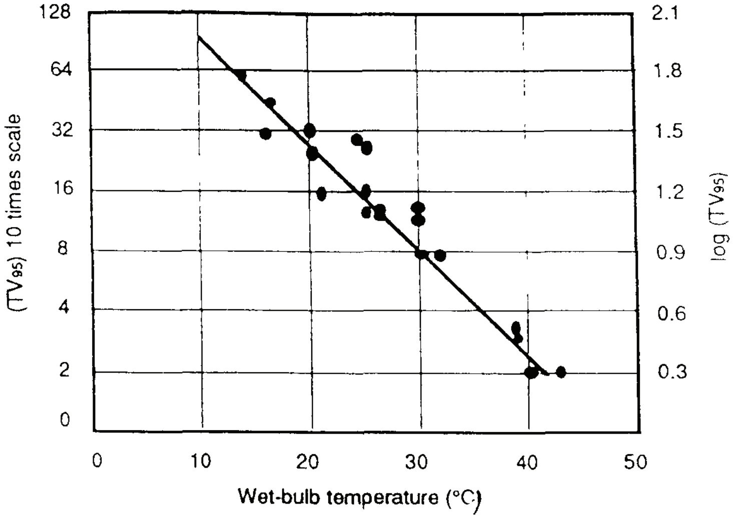

Figure 4. Time for the viability of barley to decline to 95% (TV_{95}), plotted on a 10-times scale against wet-bulb temperature. The right-hand vertical scale records log TV_{95}.

4. Temperature Goal or Temperature Regime?

The goal of aeration is often described in terms of achieving a final state, at which insect reporduction (and other losses) stop. This is not a sensible goal, if the final goal is achieved only after a great deal of damage has already occurred. The real goal of aeration is not a final, ideal, state but a cooling regime that minimizes total damage, e.g. that from insects or that caused by loss of viability.

In general terms, aeration will result in a temperature regime of $(T_o)_{WB}$ for time t_o, $(T_1)_{WB}$ for time t_1, etc. Under such conditions, Eq 7 applies (for insects, protectants and viability).

$$\frac{\ln(\text{damage})}{\text{constant}} = (T_o)_{WB} \cdot t_o + (T_1)_{WB} \cdot t_1 + (T_2)_{WB} \cdot t_2 + \text{etc}$$

$$= \Sigma(T_i)_{WB} \cdot t_i \qquad \text{Eq 7}$$

For insect control, the marginal benefit of cooling below the threshold value, T_o, is small. Therefore Eq 8 applies

$$\ln(\text{damage}) = \text{constant } \Sigma(T\text{-}T_o)_{WB} \cdot t \qquad \text{Eq 8}$$

Thus, if the aim is to reduce damage, the aim is to reduce $\Sigma(T\text{-}T_o)_{WB}.t$, i.e. to reduce the weighted wet-bulb temperature time product.

This criterion applies as long as the assumption in Eqs 1-6 apply. Factors such as insect behaviour and migration, and unevenness of aeration results, are not included in these equations, but are certainly of importance.

For most insects (Desmarchelier 1988), T_O values are quite large, i.e. about $13^oC,_{WB}$. These are the kind of night temperatures that are achieved even in, by European standards, a 'hot' Australian summer. For *Sitophilus* species T_O values are about $9^oC,_{WB}$ (Desmarchelier 1988).

On dry grain, e.g. 9-10% moisture wheat, threshold dry-bulb temperature values are well above 20^oC (Desmarchelier 1988), corresponding to a wet-bulb temperature of 13^oC and grain too dry for *Sitophilus*. This is quite a difference to the goal of 15^oC(dry-bulb) set by Burges and Burrell (1964). This dry-bulb goal was, however, set for the "British climate" and is a reasonable one for grain of about 60%e.r.h. This problem has been that the goal set for the "British climate" has been used in circumstances where it is not appropriate.

For loss of protectants or viability, there is no mathematical equivalent to T_O, although there is an economic equivalent. For storage period of less than 1 year, there is no real benefit in reducing loss of viability by about 0.1%, or doubling the half-life of a protectant from 2 to 4 years. The 'mathematics' in the equations may hold true down to low temperatures, but the cost savings do not.

In summary, reduction in damage, rather than achieving an 'ideal' goal, is the aim of aeration, and the best criterion for reduction is damage in reduction of the weighted wet-bulb temperature time product.

5. Cost optimization

In my opinion, the aim of aeration is not to achieve the optimal low temperature from aeration, but to use it, along with any other method, to achieve the economically optimal solution. There is no universal optimal solution, but rather a series of solutions that are optimal for different of circumstances (Desmarchelier 1990).

For example, consider the case of insect control on Australian wheat. Here wheat is harvested in the first summer month (called month 1) and wet-bulb temperatures of about $13^oC,_{WB}$ can, theoretically, be achieved by aeration in Month 1, but 9^oC_{WB} cannot be achieved until month 4-5. Thus *Sitophilus* species cannot be fully controlled by aeration, but at low temperatures on 12% moisture wheat, they can be controlled by a low dose *(about 0.5g/t)* of fenitrothion. Here one economically optimal solution is to use aeration with a low dose of fenitrothion, or other suitable protectant.

Grain stored for more than a few months in Australia is preferentially stored in either aerated or sealed storages. Thus an aerated storage may be outloaded in month 9 (e.g. at the end of Winter). From Eq 7, an x^{o}C reduction in month 1 is e^{x} (about 3000t) times more effective than an x^{o}C reduction in month 8 (assuming no subsequent change in temperature). Under these conditions, it makes little sense to aerate in Winter, whereas aeration in Summer is very useful. Thus aeration is being progressively turned off early in Australia, principally to save energy, but also to prevent moisture build-up near ducts.

As we have seen, aeration slows down the increase in insect populations, slows down the rate of loss of viability and slows down the rate of loss of protectants (thus enabling use of a lower dose). It is also effective in controlling moulds. This is obviously the case where the grain is dried, but it is also true for low energy cooling. First cooling slows down moisture migration, so that the difference between the average moisture content and that in wet regimes is reduced by cooling (thus enabling a higher average value). Second, cooling raises the R.H. required by moulds (Lacey et al 1980) and third, it lowers the R.H. in equilibrium with grain of a given moisture content (cf. FIg. 1).

The economically optimum strategy for aeration depends on climate, on harvest condition and on end-use. There are, in fact, a series of strategies, rather than a single strategy.

The importance of the concept of reducing weighted wet-bulb temperature time products is that is forms a framework enabling the benefits of cooling to be assessed across a range of climates, including those previously judged 'unsuitable' for aeration.

7. Overall Conclusion

This talk has presented a novel view of aeration and some analyses of theoretical interest. Because so much data has been covered, it has been necessary to be selective. An appropriate aeration regime, for individual situations, cannot be obtained from the data presented in this talk. The cited references need to be consulted, or my "Aeration Strategy Manual" (Desmarchelier 1990).

None the less, I hope this talk will lead to increased use of aeration in 'hot' climates, as well as to an improved use overall.

References

Burges, H.D. and Burrell, N.J. Cooling bulk grain in the British climate to control storage insects and to improve keeping quality. J. Sci. Fd. Agric. 15, 32, 1964.

Navarro, S. Donahaye, E. and Calderon, M.,(Navarro 1973). Studies on aeration with refrigerated air - I. Chilling of wheat in a concrete elevator. J. Stored Prod. Res. 9, 253, 1973.

Desmarchelier, J.M. (1988). The relationship between wet-bulb temperature and the intrinsic rate of increase of eight species of stored-product coleoptera. J. Stored Prod. Res. 24, 107-113.

Desmarchelier, J.M. (1990) Aeration Strategy Manual. CSIRO, Division of Entomology, Australia.

Ellis, R.H. and Roberts, E.H. (1980). Improved equations for the prediction of seed longevity. Amm Bot. 45, 13-30.

Foster, G.H. and Tuite, J. (1982) in Storage of Cereal Grains and their Products (C.M. Christensen, ed), American Association of Cereal Chemistry, St Paul, Minnesota, USA, pp117-143.

Lasseran, J.C. (1988) in Preservation and Storage of Grains, Seeds and their By-products (J.L. Multon, ed). Lavoisier Publishing Inc. Paris, France. pp 664-748

Lacey, J. Hill, S.T. and Edwards, M.A., (1980). Micro-organisms in stored grains: Their enumeration and significance. Trop Stored Prod Inf. 39, 19-33.

Pomeranz, Y. (1982) Biochemical functional and nutritive changes during storage in Storage of Cereal Grain and their Products (C.M. Christensen, ed) American Association of Cereal Chemists St Paul Minnesota USA. pp 170

Renard, H.A. in Conservation et Stockage des Grains et Graines et Produits Derives, (J.L. Multon, ed), Technique et Documentation Lavoisier, Paris, France, 1982, p 1044-1082.

Sutherland, J.W., Banks, P.J. and Griffiths, H.J., (1971). Equilibrium heat and moisture transfer in air flow through grain. J. Agric Engng. Res. 16, 368-386.

Wan Haibin and Desmarchelier, J.M., (unpublished data.)

Wilson, S.G. (1986). Simulation of thermal and moisture boundary-layers during aeration of cereal grain. Mathematics and computers in Simulation 30, 181-8.

UN REGARD NOUVEAU SUR LA VENTILATION

J.M. DESMARCHELIER

SCIRO, Division of Entomology
P.O. 1700. ACT 2610, Australia

RESUME

Les méthodes de ventilation classiques visant à obtenir des températures définies ne sont pas appropriées aux climats dont le degré hygrométrique varie à la réception, ce qui est le cas des climats chauds "désertiques".

La ventilation ne refroidit pas le grain à la température de l'arrivée de l'air mais abaisse plutôt le point de rosée au niveau de la température de l'arrivée de l'air. Ainsi, plus le grain est froid, plus il devient humide. La température humide obtenue par ventilation constitue un meilleur critère de stockabilité que la température sèche car elle intègre à la fois la température et le degré hygrométrique.

Dans le cas où le degré hygrométrique varie, les méthodes de ventilation devraient prendre en compte la température humide. Elle devraient aussi mettre l'accent sur le régime de température humide et non sur le résultat final.

Au-dessus de certaines températures "seuil", réduire davantage les températures humides ne sert pas à grand chose. Si les températures sont pondérées de façon à refléter ces seuils, la méthode optimale de ventilation doit tendre à minimiser le régime de température humide pondérée.