HGCA

RESEARCH REVIEW No. 38

BULK STORAGE DRYING OF GRAIN AND OILSEEDS

SEPTEMBER 1998

Price £7.00

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by

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This is the report of a study funded by HGCA, which started in April 1997 and lasted for one year. The work was funded by a grant of £16,028 (HGCA project no. TT13/1/96).

CONTENTS

Summary

This document reviews the technical background to the drying of grain in bulk stores with air at near-ambient temperatures. It covers the ground necessary to inform and guide store operators.

Bulk storage drying of grain is an economic technique because it makes use of 'free' solar heat available in ambient air. However, to access this energy effectively without compromising grain quality requires a standard of management attainable only by those who understand the basics of the process. These basics relate firstly to relevant properties of the grain in its interaction with air and secondly the influence of weather on the quality and drying potential of the air.

The most obviously important property of the grain is its moisture content. An explanation of the 'wet-basis' convention used in the grain trade also shows why the loss of mass is always more than the moisture removal indicates. Grain exposed to air gains or loses moisture depending upon whether the equilibrium water vapour pressure of the grain is above or below that of the ventilating air. This 'equilibrium moisture content' is strongly dependent upon air relative humidity but is also affected by temperature. The relationship is also dependent upon crop type. Information on these variations is given.

Moulds growing on grain are also sensitive to the relative humidity and temperature of the ambient environment. A particularly important level of relative humidity is that (about 65 %) below which moulds cease significant growth. Through the 'equilibrium moisture content' relationships, this humidity can be mapped to safe storage moisture contents specific to crop types. The rate at which grain will deteriorate is also related to the condition of the environment but is not easily quantified in the very variable environment experienced by grain when ventilated with ambient air. The derivation of a storage index, from 'steady-state' safe storage lives, is explained.

The other property of grain of particular importance to drying and storage is its resistance to the flow of air. This resistance is fundamental in determining the size of fan required to ventilate a given depth of crop to achieve drying at a rate that balances power consumption against loss of grain quality. The interaction of these factors, including the constraints imposed by main and lateral ducts, is explored by worked example.

Historical weather data are used to illustrate the general level and range of variation in temperature and relative humidity to be expected within the harvest period. It is shown that in most years the relative humidity will be too high for effective drying for a large proportion of the time, particularly over night. It is necessary therefore to control the air supply in some way. The simplest strategy is to ventilate intermittently in response to relative humidity changes. However, it is more common to employ some form of air conditioning. Heating using humidity-modulated gas or diesel fired units are the cheapest option. Dehumidification by heat pump is an attractive technical option with a low running cost. However, the advantages have to be balanced against a higher capital cost.

For a bulk storage dryer the control of the air conditioning and ventilation is more difficult than it is for a heated-air dryer. Contemporary control systems use semi-automatic control in which the air is modulated automatically by humidistat but in which adjustment of the set point with the progress of drying has to be done manually. Fully-automatic control requires automatic feedback on the progress of drying within the grain bed. Current research has shown that such feedback can be obtained by using a mathematical model of drying to infer moisture changes from temperature changes. The research has also suggested a different approach to the adjustment of the set points.

I. What is bulk storage drying?

Bulk storage drying of grain is carried out in static bulks, usually in the place where it will be stored, by the through flow of air at or near ambient temperatures. 'Near' is conventionally taken to mean no more than 5°C above ambient; because of this the method is often termed 'near-ambient' drying. It is a slow process measured in days and in extreme cases weeks (see Table 1 on the next page).

The temperature rise of 5°C is a maximum value and will not often be necessary. A rise of between 0.5 and 2°C will result from the work done by the fan in forcing the air through the grain. Usually any additional heat is supplied by some form of simple heater situated at the intake of the fan. The purpose of the heat is to increase the drying power of the air by reducing its relative humidity. This reduction may also be accomplished by the use of a heat pump dehumidifier, in which case water is condensed from the incoming air and the necessary temperature rise is less.

Recently there has been a great deal of interest in stirring the grain during the drying process. This is claimed to give faster and more uniform drying and to allow the use of higher temperatures. The method is discussed in greater detail in Chapter V.

Bulk storage drying was practised by the Romans. However, in modern times, the method was developed in, and after, the final years of the Second World War as the introduction of combine-harvesters created the need for drying threshed grain on an unprecedented scale. Early bulk storage drying was carried out in grain silos or bins. This practice is still common in other parts of the world notably in North America but in the UK it is now more commonly implemented in 'flat' stores in which the grain may be held in beds from 2 m to 4 m deep. It may be that increasingly rigorous standards of hygiene, and maintenance of provenance, will induce a move back towards bins.

The interaction of all the variables involved in storage drying is exceedingly complex. There is an infinity of combinations of crop type, moisture content, pressure resistance and bulk density to name only the important variables relating to the crop. An even greater problem is posed by the unpredictability of the weather. No two years, months, days or hours are alike and to specify a storage system that would work in all possible conditions, and be economic, is probably unrealistic. As yet storage drying has to be a technique for those parts of the country where grain can reasonably be harvested at 20% or less and within the months of August and September. (In fact there has to been a trend to increase combine capacity and most operators probably aim to harvest at less than 20%.) Even then it may be necessary to have contingency planning for years in which the harvest is either very wet or very late, or where the seasonal deterioration is premature. Such contingency planning may be to remove one or two percentage points of very wet grain either using a small heated-air dryer or resorting to contract drying.

Although it was developed empirically, the method has proved to be extremely difficult to understand by experiment alone. It was just not possible to examine all the variables within a seasonal time scale, always with unique inputs of weather and grain moisture content. In the last thirty years, computer-based mathematical modelling has added greatly to our understanding of the process.

Table 1. Bulk storage drying versus batch or continuous-flow heated air dryers.

	Bulk storage drying	**Heated-air drying**
Speed of drying	Slow; days and weeks	Fast; hours
Specific energy consumption, kWh per kilogram water evaporated	0.3 to 19	1 to 3
Energy consumption, kWh per tonne dried grain assuming drying from 20 to 15%	19 to 1200	57 to 178
Heat damage	Unlikely	Main threat to quality
Spoilage by mould	Main threat to quality	Unlikely
Grain handling	Relatively simple. Front – end loaders cope with variable rates of harvest .	Conveyors, elevators and buffer storage necessary
Operation	Requires operator understanding	Follow manufacturers instructions
Capacity	Dependent upon initial moisture content of grain; sensitive to weather	High grain moistures can be coped with; insensitive to weather

II. Properties of grain

Grain moisture content

Wet or dry basis?

In agriculture, moisture contents are normally quoted on a percentage wet basis, i.e. a moisture content of 20 % w.b. means that 20% of the total mass is water and 80% is dry matter. For engineering calculations it is necessary to express the moisture content on a dry basis, i.e. the mass of water as a percentage of the mass of dry matter. Thus 20% becomes 20/80 = 25% d.b. The relationships between wet and dry basis are presented more formally in Appendix 3. Also included in Appendix 3 are useful formulae for calculating the quantities of water removed when drying over different moisture ranges.

Mass of moisture removed

Table 2. The mass of water removed in drying grain is always greater than that indicated by 'percent moisture removal'.

Calculated for drying to 15% e.g. wheat, barley or oats

Initial moisture content, % w.b.	16	18	20	22	24
Moisture removed, % w.b.	1	3	5	7	9
Constant initial mass					
Initial mass of grain, t	100	100	100	100	100
Mass of water removed, t	1.2	3.5	5.9	8.2	10.6
Constant final mass of 100 tonnes					
Initial mass of grain, t	101.2	103.7	106.3	109.0	111.9
Mass of water removed, t	1.2	3.7	6.3	9.0	11.9

Calculated for drying to 8% e.g. oilseed rape

Initial moisture content, % w.b.	9	11	13	15	17
Moisture removed, % w.b.	1	3	5	7	9
Constant initial mass					
Initial mass of grain, t	100	100	100	100	100
Mass of water removed, t	1.1	3.3	5.4	7.6	9.8
Constant final mass of 100 tonnes					
Initial mass of grain, t	101.1	103.4	105.8	108.2	110.8
Mass of water removed, t	1.1	3.4	5.8	8.2	10.8

Equilibrium moisture content

The equilibrium moisture content of the grain is the moisture content at which it is in equilibrium with the 'moisture content' or relative humidity of the surrounding air. It is an extremely important quantity for two reasons.

- It is this balance between the air and the grain, which determines whether the grain wets or dries and to a certain extent how quickly this happens.
- It is fundamental to the determination of 'safe' moisture contents for storage.

Given that, for micro-organisms, grain kernels represent a nutrient supply in excess, then what really triggers and to some extent controls the level of biological activity particularly as expressed by microbial activity, is relative humidity. In broad terms, bacteria and moulds do not grow well at relative humidities less than 85% and 65% respectively. Thus grains stored at moisture contents below those representing equilibrium with air at 65% r.h. are unlikely to deteriorate significantly. At 15°C and 65% r.h. the equilibrium moisture content of most cereal grains is in the order of 14% w.b. Hence a value close to this is usually set as the required target moisture content for drying.

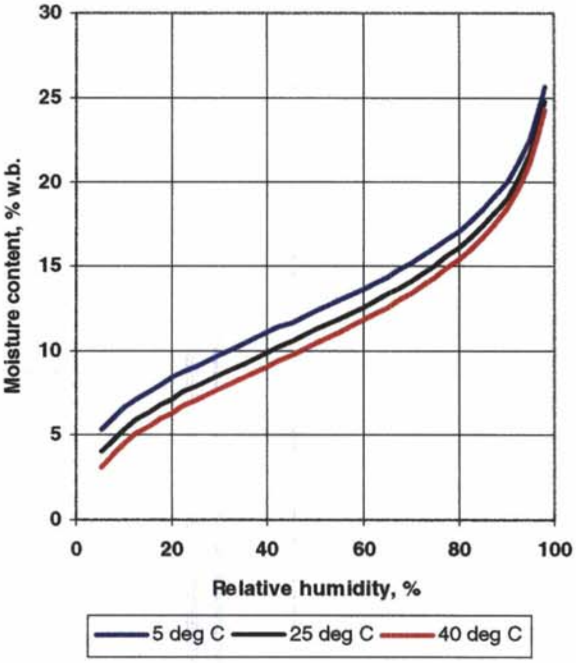

Figure 1. Equilibrium moisture curves for wheat illustrating the effect of temperature in reducing the equilibrium moisture content at a given relative humidity. (Sun & Woods, 1994a & b)

The equilibrium relationship between the moisture content and relative humidity is usually plotted as one or more S-shaped curves (Figure 1). If a single curve is plotted, this will usually be for the single temperature of 25°C. More than one curve may be plotted either to illustrate the small but important variation with temperature or to show how the relationship is affected by whether the equilibrium is reached by drying (desorption) or wetting (sorption). This small discrepancy between the two curves is termed hysteresis. It means that if grain, which has been dried, is exposed to the air with which it was initially in equilibrium it rewets to a lower moisture content than originally. This effect is quite important in ensuring that once grain is dried, and in store, it does not rapidly return to higher moisture levels.

The temperature effect is important for two reasons. Firstly, it may mean than in controlling a bulk storage dryer either the target moisture content or the target relative humidity may need modifying. Secondly, the target moisture content needs to be set at a level which will be safe for all the conditions to which the stored grain be exposed. For example, grain dried in a northern temperate climate to be safe for storage at say 14% m.c.w.b. and an average temperature of say 10°C will generate a safe relative humidity of 65%; ship that same grain to West Africa and allow the bulk temperature to rise to 25°C and the interstitial humidity will increase to 70%. This is approaching the level at which biological activity could begin to increase.

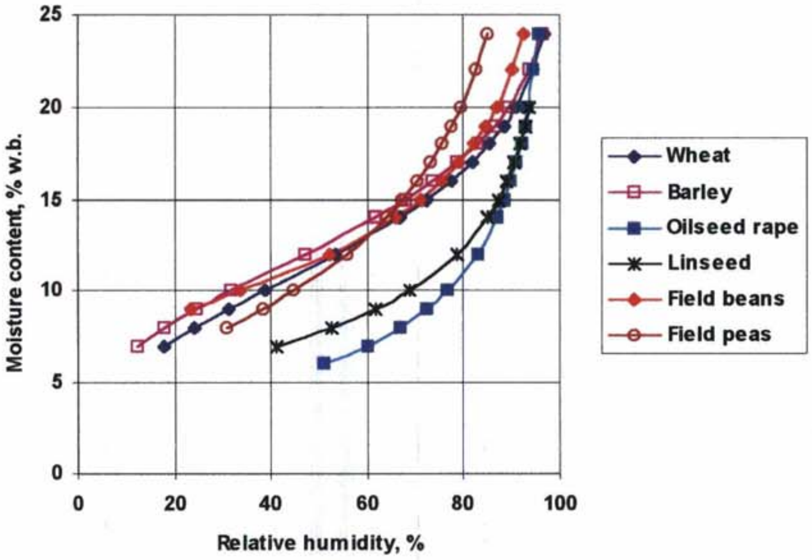

Figure 2. Comparison of data for several seeds to show the lowering of the equilibrium moisture contents of oilseed rape and linseed as a consequence of their high oil content. Data for wheat and barley calculated from Chung-Pfost equations derived by Sun & Woods (1994a & b), for oilseed rape from Modified-Halsey equation with coefficients derived by Nellist & Bruce (1992), and for linseed, beans and peas by interpolation of the data of Sijbring (1963)

Table 3. Equilibrium moisture contents, % w.b., for some common crops as a function of moisture content and at 15°C. Data for wheat and barley calculated from Chung-Pfost equations derived by Sun & Woods (1994a & b), for oilseed rape from Modified-Halsey equation with coefficients derived by Nellist & Bruce (1992), for linseed, beans and peas by interpolation of the data of Sijbring (1963).

Relative humidity, %	**Crop**					
	Wheat	**Barley**	**Oilseed Rape**	**Linseed**	**Field Beans**	**Field Peas**
30	8.8	9.8	4.3	6.1	9.6	7.9
40	10.2	11.1	5.1	6.9	10.6	9.3
50	11.5	12.4	5.9	7.8	11.7	10.9
60	12.9	13.8	7.0	8.8	13.0	13.0
65	13.7	14.5	7.7	9.5	13.8	14.3
70	14.6	15.3	8.5	10.2	14.7	15.9
75	15.5	16.2	9.6	11.2	15.8	17.8
80	16.6	17.3	11.0	12.4	17.2	20.4
85	17.9	18.6	13.0	14.0	19.1	24.0
90	19.6	20.3	16.1	16.6	21.9	29.5
95	22.3	22.9	22.8	21.7	27.2	40.0
98	25.6	26.1	33.9	29.7	35.1	55.1

Because of the presence of the oil, the equilibrium moisture contents of seeds like rape and linseed are several percent lower than are those for cereals. It follows that safe moisture contents are also several percent lower (Figure 2, Table 3). It is interesting to note that, if the moisture contents of such seed are expressed on an oil-free basis, the equilibrium moisture contents are very similar to those of cereals i.e. it is the carbohydrate material in the kernels which is involved in the desorption and sorption of water.

Safe storage time

For wet grain at near-ambient temperatures, deterioration in quality is most likely to be as a result of mould growth. Unless accelerated by the action of moulds and bacteria, changes such as reduction in viability or increase in fat rancidity are more gradual. So safe storage times have been based upon the time to the appearance of 'visible mould' assessed in experiments in which grains were stored at ranges of moisture contents (and hence equilibrium relative humidities) and temperatures.

In the experimental work the various storage environments were maintained constant or at steady state. Grain waiting to be, or being, dried is not at steady state. It is passing through a range of temperatures and humidities imposed either by changing ambient conditions, by its own respiration, or by the passage of the drying front. To try to account for these changes, in situations where they are either measurable or predictable, the safe storage times may be used to produce a 'storage index'.

The 'storage index' is calculated as follows. Say that for a particular combination of temperature and relative humidity the safe storage time was n days, then after n days the amount of storage time used up would be $n/n = 1$. After only $n/2$ days the amount of storage time used would be $0.5n/n = 0.5$ i.e. a 'storage index' of one-half.

In this example the temperature and humidity were assumed constant; what if they vary as in drying? The solution is to assume that it is permissible to calculate the index by adding the fractions of storage time used at each condition until this reaches unity and the safe storage time is then considered complete. Although clearly a rather crude measure, calculating the 'storage index' is somewhat better than just applying the steady-state values to average conditions and is used world-wide in research into bulk storage drying. The values for wheat given in Table 4 are derived from Canadian research, which in turn built upon earlier Dutch data. Similar data for oilseed rape are given in Table 5. (See Appendix 5 for more useful charts).

As our knowledge of respiration, and the growth of moulds, improves it will be possible to replace the storage index by criteria, which will both identify specific areas of deterioration within a bulk and provide a better quantification of the deterioration. The computer simulation of bulk storage drying developed at Silsoe Research Institute already contains a procedure for estimating the respiration rate and hence any contribution made to drying by the heat and moisture produced particularly during periods when the ventilating fans may be switched off. Any loss of dry matter is also estimated.

Table 4. Approximate safe storage times for wheat based on the time to the appearance of visible mould given by the Frazer & Muir (1981) equations (see Appendix 5). The table is designed to show the importance of reducing both grain moisture content and temperature.

Temperature, °C	Moisture content, % w.b.				
	14	16	18	20	22
5	3 years	1 year	5 months	2 months	6 weeks
10	1.5 years	7 months	3 months	5 weeks	3 weeks
15	11 months	4 months	6 weeks	3 weeks	2 weeks
20	5 months	2 months	3 weeks	2 weeks	6 days
25	3 months	5 weeks	2 weeks	5 days	3 days

Table 5. Approximate safe storage times for oilseed rape based on the equations of Muir & Sinha (1986) correlating the data of Kreyger (1972) (see Appendix 5). The table is designed to show the importance of reducing both grain moisture content and temperature

Temperature, °C	Moisture content, % w.b.					
	8	10	12	14	16	18
5	8 years	2 years	11 months	4 months	6 weeks	2 weeks
10	4 year	1year	5 months	2 months	3 weeks	1 week
15	1 year	5 months	2 months	3 weeks	1 week	4 days
20	9 months	2 months	4 weeks	2 weeks	5 days	2 days
25	4 months	4 weeks	2 weeks	1 week	3 days	1 day

Pressure resistance to airflow

Static pressure is the pressure of air possessed by virtue of compressive forces and which is exerted in all directions.
Superficial velocity is the velocity with which the air meets the surface through which it is to pass, irrespective of the reduction in free area caused by a perforated surface or grain.
Velocity pressure is the pressure of air possessed by virtue of its motion.
Convection is the transmission of heat by means of air movement. **Natural or free convection** is caused by differences in buoyancy. **Forced convection** is caused mechanically by means of fans.

Bulk storage drying works because it is possible to force air through beds of grain up to 4 metres deep in volume flows that are sufficient to carry away the moisture before deterioration occurs. Furthermore it is possible to do this for less energy than would be necessary if that same moisture were to be evaporated by heat derived from fossil fuel. Since the fossil energy consumption in bulk storage drying mainly depends upon the work done by the fans, the resistance to airflow offered by the grain is fundamental to the economy of drying and, of course, to the sizing of the ventilation plant.

Air passes through the grain because the pressure of the air on the inlet side is greater than that on the outlet side. Since the pressures and pressure differences are small in relation to atmospheric pressure, they are measured and expressed independently of atmospheric pressure.

If the air inlet and exhaust areas of a bed of grain are equal, the air passes through in parallel flow. For a given superficial velocity, the pressure required to generate the flow increases linearly with depth. On the other hand, to increase velocity at a given depth, a disproportionate increase in pressure is required. This behaviour can be described by the equation $P_{crop} = av^nD$, where the coefficients a and n are determined by experiment. Examples of the resistance of particular grain types are given in Figure 3.

Normally the units of velocity are m/s, but in Figure 3 they are given in the longer form, i.e. $m^3s^{-1}m^{-2}$. This is to recognise that v represents the superficial face velocity into the bed and not the velocity between the grains themselves. To convert velocity to volume flow, m^3/s, we must multiply by the cross-sectional area of the grain normal to the flow. This area will usually be the area of floor occupied by the grain. Flow requirements are often specified in terms of a volume per unit of grain mass, i.e. cubic metres air per second per tonne of grain, $m^3\ s^{-1}\ t^{-1}$. To convert this to the superficial air velocity, $m^3s^{-1}m^{-2}$ or m/s, multiply by the grain depth in metres and the bulk density in tonnes per cubic metre (i.e. hectolitre mass divided by 100).

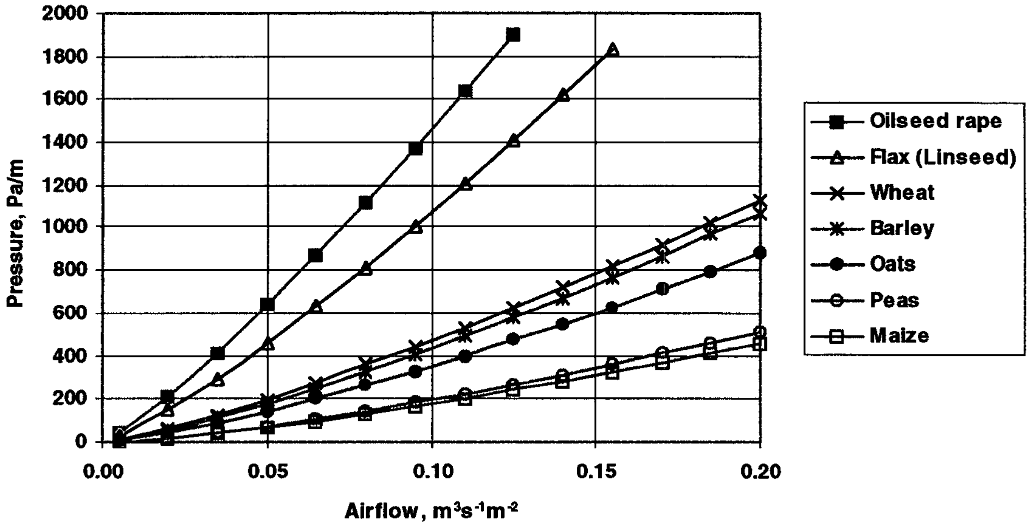

Figure 3. Pressure resistance curves for common crops (See Appendix 6 for more detail).

As can be inferred from Figure 3, the pressure resistance of seeds is very dependent upon their size. The smaller the seed, the higher the resistance to airflow. Thus, in Figure 3, oilseed rape, followed by flax (linseed), generate the highest pressures for a given airflow. These curves represent the pooled results from several data sets and there can be quite wide variations depending upon the source of the data, the degree of packing and the amount of contamination with rubbish. More information on these variations is given in Appendix 6. The worst case found was that of oilseed rape where the highest and lowest average predicted pressures differed by a factor of 5.6. Wheat and barley grains have a very similar resistance to each other and this is less than half that of flax. Oats have a slightly lower resistance than wheat or barley. Peas and maize have the lowest resistance of the crops plotted in Figure 3.

II. Properties of ambient air

Basic psychrometry

Although air is a mixture of several gases it may, for our purposes, be regarded as a mixture of air and water vapour. Typically, on a warm summer day, one kilogram of air will contain about 0.01 kilograms of water, i.e. less than one percent by mass. This may seem, and is, a very small amount. It is however critical. Air at a temperature of 25°C and containing 1% by mass (i.e. 0.01 kg/kg) of water has 50% of the mass of water vapour that it can hold. If it were to be cooled to 14°C it would contain as much water vapour as it could hold, i.e. it would be 100% saturated. Any further cooling and it would have to lose water by condensation. Hence the dews which are characteristic of periods such as those experienced in September when diurnal swings in temperature can be very large.

Also it is only when air is less than 100% saturated that it can pick-up and carry away additional water vapour and so be used as a drying agent. Thus in bulk storage drying, the relative humidity, i.e. the degree to which the air is saturated with water vapour, is arguably more important than its temperature. The relationship between air and water vapour constitutes a branch of science called psychrometry and an understanding of the relationship is fundamental to an understanding of bulk-storage drying. Appendix 8 presents some of the common terms and formulae.

The relationship is commonly represented by means of a psychrometric chart, of which Figure 4 is a simplified version. A full chart would include information on such properties as the air enthalpy and specific volume. In particular it would have lines representing the 'wet-bulb' process. This process is fundamental to an understanding of bulk storage drying, not just because of its importance as a means of measuring relative humidity, but as the basis of any calculations on the drying capacity of the air.

In Figure 4 the dry basis moisture content of the air is plotted on the left-hand axis against dry bulb temperature on the base axis. At each temperature there is a maximum amount of water that the air can contain as vapour; the line marked as having a relative humidity of 100% represents this condition. At any point along this uppermost line the air is saturated and at its saturation vapour pressure. Below the 100% line there are a series of curves marked as having relative humidities from 90 to 20%. These lines represent the ratio of the partial pressure of the water vapour in the unsaturated air to the vapour pressure at saturation.

In Figure 4 the point of intersection of the continuous red and blue lines represents air at a temperature of 20°C and 50% relative humidity and having an equivalent moisture content or absolute humidity of 0.00762 kg water/kg dry air. If that air were to be cooled then its state would move left along the blue line and, although no moisture is being added, its relative humidity increases. When the temperature reaches 9.3°C, the blue line meets the saturation line. At this point it is not possible to cool the air further without reducing the moisture content, i.e. condensation would occur. The air has reached its dew-point temperature.

If, however, the air is not cooled in a simple manner but is passed through a damp sponge or across a water surface, it will cool by converting some of its sensible heat into latent heat of vaporisation. The temperature of the air still reduces but this time, moving left up the red line, its moisture content increases such that it reaches 100% at 13.8°C, a temperature termed the wet bulb temperature, which is higher than the dew point temperature. The difference between the dry and wet bulb temperatures is termed the 'wet bulb depression'. Although there has been a transfer of heat from air to water vapour, the total heat content, or enthalpy, of the air remains about the same, i.e. the process is approximately adiabatic.

The wet bulb process is important for two reasons.

- It is the basis of the wet- and dry-bulb thermometer, which is one of the cheapest and yet accurate means of measuring relative humidity that we have particularly when the air is close to saturation.
- It provides a first approximation to what happens when air is passed through a bed of damp grain.

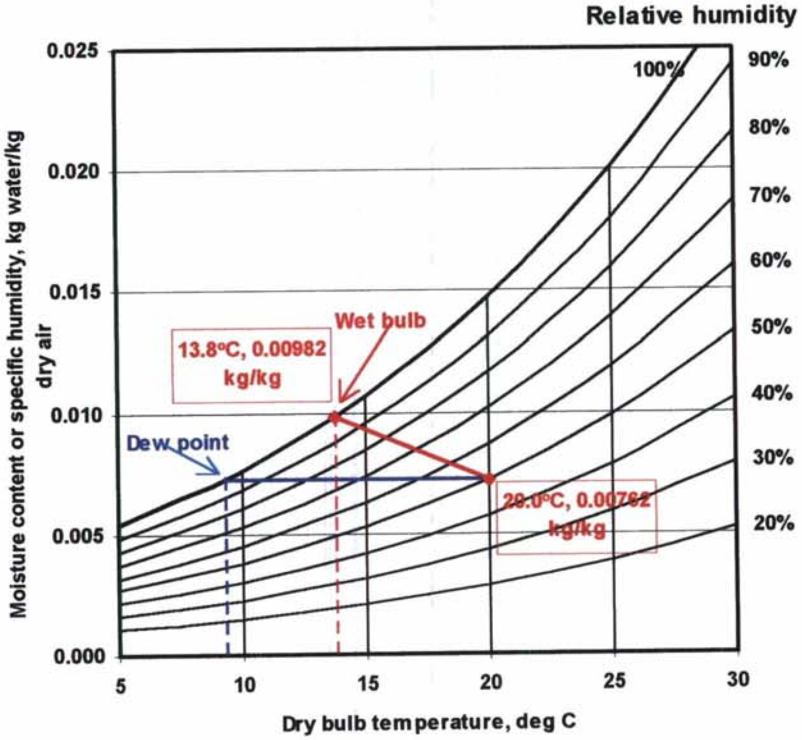

Figure 4. Simplified version of the psychrometric chart

Approximate carrying capacity of air

Whilst the temperature and humidity of air in contact with wet grain tends to follow the wet-bulb line, the process seldom continues to complete saturation. Furthermore the air will tend to lose some sensible heat to the grain and therefore deviate somewhat from the wet-bulb line. The equilibrium value reached is sometimes termed the 'pseudo wet-bulb', or 'pseudo saturation', temperature. The effect of grain moisture content on this temperature will be discussed later. For the present purpose it means that even in passing through wet grain, one kilogram of air will not remove as much moisture as indicated by the wet-bulb relationship. It has been found that, for approximate calculations, it is better to assume that the air will follow the wet bulb line but that it will not exhaust at a relative humidity greater than 94%.

Table 6. Comparative drying capacity of ambient air, before and after heating by 5°C. Based upon pick-up along the wet bulb line until 94% saturation.

Ambient relative humidity, %	**Ambient air temperature, °C**	**Volume of air per unit mass water, m^3/kg**		**Volume to remove ½% m.c.w.b. in 24 hours from grain initially at 20% m.c.w.b., m^3 s^{-1} $tonne^{-1}$**	
		Ambient air	**Ambient + 5°C**	**Ambient air**	**Ambient + 5°C**
60%	**5**	799	404	0.057	0.029
	10	657	339	0.047	0.024
	15	555	292	0.040	0.021
	20	481	256	0.035	0.018
70%	**5**	1129	473	0.081	0.034
	10	929	400	0.067	0.029
	15	785	347	0.056	0.025
	20	680	306	0.049	0.022
80%	**5**	1932	568	0.139	0.041
	10	1591	485	0.114	0.035
	15	1346	424	0.097	0.030
	20	1166	378	0.084	0.027
90%	**5**	6757	709	0.486	0.051
	10	5572	613	0.401	0.044
	15	4721	541	0.339	0.039
	20	4084	489	0.294	0.035

Based upon these assumptions, Table 6 presents the approximate evaporative capacity of ambient air calculated for ambient temperatures from 5°C to 20°C and relative humidities from 60 to 90%. The third column shows that the volume of air required to remove unit mass of water increases as ambient relative humidity increases and ambient temperature falls. Also, over the ranges given, change in relative humidity has a far greater effect than change in temperature. There is a more than eight-fold increase in air requirement as relative humidity increases from 60 to 90%.

However, the relative humidity of the air is not independent of temperature. For example, if, in Figure 4, we start at the dew-point marked at 9.3°C and move to the right along the blue line, a 6°C rise in temperature would cause the relative humidity to decrease from 100% to 70%. The values in the fourth column of Table 6 show the considerable effect that heating the air by

5°C has on reducing the volume of air required to remove unit mass of water. The reduction is particularly large at 90% relative humidity because temperature rise causes a reduction to 65% and therefore decreases the air volume requirement in line with the humidity effect already seen in the Table.

The new relative humidity, which will result from a given temperature rise, can be calculated with sufficient accuracy for practical purposes from $\phi_{new} = \phi_{old}(1 - 0.06\Delta T)$, where ϕ_{new} = new relative humidity, %, ϕ_{old} = old relative humidity, %, and • T = temperature rise, °C. Conversely the required temperature rise can be calculated from $\Delta T = (\phi_{old} - \phi_{new})/(0.06\phi_{old})$

In columns five and six of Table 6 the data are presented in terms of the volumes required to remove 0.5% w.b. moisture content in 24 hours from grain initially at 20% w.b. The relevance of these figures is that, for planning purposes, it is necessary to form some idea of the size of fan necessary to supply sufficient air for drying. Over many years it has been found that a useful guide is to assume that a volume flow of 0.05 m^3/s per tonne will reduce the moisture content of grain, initially at 20% m.c.w.b., by 0.5 percentage points in 24 hours.

Whilst the average drying capacity of ambient air may be in the order of 0.05 m^3/s per tonne of grain, this will be the case only if the average relative humidity stays within the range 45 to 73% for temperatures from 0 to 30°C (Table 7). To ensure that this can be achieved, most bulk storage drying systems include some means of modifying the air relative humidity.

Table 7. Combinations of temperature and relative humidity at which an airflow of 0.05 m^3/s per tonne of wet grain at 20% m.c.w.b. would remove 0.5% m.c.w.b. in 24 hours assuming moisture pick-up along the wet bulb line to 94% rh.

Temperature, °C	0	5	10	15	20	25	30
Relative humidity, %	44.5	55.8	62.0	66.3	70.2	71.8	73.3

The commonest of these methods is air heating. For practical purposes it can be assumed that one kW of heat will raise the temperature of 0.83 m^3/s of air by one degree Celsius. Thus for a rise of 5°C a flow of 0.05 m^3/s per tonne implies an equivalent heater size of 0.3 kW per tonne of grain dried. In comparison if the dryer fan is operating against a pressure of 100 mm WG (1000Pa) and has an efficiency of 50%, then the power required to pump the air will be 0.1 kW/tonne. Table 6 shows that, even at relative humidities as high as 90%, a rise of 5°C is adequate to produce the desired improvement. Rises greater than 5°C should not be necessary and may increase the risk of grain spoilage (Chapter III).

Weather

Weather varies from year to year, from month to month, from day to day and hour to hour and, in spite of improved forecasting, these variations are extremely difficult to predict. If a bulk storage dryer is to be managed such that maximum advantage is taken of the free solar energy without compromising grain quality, then some knowledge of typical weather patterns is necessary. The following data illustrate the sort of air conditions that are likely to occur during the normal drying season.

Beginning with the general level of ambient temperature, it is probably significant to the relative popularity of the method in the British Isles that, on the whole, our summers are rather cool. Even the fact that levels of relative humidity tend to be higher than on mainland Europe may be turned to advantage in minimising the overdrying of deep beds.

A study (reported by Nellist, 1988) to find the effect of air temperature and relative humidity on the continuous airflow necessary to dry a 2.5 m bed wheat from 20 to 15% w.b., confirmed that the average specific airflow of 0.05 m^3 s^{-1} t^{-1} was a reasonable working value at temperatures in the range 15 to 18°C. At lower temperatures, slightly more air was needed to maintain the drying rate and finish drying within the target time. However, the grain was not at risk of mould whereas, as temperatures rose above 18°C, the increasing risk of spoilage required significant increases in specific airflow.

In the light of these results, an analysis of data on mean daily temperatures and relative humidities recorded at Ringway, Manchester, for the three months July, August and September over the twenty-year period 1951-1970, provides some interesting conclusions.

- Taken over the whole twenty years and all three months, the average daily ambient temperature and humidity were 14.6°C and 78% respectively, i.e. about where we would expect to fit in with the baseline specific airflow. These values are also close to those taken to be the standard ambient conditions in grain dryer testing (a temperature of 15°C and relative humidity of 80%). Of course there was considerable variation in the daily means and the total spread was from 6 to 24°C. However, a mean of 18°C, the temperature above which biological activity begins to accelerate, was exceeded on only 8% of the days.

- Similarly, the relative humidity ranged from 47 to 96%; in this case the mean daily relative humidity exceeded 65% on 94.5% of the days. Thus the overall danger of overdrying does not seem high and for successful drying either fan control or some heating, even if only that provided by the fan work, would have been required on most days.

- Over the three months, the mean daily temperature fell in the order of 4°C to 5°C.

- Maximum daily temperatures fall more steeply than daily means, i.e. very warm days tended to be confined to July and early August. This underlines the importance of drying earlier rather than later. Delays in harvest which push the drying back into late September and October can seriously affect drying rates. Again near-ambient drying is not a technique for late and wet harvest areas.

Daily mean temperatures give some indication of general levels but do not provide much information on the diurnal variations, which are crucial to the control strategy for a dryer. For this we need hourly data. Figures 5 and 6 compare hourly data recorded over the period 15 to 31 August in a cool year and location (Waddington, Lincolnshire in 1963) and in a warm year and location (Heathrow, Middlesex in 1957). Both figures show that the daily variations in temperature tend to be mirrored by opposite changes in relative humidity. On some days changes in relative humidity reflect changes in temperature quite closely but overall the correlation is weak (Figure 7).

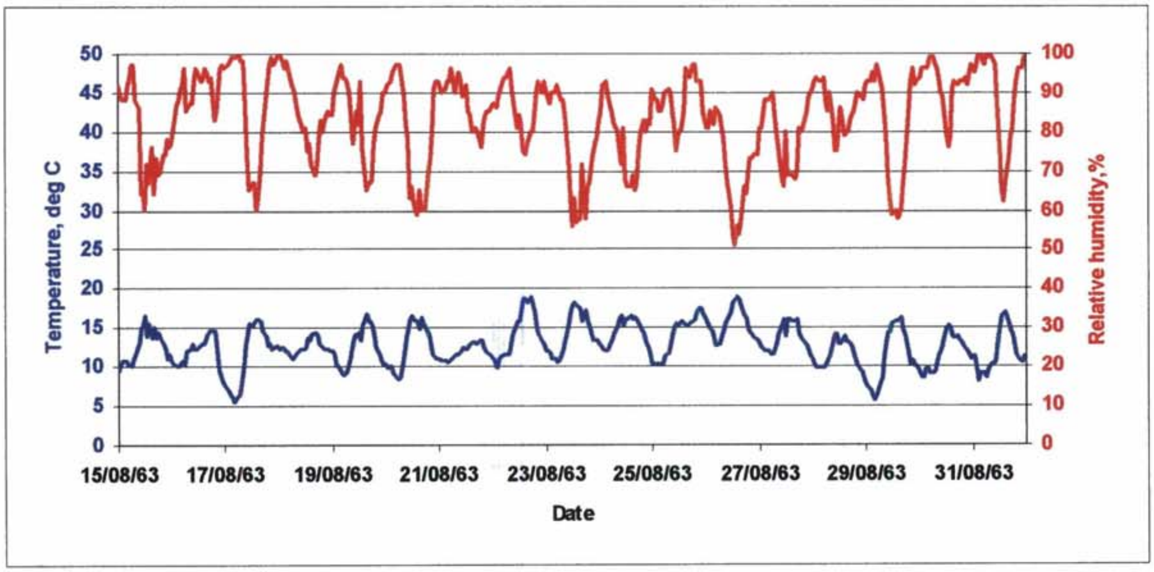

Figure 5. Variation in hourly ambient temperature and relative humidity over the period 15 to 31 August at Waddington, Lincolnshire in 1963.

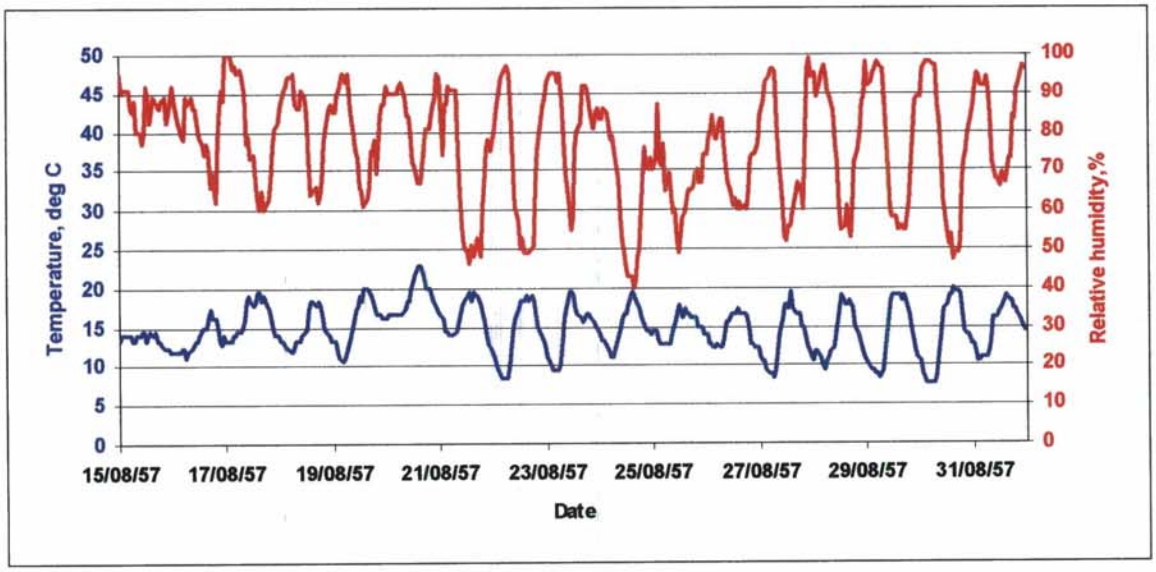

Figure 6. Variation in hourly ambient temperature and relative humidity over the period 15 to 31 August at Heathrow, Middlesex in 1957.

The difference between the two seasons is reflected in the statistics of Table 8: -

- As a measure of drying potential of the two seasons, the mean hourly vapour pressure deficit at Waddington was not much more than half that at Heathrow.
- At Waddington the mean hourly temperature was 12.8°C but oscillated between 5.5 and 18.8°C. Temperatures in excess of 18°C occurred for no more than 2.2% of the total time.

At Heathrow the mean was greater, 14.8°C and the range 7.8 to 22.8°C led to 18°C being exceeded for 18% of the total time.

- At Waddington the mean hourly relative humidity was 84% compared to 77% at Heathrow. As would be expected relative humidities of 100% were experienced at both locations but Waddington only ranged down to 51% compared to 40% at Heathrow. At Waddington and Heathrow respectively, the relative humidity exceeded 65% for 91 and 75% of the total time. Similarly relative humidities in excess of 95% were experienced on 7 and 15% of occasions.

- Although in practice these relative humidities would be reduced by the effect of heat from the fan, they still imply that some form of control of the ventilating air would be desirable.

Table 8. Statistics derived from hourly weather data for three months recorded at Waddington, Lincolnshire in 1963 and at Heathrow, Middlesex in 1957 over the period 15 to 31 August.

Property	Waddington, 1963	Heathrow, 1957
Mean hourly vapour pressure deficit, kPa	0.268	0.428
Mean hourly temperature, °C	12.8	14.8
Range in temperatures, °C	5.5 – 18.8	7.8 – 22.8
Proportion of time exceeding 18 °C	2.2%	18%
Mean hourly relative humidity, %	84	77
Range in relative humidities, %	51 – 100	40 – 100
Proportion of hours exceeding 65% r.h.	90.7%	75.2%
Proportion of hours exceeding 95%	14.5%	6.6%

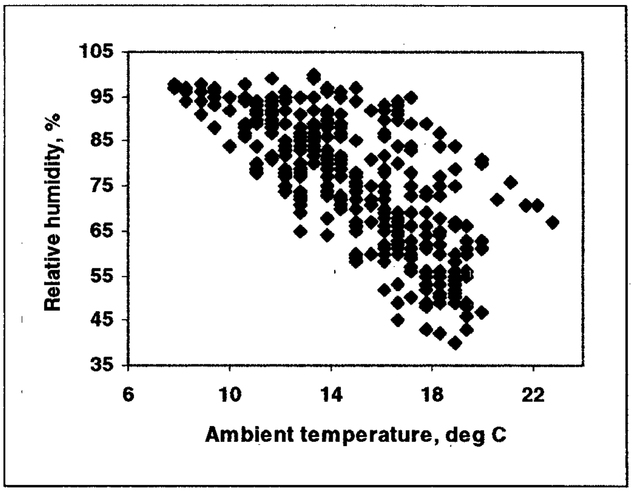

Figure 7. The correlation between hourly ambient temperatures and relative humidities is not strong. Hourly pairs of relative humidity and temperature recorded at Heathrow, Middlesex, over the period 15 to 31 August 1957.

If a deep bed is to dry as quickly as a shallow bed exposed to air of the same quality, then the depth and speed of movement of the drying zone must be increased proportionately. This requirement is conveniently expressed by specifying airflow requirements in terms of the volumes of air per unit mass of grain, the specific airflow. However, although it is possible to design a dryer to have a specific airflow for a certain grain at a certain floor depth, it is not easy to adjust flow to achieve other conditions for say other crops or other moisture levels. Although greater flexibility is often provided by the use of two or more fans and, in the future, may include fan speed control, the main means of adjusting for conditions is to alter bed depth.

Achieving the required airflow

The volume of air delivered by a fan through bed of grain depends upon the balance of the variation on fan pressure with volume (the fan characteristic curve) with the resistance of the crop and ducting system (Figure 9).

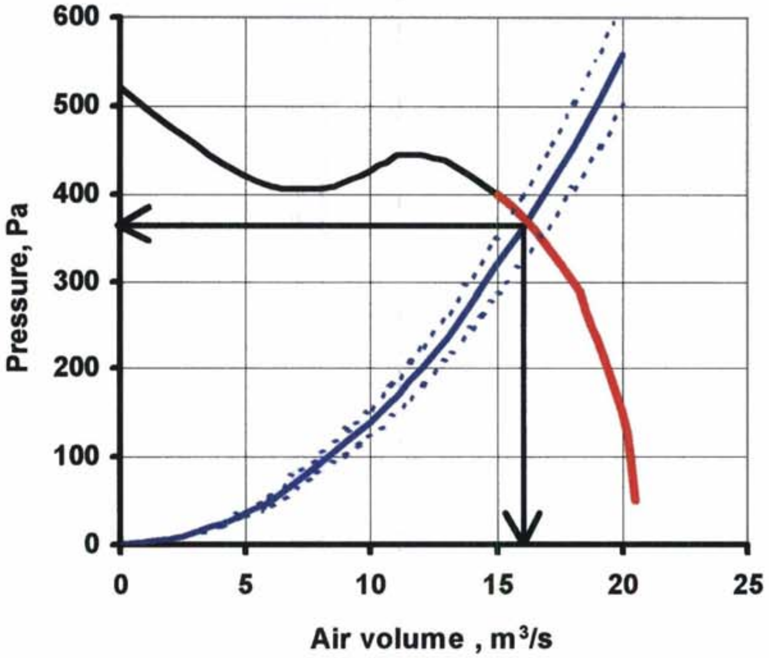

Figure 9. The air volume and pressure delivered by a fan is given by the intersection of the fan and system characteristics. The complete fan characteristic is represented by the black line but is overlaid by a red line to show the useful operating range. The blue line represents the system resistance and intersects the fan characteristic at a pressure and volume of 380 Pa and 16 m^3*/s respectively. The dotted lines represent variations in system characteristic. Such variations may be caused by a number of factors, but principally by variations in seed type and depth in established plant.*

III. Drying in deep beds

The 'drying zone'

The initial consequence of ventilating a deep bed of moist grain is for the temperature within the whole bed to reduce (or occasionally to rise) to the 'pseudo wet-bulb' temperature at which the air and grain are in vapour pressure equilibrium. As ventilation continues, grain nearest to the air inlet begins to dry. As its moisture content falls, its temperature begins to rise until it will reach that of the incoming air. At that point, grain moisture will be in equilibrium with the incoming air. As the grain dries it releases moisture more slowly so that air passing through the bed has the capacity to evaporate additional moisture from the grain that is further along the air path. Thus there becomes established a 'drying zone', across which the moisture content of the grain reduces from wet to dry. At the same time the temperature increases from the pseudo wet-bulb near the grain surface to the inlet air temperature at its base. Figure 8 shows typical changes in temperature and moisture with depth and time in a bed ventilated with air at a constant flow, temperature and relative humidity.

While the drying zone remains within the bed, the air exhausting from it will carry away as much moisture as it can reasonably do. As the leading edge of the drying zone passes through the surface, the humidity of the exhausting air will fall and with it the overall rate of drying. Thus, for economy, it is vital to retain the drying zone within the bed for as large a proportion of the total drying time as possible. However, taken to its logical conclusion, this would mean that when the required average moisture content is reached, the grain at the bottom, and top, of the bed would be dry and wet respectively. This may have two consequences. Firstly, the grain at the bottom will be overdried and secondly, the grain at the top will still be at risk of moulding. Thus in practice it is necessary to try to choose ventilation strategies which ensure that the wettest layers are reduced to a safe level without excessive overdrying of the driest.

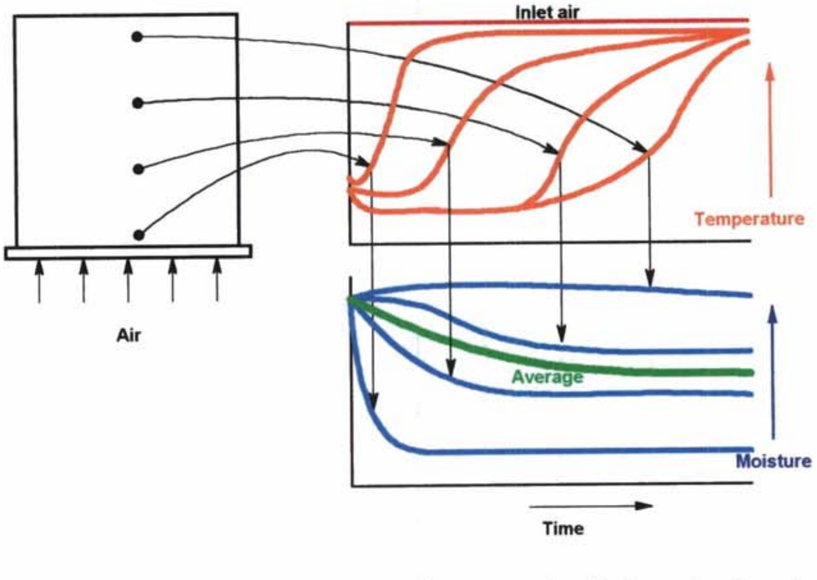

Figure 8. Temperature and moisture changes with time in the drying of a deep bed.

The following example considers the balancing of a single proprietary fan against the combined resistance of a duct system and crop. The pressure generated by the fan can be expressed as a quadratic function of the volume flow

$$P_{fan} = c - dQ - fQ^2$$

where P_{fan} = fan static pressure, Pa, Q = the total flow, m^3/s and c, d and f are coefficients derived from manufacturers data of fan performance. The combined resistance of duct, floor and crop (Chapter II) can be expressed by

$$P_{sys} = av^nD + bv^2$$

where P_{sys} = system pressure, Pa, v = velocity across the dryer floor, m^3 s^{-1} m^2, a = coefficient of resistance across the crop, Pa s^n m$^{-(n+1)}$, n = exponent of velocity, D = depth of bed, m, and b = coefficient of system resistance, Pa s m^{-3}. The total flow through the dryer is the product of the superficial velocity and the floor area, and the superficial velocity is the product of the specific airflow with the bed depth and bulk density, i.e. $Q = v\,A = v_{sp}\,D$ • A, where A = floor area, m^2, v_{sp} = specific airflow, m^3 s^{-1} t^{-1}, D = depth and • = crop bulk density, t/m^3. The only valid operating points are those at which $P_{fan} = P_{sys}$

At the top of its pressure range, the example fan was capable of delivering 18.6 m^3/s at 1744 Pa. However, more normally it would not be expected to operate in excess of 1500 Pa, at which it would deliver 22.6 m^3/s (Figure 10). If we assume that this chosen maximum pressure will be the operating point for a 4 m bed of wheat, then, by equating the fan and system characteristic, we find that we need to adjust the airflow to 0.08 m^3 s^{-1} m^2. This requires a corresponding floor area of 285 m^2, which in turn equates to a grain capacity of 868 tonnes (Table 9). The resulting specific airflow, 0.026 m^3 s^{-1} tonne^{-1}, is little more than half of the value, 0.05 m^3 s^{-1} tonne^{-1}, often quoted as the design requirement for a drying floor. However, for the duct and crop resistance as defined, it is not possible to achieve 0.05 m^3 s^{-1} tonne^{-1} with a pressure of 1500 Pa. Note that although the system characteristic was evaluated at a range of airflows to give the red line in Figure 10, balance would only be achieved at its intersection with the fan characteristic.

Table 9. Successive computations of the balance of fan delivery against system pressure.

	1	2	3	4	5	6
Balancing pressure, Pa	**1500**	1200	**1500**	1734	**1000**	580
Volume flow, m3/s	22.6	26.8	22.6	18.7	29.6	34.7
Crop	**Wheat**	Wheat	**Rape**	Rape	**Wheat**	Wheat
Bed depth, m	**4.00**	2.47	**1.28**	1.90	**4.00**	1.78
Specific airflow, m^3 s^{-1} t^{-1}	0.026	**0.050**	0.090	**0.05**	0.019	**0.050**
Floor area, m2	**285**	285	285	285	**513**	513
Dryer capacity, tonnes	868	537	252	373	1560	693

By reducing the bed depth to 2.47 m, a new characteristic curve (the blue line) intersects the fan characteristic at the lower pressure of 1200 Pa but higher flow of 26.8 m^3/s. The specific airflow is now 0.05 m^3 s^{-1} tonne^{-1} but the dryer capacity has been reduced to 537 tonnes.

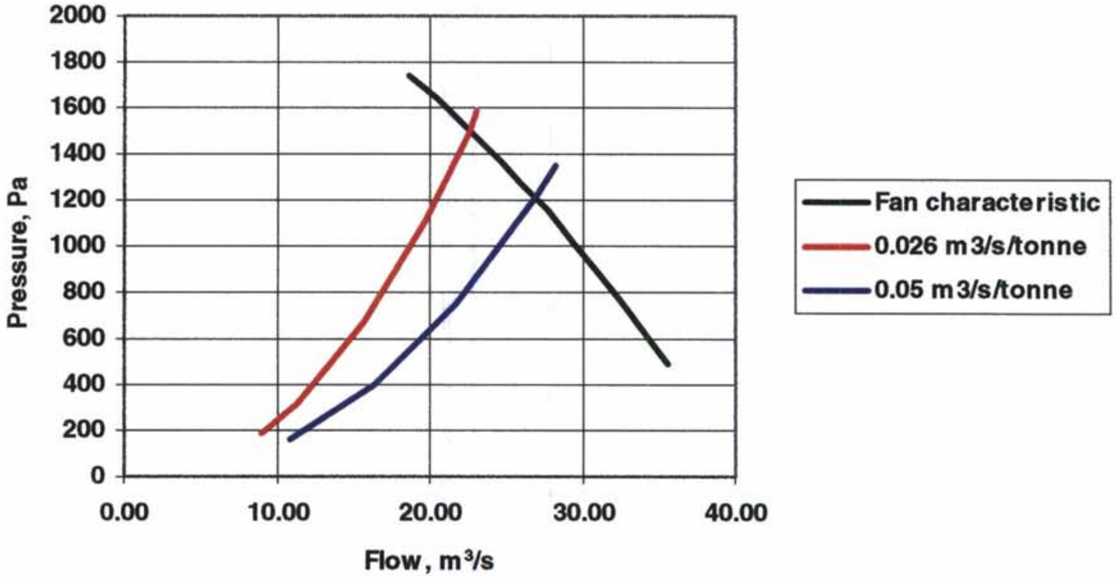

Figure 10. Balance of fan characteristic and two system curves for constant specific airflow and varying bed depth.

If the same dryer were to be used for oilseed rape, then the system curve would be changed by new values of the coefficients of pressure resistance and of bulk density. Then the chosen maximum working pressure of 1500 Pa would still equate to a volume flow of 22.6 m^3/s but would require a bed depth of only 1.28 m. The corresponding specific airflow would be increased to 0.09 $m^3 s^{-1}$ $tonne^{-1}$. The capacity of the dryer for oilseed rape would be 252 tonnes. To reduce the specific airflow to 0.05 $m^3 s^{-1}$ $tonne^{-1}$ it would be necessary to increase the depth to 1.9 m. However, this would increase the fan pressure to 1734 Pa, which is almost at the maximum for this particular fan. The fan delivery would be reduced to 18.7 m^3/s but the dryer capacity would be increased to 373 tonnes.

This example has served to demonstrate that the actual specific airflow achieved in a dryer is a complex combination of several variables, some of which are subject to considerable variation. Precise definition of the actual balance of flow will rarely be possible.

Interaction of bed depth and fan pressure with moisture content

Traditional recommendations of airflow in the order of 0.05 $m^3 s^{-1}$ $tonne^{-1}$ are based upon the assumption that the initial moisture content will be 20% and that it is necessary to remove ½ % moisture per hour. Computer studies show that ½ %/hour is unnecessarily demanding for drier grain and inadequate for wet grain. For the latter, drying rate must be increased by increasing the specific airflow. In most systems this will be by reducing bed depth.

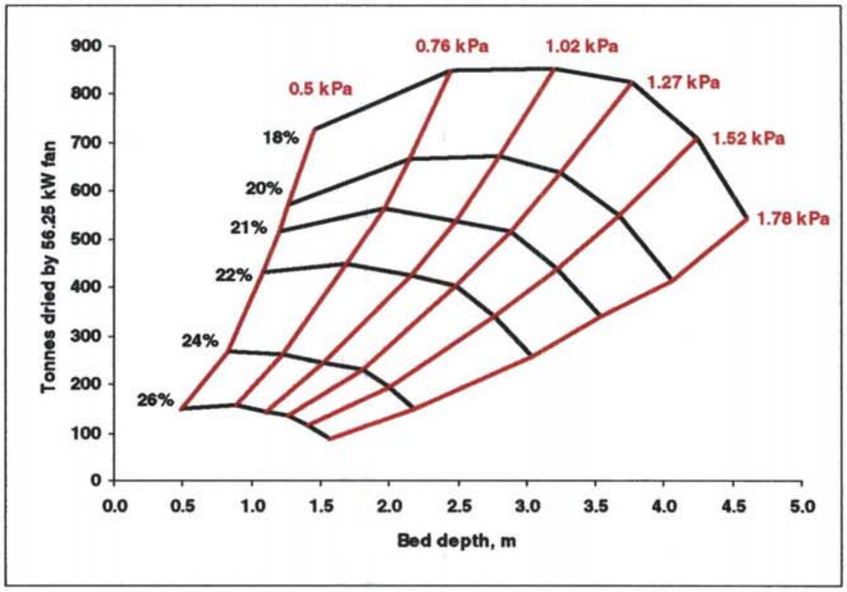

Figure 11. The quantity of grain that can be dried by a fan depends upon the interaction of the fan characteristic with the system curve. In this particular case output is maximised at pressures between 800 and 1200 Pa. Fan capacity decreases sharply with increasing moisture content

These relationships are further illustrated by Figure 11. This shows the number of tonnes of wheat a 56¼ kW fan would be capable of drying by continuous ventilation with ambient air heated by fan power only. The results are based upon computer simulation of the specific airflows required to complete drying from a range of initial moisture contents and within reasonable time and without spoilage (Nellist & Brook, 1987). Each combination of moisture content and depth was simulated twenty times using historical weather data from Waddington, Lincolnshire for the years, 1951 to 1970. The results presented are the means. The chart is designed to show the interaction of three variables, bed depth (the base axis), initial moisture content (lines of constant initial moisture content are shown in black) and fan pressure (lines of constant fan pressure are shown in red. The chart shows that:-

- The capacity of the fan is very much reduced at high moisture contents even at the highest possible pressures. Thus at 26% w.b. the capacity is less than 200 tonnes and the maximum possible depth is only just over 1.5 m. Furthermore, as bed depth increases from 0.5 to 1.5 m, the capacity of the dryer becomes less because of the reduction in total flow.
- As initial moisture content falls, the possible bed depths increase but the dryer capacity is always least at the highest pressures. However, particularly as the initial moisture content falls below 20%, the greatest capacity is given by the medium pressures i.e. there seems to be an optimum between 760 and 1000 Pa.

It can be concluded that alteration of bed depth is a necessary means of controlling airflow in a bulk storage dryer and that it is a mistake to load the fan to excessive pressures. However, the problem of reducing dryer capacity is very serious and explains why bulk storage drying tends to be confined to the drier parts of the country and is often backed up by some heated-air drying capacity.

What is static pressure regain?

Static pressure regain is the phenomenon by which the static pressure increases from the entrance to the blind end of a ventilating duct from which air is exhausting through the walls.

The **total pressure** of the air entering a ventilation duct is the sum of the **static** and **velocity** pressures and is sustained by the combined resistance to flow presented by the duct walls and the surrounding crop. However, this sideways flow results in a reduction in the total volume of air moving along the duct and, in a duct of constant cross section, the air velocity must reduce. This in turn causes a progressive reduction in velocity pressure, which, because the total pressure remains constant, has to be compensated by a progressive increase in static pressure. This is the static pressure regain. Now since the velocity of the air exhausting normal to the duct walls depends upon the static pressure, this sideways velocity also increases progressively along the duct. The consequence is that for a long duct, the grain most at risk of being under ventilated is that nearest to the duct entrance. In extreme cases the flow through the crop nearest to the main duct may not just reduce to zero but may become negative i.e. air is drawn down into the duct. It follows therefore that it is bad practice to reduce the depth of grain along a duct (Figure 12).

Static pressure regain is kept to reasonable levels by limiting maximum velocities at the entrances to ducts to less than 10 m/s. This is equivalent to a velocity pressure of 60 Pa, which is less than 4% of the maximum pressure at which the duct may be expected to operate. For very long ducts, the static pressure regain can be eliminated by tapering the duct, so that the reduction in cross-sectional area maintains a near-constant velocity along the duct. A practical alternative to tapering is to use stepped ducts.

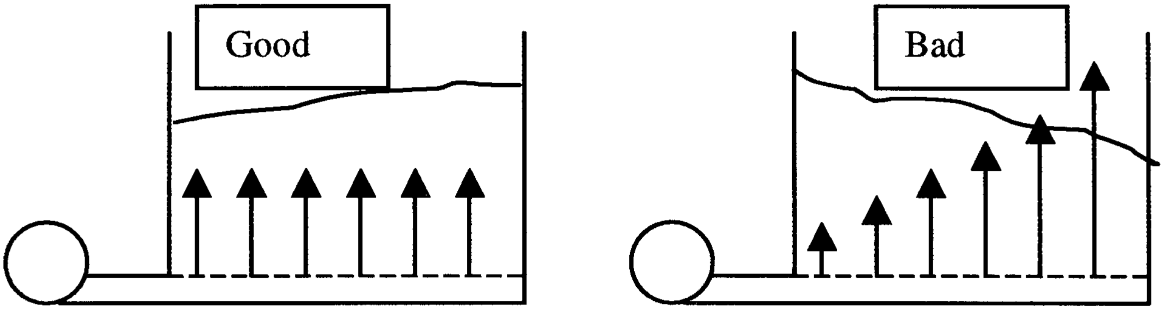

Figure 12. Static pressure regain is exacerbated by reducing grain depth along the duct length.

Note that in sucking systems, static pressure regain is more of a problem since it acts further to increase an already increasing velocity pressure so that an even greater proportion of the air is drawn in close to the duct exit. For this reason, sucking is limited to systems using large plenum chambers and short duct runs.

Effect of limiting duct velocity on duct sizing.

For a system the total flow, Q, is the product of the total floor area, the depth and density of the grain and the desired specific airflow i.e. $Q = A_{floor} D\rho\ v_{sp}$ .If the flow entering the main duct is also limited to 10 m/s, then $Q \le 10A_{duct}$, and if there are n ducts, $Q \le 10nA_{lateral}$ so that $n = A_{duct}/A_{lateral}$ and $n = (A_{floor} D\ \rho\ v_{sp})/(10A_{lateral})$. For example, if D = 4 m, ρ = 0.78 t/m^3, v_{sp} = 0.05 m^3 s^{-1} t^{-1} , $A_{lateral}$ =0.1 m^2 and A_{floor} = 285 m^2 then n = (285 x 4 x 0.78 x 0.05)/(10 x 0.1) = 44.5 say 45 laterals. If the laterals are spaced at 1 m centres then length of laterals =285/45 x1 = 6.3 m.

Equating expressions for the volume flow, $10nA_{lateral} = A_{floor} D\ \rho\ v_{sp}$. Also if the lateral ducts have length, l m and are spaced at w m centres, then $A_{floor} = w\,l\,n$ and so $A_{lateral} = w\,l\,D\ \rho\ v_{sp}/10$. Thus if we wish to have longer laterals we must either reduce the spacing, w, or increase the lateral cross-sectional area, $A_{lateral}$.

IV. Dryer control

The previous chapter has shown that the design of a conventional bulk storage dryer is very much constrained by the characteristics of crop, floor and duct resistance and by the pressures attainable by agricultural fans. Within the limits set by these characteristics, the drying rate can be controlled either by the adjusting the bed depth or by modifying the operation of fans and/or heaters.

Semi-automatic control

A number of control strategies for fans and heaters can be implemented by proprietary commercial controllers. These devices switch fans or heater or both after comparing readings of relative humidity and/or temperatures with predetermined upper, and lower, set points of relative humidity and/or temperature. The temperature option is included for use in cooling after drying. The lower relative humidity set point is usually set to a value, say 30%, which will seldom be reached but which might cause excessive overdrying if it were. At the start of drying the upper relative humidity set point will usually be set high, 100% even, and progressively reduced in line with the progress of drying. One commonly used set of rules is as follows:

Moisture content of the wettest layer	Relative humidity set point
Greater than 20% w.b.	100%
Less than 20% but greater than 18% w.b.	83%
Less than 18% but greater than 16%	72%
Less than 16%	62%

Although modern controllers can implement such schemes they can do so only in a semi-automatic way. The store operator has to be able to judge when the moisture content of the wettest layer of a large bulk has reduced to one of the switching levels and must then enter the new set-point manually. The rules can be implemented either by controlling the fans or the heaters or both.

- **Fan on-off.** The fan is switched off if the measured relative humidity rises above or falls below upper and lower set points respectively. In one study by computer simulation (Nellist & Bartlett, 1988) it was shown that, compared with continuous ventilation, this policy reduced energy consumption and increased the probability of success at conventional, or higher, flow rates but did increase drying times slightly.
- **Fan run continuously with heater control.** Depending upon the type of heater and the difference between the upper and lower set point, the relative humidity may either be simply constrained below the upper set point or controlled within a narrow band. This strategy is suitable for systems using propane gas heaters.
- **Fan on-off and heater control.** At least one proprietary controller will implement heater control during 'off-peak' electricity periods, when relative humidities are likely to be at their highest, and revert to fan on-off control during on-peak periods, when lower daytime relative humidities will minimise the switching necessary. The computer study referred to above showed that this policy was the most economic means of using electric heating and was comparable to using propane heating on- and off-peak.

Fully automatic control

Whilst experience has shown that all of these semi-automatic policies can work, they depend very much upon the judgement of the operator in timing the adjustment of the set points. This judgement has to be based on inadequate knowledge, certainly of the state of the grain and usually of the trends in ambient air conditions.

Climatic feedback

A recent development aimed at reducing this dependence on the operator has been a controller in which the set point is adjusted automatically so as to maintain an average relative humidity of 65% over the whole drying period. At the start of drying the set point is set at 65% and, provided that the air is more humid than this, the controller will switch in the air conditioning. If now the relative humidity falls below 65% and the heaters are switched off, then the accumulated average relative humidity must also fall below 65%. To counteract this, the controller changes the set-point upwards to allow wetter air to be blown, thereby increasing the accumulated average relative humidity back towards 65%. It is important to note that this strategy requires no feedback on the state of the crop and that, although the store operator has to make a judgement about the completion of drying, precise identification of the end point is only important in preventing unnecessary ventilation. This strategy was tested by computer simulation and is now available commercially. There is no reason to doubt that the strategy will work in practice.

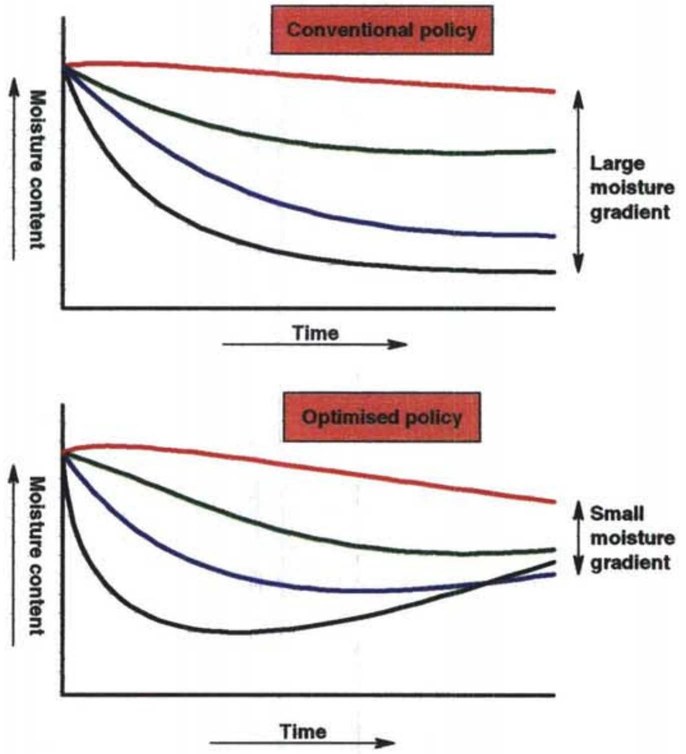

Figure 13. Compared with a conventional strategy the improved strategy attempts to reduce overdrying by rewetting the bottom layers.

Grain moisture feedback

In recent, and as yet unpublished, work at Silsoe Research Institute, a means of obtaining automatic feedback on the state of the crop has been developed. The method uses a mathematical model (Sharp, 1982, Sharp et al, 1982, Sharp, 1984, Brook, 1987, Jilek, 1994 a & b) of the drying process to infer changes in the moisture profile through the bed from changes in the temperature profile. Compared to any form of moisture sensor, temperature sensors are cheap and robust. The method was developed as a means of implementing improved control strategies. However, there is no reason why the method should not be used fully to automate existing conventional strategies such as those discussed as semi-automatic.

Improved switching strategies

In seeking to improve existing switching strategies, a computer program was developed which by repeated running of a model of grain drying was able to search for both the right size of fan and heater and the best means of operating them (Ryniecki & Nellist, 1991a). This search indicated that, instead of a progressively reducing the relative humidity upper set point, it would be better to have a progressively increasing set point (Ryniecki & Nellist, 1991b). This sequence was better mainly because of the reduction in over drying. Basically the concept is to use relatively dry air at the beginning of the drying and allow the bottom layers to overdry. As drying progresses the relative humidity set point is allowed to rise and in consequence rewet the bottom layers (Figure 13). The now drier air proceeds to the upper layers and continues to dry them. Even when the search procedure began with the conventional stepped-down set-point sequence it would reverse the order to one of step-up. As indicated in the previous paragraph the feedback on the progress of drying obtained from measurements of bed temperature is essential for the implementation of improved policies of this sort.

V. What other technologies or systems are potentially available?

Dehumidifiers

An alternative means of improving drying capacity is to use a heat pump 'dehumidifier'. In this device, cooling of a proportion of the ambient air to below dewpoint temperature removes latent heat by condensation of water. This heat is pumped across from the evaporator to the condenser and returned to the air. Mixing the resulting warm, and dry, air with additional ambient air produces air, which is not only controlled at the desired humidity, but which is at a lower temperature than it would have been if it had simply been heated.

By producing a very stable air condition, dehumidifiers greatly reduce uncertainty. Furthermore, the energy used is only about one-quarter of that used by electrical heating. Their main drawbacks are their high capital cost and, if used over enthusiastically, the possibility that overdrying costs will seriously reduce the energy savings.

Stirring

This is a relatively new technique, which maintains the porosity of the grain and will prevent the formation of a crust. By definition the drying zone is destroyed so that the exhaust air will have a lower humidity than in the unstirred case for a much longer proportion of the drying time. It would not be expected to use less fuel but it should reduce risk of spoilage and avoid overdrying. It has been proposed that stirring allows much higher air temperatures to be used but it is probable that shallower bed depths as in batch, or continuous-flow, dryers would be more economical. However, installing a stirrer within an existing store may be a cheaper way of increasing capacity than either building a store extension or installing a supplementary heated-air dryer.

VI. Measurements and equipment

Moisture measurement

Methods for the grain laboratory

Although it seems a simple concept, it is not easy precisely to define what is meant by moisture content in a biological material such as grain. This is because water is held within the grain in a whole variety of states ranging from free water through single molecular layers to water chemically bound with other constituents. For practical purposes, moisture content is taken to be the mass of water removed when the grains are dried to constant mass in specified air temperatures. Routine standard methods for commercial use have been calibrated against reference standards.

For **cereal grains, British Standard BS 4317: Part 3** is the standard routine method and is identical with the **International Standard ISO 712**. Duplicate 5 g samples of **ground** grain are dried for two hours in a ventilated oven at a temperature is 130°C. Grain which is wetter than 17% must be pre-dried prior to grinding. Although this requirement may not cause any problems in grain trading where moisture contents will generally be less than 17%, in grain drying we are often dealing with moisture contents well in excess of 17%. In these circumstances, the necessity to pre-dry is not only an extra time consuming operation but also increases the likelihood of error. Thus drying engineers tend to prefer the American standard **ASAE S352** which uses the same reference temperature, 130°C, but does not require the grain to be ground. Instead the residence times are increased to 19, 20 and 22 hours for wheat, barley and oats respectively. The differences in moisture content given by these two standards are insignificant for practical purposes (Bowden,1984).

For **oilseeds, BS EN ISO 665 : 1995** requires that 5-10 g samples are dried to constant weight at a temperature of 103°C ± 2°C. The corresponding ASAE standard for oilseed rape retains 130°C and stipulates a drying time of 4 hours.

A method for the farm kitchen. The standard methods use relatively small quantities (5-10 g) of grain and require laboratory quality ovens and analytical balances not usually available on farms. However, it is possible to obtain very good results using a kitchen balance and a domestic oven, provided the latter has reasonable control of temperature (say within ±5°C). Of course larger quantities of grain are needed and the method can no longer be regarded as a standard. One method, which can make use of a very simple balance, is to weigh out a quantity of grain equivalent to the mass of one hundred large (150mm) steel nails. At the completion of the ovening, the grain is rebalanced by the removal of nails. The number removed gives the moisture content to the nearest percentage point.

Moisture meters

The attraction of the gravimetric methods described above is that they measure the mass of water directly and require no calibration. Their disadvantage is the time taken; a minimum of two hours for ground grain and overnight for whole grain. Thus there have been many attempts to find methods of determining moisture content within a few minutes at most.

Rather than measuring moisture content directly, such rapid methods usually measure some property that is markedly affected by, and hence can be correlated with, moisture content.

Two types of instrument dominate the market for moisture meters; one measures the electrical resistance or conductivity of the grain solid and the other measures the attenuation of an oscillating current. Usually the more expensive the meter the better its accuracy but no rapid meter compares well with oven results. It remains sound advice either to use the same model of moisture meter as your merchant or at least to calibrate your instrument against his.

- In the **electrical resistance** type of meter, the grain normally has to be ground to a meal, which is then compressed to a standard pressure. It is therefore unaffected by variations in bulk density of the grain.

- The advantage of the alternative **capacitance** type is that it unnecessary to grind the grain and much larger samples can be taken. However, the results can be affected by bulk density. Thus the best meters of capacitance type employ systems that automatically compensate for changes in grain bulk density. (Some capacitance meters now have the facility to give a direct reading of the bulk density or hectolitre mass.)

Sampling. Relative to the grain bulk as a whole, the quantities of grain tested for moisture content are very small. It is therefore very important to follow accepted sampling procedures. (See, for example, Wilkin (1991)).

Measurement of relative humidity

Dewpoint measurement

The best method is to measure the dew-point temperature, i.e. the temperature at which the water vapour begins to condense on a cooling surface. The saturated vapour pressures of the air at the dew-point, and dry-bulb, temperatures are readily obtained from standard tables or formulae and the relative humidity is obtained directly from the ratio of these two quantities. This is a fundamental method which requires no calibration and for which the accuracy depends only upon the accuracy with which the temperatures can be measured. Unfortunately elaborate servo-systems are necessary for the control of temperature of the cooled surface and 'cooled-mirror' dew-point meters tend to be too expensive for farm use.

Wet and dry bulb thermometer

For accuracy, the best alternative to direct measurement of dew point is a wet and dry bulb thermometer. This instrument contains two temperature sensors located in a stream of the air being measured. One sensor is exposed directly to the air and measures its sensible temperature; the second sensor is wrapped in an absorbent wick, which is kept supplied with water from a small reservoir. In this case the stream of air passing over the wick evaporates water and in so doing cools the wick and the temperature sensor. The equilibrium temperature is known as the 'wet-bulb temperature' and is directly dependent upon the dry bulb temperature and the relative humidity of the air. A proprietary wet- and dry-bulb thermometer will normally be supplied complete with a chart, tables or formulae relating dry-bulb temperature and wet-bulb depression to relative humidity. The problem with these instruments is that they require regular inspection and servicing to replenish the water supply and the wet-bulb wick. The latter can become fouled by dust and sometimes by microbial growth.

Capacitative sensors

It is far easier but probably less accurate to use some form of sensor having an electrical output directly proportional to relative humidity. The most popular are of the 'capacitative' type in which is measured the attenuation of a high-frequency oscillating current through a small section of a hygroscopic polymer. These systems require calibration and frequent checks of the calibration and of the cleanliness of the sensor or any filter with which the sensor is protected. Most suppliers would claim that the accuracy and reliability of these sensors has improved considerably over the last few decades.

Temperature measurement

Ambient temperature (and humidity) can normally be measured in the fan housing. The sensors should be in shaded position sufficiently close to the inlet of the fan for them to be gently ventilated. It is important to have easy access for maintenance.

It is worth experimenting to find a suitable location for one or more temperature sensors in the main duct. The location should be at least two or three fan diameters downstream of the fan inlet or possibly located at the entrance to the second or third lateral.

During drying, temperatures in the grain bed can provided a good indication of the location of the drying front. Between periods of active drying or during storage, bed temperatures provide an indication of the general level of temperature and of the presence of hot spots. The presence of hot spots can be found also by a short period of ventilation; this will drive warm air to the surface.

Mercury-in-glass thermometers are useful for calibration checks and may be used satisfactorily in locations such as fan housings often as part of a wet- and dry-bulb psychrometer. However, proprietary electronic sensors incorporated into a variety of carriers such as spears and psychrometers are available.

Pressure measurement

Traditionally static and velocity pressures have been measured by the displacement of water in a U-tube (or inclined tube gauge) and expressed as a height of the supported water column either in inches (in. W.G.) or millimetres (mm. W.G.). The advantage of working in such units is that, provided a ruler scale is available, a U-tube manometer needs no calibrating other than the setting of the zero. Nowadays, electronic manometers are more widely available and offer the opportunity of working in the correct SI units of Pa or kPa. (Pascals are converted to mm WG by dividing by 9.81). Note that the pressures produced by agricultural crop fans are in the order of 0 to 150 mm W.G. (0 - 6 in. W.G.) which equates to 0 to 1.47 kPa; this is approximately two orders of magnitude less than atmospheric pressure, 101 kPa.

The most important static pressure to measure is that in the main duct at a point near to the fan but where the air velocity has been reduced by duct expansion. This pressure will provide some idea of the fan delivery and in extreme cases might indicate stall conditions.

Fans

For a comprehensive discussion of the use of fans in agriculture, see Cory (1991 a,b & c)

Fans for bulk storage dryers will be driven either electrically or by engines, usually diesel-powered. In both cases frequent starting and stopping may be expensive in starting load or fuel. For electric fans, starting load can be minimised by the use of 'soft-start' techniques (Kneeshaw, 1986). In the future we may expect to see fan speed control become an economic reality as the increasing application of this technology, in industry generally, reduces cost. Another widely used strategy is to source the total flow by two fans rather than one. This not only means that the starting loads can be split and staggered but it also provides for the ventilation of a store which may only be half full or require a conditioning airflow.

Most drying fans are sold with matched heaters (electric or propane) that allow rises up to 5°C. Heat provides insurance but usually adds to drying cost and can cause overdrying. Control strategy becomes important. Most heater controllers now modulate humidity rather than temperature

Fans for bulk storage dryers are of two types, axial and centrifugal.

Axial. In axial fans, the fan casing is a short straight tube containing a propeller-like impeller together with some straightening vanes. Air is drawn in through one end of the tube and expelled at the other without changing direction. Axial fans are noisier than centrifugal but can be fitted with silencers. They are capable of delivering large volumes at relatively low pressure. Two-stage axial fans can achieve higher pressures. In some two stage axial fans it is possible to switch off one stage to achieve air at pressures suitable for conditioning. Two-stage axial fans are also often used in pairs as discussed above.

Centrifugal. The casing of a centrifugal fan might be described as snail-like. Air is drawn through an aperture in the side of the fan into the centre of an impeller, which resembles a water wheel. The air is thrown out by this wheel at right angles to its original direction and leaves tangentially to the impeller through an aperture on the outer edge of the casing. Centrifugal fans are inherently quieter and are capable of delivering higher pressures than axial fans but tend to be more expensive. Fans with backward-curve impellers are normally used because they do not overload (i.e. draw excessive power) when operating against low resistance such as when the store is empty.

Starting fan motors

Star-delta starter. An electro-mechanical device for limiting the starting current drawn by three-phase induction motors. When the three stator windings of the motor are initially connected in a 'star' configuration they present a higher impedance to the 415 volt phase supply than when connected direct on line in the delta or running configuration. This limits the current until motor speed builds up and develops a back e.m.f., which acts to limit the current.

Soft start. An electronic device for limiting the starting voltage of a three-phase induction meter by applying the voltage in short pulses which are increased in duration and cease completely as the motor reaches full speed.

Would fan speed adjustment be useful? The fan laws.

Fan speed modification is possible if there is a transmission line between the drive motor or engine and the fan impeller. Electronic speed controls for electric motors are becoming more widely used in industry generally we may expect to see their cost reduce and become a feasible means of altering speed for agricultural fans.

The effect of a change in fan speed, N, on the volume, Q, pressure, P and power consumption, K, is as follows:-

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \quad ; \quad \frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^2 \quad ; \quad \frac{K_1}{K_2} = \left(\frac{N_1}{N_2}\right)^3$$

Now the fan efficiency is given by $\varepsilon = QP/K$, and because the system resistance usually varies as the square of the volume, the efficiency at the new operating point will be the same as at the old.

Fan speed variation would provide a means of matching fan characteristic to system resistance. Where the balance pressure is less than the practical limit of 1700 Pa, then the speed could be increased to increase the pressure and hence specific airflow at a given depth. This would be an alternative either to reducing bed depth or to reducing floor area to force the fan back up its characteristic curve. However, power requirement increases as the cube of the speed so that it could only be justified as a stratagem for wet years. Conversely either in a dry year when specific airflow could be reduced or for conditioning after drying as such has been completed, the fan speed could be reduced.

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BS 4317 : Part 23 : 1990	Determination of bulk density of cereals called `mass per hectolitre' (Reference method)
BS 4317 : Part 26 : 1991	Measurement of temperature of grain during bulk storage (ISO 4112 :1990)
BS 4317 : Part 32 : 1996	Determination of bulk density of cereals, called ‘mass per hectolitre’ (Routine method) (ISO 7971-2 : 1995)

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ISO 711 : 1985	Cereals and cereal products - Determination of moisture content (Basic reference method)
ISO 712 : 1985	Cereals and cereal products - Determination of moisture content (Routine reference method)
ISO 950 : 1979	Cereals - Sampling (as grain)
ISO 951 : 1979	Pulses in bags - Sampling
ISO 4112 : 1990	Cereals and pulses - Guidance on measurement of the temperature of grain stored in bulk
ISO 4174 : 1980	Cereals and pulses - Measurement of unit pressure losses due to single-dimension air flow through a batch of grain.
ISO 7002 : 1986	Agricultural food products - Layout for a standard method of sampling from a lot

Appendix 2. Symbols.

a	coefficient in equation for pressure resistance of crop, Pa s^n $m^{-(n+1)}$
a_w	water activity (equivalent to $\phi/100$), ratio
c	coefficients in equation for pressure resistance of duct resistance, Pa s^2 m^{-3}
m_d	mass of dry matter
m_f	final mass of grain.
m_o	initial mass of grain
n	exponent of velocity in equation for pressure resistance of crop
p	open perimeter of duct cross section, m
v	superficial velocity of air into the crop (i.e. across the dryer floor), m^3 s^{-1} m^2
v_{sp}	specific airflow (volume flow of air per unit mass of damp grain), m^3 s^{-1} $tonne^{-1}$
w	mass of water
w_{od}	mass of moisture removed by overdrying
w_{rem}	mass of moisture removed
A	area of cross section, m^2
A_{duct}	area of cross section of main duct, m^2
A_{floor}	area of dryer floor, m^2
$A_{lateral}$	area of cross section of lateral duct, m^2
D	depth of crop bed, m
D_e	effective depth of crop bed = $D + D_s$, m
D_s	additional depth compensating for non-linear flow at base of bed, m
H	moisture ratio or absolute humidity of dry air, kg water/kg dry air
K	fan power, kW
M	grain moisture content, % wet basis
M_o	initial moisture content of grain, % wet basis.
M_f	final moisture content of grain, % wet basis
M_{f1}	required final moisture content, % wet basis
M_{f2}	moisture content of overdried grain, % wet basis
P_{as}	saturation vapour pressure at the dry bulb temperature, kPa
P_{asx}	value of P_s given by Equation (2)
P_{asw}	saturation vapour pressure at wet bulb temperature, kPa
P_{at}	atmospheric pressure, kPa
P_{av}	partial vapour pressure of the unsaturated air, kPa. This is the same as the saturated vapour pressure at the dew-point.
P	pressure drop, Pa across bed of depth, D, m
P_{brick}	pressure drop across loose brick floor, Pa
P_{crop}	Pressure drop through crop, Pa
P_{fan}	fan pressure, Pa
P_{sys}	combined resistance of crop and duct system, Pa
P_{total}	combined resistance of crop and duct system, Pa
Q	volume delivered by fan, $m^3/s = v_{sp} D A \rho$
S	width of a single duct system or distance between ducts in a multiple duct system, m
T	grain temperature, °C

T_a	dry bulb temperature, °C
T_w	wet bulb temperature, °C
X	moisture content, % d.b.
ε	Fan efficiency, ratio or % as appropriate
ν	specific volume, m^3/kg of dry air.
ρ	crop density, tonne/m^3
θ	time to appearance of visible mould, days
ϕ	relative humidity, % (Note. Water activity, a_w is equivalent to ϕ /100)

Appendix 3. Moisture content – useful formulae

Converting between wet and dry basis

Results of moisture content determinations are normally reported on a wet basis i.e. as a percentage of the original wet mass (indicated by the suffix '% w.b.). They may also be reported on a dry basis i.e. as a percentage of the bone-dry mass or dry matter (indicated by the suffix '% d.b.' or 'd.b.' if expressed in decimal form). These two moisture contents are defined and related as follows:

$$M = 100\left\{\frac{w}{m_d + w}\right\}$$

and

$$X = 100\left\{\frac{w}{m_d}\right\}$$

where M = moisture content, % w.b.
X = moisture content, % d.b.
w = mass of water
m_d = mass of dry matter

To convert dry basis to wet basis

$$M = 100\left\{\frac{X}{100 + X}\right\}$$

and to convert wet basis to dry basis

$$X = 100\left\{\frac{M}{100 - M}\right\}$$

Moisture removed in drying

The mass of water to be removed from a given mass of wet grain is given by

$$w_{rem} = m_o\left\{\frac{M_o - M_f}{100 - M_f}\right\}$$

where w_{rem} = mass of moisture removed

m_o = initial mass of grain
M_o = initial moisture content of grain, % w.b.
M_f = final moisture content of grain, % w.b.

Similarly, if the dry mass is known

$$w_{rem} = m_f \left\{ \frac{M_o - M_f}{100 - M_o} \right\}$$

where m_f = final mass of grain.

For the mass of dry matter, the mass of water removed is given by

$$w_{rem} = m_d \left\{ \frac{M_o - M_f}{(100 - M_o)(100 - M_f)} \right\}$$

To calculate the final mass of grain from the initial mass use

$$m_f = m_o \left\{ \frac{100 - M_o}{100 - M_f} \right\}$$

Similarly, to calculate the initial mass of grain from the final mass use

$$m_o = m_f \left\{ \frac{100 - M_f}{100 - M_o} \right\}$$

The moisture removed by overdrying, w_{od}, is given by

$$w_{od} = m_o \left\{ \frac{(100 - M_o)(M_{f2} - M_{f1})}{(100 - M_{f1})(100 - M_{f2})} \right\}$$

where M_{f1} = required final moisture content
M_{f2} = moisture content of overdried grain

Appendix 4. Equilibrium moisture contents of common crops

Common terms used in sorption.

Sorption is the taking up of a gas or liquid by a solid either by absorption or adsorption. In **adsorption** the molecules of gas or liquid become attached to external and internal surfaces of the solid. In **absorption** the molecules penetrate into the interior of the solid or cells, often entering into chemical combination. Both processes operate in the sorption (wetting) of moisture by grain. **Desorption** (drying) is the removal of either adsorbed or absorbed gas or liquid from the solid.

Hysteresis is the term used to describe the lag of an effect behind its cause. For grain the sorption curve lags the desorption curve and forms a hysteresis loop. Repeated wetting and drying causes the loop to disappear.

Equilibrium moisture content is the moisture content at which the grain is in equilibrium with the relative humidity of the surrounding air.

Equilibrium relative humidity is the relative humidity of the air at which it is in equilibrium with the grain with which it is in close contact.

In the context of equilibrium moisture content, sorption and desorption isotherms are lines joining equilibrium combinations of moisture content and relative humidity determined at the same temperature

Wheat

Equilibrium moisture contents for **wheat** (Table 10) were calculated from the Chung-Pfost equation using coefficients found by Sun & Woods (1994a) to fit all the data from their survey of 28 published sources.

$$X = \frac{1}{0.166} \ln\left[\frac{(T+64.9)\,\ln(\phi)}{479}\right]$$

Barley

Equilibrium moisture contents for **barley** (Table 11) were calculated from the Chung-Pfost equation using the coefficients derived from the data of Bakharev(1948) by Sun & Woods (1994b)

$$X = \frac{1}{0.167} \ln\left[\frac{(T+66.6)\,\ln(\phi)}{600}\right]$$

Table 10. Equilibrium moisture contents for ***wheat****. Table values are given in % wet basis i.e.* $M = 100X/(100+X)$

Temperature, °C	**Relative humidity, %**											
	30	**40**	**50**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**98**
5	9.5	10.8	12.2	13.6	14.3	15.1	16.1	17.1	18.4	20.1	22.8	26.0
10	9.2	10.5	11.8	13.2	14.0	14.8	15.8	16.8	18.2	19.9	22.6	25.8
15	8.8	10.2	11.5	12.9	13.7	14.6	15.5	16.6	17.9	19.6	22.3	25.6
20	8.5	9.9	11.2	12.7	13.4	14.3	15.2	16.3	17.6	19.4	22.1	25.4
25	8.2	9.6	11.0	12.4	13.2	14.0	15.0	16.1	17.4	19.2	21.9	25.2
30	8.0	9.3	10.7	12.1	12.9	13.8	14.7	15.8	17.2	18.9	21.7	25.0
Mean	**8.7**	**10.1**	**11.4**	**12.8**	**13.6**	**14.4**	**15.4**	**16.5**	**17.8**	**19.5**	**22.2**	**25.5**

Note. Values given by the same equation with coefficients derived from analysis of desorption data only are in the order of 0.2% mc.w.b higher in the practical range of temperatures and relative humidities.

Table 11. Equilibrium moisture contents for ***barley****. Table values are given in % wet basis i.e.* $X = 100X/(100+X)$

Temperature, °C	**Relative humidity, %**											
	30	**40**	**50**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**98**
5	10.4	11.7	13.0	14.3	15.1	15.9	16.8	17.8	19.1	20.8	23.4	26.5
10	10.1	11.4	12.7	14.0	14.8	15.6	16.5	17.6	18.8	20.5	23.1	26.3
15	9.8	11.1	12.4	13.8	14.5	15.3	16.2	17.3	18.6	20.3	22.9	26.1
20	9.5	10.8	12.1	13.5	14.3	15.1	16.0	17.1	18.3	20.0	22.7	25.9
25	9.2	10.5	11.9	13.2	14.0	14.8	15.8	16.8	18.1	19.8	22.5	25.7
30	8.9	10.3	11.6	13.0	13.8	14.6	15.5	16.6	17.9	19.6	22.3	25.5
Mean	**9.6**	**11.0**	**12.3**	**13.7**	**14.4**	**15.2**	**16.1**	**17.2**	**18.5**	**20.2**	**22.8**	**26.0**

Appendix 5. Safe storage times of common crops at steady state

Terms relating to grain quality

Storage index is the cumulative fraction by which the **safe storage life** of a bulk of seed has been used. It is accumulated from successive fractions of storage life for each increment of temperature and humidity experienced by the seed. Storage life is fully utilised when the storage index reaches unity.

Respiration. The process by which living organisms oxidise food reserves to carbon dioxide and water with the release of energy.

Bacteria. A class of microscopic unicellular or filamentous plants without chlorophyll or well-defined nucleus.

Mould. Any one of various small fungi (*Mucor*, *Penicillium* etc) of different classes forming wooly or fluffy growths on foodstuffs and other organic materials.

Microbe. A microscopic organism.

Microflora. Microscopic plants. The population of microscopic organisms present on grain surfaces, for example.

Mycotoxin. A toxin produced by fungi.

Seed germination or viability is the ability of a seed to sprout under favourable conditions of temperature and moisture content. Germination capacity is the percentage of a seed population that will sprout under standard conditions of temperature and moisture content and within a specified time limit. In some years, wheat may sprout in the ear before harvest. Not only may this process be stopped by dehydration either in the field or in a dryer but the sprouts may not be visible. Nevertheless grain quality may be seriously affected. In the case of wheat, the Hagberg number will be reduced.

Wheat

Safe storage times for wheat are based on the equations developed by Frazer and Muir (1981) using the data of Kreyger (1972) from Holland together with data of their for Canadian wheat. The equations are

(a) for moisture contents between 12 and 19%

$$Log_{10}(\theta) = 6.234 - 0.2118M - 0.0527T$$

(b) for moisture contents between 19 and 24%

$$Log_{10}(\theta) = 4.129 - 0.0997M - 0.0567T$$

where θ = time to appearance of visible mould, days
M = grain moisture content, % wet basis
T = grain temperature, °C

For purposes of drying these equations may reasonably be applied to barley and oats.

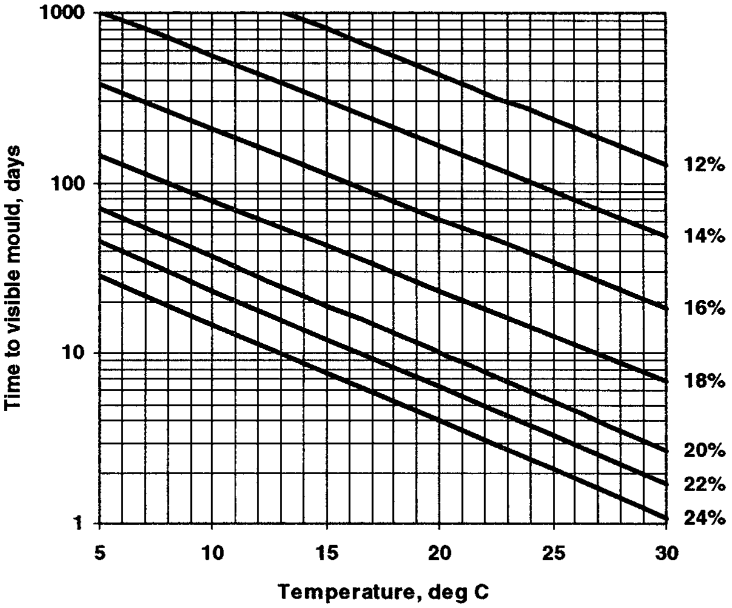

Figure 14. Dependence upon temperature and moisture content (% w.b) of time to the appearance of visible mould on wheat as predicted by the equations of Frazer and Muir.

Oilseed Rape (Canola)

Safe storage times are based on the equations developed by Muir and Sinha (1986) using the data of Kreyger (1972) from Holland. Muir and Sinha noted that Kreyger's data based on germination studies agreed well with those of Burrell et al (1982) for time to the development of visible mould. A fuller discussion can be found in Nellist and Bruce (1992). The equations are

(a) for moisture contents less than 11%

$$\theta = \exp(14.331 - 0.6954M - 0.1589T)$$

(b) for moisture contents greater than 11%

$$\theta = \exp(12.153 - 0.4743M - 0.1451T)$$

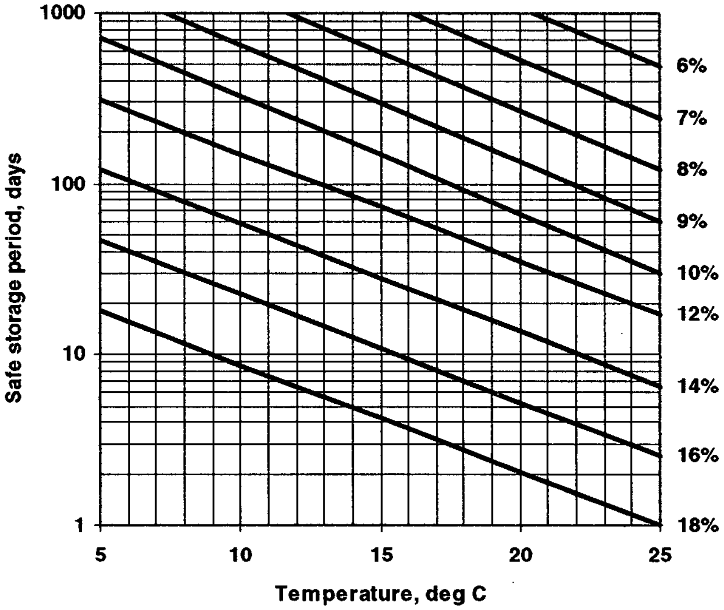

Figure 15. Dependence upon temperature and moisture content (% w.b.) of safe storage time for oilseed rape.

Appendix 6. Pressure resistance to airflow of common crops

The change in pressure across unit depth of a bed of seed is conveniently represented as a power function of velocity, Equation 5.1.

$$P = a\,v^n D \tag{6.1}$$

where P = pressure drop, Pa across bed of depth, D m
v = superficial velocity of air into the bed, $\mathrm{m^3 s^{-1} m^{-2}}$
a = experimentally determined coefficient, Pa $\mathrm{s}^n\ \mathrm{m}^{-(n+1)}$
n = experimentally determined exponent of v,

The coefficients in Table 13 were derived by pooling the data of ASAE (1988), Barrowman and Boyce (1966), Matthies and Petersen (1974), Bartlett (1975), Nellist and Rees (1967), and Muir and Sinha (1986).

Table 13. Average values of the coefficient, a and exponent, n for some common crops

Crop	a, Pa $\mathrm{s}^n\ \mathrm{m}^{-(n+1)}$	n
Red clover	48200	1.14
Oilseed rape	22695	1.19
Flax (Linseed)	18158	1.23
Wheat	8468	1.25
Barley	8529	1.29
Oats	7450	1.33
Peas	4900	1.40
Maize	4019	1.35

There is considerable variation in the published data for pressure resistance. It is caused mainly by differences in seed size, in compaction of the bulk and by contamination with rubbish. Table 16 illustrates the extent of this variation by listing ratios of maximum to minimum predicted pressures for some of the data used to develop Tables 14 and 15.

Multiply an appropriate value, or interpolated value, of the pressure by the bed depth to obtain the total pressure drop through the grain.

If required, convert Pascals to mm W.G. by dividing by 9.81 or to inches W.G. by dividing by 249. The following table repeats the data of Table 5.2 converted to mm W.G.

Table 14. Dependence of pressure drop per unit depth, Pa/m, on superficial velocity. Calculated using the coefficients of Table 10.

Velocity, $m^3s^{-1}m^{-2}$	Red clover	Oilseed rape	Flax (Linseed)	Wheat	Barley	Oats	Peas	Maize
0.005	115	41	27	11	9	7	3	3
0.020	557	215	148	63	55	42	20	21
0.035	1055	418	294	127	112	88	45	44
0.050	1584	640	457	198	178	140	74	71
0.065	2137	875	630	275	250	199	107	101
0.080	2708	1120	814	357	327	262	143	133
0.095	3293	1374	1005	443	408	329	182	168
0.110	3893	1637	1204	532	493	400	223	205
0.125	4503	1906	1408	625	582	473	267	243
0.140	5124	2181	1619	720	674	550	312	284
0.155	5755	2463	1835	818	768	629	360	325
0.170	6394	2749	2055	919	866	711	410	369
0.185	7041	3040	2281	1021	965	796	462	413
0.200	7695	3336	2510	1126	1068	882	515	459

Table 15. Dependence of pressure drop per unit depth, mm W.G./m, on superficial velocity. Calculated from Table 11 by dividing by 9.81.

Velocity, $m^3s^{-1}m^{-2}$	Red clover	Oilseed rape	Flax (Linseed)	Wheat	Barley	Oats	Peas	Maize
0.005	12	4.2	2.7	1.1	0.9	0.7	0.3	0.3
0.020	57	22	15	6.4	5.6	4.3	2.1	2.1
0.035	108	43	30	13	11	8.9	4.6	4.5
0.050	162	65	47	20	18	14	7.5	7.2
0.065	218	89	64	28	26	20	11	10
0.080	276	114	83	36	33	27	15	14
0.095	336	140	102	45	42	34	19	17
0.110	397	167	123	54	50	41	23	21
0.125	459	194	144	64	59	48	27	25
0.140	522	222	165	73	69	56	32	29
0.155	587	251	187	83	78	64	37	33
0.170	652	280	210	94	88	73	42	38
0.185	718	310	232	104	98	81	47	42
0.200	784	340	256	115	109	90	52	47

Table 16. Illustrating the extent of variation in pressure drops predicted by published data.

Crop	Ratio of maximum to minimum predicted pressure.
Maize	1.2
Oats	1.5
Wheat	1.8
Barley	2.2
Flax (Linseed)	3.5
Oilseed rape	5.6

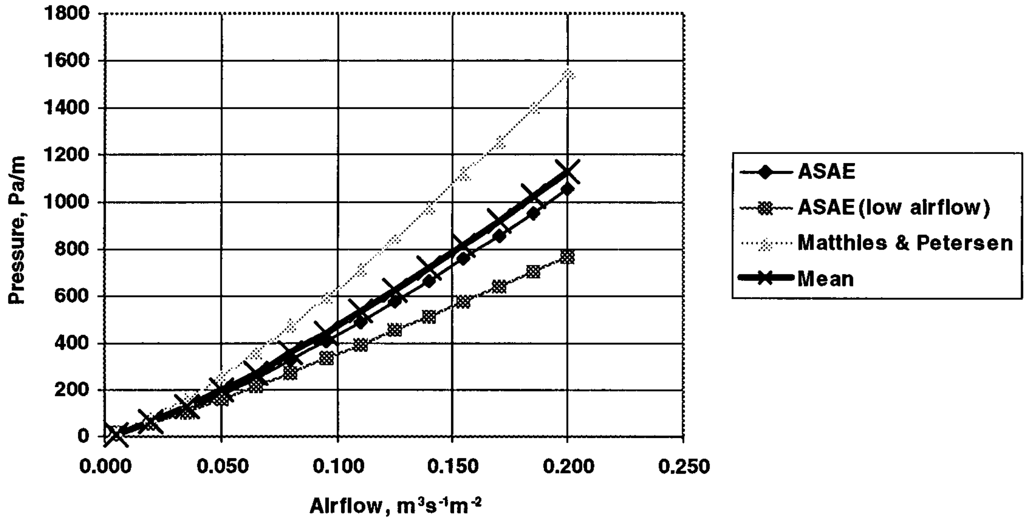

Figure 16. Variation in the pressure resistance of wheat as affected by data source.

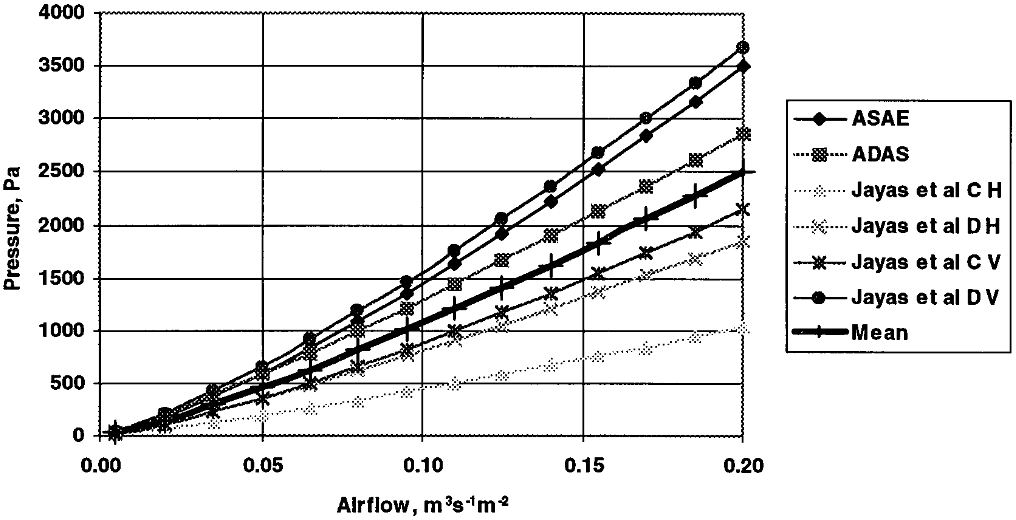

Figure 17. Variation in the pressure resistance of flax (linseed) as affected by data source and whether clean(C) or dirty(D) and whether flow is horizontal (H) or vertical (V) (Jayas, Alagusundaram and Irvine, 1991). The lowest resistance is that of clean seed in the horizontal direction; the highest is dirty seed in the vertical direction.

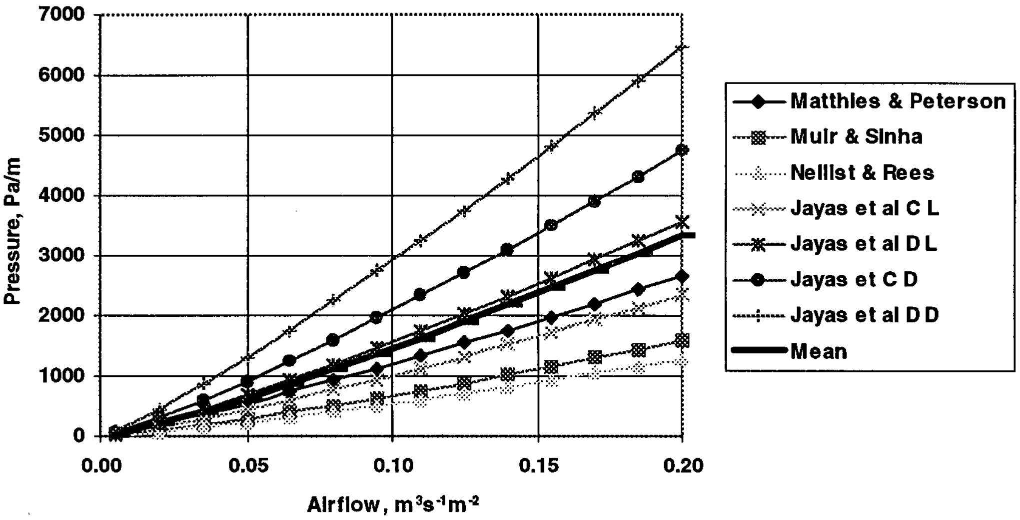

Figure 18 Variation in pressure resistance of oilseed rape as affected by data source and whether seed is clean (C) or dirty (D) or whether loosely(L) or densely (D) packed. The data of Nellist and Rees (1967) and Muir and Sinha (1986) predict lower pressures and lie outside the range covered by the variations examined by Jayas, Sokhansanj & Sosulski (1991).

The additional resistance of the non-linear flow at the base of a duct ventilated floor can be allowed for (Nellist, Dumont and Marchant, 1977) by increasing the depth by an amount D_s where

$$D_s = S\left(-0.455\ln\left(\frac{p}{S}\right)-0.232\right) \qquad 6.2$$

and S = width of a single duct system or distance between ducts in a multiple duct system, m

p = open perimeter of duct cross section, m.

The effective depth, D_e, then equals $D + D_s$

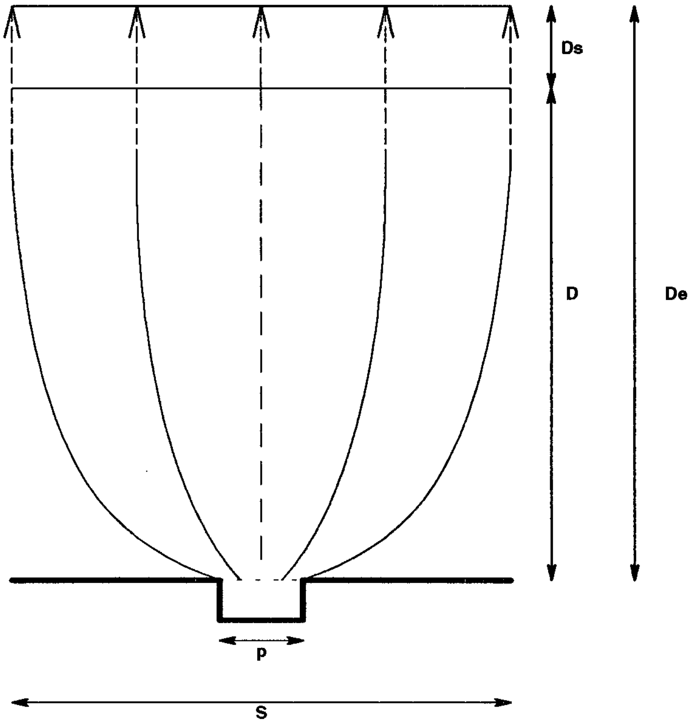

Figure 19 Non-linear flow in a duct ventilated system can be allowed for by estimating an effective depth. This diagram explains the dimensions used in Equation 6.2 and Figure 20.

The flow in the duct systems supplying the air to the crop will usually be fully turbulent and the resistance pressure will vary as the square of the velocity. So the total pressure will be given by Equation 6.3

$$P_{total} = cv^2 + av^n D_e \qquad 6.3$$

where the coefficient, c, can be taken to be 13000 if v is the superficial velocity normal to the drying floor (i.e. not the velocity in the ducts themselves). The duct system should be designed so that duct velocities do not 10 m/s.

For a brick drying floor, the flow will be reasonably linear but the pressure drop through the bed should be increased by the resistance of the floor given by equation 6.4.

$$P_{brick} = 14873v^2 \qquad 6.4$$

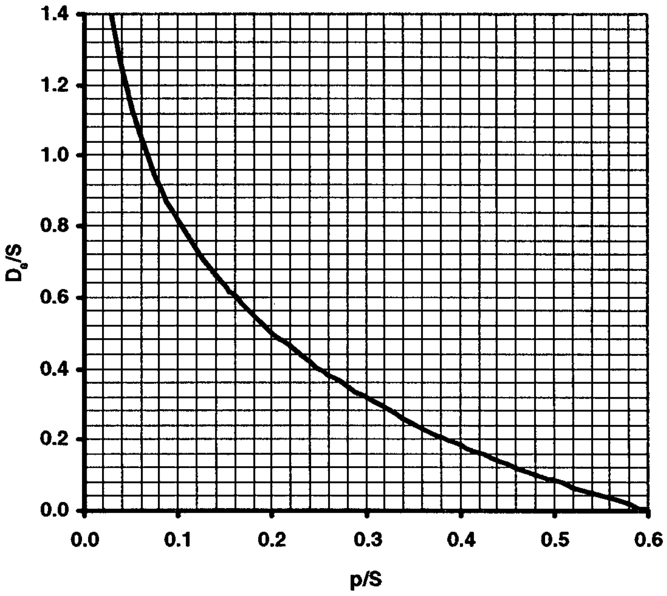

Figure 20. To find the extra depth to add on to allow for non-linearity of flow, use this chart to find D_s/S *for calculated value of p/S. Multiply* D_s/S *by S to obtain* D_s*.*

Appendix 7. Bulk densities and storage volumes.

What is the mass per hectolitre?

The mass per hectolitre is the ratio of the mass of a cereal to the volume it occupies after being poured into a container under well-defined conditions. The routine method uses a one-litre container and the reference method a 20-litre container. It is expressed in units of kilograms per hectolitre at a stated moisture content. It is, of course, a measure of bulk density although not necessarily a good indicator of the density of a large bulk of several tonnes. Also bulk density, as such, is better expressed in units of either tonnes or kilograms per cubic metre.

Table 17. Bulk density and storage volumes of common crops.

Crop	Wheat	Barley	Oats	Oilseed rape	Peas	Beans
Hectolitre mass, kg/hl	78	70	56	69	84	86
Bulk density, tonne/m^3	0.780	0.700	0.560	0.690	0.840	0.860
Specific volume, m^3/tonne	1.28	1.43	1.79	1.45	1.19	1.16
Floor area, m^2/ 100 tonnes at bed depths:-						
2 m	64	71	89	72	60	58
3 m	43	48	60	48	40	39
4 m	32	36	45	36	30	29

Appendix 8. Psychrometric properties of air

Some common terms in psychrometry

A **psychrometric chart** is a graphical representation of the physical and thermal properties of atmospheric air

Vapour pressure is that part of the total pressure contributed by the water vapour. The **saturation vapour pressure** is the pressure, at a constant temperature, at which the water vapour in the air is in equilibrium (neither giving or receiving water) with an adjacent plane surface of water or ice. The **partial vapour pressure** is the pressure of the water vapour in unsaturated air.

The **dew point** is the temperature at which the vapour pressure of the water vapour in the air is equal to the saturation vapour pressure over water or ice. The dew point temperature is the temperature at which condensation occurs when the air is cooled at constant humidity and atmospheric pressure

Condensation is the conversion of water from the vapour to liquid phase that occurs as air is cooled below its saturation vapour pressure.

Dry bulb temperature is the temperature of moist air indicated by an ordinary thermometer

Wet bulb temperature is the equilibrium temperature sensed by a thermometer bulb when covered with wet gauze and exposed to a humid atmosphere.

Pseudo wet-bulb temperature. In the context of drying, the pseudo-wet bulb temperature is that reached in the zone ahead of the drying zone in a deep bed. The air is prevented from reaching the true wet bulb temperature because moisture uptake is limited by the equilibrium relative humidity of the grain and in addition some heat transfer between grain and air may cause a departure from the wet bulb line.

A **hygrometer** is a device that measures relative humidity.

A **dew point meter** is a device that determines the dew point temperature of air. This is normally done by determining the temperature at which condensation occurs on a cooled surface. If the device also measures dry bulb temperature, and is thereby able to compute and output the relative humidity, it becomes a dew-point hygrometer.

Relative humidity is the ratio of the actual pressure of the water vapour in the air to the pressure if the air were saturated with water vapour at the same temperature. It is conventionally expressed as a percentage but used in ratio form in equations. In microbiology, the ratio form is often termed **'water activity'**.

Relative humidity is defined as $\phi = 100\frac{P_{av}}{P_{as}}$ (7.1)

where

ϕ = relative humidity, % (Note. Water activity, a_w is equivalent to $\phi/100$)

P_{as} = saturation vapour pressure at the dry bulb temperature, kPa

P_{av} = partial vapour pressure of the unsaturated air, kPa. This is the same as the saturated vapour pressure at the dew-point.

Vapour pressure deficit is the difference between the saturation vapour pressure and the partial vapour pressure at the given dry bulb temperature. i.e. $P_{vpdef} = P_{as} - P_{av}$ or $P_{vpdef} = P_{as}(1-\phi/100)$

Saturation vapour pressures at the dry bulb and dew-point temperatures are conveniently calculated by the equation of Lowe (1976):

$$P_{as} = 0.01(a_0 + T(a_1 + T(a_3 + T(a_4 + T(a_5 + a_6 T)))))) \qquad (7.2)$$

where T = temperature, °C

$a_0 = 6.107799961$

$a_1 = 4.436518521 \times 10^{-1}$

$a_2 = 1.428945805 \times 10^{-2}$

$a_3 = 2.650648471 \times 10^{-4}$

$a_4 = 3.031240396 \times 10^{-6}$

$a_5 = 2.034080948 \times 10^{-8}$

$a_6 = 6.136820929 \times 10^{-11}$

If $T<0$ then $P_{as} = -0.00486 + 0.85471 P_{asx} + 0.2441 P_{asx}^2$

(7.3)

where P_{asx} = the value of P_{as} given by Equation (2)

The partial vapour pressure of the unsaturated air can be calculated from measurements of wet and dry bulb temperatures by the following equation:

$$P_{av} = P_{asw} - 0.00066(1 + 0.00115T_w)(T_a - T_w)P_{at} \qquad (7.4)$$

where P_{asw} = saturation vapour pressure at wet bulb temperature, kPa

T_w = wet bulb temperature, °C

T_a = dry bulb temperature, °C

P_{at} = atmospheric pressure, kPa (If barometric pressure is not known use 101 kPa.)

Absolute humidity (or mixing ratio), the mass of water per unit mass of dry air, is given by:

$$H = 0.622\frac{P_{av}}{(P_{at} - P_{av})} \qquad (7.5)$$

or

$$H = 0.622\left(\frac{\phi\, P_{as}}{P_{at} - \phi\, P_{as}}\right) \tag{7.6}$$

where H = absolute humidity , kg water/kg dry air.

Specific volume, the volume of moist air per unit weight of dry air is given by

$$v = \frac{287(T+273)}{P_{at} - P_{av}} = \frac{287(T+273)}{P_{at}}(1+1.608H) \tag{7.7}$$

where v = specific volume, m3/kg of dry air.

Specific energy consumption is the energy used per unit mass of water evaporated.

Specific heat capacity is the heat required to increase unit of mass by one unit of temperature.

Drying potential of ambient air

Table 18. Effect of air temperature and relative humidity on the volume of air required to remove unit mass water, m^3/kg. These approximate calculations assume that the air cools along the 'wet-bulb' line until the relative humidity has reached 94%.

Relative humidity, %	**Ambient temperature, °C**							
	0	**5**	**10**	**15**	**20**	**25**	**30**	**Mean**
20	447	341	275	228	194	168	148	**257**
30	523	396	323	271	231	202	179	**303**
40	628	475	390	328	282	247	221	**367**
50	779	589	486	402	356	313	282	**458**
60	1023	772	640	543	473	419	378	**607**
70	1472	1108	920	786	686	613	554	**877**
80	2586	1920	1605	1380	1203	1076	980	**1536**
85	4124	2995	2503	2165	1888	1695	1543	**2416**
90	9923	6819	5648	4898	4386	3907	3449	**5576**
Mean	**2389**	**1713**	**1421**	**1222**	**1078**	**960**	**859**	**1377**

Table 19. Effect of air temperature and relative humidity on the volume of air required to remove 0.5% moisture content wet basis in 24 hours from grain initially at 20% moisture content wet basis, m^3/s *per tonne. These approximate calculations assume that the air cools along the 'wet-bulb' line until the relative humidity has reached 94%.*

Relative humidity, %	**Ambient temperature, °C**							
	0	**5**	**10**	**15**	**20**	**25**	**30**	**Mean**
20	0.032	0.025	0.020	0.016	0.014	0.012	0.011	**0.019**
30	0.038	0.028	0.023	0.019	0.017	0.014	0.013	**0.022**
40	0.045	0.034	0.028	0.024	0.020	0.018	0.016	**0.026**
50	0.056	0.042	0.035	0.029	0.026	0.023	0.020	**0.033**
60	0.074	0.055	0.046	0.039	0.034	0.030	0.027	**0.044**
70	0.106	0.080	0.066	0.057	0.049	0.044	0.040	**0.063**
80	0.186	0.138	0.115	0.099	0.086	0.077	0.070	**0.110**
85	0.296	0.215	0.180	0.156	0.136	0.122	0.111	**0.174**
90	0.713	0.490	0.406	0.352	0.315	0.281	0.248	**0.401**
Mean	**0.172**	**0.123**	**0.102**	**0.088**	**0.077**	**0.069**	**0.062**	**0.099**

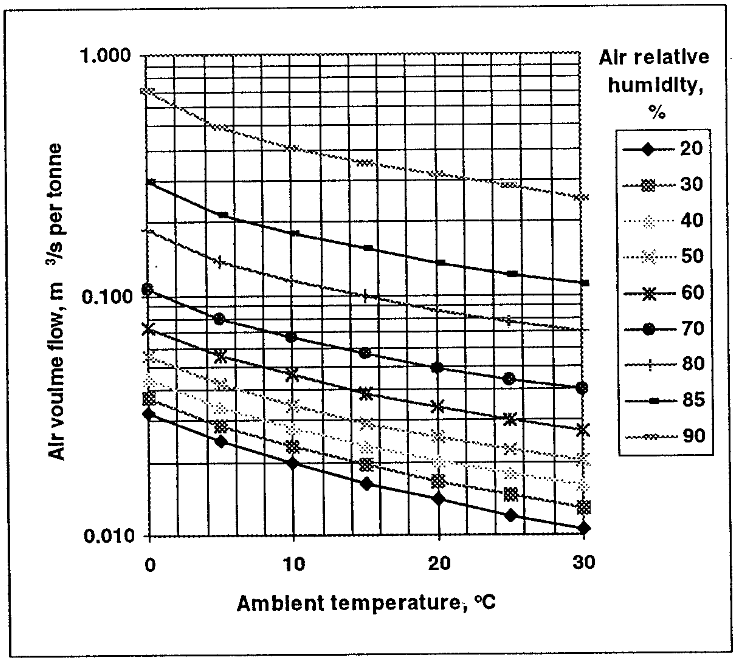

Figure 21. Effect of temperature and relative humidity of ambient air on the approximate volume of air required to remove 0.5% m.c.w.b. in 24 hours from wet grain at 20% m.c.w.b.