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DOSING STRATEGIES FOR LOW OXYGEN ATMOSPHERE REPLACEMENT IN FLOOR STORED GRAIN

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ABSTRACT

In silo bins modified atmospheres can easily be applied via the aeration system in the bin floor, but dosing of floor-stored bulks is less straight forward. All treatments rely on sheeting to achieve a high level of seal. A propane burner is a suitable atmosphere source provided that the exhaust gas can be cooled before entry into the grain.

In maintaining the atmosphere under a continuously running gas input from such a generator, care needs to be taken to avoid internal circulation of pockets of high oxygen levels, which can persist for long periods even in the absence of adverse weather conditions. Experiments on the distribution and location of gas input points, variation of gas input flow rates, and manipulation of the degree of sealing achieved at different locations round the periphery of the bulk, are described as part of a back to back study between mathematical modelling and practical gas application and monitoring in a floor store.

The maintenance flow rate for a box-shaped bulk was similar to that of a silo bin of similar capacity, calculated as 4.965 + (0.0110 x tonne weight of bulk) m^3/h. Maintenance flow rates for sloping bulks were higher. When the distribution of leak sources was biased towards one end of the store, the replacement atmosphere was best introduced at the opposite end. This advantage was reduced when the sites of leakage were more generally distributed.

INTRODUCTION

Cereals form by far the largest cultivated crop world-wide. The problem facing an industry relying on a decreasing number of control measures to maintain increasingly high standards in agricultural products such as cereals, is the lack of suitable alternatives developed to the point where practical uptake can be started. The expectation today is for greener, less chemical-based control options. The technique of modifying and controlling the atmosphere of an enclosure provides an essentially physical control method which offers the prospect of achieving an elusive goal; a reduction both in the levels of pesticide residues and in the numbers of live pests present.

Although the use of modified atmospheres (MA) is widely recognised as providing a realistic alternative to existing control measures in grain storage, information on their practical application and use is not available in a form for immediate uptake by store keepers. In many parts of the world, the specialist equipment required to provide the atmosphere is not easily obtainable, and more information is needed on the temperature and humidity ranges over which MAs work most effectively against different pest species. The conditions under which grain is stored generally do not provide for atmosphere containment, most installations being geared for quite the opposite, forced aeration being extensively used to cool and dry the grain. However, as for fumigation, sealing methods can be employed that are suitable for continuous flow MA applications.

In silo bins provision of a sufficient gas flow to the aeration ducting in the bin floor will rapidly establish the applied atmosphere throughout the grain. With a sufficient flow the surface of the grain can be left uncovered, but provision of a sheet reduces the maintenance flow rate required by 90% (McGaughey and Akins, 1989). Further improvements can be achieved by sealing grain auger entrance points and all sources of air ingress at the base (Conyers *et al.,* 1996; Bell *et al.,* 1997). To provide an atmosphere capable of disinfesting a floor-stored grain bulk from insect and mite pests many additional factors need to be taken into account. Firstly the degree of seal achievable is less than for a weather-proof silo bin. Secondly the geometry of the bulk creates difficulties for distribution of the atmosphere. The comparatively shallow grain layer is no less vulnerable to temperature gradients than those occurring in bins and wind may result in interruptions to the effective exposure under gas in various parts of the bulk, affecting the performance of treatments. The experiments described below set out to investigate the best strategy for gas application, and to discover how to configure a bulk to optimise conditions for successful treatments.

METHODS

Floor stores

Three floor store trials were undertaken with feed wheat at the new grain storage facility at CSL. All were carried out in the same store. The store has a smooth concrete wall on one side and corrugated metal on the other. The far end wall was provided by a movable wooden barrier (3.2 m high and 10.1 m wide), 'L'-shaped in cross-section, which faced into the store with a dead space under the base foot. Trial 1 had a sloping front to the grain heap, which continued to the front wall (13 m long in total) and held 270 tonnes of wheat (Fig. 1). At the front wall of the store, comprising metal sheeting and half wooden slats lined with laminate sheeting, the grain reached a height of 1.3 m. Trial 2 had a slightly reduced 250 tonne bulk of wheat and was similarly shaped to the first except that the slope went right to the floor (Fig. 2). Trial 3 completely filled the store (14 m long, 375 tonnes of wheat) and used the full height of the front retaining wall (Fig. 3). The surface of the grain and the interior of the back wall were sheeted as was the front wall for the third trial. The floor of the store had 13 recessed aeration ducts (numbered from the front) covered by metal grills running across the full width at regular intervals. These were fed from a common plenum behind the concrete wall. Each aeration duct opening to the plenum was sealed including the one through which the hose supplying gas from the burner gas generator was inserted.

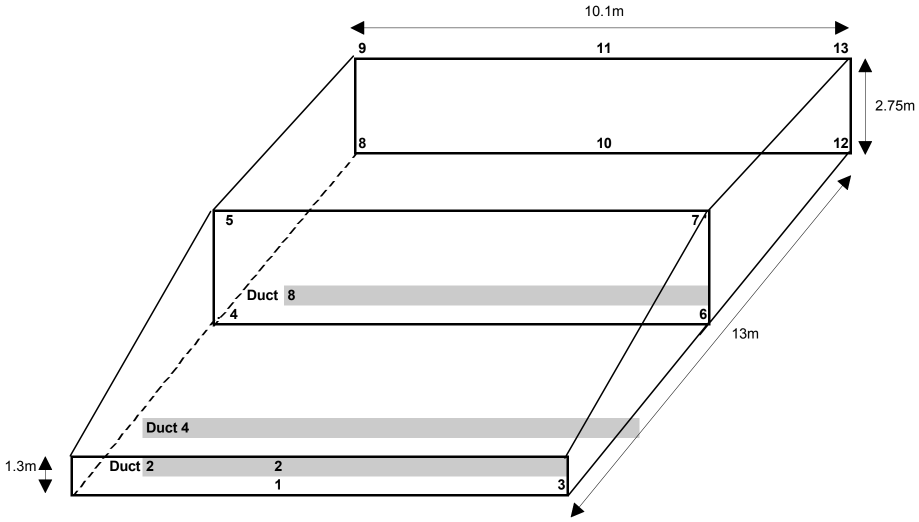

Fig. 1. Floor store layout with input ducts used and atmosphere sampling positions for 250 tonnes of wheat in first trial.

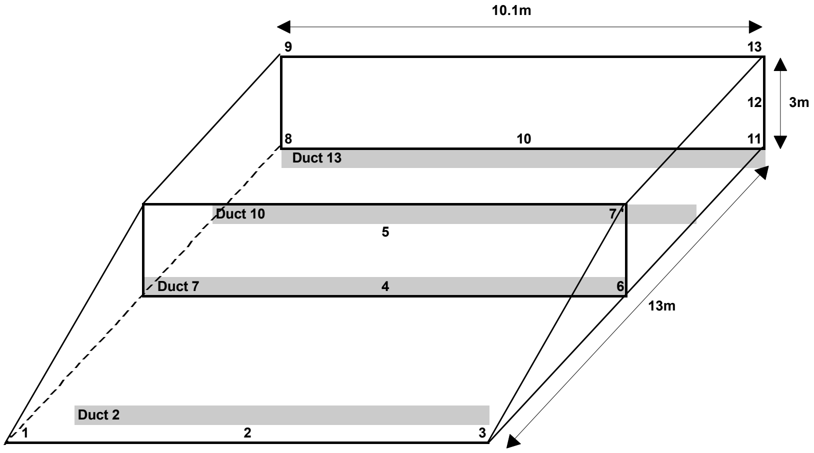

Fig. 2. Floor store layout with input ducts used and atmosphere sampling positions for 250 tonne bulk of wheat with a sloping front.

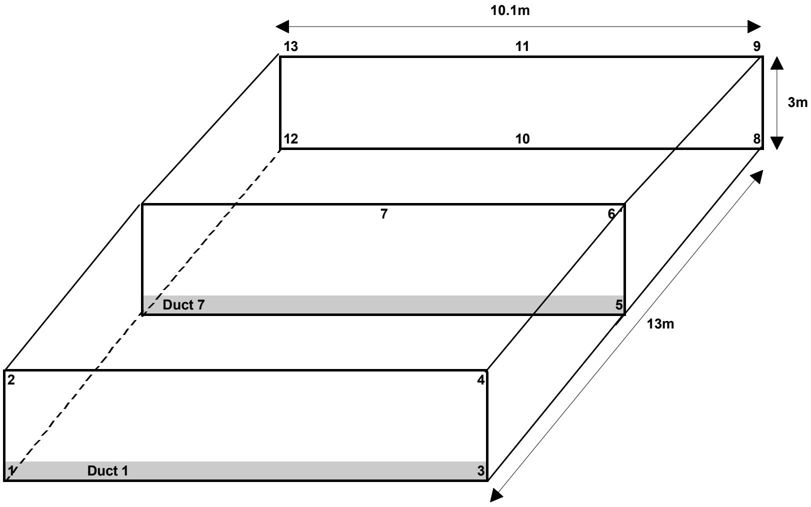

Fig. 3. Floor store layout with input ducts used and atmosphere sampling positions for a 375 tonne box-shaped bulk of wheat.

Monitoring the gas constituents and preparations for atmosphere application

All gas monitoring of the output content and the generated atmosphere within the floor stores was carried out using 2 mm nylon sampling lines. Fifteen lines were inserted into the grain and pushed down to various depths to give a representative profile of the distribution of the generated atmosphere within the store. Thermocouples were also inserted into the grain to record temperatures throughout the trials. Ambient temperature, wind speed and direction were measured within the building throughout the trials. All trials employed a unique sampling and detection system built by CSL. This was programmed to move through each of the sampling lines every eight minutes, providing a complete set of readings every two hours. The instruments were connected in series and consisted of four analysers for oxygen (O_2), carbon dioxide (CO_2), carbon monoxide and nitrous oxide respectively. The data from each sample were recorded on a chart recorder along with temperature, pressure, wind speed and direction.

Assessment of the MA establishment results

The aim of each trial was to find the lowest gas flow rate, which would hold the floor stores at or below 1% O_2 using different gas input positions in relatively calm conditions. A series of flow rates were used for each gas input position and the change in O_2 content for each was noted. A value for the maintenance rate was identified as the flow rate with no change in the O_2 level. The temperature and wind data were measured to assess their effect on the gas levels achieved in the grain bulks.

PRACTICAL EXPERIMENTS

Trial 1: 270 tonne grain bulk sloping to less than half maximum depth at front

The objective of this trial was to examine the effect of different gas application positions on the ability to bring the grain bulk below 1% O_2. The atmosphere replacement was started with a flow of 16 m^3/h through aeration duct number 2 near the front of the bulk (Fig. 1). This flow rate was continued throughout the trial. The O_2 content of the incoming gas ranged from 0.1 to 0.5% throughout the course of the trial. The interior of the rear grain wall was sheeted with 125 μm polythene, which has good tensile strength. Problems were encountered in achieving a consistently good seal at the edges where the bulk sloped. The O_2 level at the front quickly fell below 1% but the rest of the store remained well above this value. When the O_2 readings at the centre reached a plateau, bottom sample positions 4 and 6 averaged out at 3% whereas the surface was closer to 10%. At the back wall the bottom positions averaged 7% and the surface was 10% except the middle surface (position 11), which was even higher at 15%.

For the second stage of the trial the input position was moved backwards 2 m to duct 4. This move did not achieve any improvement on the O_2 levels and it was only when the input was moved back to duct 8 that the levels dropped further. At the end of this period all positions throughout the bulk were below 1% except back left bottom and back right bottom (Fig. 1) which were at 1.8 and 1.3% O_2 respectively, and an area on the right hand side of the bulk at the surface which fluctuated between 2 and 3% O_2. Modelling studies have shown that rear (or front) positions can represent ‘dead’ areas where diffusion of the generated atmosphere is slowest, and had more time been allowed, these may have been brought to below the required level.

TABLE 1
Ambient and grain temperatures during Trial 1

Temperature (ºC)	Position		
	Ambient	Surface	2 m depth
Average	5.9	7.8	11.7
Minimum	-1.3	6.8	11.1
Maximum	14.9	9.6	12.4

The prevailing environmental conditions may have had some affect on the O_2 levels in the bulk, although the times of higher wind activity within the store did not seem to equate with losses of the generated atmosphere. The temperature record shows a daily maximum difference between the surface of the grain and ambient of 8.0ºC with a diurnal range of a similar magnitude (Table 1). This rise and fall in temperature may be responsible for similar changes in O_2 at some surface positions at the middle and rear of the store. This probably indicates areas where the sealing of the sheeting was inadequate. Had a better seal been achieved, a much lower maintenance flow rate than 16 m^3/h would have been recorded for this bulk.

Trial 2: 250 tonne grain bulk sloping to the floor

This trial investigated the effect of gas input rate on the efficacy of each gas input position, utilizing a slightly altered bulk configuration to trial 1 by removing about 20 tonnes of grain at the front edge. The generated atmosphere was introduced through duct number 2 at a flow of 18 m^3/h at the bottom of the slope (Fig. 2). An O_2 content of <0.2% was achieved at this flow rate and was maintained throughout the course of the trial. However, the O_2 content in some areas at the back wall did not drop below 12%. The flow rate was reduced to 9 m^3/h to see if a lower flow rate would introduce a different distribution of gas concentrations within the enclosure. No basic change was observed and one position, number 11 at the back right bottom, never fell below 15.3% throughout this phase of the trial. A further sheet was added to the back grain wall on its outside, and was run right down to the floor. Subsequently, a tear was discovered in the original sheeting in the corner of the grain wall, incurred during the initial loading of the grain.

For the second stage of the trial the input position was moved to duct 10 and the input flow rate was increased to 15 m^3/h. This action managed to keep the O_2 level at the bottom of the slope below 1% and the same was true for the middle section of the grain bulk. Here the only high O_2 position was on the right hand side where sealing the sheet on the sloping grain bulk to the corrugated steel wall had been a problem. Most positions at the back wall fell below 1% as well, helped in part by the additional sealing of the back wall, though O_2 levels at the back right bottom (Fig. 2) remained high. A decrease in flow to 12 m^3/h initially held the O_2 contents below 1% except for the localised problem points mentioned above, but then the O_2 levels began to increase above 1%, particularly at the rear wall. A further decrease to 9 m^3/h made the situation worse, again principally at the back wall. At this time the rear grain wall was vulnerable due to the gusting of the wind in the building. This period also coincided with an increase in the ambient temperatures above those of the grain bulk (Table 2) and these conditions were likely have accentuated the leakage from the rear of the bulk as there was noticeable movement of the sheeting across the rear grain wall.

TABLE 2

Ambient and grain temperatures during Trial 2

Temperature (°C)	Position		
	Ambient	Surface	1 m depth
Average	11.3	9.9	9.3
Minimum	0.6	8	9.1
Maximum	22.3	11.9	9.5

In the last phase of the trial dosing was moved to duct number 7 which was under the top of the slope and the flow rate was again increased to 15 m^3/h. No improvement in the O_2 level was noticed indicating that the prevailing windy weather was continuing to pump air into the rear of the store. The final input position at the same flow rate was duct 13 which was actually under the rear grain walling near the major leakage site. An improvement was seen in the rear positions but there was a considerable loss of generated atmosphere over the front and middle sections of the grain bulk.

The result from this trial showed that for a grain bulk with a slope, with leaks at the back wall and along the sides where sheeting was tucked at the store walls, a frontal or central gas input position was able to bring O_2 levels down to 1% or less at most points. A rear input position near the principal sources of leakage was totally ineffective in achieving atmosphere replacement. The trial also showed the importance of the use of a strong plastic sheeting to achieve a very good level of sealing of vulnerable areas prior to introduction of grain and that sealing with sheeting is more effective inside the grain walling. The maintenance flow rate for this bulk was between 12 and 15 m^3/h.

Trial 3: 375 tonne box-shaped bulk with no slope

To compare the performance of different dosing positions in bulks with and without a front slope, the store was filled to form a box-shaped bulk of even depth. With this shape of bulk the 3-m front wall was well sealed with sheeting, as were the sides of the bulk for the full length of the store. The generated atmosphere was firstly introduced at the front into duct 1 (Fig. 3), commencing with a flow rate of 15 m^3/h. An O_2 content from the burner of <0.2% was achieved at this flow rate and was maintained throughout the course of the trial. The flow rate was reduced to 11, then to 9 and finally increased to 12 m^3/h.

One position, number 12 at the back right bottom (Fig. 3) was never lower than 14.7% O_2 throughout the trial due to a subsequently discovered tear in the sheeting in the corner of the grain wall. In spite of the use of extra sheeting in this area, the defect could not be eliminated as it was under the dead space of the rear grain wall. This highlighted once again the importance of the initial lining of the store and sheeting to achieve a good seal. Apart from this point there were periods in all 4 flow rates where the O_2 contents of the store dropped below 1%. This showed that the maintenance rate for this frontal dosing position could be as low as 9 m^3/h. Ambient temperature in this trial was always below the surface temperature, on occasion by as much as 10ºC and there was considerable diurnal oscillation (Table 3). However there was little evidence from the O_2 levels within the bulk, even for the back right bottom position, which was obviously a site of leakage, that temperature change was having any marked effect.

TABLE 3
Ambient and grain temperatures during Trial 3

Temperature (ºC)	Position		
	Ambient	Surface	1 m depth
Average	3.5	15.0	9.8
Minimum	-2.8	14.3	8.2
Maximum	10.5	15.5	11.3

The input point was then moved to duct 7 and the flow was continued at 12 m^3/h. The O_2 level started to increase throughout the store, and reached an average of 3%, when there was a loss of records due to a sampler malfunction.

This demonstrated that with this uniformly shaped bulk, the input was best arranged from one end. The results suggested that a maintenance flow rate at or below the lowest rate tried, 9 m^3/h, could be adequate to hold the low O_2 atmosphere. Fig. 4 shows a model produced from the results of seven earlier trials treating bins with a similar MA (first six described in Bell *et al.,* 1997) for predicting the flow rate required to maintain a 1% O_2 level within a bin of known capacity. The linear scale for grain weight with a line going through the origin gives a slope of 0.0110. For field use a line parallel to the basic regression at the mean of the 95% prediction interval was selected. This should mean that 95% of all bin sizes will have maintenance flow rates which would not exceed the model:

Flow Rate of MA (m^3/h) = 4.965 + 0.0110 x Weight of the Bin Contents (tonnes)

The result for the 375 tonne store approximates to this relationship. Therefore with a good level of sealing, maintenance rates in floor stores similar to those achieved in bins are possible. It would also indicate that floor store bulks give better results when they are box-shaped rather than with a sloping face.

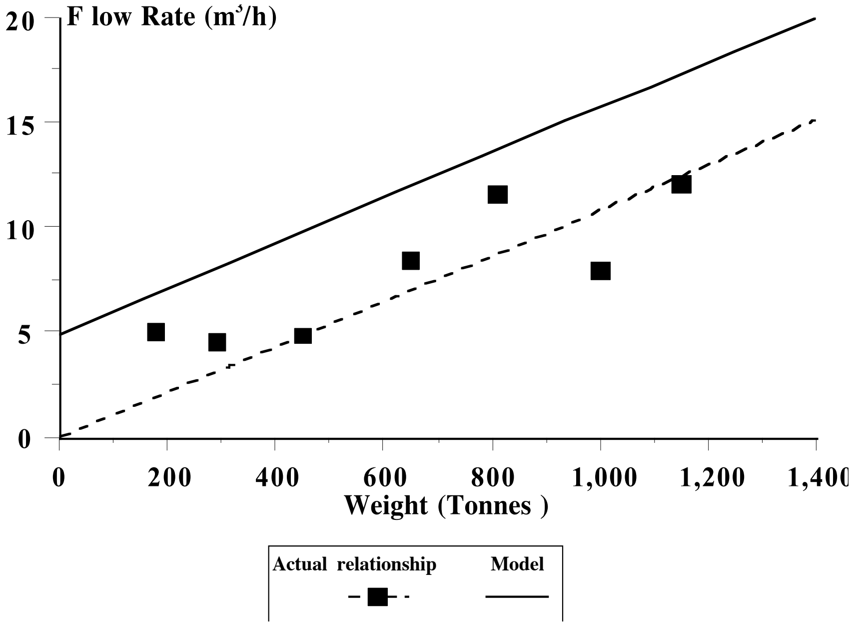

Fig. 4. Model for predicting flow rates from bin weights.

COMPUTATIONAL SIMULATIONS OF ON-FLOOR GRAIN STORAGE

Previous work by the authors developed an approach using Computational Fluid Dynamics (CFD) techniques for predicting the gas flows, pressures and temperatures inside grain stores. The method solves the differential equations, which describe heat and mass transfer within the grain, and produces details of the gas flow throughout the store. The grain is treated as a porous medium and, by defining the boundary conditions in an appropriate way, meteorological data (wind speed and ambient air temperature) can be employed to model a realistic storage environment.

Two floor store shapes have been used for simulations, the sloping fronted bulk of 250 tonnes capacity and the box-shaped bulk of 375 tonnes capacity, as used in trials 2 and 3. In each case the dimensions of the store, the covering sheet, and the inlets and outlets were reproduced in the CFD model.

The physical properties of the grain bulk

Modelling the gas flow and heat transfer in a grain store requires physical and thermal properties of the grain. The properties used throughout are given in Table 4 for wheat at 13% moisture content (w.b.) (ASAE 1995), although the model is applicable to any grain type if the corresponding properties are known. It is assumed that these are constant and uniform throughout the store within the operative range. The properties of the gases involved, N_2, CO_2 and O_2, have been taken from Bejan (1993), whilst diffusion coefficients can be found in Bird *et al.* (1960).

The equation relating pressure gradient to gas flow velocity in the grain was taken from ASAE Standards 1992, because it applies in the low velocity regimes encountered in this work. However, because the natural alignment of grain kernels produces less resistance horizontally (Kumar and Muir, 1986), a 15% difference in resistance between horizontal and vertical directions was assumed.

TABLE 4

Thermal and physical properties used in the CFD model

Bulk density, $_b$	757.16
Bulk specific heat, c_b	1929.7
Bulk conductivity, k_b	0.1317
Volume porosity,	0.4
O_2 Diffusion coefficient, D_1	1.629_10^{-5}
CO_2 Diffusion coefficient, D_2	1.592_10^{-5}

Simulation

The CFD package CFX 4.1 (CFDS 1995), was used to solve the time-dependent, non-linear differential equations, which describe the heat and mass transfer within the grain store. The equations have been described by Bibby and Conyers (1998), so will not be repeated here. This is a finite-volume based code, which uses body-fitted co-ordinates where the geometry is non-orthogonal and is thus able to reproduce complex shapes. The store geometry is subdivided into volumes, usually called cells, in which the differential equations, converted into numerical form, are solved. The number of cells used depended on the store being modelled, and ranged from 60,000 to 750,000. Small cells, about 30 mm thick, were placed near leakage points.

Leakage was modelled by ascribing a low porosity to the cells adjacent to the leakage points. Values for the porosity were derived from small scale grain bin trails carried out by ADAS, and varied from 0.05 to 0.083 (c.f. grain = 0.4). These porosities correspond to average leakage gaps of 0.15 to 0.2 mm, respectively. The parameters of primary interest were the gas concentrations in the grain, particularly oxygen, and the temperatures, and their variation with time. Time steps of up to 1 h were used in the simulations, although steps as short as 2 minutes were necessary in some cases to maintain numerical stability.

Boundary conditions

Wind flowing around the store creates a pressure field which either causes air to flow into or gas to flow out of leaks (narrow gaps) in the retaining walls and around the edge of the sealing sheet depending on their position in relation to the prevailing wind. Initially, pressure coefficients (Bibby and Conyers, 1998) were used to calculate mass flows through these gaps, which were then specified as boundary conditions. Here, a more realistic method was used in which a part of the silo surroundings was incorporated into the model. In either case the temperature of the incoming air was set to the measured ambient temperature at each time step.

The floor and retaining walls of each store were assumed to be adiabatic, i.e. no heat transfer. The plastic sheet covering the grain was modelled as a very thin membrane directly on top of the grain surface. This acts as a barrier to gas flow but allows heat transfer by conduction. Its temperature was assumed to be equal to the ambient temperature.

Gas (MA) was injected through the ducts in the floor normally used for aeration. In the model these inlets were defined as mass flow boundaries with fixed flow rates. Mass fractions of O_2 and CO_2 in the injected gas varied slightly with time, hence measured values were used at each time step. Gas temperature was assumed to be the same as the ambient temperature and was updated at each time step.

Computer simulation of 250 tonne sloping fronted floor store

The store with retaining walls on three sides and a sloping front face, is shown schematically in Fig. 2. The simulations include diurnal variations in ambient temperature between 2ºC and 12ºC, but not wind, and a gas input rate of 15 m^3/h. Initially simulations demonstrated the importance of having some means of escape (leakage) for the trapped air, particularly at positions near the front of the slope and at the back of the bulk. Normally, leakage along the edges of the covering sheet should allow the store to be purged completely in about 50 h. The simulation showed that the most rapid purge, 40 h, is obtained if the gas injection position is at a point furthest from the main leaks, in this case introducing gas at the front of the slope. In this way the atmosphere inside the bulk is carried towards the leakage points at the back wall. In practice, the positions of leaks are not always known. The fact that such complete purging was only partially achieved in practice suggests that leak sources were greater than predicted or that there were unidentified paths for ambient oxygen to enter the grain bulk, such as cracks in aeration ducts or porous retaining walls.

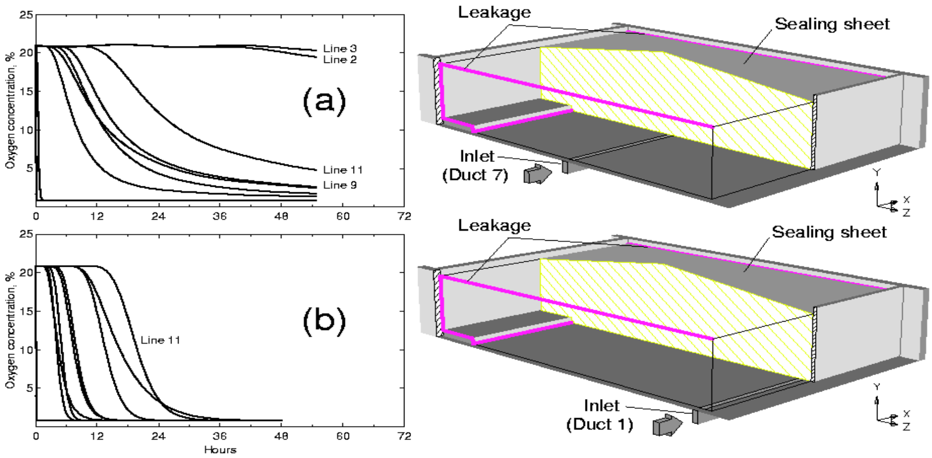

Fig. 5. Predicted oxygen concentrations during purging at sampling points in a 375 tonne grain floor store with a front retaining wall, using two gas injection positions. Purge flowrate (15 m^3/h), and back wall edge leaks and sealing sheet side-edge leaks are the same in both cases. (a) Gas injection near the middle (Duct 7); (b) Gas injection near the front (Duct 1).

Computer simulation and validation of trial in a 375 tonne box-shaped floor store

The store with retaining walls on all sides, is shown schematically in Fig. 3. The simulations include diurnal variations in ambient temperature between 2ºC and 12ºC, but not wind. Fig. 5 shows predicted oxygen concentrations during the purge phase. Surprisingly, purging using a central duct, Fig. 5(a), is not efficient, despite the presence of sheet side-edge leaks. This was the situation observed in practice. In the simulation, sampling positions 2 and 3, in the front corner at the bottom and top respectively, still show high oxygen concentrations after 54 h. This appears to be due to a combination of two factors. First, the gas and air must flow upwards to escape at the front but the flow resistance of grain is higher in the vertical direction than the horizontal direction, and second, lower resistance to flow towards the back because of a greater area for leakage at the back compared with the front. Fig. 5(b) shows the same improvement to be gained by siting the injection position as far away as possible from the main leaks, as was shown for the bulk with the sloping front. Purging was completed in approximately 40 h. It was slightly longer in practice.

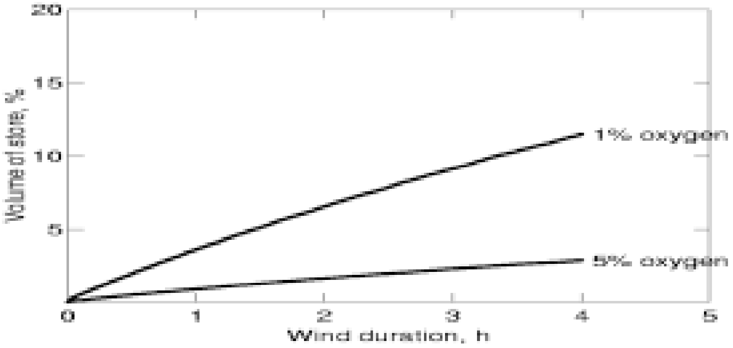

Fig. 6. Predicted growth of the volume affected by a 1.0 m/sec wind, in a 375 tonne grain floor store with a front retaining wall. Initial oxygen concentration is 0.8%. Gas injection flow rate 7.5 m^3/h.

Fig. 6 shows the predicted ingress of oxygen as a result of a 1 m/s wind to the rear of the store, as occurred during the second trial. The leakage gaps in this case are assumed to be 1.5 mm, a worst case condition. Approximately 11% of the grain bulk volume contained above 1% O_2 after 4 h. Wind penetration occurs both around the edges of the covering sheet and through side-wall gaps. This occurred despite a MA maintenance flow rate of 7.5 m^3/h. Cessation of the wind allowed a restoration of the atmosphere to below 1% O_2 within a few hours. Studies on the efficacy of low O_2 exposures against insects have indicated that interruptions of up to 16 h at O_2 levels up to 5% can be tolerated without a need to increase the overall treatment exposure time (Conyers and Bell, 1996).

CONCLUSIONS

(i) The shape of a floor-stored grain bulk grain has important implications for the degree of sealing achievable and may influence atmosphere maintenance rates, but does not fundamentally influence gas application strategy. Level bulks offer the best prospects for efficient treatments.

(ii) Low oxygen atmospheres can only be maintained effectively if store floors and walls are reasonably gas tight.

(iii) If the major leak positions are concentrated in one area and their position can be defined, then the most efficient purge is obtained when the MA injection position is placed at the opposite end of the bulk.

(iv) The predictions show that under windy conditions the pressures created by MA injection are unable to prevent air penetration into floor stores with injection rates of up to 15 m^3/h into 250 tonnes. Interruptions to the atmosphere replacement are to be expected.

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