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Optimising the use of grain stirrers to enhance on-floor drying

by

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1. ABSTRACT

Grain stirring by vertical augers is a method of mixing grain in bulk stores. It is used to remove the gradients in moisture content (m.c.) that develop when drying a deep bed, and before or after drying. The stirring process adds an extra dimension to bulk drying because it can be used in various ways, *e.g.* speeding up the drying of the upper layers to reduce risk from fungi, reducing over-drying of the lower layers, and allowing higher temperature air to be used that can increase drying rate. The aim of this project was to examine how stirring influences drying, and how the potential advantages can be best exploited, with a particular focus on potential to save costs for users. A simulation model of bulk drying was used for the study, plus a new element to simulate the action of stirring on the grain bed. This model was validated successfully against a 25t wheat drying experiment at The Food and Environment Research Agency (Fera) in 2010, drying of two such bins in 2012, one stirred and one static, a published drying test for an 86t bin using higher air temperature, and data from a farm bulk store in 2012, one block of which was stirred, one static.

The simulation model generated performance data for drying wheat from m.c. values of 24 – 16% to a target of 14.5%, at bed depths of 4, 3 and 2m using 20 years of weather data from Lincs. Risk of fungal toxin was calculated, and only treatments giving 19 or 20 years without risk were counted as successful. A range of drying approaches was tested.

When using the drier with r.h. in the plenum regulated to 62%, stirring the bed continuously reduced the risk of fungal toxin Ochratoxin A (OA) substantially, compared with a static bed, and hence allowed grain at 2% higher m.c. or 1m higher depth to be dried. But drying with stirring took substantially longer and the fuel and electricity costs were higher. So, when using near ambient air temperature, stirring was only helpful if otherwise there was a risk of OA as judged by the HGCA Safe Storage Time Calculator.

Stirring allowed use of higher plenum air temperatures, within constraints of component design and safety. Use of higher air temperature when stirring, e.g. 30°C, reduced drying time substantially compared with using near ambient air temperature, Electricity cost was reduced because the fan and stirrers were used for a shorter time but fuel use was generally increased.

Guidelines set out which drying problems would, and would not, be addressed by stirring, and how to make best use of a stirring system.

2. SUMMARY

2.1. Introduction

Grain needs to be dried following harvest to avoid problems associated with fungi and mites during subsequent storage. In most seasons, on-floor drying, using ambient or heated air can be effective and economical but still requires considerable skill. In poor seasons, an on-floor system will incur considerable costs and may not achieve good enough results, however skilful the operator.

In a conventional on floor drier, the grain is static and drying proceeds from bottom to top. Grain at the top of the bed remains close to the initial moisture content (m.c.) until drying is nearly complete. In contrast, when vertical augers mix the grain bed during drying, layers of wetter grain are mixed into the mass, drying them more quickly and thus reducing the risk of spoilage by fungi. Other benefits of stirring in terms of quality and cost are available, in principle, whatever the season. For example, overdrying can be avoided so it may be possible to exploit different, and potentially more energy-efficient, drying strategies. If a greater depth of grain can be used, this would allow more grain to be dried with an existing drying floor.

This study examined stirring and how to integrate it with on-floor drying practice. The aim was to calculate drying performance with and without the use of stirring (likely success, drying time and cost) so as to help growers decide whether to invest in a stirring system and to show, with user guidelines, how to get the maximum benefits from a stirring system. This was tackled by developing and exploiting an integrated simulation model of stirring and drying, used with historical weather records, to run a wide range of drying scenarios.

2.2. Development of the new model

“Storedry” is a simulation of bulk drying which has been used for several HGCA projects. The new model of stirring was implemented as modifications to Storedry, and represented the essential features of the action of vertical augers on the grain bed.

The first stage of the new stirring model considers the action of a single auger, embedded in a grain mass but not moving laterally, which has been running for long enough to produce a stable flow pattern of grain. A circulation zone is formed in the grain by the action of the stirrer. Grain is lifted by the auger to form a cone at the bed surface. The moving mass of grain below the surface also formed a cone that extends from the bottom of the auger to meet the cone on the surface base to base (Figure 1). The assumption was made that the circulation of grain due to the action of the auger was enough to completely mix the grain in the circulating zone. This is justified by the slow lateral speed of augers that are lifting grain at quite high flow rates. The conical shape of the

circulating zone implied that differing proportions of the drying model's grain layers were entrained (i.e. drawn into the circulating zone), small amounts at the point and larger amounts at the widest part of the cones. The m.c. and temperature in the circulating zone were calculated from the m.c. and temperature of the grain in each layer and the mass of grain entrained from each layer. Lateral distribution from the stationary auger was modelled by combining at each layer the appropriate proportion of grain in the mixed volume with that not entrained by the auger.

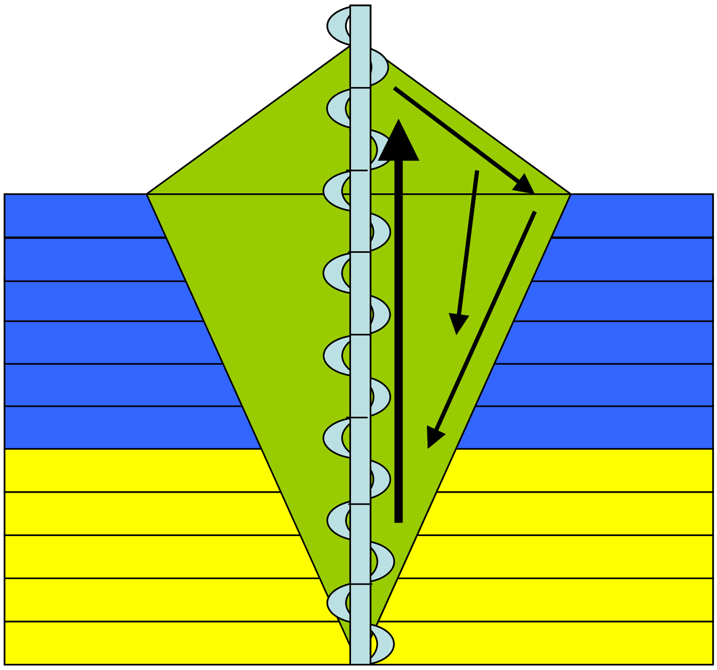

Figure 1. Circulation zone formed by auger (green), with arrows indicating grain flow direction and speed.

Movement of the augers around the grain store was modelled as follows. Storedry was modified to simulate drying in many "mini" grain beds in parallel, only one of which was stirred each hour. The model allowed for 20 such beds, enough to allow a realistic pattern of auger movement around the store to be defined. As the auger moved from one bed to the next, mixing of grain between the mini-bed just stirred and the next in the stirring sequence was modelled by a similar procedure as already described.

There is some evidence that stirring reduces air resistance, but only marginally unless the grain was compacted or deteriorated. Such a reduction would allow more airflow if the fan were capable of providing it. The stirring model was developed to allow a reduction in air resistance to occur.

In the new model, mixing and averaging was applied to physical parameters, *i.e.* moisture content and temperature, but was not appropriate to biological quality attributes, *i.e.* the progress towards the risk of Ochratoxin A (OA) and the loss of grain viability. So the new model takes a conservative approach by finding the layer in the bed before stirring in which biological attributes are worst and ascribing them to all the other layers in the bed after stirring.

The model allowed simulation of running the fan and heater for a time before starting stirring, and of stirring to even out the bed once drying was finished. An option to start with a non-uniform bed of grain was added, so that drying of grain in layers of different initial m.c. could be simulated.

Approximately 750 lines of code were needed to implement the changes described above.

2.3. Validation of the model

Validation was done in four stages. First, the model was run at ‘standard’ near-ambient drying conditions and the results with stirring were compared qualitatively with results when stirring was not used. This allowed the behaviour of the stirred bed drier to be checked to ensure it was reasonable. Second, the measured conditions in experiments carried out on 25t bins of wheat at the Food and Environment Research Agency (Fera) in 2010 and 2012 were used to run the model to predict conditions of temperature and moisture content in the bed during drying. These predictions were then compared with measurements. Third, an experiment reported in the literature in an 86t bin of wheat using a higher air temperature, 38^{o}C, was simulated and results compared with those reported. The fourth stage was to measure performance on a commercial site of stirred versus static drying and validate the model against these data.

The behaviour of the simulation model when run at ‘standard’ drying conditions was in line with expectations from principles already well understood, in that the entrainment of grain into the mixed zone reduced with increasing depth and the exhaust air relative humidity (r.h.) fell as stirred drying proceeded and so gave a reduced drying rate. Agreement with the within-bed data from the 25t wheat drying experiments at Fera was good in the important respects, particularly drying time, approach to and level of final m.c., effect of each mixing event on m.c. through the bed and rapid reduction of m.c. of surface layers to a lower value. Within the bed, the simulated drying rate of the middle layers was too fast, despite which, agreement was good in other respects. Simulation of the experiment reported in the literature in which an 86t bin of wheat was dried and stirred gave results which agreed very well with the measured overall performance. Wheat on the commercial site in 2012 needed little drying so the model was tested in low moisture removal conditions but results did not raise any doubts about its performance.

The overall conclusion from the validation work was that the model was sufficiently good over the range of m.c. encountered in the experiments and, because it was based on well-understood physics of drying, could be used with confidence over a wider range than found in validation experiments.

2.4. Simulations to explore the performance, effectiveness, energy saving and cost saving potential of stirring in normal on-floor drying

In this study, 21 sets of simulations of various drying systems were run to produce data on their likely performance under a wide range of conditions. By comparing performance in various ways, the benefits and drawbacks of one system versus another, or of one choice of operating condition versus another, was shown. First, static and stirred beds were compared under input conditions normal for a static bed drier. Then various approaches were used to find out how best to take advantage of the stirring system. Bed depths of 2-4m and initial m.c. values of 24-16% were used.

To enable a fair comparison, stirred drying was compared with best performance from static bed drying. This was found to be with the fan running continuously and a powerful heater set for 62% r.h. in the plenum. Under these conditions, stirring was very effective in reducing the progress towards risk of OA because, at higher values of initial m.c., stirring avoided the persistence of wetter grain at a condition that favoured fungal growth. Where a static bed approach resulted in risk of OA, stirring the same bed allowed drying without risk of OA from an initial m.c. of about 2% m.c. higher or for a grain bed depth 1m deeper than the limit for static bed drying. Over-drying of the bed as a whole was reduced by stirring. However, compared with static bed drying, stirring made the drying considerably less efficient and so increased drying time and cost of fuel and electricity. Drying is less efficient because air within the bed can only saturate as far as the surrounding grain moisture allows. The higher the m.c. of the grain the more saturated the surrounding air can become. Stirring the grain lowers the m.c. at the surface because drier grain is brought up from lower levels, and so the amount of water that is carried away per unit of air exiting the surface is also lowered.

In approaches where the r.h. in the plenum was regulated, drying performance was a compromise. Stirring reduced over-drying and the risk of OA but increased drying time and electricity and fuel costs. When the initial m.c., and hence the risk of OA, was not high, a useful approach was to stir to eliminate m.c. gradients only when the target average m.c. had been reached. This approach gave less over-drying than static bed drying and hence faster drying, lower fuel and electricity cost. Drying with stirring down to 18% m.c. and then stirring only once the average m.c. was reached gave a compromise between avoidance of OA risk and drying efficiency, and was effective for grain not over 20% initial m.c.

Using fewer augers, and hence stirring any location less often, reduced drying time and improved energy efficiency but the risk of OA increased at higher initial m.c.

Lower airflow increased drying efficiency but extended drying time, whilst higher airflow did the opposite.

Regulating plenum air temperature rather than r.h., and heating that air to 20°C or more, resulted in quicker drying, much reduced risk of OA and little over-drying. If using this approach, a plenum temperature of 30°C produced the best compromise between drying speed, energy use and tendency towards over-drying. Electrical energy use was greatly reduced at elevated air temperatures because of the shorter drying time, but fuel energy use was increased compared with static bed drying.

Drying rates achieved when drying with a static bed or continuous stirring and a regulated plenum r.h. were in line with the rate expected for a bulk drier of 0.5% m.c. per 24h. This rate could be increased substantially by using stirring together with plenum air temperature raised to 30°C and above.

2.5. Development of user guide-lines to show how to achieve the full range of benefits from stirring

The first area explored is whether a stirring system is likely to help solve various drying problems, *e.g.* high costs or slow drying rate, better than alternative investments. Addition of stirring to a standard drier may only be justifiable after the implementation of several other approaches to keeping the risk of OA low. These approaches include using a higher airflow (more fan capacity) and an increase in the heater power available.

Then, drying problems are considered from the viewpoint of whether a stirring system retro-fitted to the existing drier would be likely to be of benefit. In this scenario, the main problem that would be addressed is when grain is at risk of OA according to the HGCA Grain Safe Storage Time (s.s.t.) Calculator. If the s.s.t. is shorter than the time needed for the drying front to reach the surface, the surface grain would be at risk of OA. Stirring throughout drying would reduce the risk very substantially. However, the problem of high fuel and electricity costs would not be reduced by simply stirring an existing drier, because stirring reduced drying efficiency.

If, however, the drier is designed to use stirring with higher plenum air temperature, drying rate can be increased using this approach while OA risk and electricity cost can be reduced. The problem of high fuel cost will not be solved because even at higher plenum temperatures, stirring did not reduce fuel use.

If a stirring system is available, stirring the grain bed before drying can help the drying to be more uniform across the store. Thereafter, whether stirring will be helpful depends on the grower's priorities for drying. If operation at elevated plenum temperature is an option and if short drying time, low electricity cost or both are priorities, then the drier can be run with air temperature raised to at least 30^{o}C. This option will, however, increase fuel cost compared with static bed drying. If initial m.c. is above 18%, sampling should be done to check OA risk using the s.s.t. calculator and if there is a risk, stirring during drying will reduce it. If operation at higher temperatures is not possible, or if fuel costs are priority, then plenum air r.h. regulation to around 62% without stirring will give rapid drying. Fuel efficiency will be better than using higher temperature with stirring. Once the average m.c. of the grain bed has reached the target of 14.5% (for example), drying can be stopped and stirring used if it is necessary to even out gradients in the bed.

2.6. Conclusions

Work to validate the model showed that:-

1. The behaviour of the simulation model was in line with expectations in that, compared with a static bed, stirring reduced the m.c. of the grain near the surface, thus lowering the rate of spoilage and the risk of OA. But the reduced m.c. at the surface also lowered the exhaust air r.h. as drying proceeded, which resulted in a reduced drying rate of the stirred bed.
2. Considering the validation work overall, agreement of the model with the data from the 25t wheat drying experiment at Fera in 2010 was good in the important respects, particularly drying time, approach to and level of final m.c. Validation against data from a stirred and a static bin at Fera in 2012 showed that the model predicted the overall drying behaviour of both bins well and, although stirring in the model was less vigorous than in practice, the accumulated effect was sufficient to mix the bed to a similar degree. The drying fronts in the model were steeper than measured but this did not affect drying time, which was well predicted. Because the wheat on the commercial site in 2012 needed little drying, data could not be had for drying using significantly higher air temperature. Testing of the model in these low moisture removal conditions did not raise any doubts about its performance, and indeed together with the data from the bin experiments, allowed the relationship between m.c. and air r.h. to be confirmed. Simulation of a published experiment in which an 86t bin of wheat was stirred and dried with air at a higher temperature gave results which agreed very well with the measured overall performance. Because the drying time was well predicted, the fuel and electricity use were also, as they are the product of running time and heater and fan power. Overall, the model proved to be sufficiently good over the range of m.c., air temperature and stirring rate encountered in the experiments. Because it is based on well-understood physics of drying, the model, it was concluded, could be used with confidence over a wider range than found in validation experiments.

Extensive use of the simulation model showed that:-

3. For comparison with a stirred bed, the best performance from a static bed drier was to run the fan continuously and to use quite a powerful heater set to regulate plenum r.h. to 62%. Under this fan and heater use, stirring was very effective in reducing the progress towards risk of OA. Where a static bed approach resulted in risk of OA, stirring the same bed allowed drying without risk of OA from an initial m.c. of about 2% m.c. higher or for a grain bed depth 1m deeper than the limit for static bed drying.
4. Compared with static bed drying in identical conditions, stirring the grain bed continuously whilst drying made the drying less efficient and increased drying time and cost of fuel and electricity, but over-drying of the bed as a whole was reduced. Efficiency was reduced because the exhaust air was less saturated when stirring.
5. With 62% r.h. plenum air, performance of drying was improved compared with a static bed by stirring only when the target average m.c. had been reached, avoiding the need to continue drying the wetter part of the bed. This approach gave faster drying, lower fuel and electricity cost and less over-drying.
6. Using fewer augers, and hence stirring any location less often, reduced drying time and improved energy efficiency. But at higher initial m.c. the beneficial effect of stirring on risk of OA was reduced. Lower airflow when stirring extended drying time, reduced electricity cost but increased fuel cost and risk of OA. Higher airflow did the opposite.
7. Controlling plenum air temperature rather than r.h. and heating that air to 20^{o}C or more while stirring resulted in quicker drying and with much reduced risk of OA and little over-drying. If using this approach, a plenum temperature of 30^{o}C produced the best compromise between drying speed, energy use and tendency towards over-drying. Electrical energy use was greatly reduced at elevated air temperatures because of the shorter drying time, but fuel energy use was generally increased.
8. Drying rates achieved when drying with a static bed or continuous stirring were in line with the rate of 0.5 % m.c. per 24h, expected for a bulk drier. This rate was increased substantially by using stirring together with plenum air temperature raised to 30^{o}C and above.
9. User guidelines are presented, drawing on the simulation results in the report, that highlight which drying problems stirring is likely to help solve and which not, so as to guide investment decisions. Guidelines are also presented on how best to use a stirring system, if available, to meet the grower's priorities for drying, whether drying speed, fuel or electricity costs.