Omni-science: transformative approaches to postharvest technology

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Abstract

Postharvest technology is predicted to experience a transformation over the next couple of decades. Some of the changes may be wrought by as yet unforeseen developments in science, but others will result from the rapid evolution of computer software and hardware. Commercial software is presently available that integrates many strands of engineering science such as structural mechanics, the flow of particulate solids, the distribution of gases within buildings and thermal analysis. The software also enables interactions between these various processes, and the approach is referred to as multi-physics. Commercially available software can be tailored to account for biological phenomena such as the effects of the microenvironments in grain stores on the viability of seeds, the rate of decay of pesticides, the propensity of insect populations to increase and so on. The time is ripe to integrate these chemico-biological aspects of grain storage with multi-physics to form what might be dubbed an omni-scientific approach to postharvest technology. The development of such an approach will help unify the disparate sciences involved in grain handling, and it will provide an explicit overarching intellectual framework into which individuals' work will fit. Information and communications technology will not only enable technical problems to be addressed, but it will enable a range of specialists to contribute simultaneously to solving particular problems. Such a scenario will have a profound effect on the postharvest profession, and it will require a radically new approach to the education and formation of stored grains technologists. These specialists must continue to have deep knowledge of specialised areas of science such as genetics, analytical chemistry, fluid dynamics and so on, but they must also be familiar with the integrating software tools and a broad range of science. Postharvest professionals will need to be familiar with several scientific disciplines, i.e. they will need to be omni-scientists, whilst recognising that omniscience is unattainable.

Keywords: Omni-science, Multiphysics, Postharvest, Grains, Storage.

1. Introduction

Postharvest technology is intensely multidisciplinary. Its principal aim is to maintain desirable properties of agricultural produce between its being harvested and its end-use, which could be processing or direct consumption. In the case of stored grains technology, food grains must be stored free from insect pests and moulds, and properties such as baking quality and germination must be preserved. These goals are generally met by manipulating the physical and chemical environments within grain stores, such as grain moisture content and temperature, the intergranular atmosphere and concentrations of pesticides. If we are to manipulate the stored grains ecosystem we clearly require a deep understanding of the physics of hygroscopic porous media and fluid mechanics, the biology of insects and moulds, the biochemistry of food grains and chemical kinetics. Properties such as grain moisture content are often manipulated ex-store using grain driers, and grain may be disinfested of insects by means of equipment such as fluidized beds, aspiration cleaners and by percussive processes associated with the acceleration and impact of grain kernels.

The physics of heat and mass transfer in ventilated bulks of stored grains has been studied for several decades. Most early research was limited to studies of one-dimensional systems, and some could deal only with grain bulks that have initially uniform properties and time-invariant boundary conditions such as the temperature and humidity of the air entering the system (Barre et al., 1971, Sutherland et al, 1971). Numerical solutions, such as that developed by Boyce (1966), allow the latter restrictions to be lifted. Analyses of heat and mass transfer in three-dimensional systems were ultimately developed, firstly for grain stores that had simple geometries (Singh and Thorpe, 1993) and then for those with more realistic shapes (Thorpe, 1997). One of the main problems with early mathematical models of heat and mass transfer in stored grains is that they require a considerable degree of mathematical and computational expertise to formulate and to obtain results. The computer codes were usually developed in particular laboratories and their documentation was rarely designed to be user-friendly: the result was very little interoperability of the software between laboratories.

One impediment to progress in postharvest technology may be that some of its practitioners view the activity as a specialism. Evidence for this can be found in the postharvest literature on the development of mathematical relationships between the pressure gradient and the velocity of air flowing through stored grains. Some of the earliest attempts by Shedd (1953) and Hukill and Ives (1955) were purely empirical and have no justification on physical grounds, and they are also inconvenient to manipulate mathematically. Despite these difficulties postharvest technologists continue to use them (Kashaninejad and Tabil, 2009). An alternative approach is to regard the problem of the flow of air through bulk grains and other commodities as the flow of a fluid through a porous medium. Early attempts at tackling this more general problem were made in the 1930s by researchers such as Forschheimer (1930) and Carman (1937). Their work was later refined by Ergun (1952) whose expression for the relationship between pressure gradient and fluid flow rate accounts for physical properties such as the diameter of the particles composing a bed of porous media and the porosity of the bed. Furthermore, Ergun's (1952) equation accounts for the effects of the viscosity and density of the fluid flowing through the porous medium. An additional feature of Ergun's (1952) equation is that it has an extremely simple mathematical form. The possible isolation of postharvest technology from mainstream engineering science is also evidenced by the work of Lukaszuk et al. (2009) that purports to present data on the resistance to air flow through grains in the horizontal and vertical directions. The authors' data indicate that there is a finite pressure gradient within the grain, even when the prevailing air velocity is zero. Had the work been presented within a mainstream engineering framework, the authors may have been alerted to this paradox. More recent approaches to flow through porous media involve studying interstitial flow fields from which the behaviour of the macroscopic system can be estimated (Breugem and Rees, 2006).

Pragmatism and commercial pressures often conspire to produce *ad hoc* approaches to other areas of postharvest technology. For example, whilst experiments on the efficacy of microwave radiation as a means of disinfesting grains are valuable, they tend to be scoping studies rather than detailed definitive studies. A possible reason for this is that microwave engineering is highly specialised, and in depth studies restricted to disinfesting grains would require expertise beyond that usually available in stored grains laboratories.

Information is lost when data are averaged. However, a feature of modern science is that complex systems are being studied in unprecedented detail. Had Vayias and Stephou (2009) been working in this paradigm, they may have chosen to have presented their results on the insecticidal efficacy of an enhanced diatomaceous earth formulation in somewhat more detail. Unfortunately they chose to aggregate their insect mortality data obtained under different temperatures and present them as a function of the relative humidity of the air in which their grain samples were in contact. It is argued in this paper that if postharvest research were carried out within a framework that makes its usefulness explicit authors would present their work in a more coherent form.

Stored grains insect pests have proved remarkably sensitive to rapid acceleration as occurs when grain kernels containing developmental stages of insect pests impact with surfaces and with each other. Experiments have been carried out on practical applications of these percussive effects when grain is being turned or pneumatically conveyed (Paliwal et al., 1999), but if we are to optimise devices, we need to be able to predict the number and nature of the collisions experiences by the individual grain kernels. Insights into the behaviour of individual particles remain in the province of specialists in a domain of engineering computation known as the discrete element method.

2. Multiphysics – a contemporary approach to engineering analysis

The above discussion has highlighted two problems facing stored grains technologists. Firstly, specialised knowledge in areas such as heat, mass and momentum transfer in grain bulks, microwave heating, tracking the paths of individual grain kernels often does not exist in postharvest laboratories. Secondly, it is very difficult to transfer any expertise that may exist in one laboratory to another laboratory with the objective of making it generally accessible. However, the engineering software industry is making considerable progress in overcoming these difficulties by developing suites of software that incorporate multiphysics. The software integrates several branches of physics such as strength of materials, computational fluid dynamics, heat transfer and electromagnetic waves such as microwaves. Furthermore multiphysics software also incorporates *interactions* of several simultaneously occurring physical phenomena such as the dynamics of the motion of individual grain kernels and heat and mass transfer that may occur in fluidised bed driers. Modern software is also relatively easy to operate and much of the data entry and operation is carried out using drop-down menus. The geometry of the system being studied, a grain silo for example, is relatively straightforward to generate, and the specialised process of generating the finite difference mesh on which the governing differential equations are discretised is automated. Post processing of the results is extremely sophisticated and it allows solutions, such as the rate of cooling grain in an aerated grain silo to be animated.

Modelling the stored grains ecosystem relies on the solution of very large sets of coupled non-linear differential equations. Proprietary software incorporates efficient solvers and the codes can be parallelised so that they can be run several orders of magnitude more quickly than on a single processor. Importantly, the solution procedures are largely automated and the solution algorithms remain invisible to the user; this situation is quite different from the one prevailing when postharvest technologists wrote their own, often idiosyncratic codes.

Some of the problems in the domain of postharvest technology that multiphysics software is able to analyse include:

a) The design and operation of grain aeration systems.
b) The design and operation of grain fumigation systems.
c) An exploration of the behaviour of grain kernels in pneumatic conveying systems.
d) Tracking the locations and temperatures of individual grain kernels in fluidised bed grain drying and disinfestation devices.
e) Microwave heating of grains and insects.

By its nature, multiphysics software is extremely general and it must be tailored to suit specific postharvest applications. In some cases, such as investigating the performance of pneumatic conveyors, this may entail little more that entering physical properties of grains such as their thermal conductivity, density, coefficient of restitution and so on. In other cases, such as studying aeration systems, it is necessary to supply source terms that account for the heat of sorption when grains adsorb or desorb moisture. Contemporary multiphysics software can be accessed by many users, each of whom can contribute to solving the problems at hand. An important feature of multiphysics software is that the various branches of physics are driven by standardised interfaces, and the interactions of the branches are very simple to program.

3. Omni-science – a syncresis of the sciences

If postharvest technologists are to exploit the benefits of the rapidly developing approach to engineering science through multiphysics existing software must be supplemented by the addition of postharvest-specific information. For example, there is a need for models of the sorption and chemical kinetics of fumigants on grains, the response of insect pests of insecticides and fumigants needs to be further refined, and we need a better understanding of how insects distribute themselves throughout bulk of stored grains. The syncretisation, or seamless melding together of these chemical and biological phenomena with multiphysics gives rise to what might be dubbed omni-science. The idea of omni-science enhancing multiphysics software has several advantages for postharvest technology.

4. The postharvest research project in an omni-scientific framework

4.1. The stored grain ecosystem

An abiding interest of grains postharvest technologists is the manipulation of the stored grains ecosystem to control the spoilage of grains. One widely used method of preserving stored grains is to ventilate them with low enthalpy ambient or refrigerated air. It is important to calculate the distribution of air flow within a grain store to ensure that all regions are cooled. Thorpe (2008) has shown that these calculations are easily accomplished by multiphysics software that incorporates built-in expressions for local pressure gradients that are based on Ergun's (1952) equation. Thorpe (2008) has also shown in detail how to account for simultaneous heat and moisture transfer in beds of aerated grain. This allows the temperature and moisture content of the grains to be calculated throughout the grain store and it becomes possible to extend the physical model to include expressions for the increase in populations of insect pests. This latter extension transforms the multiphysics model into an omni-science model. Using this technique the ratio of a population to its initial population of *Rhyzopertha dominica* (F.) has been estimated in a bulk of wheat with an initial temperature of 35°C and a moisture content of 12% (wet basis) and ventilated with air that has a temperature of 10°C and a humidity of 0.007 kg water per kg dry air. Figure 1 shows the distribution ratio of the potential population to the initial population after 150 hours of aeration. This example is given to demonstrate the potential of omni-science, and to perhaps suggest areas for further research, rather than to provide a definitive representation of the phenomena involved.

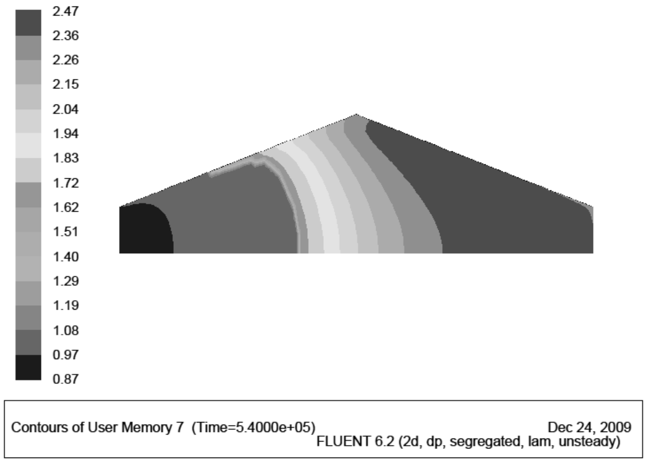

Figure 1 The ratio of potential population increase of *Rhyzopertha dominica* in wheat that has an initial moisture content of 12% (wet basis) and temperature of 35°C, after having been aerated for 150 hours with air that has a temperature of 10°C and a humidity of 0.007 kg water/kg dry air. The specific flow rate of the air is 2 litres per second per tonne of grain.

Fumigant gases such as phosphine are widely used to combat insect pests in stored grains. The low cost and simplicity of application make fumigation with phosphine a powerful weapon in the postharvest manager's armoury, but there are reports that insects are developing resistance to the fumigant over widespread geographical locations. It is therefore essential that grains be fumigated so that the concentration-time product of the fumigant in every location of a grain store ensures that all development stages of insects succumb. Multiphysics software can help postharvest technologists explore the design and operation of fumigation systems. It is straightforward to generate the geometry of a grain store of arbitrary shape – a circular silo with a conical hopper, say, and the interior of the silo is portioned into two regions that comprise the grain and the headspace. The software allows users to define an opening in the silo wall through which the fumigant is introduced and the software automatically calculates its distribution within the grain store. This requires no more than standard operation of the software, but the sorption characteristics of the fumigant on a given type of grain must be specially programmed. Figure 2 shows the estimated distribution of phosphine in a silo partially filled with cottonseed after an elapsed time of 100 hours using the sorption and chemical reaction model presented by Darby (2008). This particular example illustrates how the design of a fumigation system might be improved, and it provides an impetus to investigate the importance of sorption and chemical reaction on the uniformity of the distribution of the fumigant. An omni-scientific approach enables one to incorporate biological data into the model and calculate the concentration-time produce at each point in the grain store, and therefore infer the likely mortality of insect pests throughout the grain store.

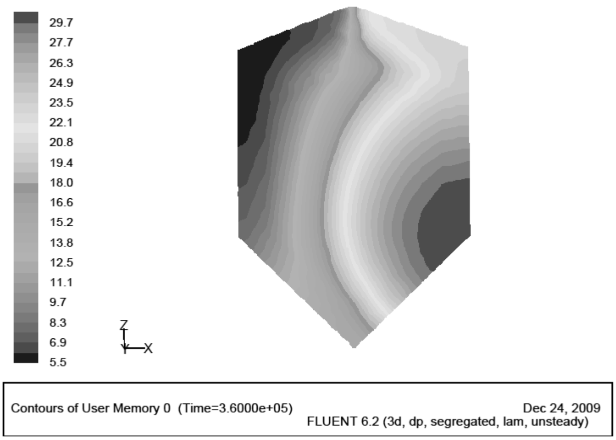

Figure 2 The distribution of phosphine concentration (mg/L) on a diametrical plane in a circular silo containing cotton seed after 100 hours of operation. The phosphine is introduced into the silo through a small hole on the lower right of the plane whence it disperses non-uniformly through the grain, the effect of which is exacerbated by the sorption on and reaction by of the fumigant on the grain.

The two applications of an omni-scientific approach to ecosystem modelling briefly outlined above demonstrate the power of the approach, and they also highlight areas in which the models can be refined. For example, further quantitative research is required in areas such as a) the movement of insects in response to temperature and humidity gradients within grain stores, and the migratory behaviour of insects that enter and leave grain stores, b) the need to generate mathematical models of the sorption and chemical reaction of fumigants in a wider variety of grains, and importantly under a wide range of temperatures and intergranular humidities, and c) more detailed models of the rates of the stages of insect development need to be produced so it is no longer necessary to rely on expressions that relate to populations with stable age distributions.

It is worth pointing out that research on stored grains should be carried out not only under those conditions expected in practice, but also at extrema of temperatures, moisture contents, gas concentrations and so on because it is the latter that are of interest if insects are to be controlled. This is a very general issue, but the requirement to consider extrema continues to recur as evidenced by the work of Vayias and Stephou (2009) who restricted their study if the insecticidal properties of pesticide-enhanced diatomaceous earth to three temperatures, namely 20°C, 25°C and 30°C, and relative humidities of 55% and 70%. These temperatures and relative humidities are typical of those found in grain stores and it may be argued that they are therefore relevant, but they are of less concern from the point of view of controlling pests. Extrema are also of great importance for evaluating mathematical models that must apply over a wide range of conditions.

4.3. Tracking individual grain kernels

There are certain operations in which it is highly desirable to be able to track the location of individual grain kernels. One operation may be the design of pneumatic conveying systems that also incorporate devices that promote insect mortality by percussion. It is also important to model the behaviour of individual grain kernels to ensure that grain silos are designed to empty thoroughly, and possibly in designing devices that sort grain kernels not only by grade, but possibly that can discriminate between infested and uninfested kernels. Fluidised bed driers are used to dry grain, and their effectiveness as thermal disinfestors is well established. One of the advantages of fluidised beds is that they promote extremely good mixing of the grains, so that grains spend only very short times in regions where the air temperature is high. This prevents grain kernels being damaged and it promotes rapid heat transfer between the air and the grain kernels. However, a disadvantage of the rapid mixing of grains in fluidised beds is that it gives rise to longitudinal dispersion that results in some grain kernels having a very short residence time, whilst others linger in the fluidised bed. A net result of this is that the efficiency of fluidised bed driers is reduced because some kernels are over dried.

In this work we shall outline one potential multiphysics application that highlights the potential power of discrete element modelling, namely the development of a novel device for emptying grain silos. Many grain silos used on farms in Australia empty be the grain falling through an opening near the base of conical hoppers, and because of the shallowness of the hoppers or their design some silos fail to empty completely. The silos therefore provide refuges for insects that may infest the following grain harvest. McDiarmid et al. (2009) have invented a device that aims to promote more complete emptying of silos. The idea is to locate the resonant frequency of the hopper containing the grain and vibrate the hopper at this frequency using a proprietary low frequency audio transducer powered by a consumer audio amplifier. This results in the hopper vibrating with a large amplitude thus promoting the emptying of the silo. The resonant frequency is established by measuring the output from an accelerator attached to the vibrating audio transducer. As the silo empties the resonant frequency changes and this is continuously monitored and the input frequency of the low frequency audio transducer is adjusted appropriately. This is an archetypal example of multiphysics in which a structure (the silo hopper) interacts with particles (the grain kernels) and from which the resonant frequency and the locations of the grain kernels may the tracked. If the silo does not empty completely biological data can be used to assess the risk of insect pests being harboured until the following harvest. This represents an extension of multiphysics into the realm of omni-science.

5. The impact of omni-science on postharvest technology

A principal motivation for proposing the idea of applying an omni-scientific approach to postharvest technology is that it provides the discipline with a coherent intellectual framework. This is because postharvest technology is a distinctly applied subject, and the ultimate aim of most laboratory and field experiments is to produce useful data. By incorporating the results into high level computer software one is likely to construct a metanarrative through which individual researchers in postharvest technology will interpret their work.

Omni-science is likely to guide research, and gaps in knowledge will become apparent as researchers strive to develop useful analytical tools. The approach will highlight the importance of studying extrema as these are not only useful from the point of good agricultural practice, but they also provide severe tests of mathematical models.

The development of multiphysics and omni-science software draws on many scientific, computational and mathematical disciplines. This will have several impacts on postharvest technology. It will help to ensure that scientific advances become available to postharvest technologists in a timely manner, and the emphasis on the ease of use and extremely thorough documentation of the software will facilitate its adoption. It will be possible to call on the advice and expertise of practitioners from a diversity of scientific and engineering disciplines not normally associated with postharvest technology. This free flow of knowledge across disciplines will result in postharvest technology being less of a specialism, and it will give rise to far more mobility of personnel into and out of the field. This will result in postharvest technology being constantly renewed with contemporary methodologies and insights. A feature of modern information technology is that it also allows information to be shared rather than simply being transmitted. This will also result in the cross-fertilisation of ideas. If end-users share the technology an omni-scientific approach could result in new developments being adopted more quickly that at present.

Postharvest technologists of the future – possibly within a couple of decades – will reflect the prevailing scientific and technological Zeitgeist. It is impossible to predict what form this will take, but it is likely that boundaries between scientific disciplines will be more porous and transparent. Institutions dealing with postharvest technology would be advised to be adventurous in their recruitment, and to be more reticent in recruiting scientists and engineers specifically with a stored products background. Educational institutions should be prepared to explore the possibilities of multiphysics or omni-science through high level graduate student projects. Exchanges of personnel between institutions with complementary missions should also be encouraged.

Although omni-science may become widespread, omniscience will remain beyond the reach of human beings but it may be approached by computer networks as presaged by Lyotard (1984). The generation and sharing of knowledge is more likely to be a result of computer mediated team work.

6. Conclusions

Stored grain technology is a distinctly applied area of activity. It is also very diverse and it encompasses disciplines such as engineering, physical chemistry, biochemistry, biology, genetics and so on. It is argued that if these disciplines are to be integrated with the aim of obtaining useful practical outcomes it is desirable to devise an overarching and unifying intellectual framework. Multiphysics is a rapidly evolving concept in the physical sciences. It is driven largely by the increasing sophistication of computer software that enables many branches of physics – mechanics, heat, sound, radiation and so on – to be integrated into relatively easy-to-use software packages. The software not only enables problems in many branches of physics to be solved, it enables *interactions* of different physical phenomena to be studied. It is further argued that multiphysics software should be supplemented by incorporating biological phenomena such as the behaviour of insects in stored grains, and therefore multiphysics would be transformed into an omni-scientific approach. This is a scenario that could be well established in a couple of decades. It would have a profound effect on postharvest technology because it would be integrated with developments in a wide range of scientific disciplines, and it would help guide both research and practice. Postharvest laboratories are likely to be enriched by having visitors and recruits from a wide range of backgrounds. If postharvest technology is to take full advantage of the emerging possibilities that omni-science can offer it is essential that scientists and engineers remain steeped in their disciplinary knowledge. However, they should also be aware of the contemporary tools available to integrate their expertise into the wider field of postharvest technology.

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