Recircaeration – a new low energy method of preserving cereal grains

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Abstract

Each year about 2,000,000,000 tonnes of cereal and other food grains are harvested, and their farm gate value is on the order of $500,000,000,000. As a result, the global grains industry is similar in value to that of the oil industry. About 5% of all grains harvested are destroyed during storage by insects, mites and fungi, and in some countries the spoilage exceeds 25%. Grains can be stored for prolonged periods of time by manipulating the stored grains ecosystem by changing the temperature, grain moisture content or the composition of the intergranular atmosphere so that insect pests cannot survive. An effective method of preserving grains is to cool them by blowing through them ambient or refrigerated air. However, because grains are hygroscopic the temperature to which grains can be cooled is a function of both the temperature and the humidity of the air used to aerate them. Ceteris paribus the dryer the air, the lower the temperature to which the grains can be cooled. Warm air cannot be used for aeration and cool ambient air generally has a high relative humidity that limits the degree of cooling that can be achieved. Grains are often stored with moisture contents such that the relative humidity of the intergranular air is less than 60%. In this work it is hypothesised that air leaving the upper surface of an aerated bulk of grain can be cooled and re-admitted to the grain at a thermodynamic state that is more favourable for cooling than ambient air. It is further hypothesised that solar energy incident on the roofs of grain stores passively dries the upper surface of stored grains thus further enhancing the behaviour of grains as a desiccant. A mathematical analysis suggests that grains can indeed be cooled by up to 5°C more using recirculated air, and this has a profoundly beneficial effect on the preservation of grains. The power consumption of the system is estimated to be about 1W per tonne of grain stored, and the energy consumption is estimated to be 250Wh per tonne per month of storage. The performance of a recircaeration system in a climate that is representative of a low altitude region in Southern Queensland in summer has been investigated. It is estimated that a population of the rice weevil, S. oryzae, would increase by a factor of about 6,400 in unaerated wheat that has a moisture content of 11% (wet basis) and a temperature of 30°C, whereas in grain that is aerated with ambient air or using the proposed recircaeration system the increases are 1500-fold and 350-fold respectively. Similar reductions in populations of the lesser grain borer, Rhyzopertha dominica are obtained. Somewhat lower relative reductions in the decay of chemical pesticides are predicted over a period of 100 days, but the benefits of aeration and recircaeration manifest themselves over greater periods of time. The marginal capital cost of the system is negligible. Solar energy passively dries the upper surface of a bulk of grains by a process dubbed desiccaeration, but the benefit of this appears to be offset by the higher overall heat load on the system. Nonetheless, this aspect of the process is worthy of further research.

1. INTRODUCTION

Each year about 2,000,000,000 tonnes of cereal and other food grains are harvested, and their farm gate value is on the order of $500,000,000,000. About 5% of all grains harvested are destroyed during storage by insects, mites and fungi, and in some countries the spoilage

exceeds 25%. Spoilage is particularly severe in tropical environments because the climatic conditions are conducive to the prolific growth of insect populations and fungi, and often the grain storage infrastructure is not well developed. Fungi and mites can be controlled by ensuring that stored grains are sufficiently dry that the relative humidity of the intergranular air is less than about 65%. Desmarchelier (1988) showed that populations of insect pests increase linearly with the wet-bulb temperature of the intergranular air in a bulk of grains. Furthermore, there appears to be minimum wet-bulb temperatures below which species of insects do not reproduce sufficiently rapidly to maintain their populations. Desmarchelier (1979) and Desmarchelier and Bengston (1979) have also demonstrated that the rates at which chemical pesticides decay on grain also increase linearly with the intergranular wet-bulb temperature. The rate at which certain grain quality indicators such as the free fatty acid content of oils seeds has been reported by Banks (1998), and the effects of the microenvironment in grain stores on seed germination has been reported by Wilson and Desmarchelier (1994). The principal conclusion of these works is that the lower the temperature and/or moisture content of stored grains the better the grains are preserved

Thorpe (2002a) points out that when grains are ventilated most of the grains acquire a thermodynamic state that is strongly dependent on the wet-bulb temperature of the air and the initial moisture content of the grains. The lower the wet-bulb temperature of the air, the lower the temperature of the grains. From the work on grain quality described above and the physics of grain storage it is clear the lower the wet-bulb temperature of the air used for aeration and grain quality are intimately connected. The principal components of a grain aeration system are shown in Figure 1.
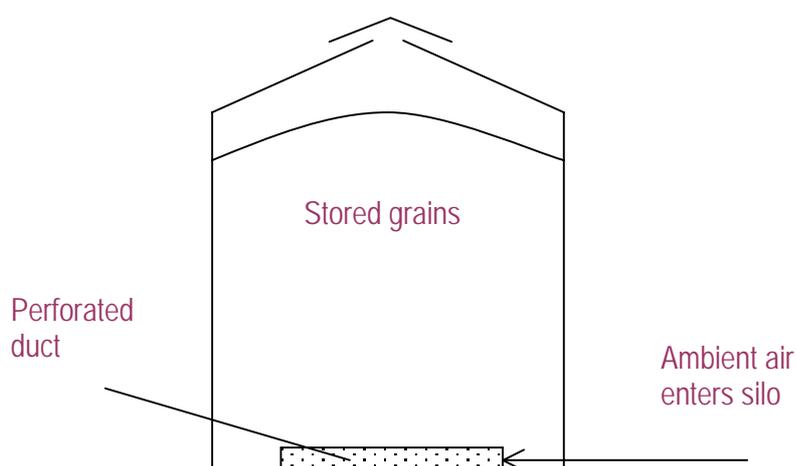
Figure 1 Components of an ambient aeration system for bulk stored grains

In the more northerly grain growing regions of Australia, such as northern New South Wales and Southern Queensland the harvest occurs in early summer, and grains must be stored over the warmest months of the year. Under such conditions, aeration with ambient air is a useful adjunct to good grain storage practice, but nocturnal wet-bulb temperatures may be 20ºC or higher. Such temperatures are not particularly conducive to good grain storage.

Wet-bulb temperature is a function of both the humidity and dry-bulb temperature of air. For example, air with a dry-bulb temperature of 20ºC and a relative humidity of 50% has a wet-bulb temperature of about 14ºC; air with the same dry-bulb temperature but that has a relative humidity of 90% has a wet-bulb temperature of about 19ºC. A difference of 5ºC in the wet bulb temperature of air used to aerate grains can make a substantial difference to maintaining grains in good condition.

Ahmad and Thorpe (1997) describe a grain cooling system that isothermally dries ambient air during the night, and this dry cool air is used to cool grain. During the day solar energy heats air in a solar thermal collector, and the warm air is used to regenerate the desiccant. Thorpe and Li (2002) presented the results of a grain cooling trial in which it was shown that desiccant beds are capable reducing the wet-bulb temperature of ambient air by up to 7ºC, and they outline the design of a commercial prototype unit. Thorpe (2002b) notes that a transpired solar collector with an area of 1m^2 is sufficient to cool 20 tonnes of grains.

In Australia grains are accepted into storage provided that they have moisture contents lower

than prescribed limits. In the case of wheat the upper limit is 12.5% and at 20ºC the intergranular relative humidity of the air is about 55%. Because of the dry conditions that often prevail at harvest time wheat is harvested typically with a moisture content of 11%, in which case the relative humidity of the intergranular air at 20ºC is about 45%. A bulk of stored grains thus constitutes a large mass of desiccant that may be used as a source of air that has a low relative humidity. It should be borne in mind that a bulk of stored grain is likely to act as an effective desiccant throughout a prolonged storage period because its moisture content changes little during the course of aeration. For example, consider grain being aerated with an air flow rate of 0.001m^3/s/tonne of grain stored and the decrease in humidity of the air as it passes through the grain is 0.005 kg water/kg grain. Hence, it takes 10/(0.005×0.001) = 2×10^6 seconds or about 550 hours for aeration to cause an average increase in moisture content by 1%. Furthermore, most of the change in grain moisture occurs in the region where the air enters the grain, so the bulk of the grain stays at approximately the same moisture content, and it may attain a lower average moisture content (Thorpe, 2002a).

2. HYPOTHESES

As a result of the above reasoning the following hypotheses are proposed:

- A bulk of stored grains is intrinsically a bed of desiccant that can provide a source of dry air to be used for cooling grains to temperatures lower than those attainable using ambient air.
- Solar radiation heats the roofs of grain stores. Some of this heat is re-radiated to the upper surface of bulks of grains that heats the upper region of the stored grains. When the grains are ventilated they dry, thus providing a source of low relative humidity air that is highly suitable for aerating the grains.

The hypotheses will be explored in this paper using a simple mathematical model of a bulk of stored grains.

3. AN EMBODIMENT OF *RECIRCAERATION*

A possible embodiment of recircaeration is shown in Figure 2. Air leaving the upper surface of the grain is cooled by either losing heat from the grain store to the surroundings, or by means of a heat exchanger (or by both mechanisms). The idea is that cool dry air is used for aeration.
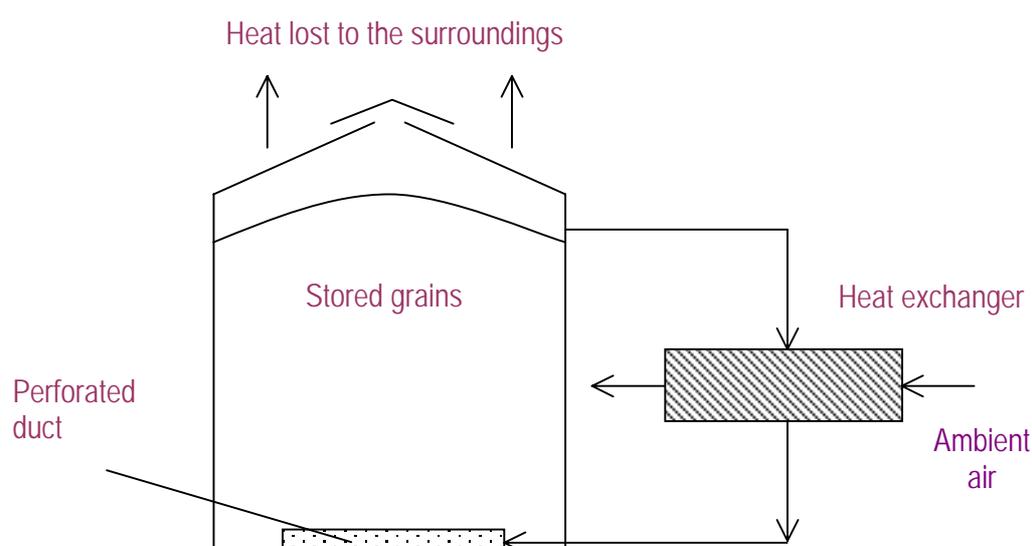

Figure 2. An arrangement of the components of a recircaeration system

4.   METHODOLOGY

Bulks of stored grains are inherently three-dimensional objects and mathematical models of such systems have been formulated (Thorpe,1997).   Although such models provide fine details of the stored grains ecosystem that may be pivotal in assessing the effectiveness of aeration they are computationally extremely demanding.   As such, they are unsuitable for extensive investigations hence in this work a simple one-dimensional model is used. However, it is believed that this model captures with sufficient accuracy the heating of the upper surface of the grains as a result of solar radiation and it is more than adequate to test the principal hypotheses posed in this paper.   The model is used to explore the following:
- The mechanism of heating of the upper surface of the grains as a result of diurnal variations in temperature and solar radiation.
- The subsequent cooling and drying of the upper surface of the grain and its effect on the overall heat loss from the system.
- The effects of the above mechanisms on the suitability of recirculating air around an aerated cereal grain store and their effect on the stored grain ecosystem compared with ambient aeration.

4.2 Mathematical analysis

It has been noted that cereal grains are hygroscopic, that is they adsorb and desorb moisture depending on the temperature and moisture content of the grains and the air surrounding them.   This has a profound effect on how bulks of grains respond when they are aerated. Detailed qualitative and quantitative descriptions have been provided by Thorpe (2002a), and here we present the volume averaged equations that govern heat and mass transfer in ventilated beds of grains. We shall confine the analysis to one-dimensional flows.

4.2.1. Mass transfer in porous media

The equation that governs the conservation of moisture within a bulk of aerated grains is

$$\rho_b \frac{\partial W}{\partial t} + f_a \frac{\partial w}{\partial x} = 0 \tag{1}$$

in which W is the moisture content of grain, kg water/kg dry grain, and w the humidity of the intergranular air, kg water/kg dry air.   The bulk density of the grain is represented by ρ_b, kg/m^3 and f_a is the flow rate of air through a cross-section of 1 m^2 of a grain bulk and it is expressed as kg dry air/(s. m^2). t and x represent time (s) and distance (m) in the vertically upwards direction respectively.

4.2.2. Heat transfer in porous media

The temperature distribution in a bed of aerated grains is given by the equation

$$\left\{ \rho_b \left(c_g + c_w W \right) + \rho_a \varepsilon \left(c_a + w c_w \right) \right\} \frac{\partial T}{\partial t} + f_a \left(c_a + w \left(c_w + \frac{dh_v}{dT} \right) \right) \frac{\partial T}{\partial x} - \rho_b h_s \frac{\partial W}{\partial t} = k_{eff} \frac{\partial^2 T}{\partial x^2} \tag{2}$$

in which c_g, c_w and c_a are the specific heats of dry grain, liquid water and dry air respectively, J/(kg.ºC), ε is the void fraction of the bed of grains, T is temperature, ºC, h_s and h_v are respectively the heats of sorption and latent heat of vaporisation, J/kg, and k_{eff} is the effective thermal conductivity of bulk grains, W/(m.ºC)

4.2.3. Sorption isotherm

Coupling between equations 1 and 2 occurs through the sorption isotherm that enables the humidity, w, of the intergranular air to be related to the temperature, T, and moisture content, W, of the bed of grains.   The latter variables are the two unknowns.   Numerous sorption isotherms have been proposed and we shall make use of the one proposed by Chung and Pfost (1967) that relates the relative humidity, r, of the intergranular air with the temperature,

T, and moisture content, W, of the grain through the expression

$$r = \exp\left(-\frac{A}{T+C}\exp\left(-BW\right)\right)$$ (3)

in which A, B and C are grain-specific empirical constants that in the case of wheat assume values of 921.65, 18.08 and 112.35 respectively. It is required to express the intergranular moisture content, w, in terms of an absolute humidity hence we make use of the following definition of relative humidity

$$r = \frac{p}{p_{sat}}$$ (4)

in which p is the vapour pressure of water in the intergranular air and p_{sat} is the saturation vapour pressure at the temperature, T, that may be estimated using the equation presented by Hunter (1988), namely

$$p_{sat} = \frac{6\times10^{25}}{\left(T+273\right)^5}\exp\left(\frac{-6800}{\left(T+273\right)}\right)$$ (5)

and from equation (4) it immediately follows that

$$p = rp_{sat}$$ (6)

and the humidity w is then determined using the equation

$$w = 0.622\,p/\left(p_{atm}-p\right)$$ (7)

in which p_{atm} is atmospheric pressure, Pa. The sorption isotherm can be used to determine algebraically the differential heat of sorption, h_s, using Hunter's (1988) analysis.

4.2.4. Radiation heat transfer between the roof and the upper surface of the bulk of grain

During the day the upper region of the grain bulk heats as a consequence of insolation on the roof and elevated ambient temperatures. Because this work is of an exploratory nature the simplified system shown in Figure 3 has been analysed. A heat balance is performed on the silo roof accounts for solar radiation striking the outer surface of the roof and some heat radiates to the sky. Heat losses to the atmosphere occur by thermal convection governed by a heat transfer coefficient, h_o. It is assumed that stratification of air and the large air gap between the under surface of the silo roof and the upper surface of the grain renders heat transfer by conduction and convection between these two surfaces negligible. However, heat is transferred by radiation between the roof and the grains, and some of this heat is conducted into the grain bulk.
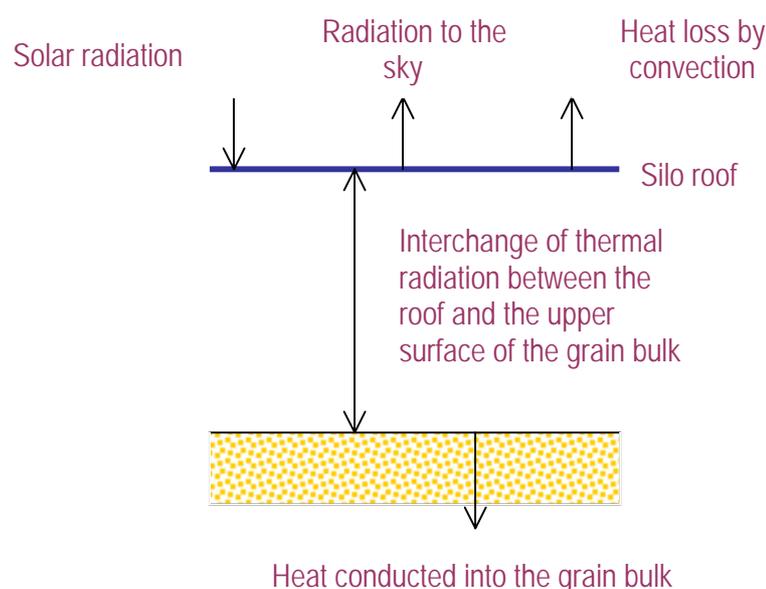

Figure 3. A representation of heat flows on a silo roof and the upper surface of a bulk

of grains

It is deemed that the silo roof and upper surface of the grain are horizontal and a heat balance on the roof of the silo may be expressed as:

$$\varepsilon_o Q_{solar} = \varepsilon_o \sigma \left((T_2 + 273)^4 - (T_{sky} + 273)^4 \right) + h_o (T_s - T_{amb}) + \varepsilon_i \varepsilon_g \sigma \left((T_2 + 273)^4 - (T_g + 273)^4 \right) \Big/ (\varepsilon_i + \varepsilon_g - \varepsilon_i \varepsilon_g)$$

(8)

in which ε_o, ε_i and ε_g are respectively the emissivities of the outer and inner surface of the silo roof and the upper surface of the grain. Q_{solar} is the intensity of the total solar radiation impinging on the outer surface of the silo roof, σ is Stefan-Boltzmann's constant, W/(m^2.K^4) and h_o is the convection coefficient between the upper surface of the roof and the atmosphere, W/(m^2.°C). T_s, T_{amb}, T_{sky} and T_g are the temperatures, ºC, of the silo roof, ambient air, the sky and the upper surface of the grain bulk respectively.

The heat balance on the upper surface of the grain may be expressed as:

$$\varepsilon_i \varepsilon_g o \left((T_2 + 273)^4 - (T_g + 273)^4 \right) \Big/ (\varepsilon_i + \varepsilon_g - \varepsilon_i \varepsilon_g) = k_{eff} \frac{dT}{dx}$$

(9)

4.2.5. Boundary conditions

The dry bulb temperature of ambient air, T_{amb}, is deemed to vary sinusoidally throughout the day, peaking at 3pm and having its minimum at 3am. In the work presented in this paper the mean temperature, T_{mean}, is set at 25ºC and the amplitude, T_{amp} is 5ºC. These values were chosen as being representative of those that prevail in the less elevated regions of SE Queensland where ambient aeration is useful, but not as effective as in more southerly climates. The diurnal temperature variation is expressed as

$$T_{amb} = T_{mean} + T_{amp} \sin(2\pi(t_h - 9)/24)$$

(10)

in which t_h is the hour of the day measured from midnight.

The total solar radiation, Q_{solar}, on the upper surface of the silo roof is a somewhat more gross approximation that that used to estimate ambient temperatures, but again useful for our exploratory purposes. It is quantified as

$$Q_{solar} = \| 1000 \sin(2\pi(t_h - 5)/28), 0 \|$$

(11)

in which $\| z_1, z_2 \|$ signifies the greater of z_1 and z_2. Equation 11 implies that the length of the solar day is 14 hours.

The temperature, T_{in}, of the air entering the silo is either deemed to be at ambient temperature when ambient aeration is being studied or it is defined as

$$T_{in} = T_{amb} + 0.2 * (T_g - T_{amb})$$

(12)

in which T_g again refers to the temperature of the upper surface of the grain. The factor 0.2 implies that the overall effectiveness of the heat exchanger combined with heat loss from the structure of the silo is 0.8. The effectiveness of commercial air-to-air heat exchangers is typically 0.6 (Cusack, *pers. comm.*), hence it is assumed that 20% of the heat of recirculated air is lost through the fabric of the silo. The pressure drop across both the secondary and process air stream is about 400 Pa, and this results in an energy consumption of about 250 Wh per tonne of grain.

The humidity, w_{in}, of the air entering the grain bulk is taken to be 0.0132 kg/kg when the effects of ambient aeration are being considered. In the recircaeration mode the humidity is taken to be that of the air leaving the upper surface to the grain bulk.

4.2.6. Ecological phenomena

4.2.6.1. Insect population dynamics

Although the rice weevil, *Sitophilus oryzae*, is well adapted to the cooler temperate climates it is an important pest insect in parts of Queensland. This is because it cannot tolerate dry conditions that prevail in grain with a moisture content of less than about 10.5% wet basis. Such dry grain is more likely to be harvested in southern regions of Australia that do not exhibit the more humid sub-tropical climates of Queensland. The rate at which populations of grain storage insects pests increase can be found from a slightly modified form of the equation presented by Desmarchelier (1988), namely

$$N_{Sp}^{t+dt} = N_{Sp}^{t} \exp\left(k_{Sp}\left(T_{wet} - T_{Sp}\right)dt\right) \tag{13}$$

in which N_{Sp}^{t} refers to the number of insects of a given species, *Sp*, at time *t* and N_{Sp}^{t+dt} is

the number after a further time of *dt* has elapsed. The parameters k_{Sp} (1/(ºC.s) and T_{Sp} are

species-specific and they are determined empirically. T_{wet} is the wet bulb temperature of the

intergranular air and T_{Sp} is a critical wet bulb temperature below which the species, *Sp*, of

insect will not reproduce.

It is suggested by Fields and Muir (1996) that a dry bulb temperature of grain in the range of 36°C-42°C exists above which reproduction ceases. In the mathematical model the population of insects is set to unity whenever these supra-optimal temperatures are exceeded. This provides an opportunity for the grain to be reinfested if the supra-optimal temperature ceases to be exceeded. Setting the population to zero instead of unity would preclude the possibility of grain becoming reinfested.

4.2.6.2. The decay of chemical pesticides

The rates at which chemical pesticides decay on bulk stored grains are a function of the wet bulb temperature of the intergranular air and they are governed by the Desmarchelier's (1979) equation

$$C^{t+dt} = C^{t} \exp\left(-dt/t_{1/2}\right)$$

$$\tag{14}$$

in which C^{t} is the concentration after an elapsed time of *t* and C^{t+dt} is the concentration

after a time *t+dt*. The parameter $t_{1/2}$ is a function of the wet bulb temperature of the

intergranular air and it is given by

$$t_{1/2} = t_{1/2}^{o} 10^{\left(k_{p}\left(20-T_{wet}\right)\right)}$$

$$\tag{15}$$

in which $t_{1/2}^{o}$ is a chemical-specific constant that represents the half-life of the chemical when

the wet bulb temperature is 20ºC, and k_{p} is an empirical constant.

5.   RESULTS

5.1   Underlying mechanisms

The process of cooling grain is illustrated by observing the behaviour of a bulk of grains that initially has a uniform temperature and moisture content and that is aerated with air that has a constant thermodynamic state.   Such a case is shown in Figures 4a and 4b that show the temperature and moisture content profiles of a bulk of wheat that initially has a temperature of 30ºC and moisture content of 11% after having been aerated with air that has a temperature of 20ºC and a relative humidity of 90% (absolute humidity, *w*=0.0132).   It shows that the leading edge of the cooling wave has travelled a distance of about 3m after 24 hours and the leading edge begins to exit the grain after about 72 hours. Grain in the vicinity of the air inlet cools to the temperature of the inlet air, namely 20ºC, but most of the grain is cooled by only

about 3ºC from 30ºC to 27ºC. This example illustrates a limitation of aeration in warm climatic regions. The moisture content of the grain in the vicinity of the air inlet increases to about 24.7% (dry basis) or 19.8% (wet basis) but it remains close to its original value of 11% (wet basis) as the cooling front traverses the bed of grain. When the temperature wave has completely traversed the bed of grain the wet bulb temperature of all the intergranular air is approximately 19ºC, a condition under which insect pests would proliferate.

The temperature profiles are similar to those predicted by the classical analytical solutions of Sutherland *et al* (1971) but their studies omitted the effects of the thermal conductivity of the grains. In their studies the grain temperatures at the trailing edges of the temperature waves would be constant and they would assume the so-called dwell temperature. It appears from Figure 4a that the effects of the lower temperature of the inlet air is transmitted through the grain by thermal conduction and that in effect a dwell temperature may not exist. It is ultimately annihilated as a result of thermal conduction.
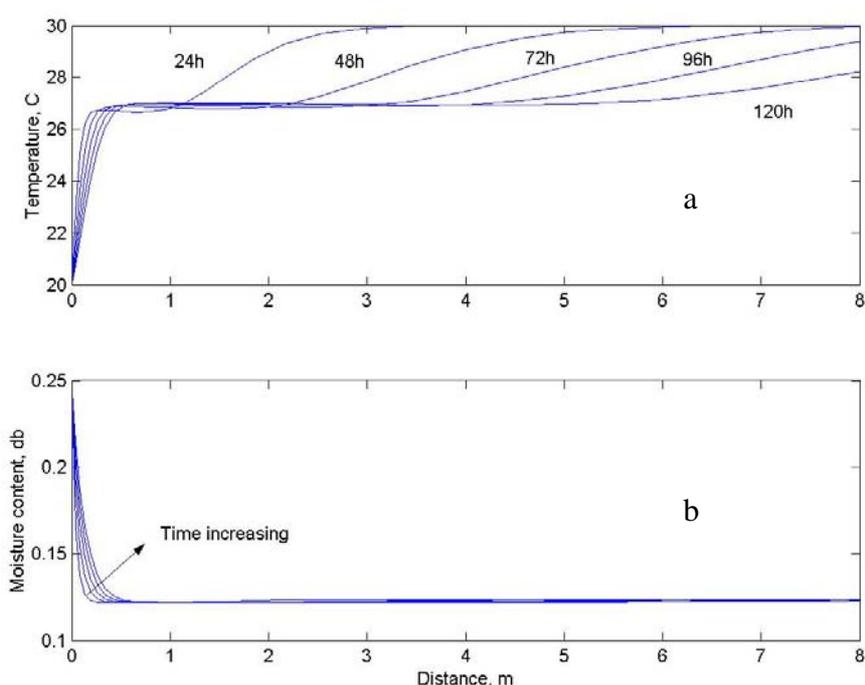

Figures 4a and 4b. The traverse of temperature and moisture waves through a bed of grains when the air flow rate is 0.008 kg/(s.m^2). It can be seen that under these conditions the grain is cooled by just over 3°C, and the moisture content of the grains remains almost constant.

The effects of aerating the same grain with air at 20ºC but that has a lower relative humidity of 50% (an absolute humidity of 0.0074 kg water/kg dry air) are depicted in Figures 5a and 5b. A notable feature is that immediately after the passage of the temperature wave the grains have cooled to about 21ºC, some 6ºC lower than in the case when the relative humidity of the inlet air is 90%. A second feature is that after 72 hours of aeration the leading edge of the temperature wave is just about to exit the grain whether it is aerated with either high or low relative humidity air. This is because for a given air velocity through the grain the speeds of the fronts depend solely on the temperature and moisture contents of the grains. It can be discerned by comparing Figures 4a and 5a that the trailing edge of the cooling wave has penetrated a shorter distance into the grain when it has been aerated with dryer air than when aerated more humid air. The moisture content profile in grain aerated with air with a relative humidity of 50% is markedly different from that aerated with 90% humidity as can be seen by comparing Figures 4b and 5b. When the grain is aerated with low relative humidity air the air in the vicinity of the air inlet is about 13% dry basis (11.5% wet basis), much less than when aerated with high relative humidity air. Figure 5b illustrates somewhat strikingly that grain

aerated with low humidity air is drier throughout the bed. In the case depicted in figure 5b the grain moisture content in region upstream of the temperature wave is about 0.35% lower than the initial grain moisture content. As noted above, the wheat has cooled by about 9ºC, hence wheat dries by about 1% for every 25ºC the grain cools as a result of the passage of a cooling wave. This is in keeping with the well established rule of thumb reported by Thorpe (2002a)
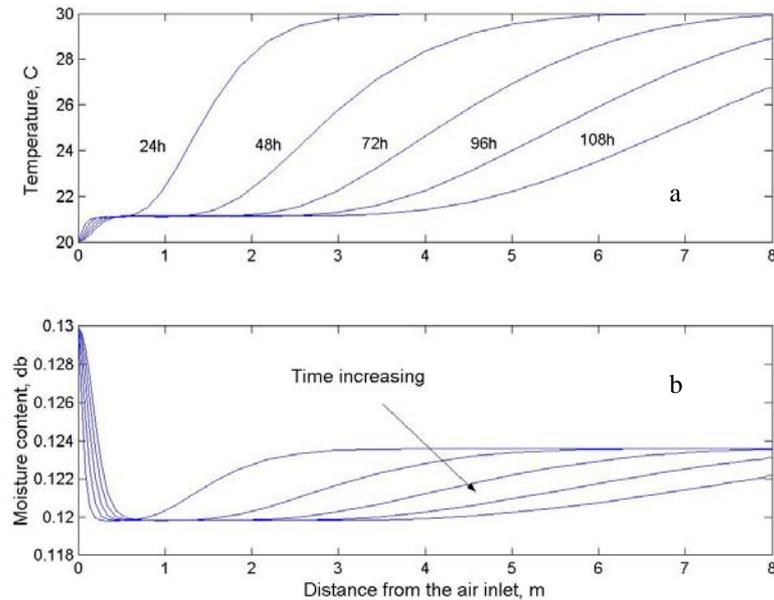

Figures 5a and 5b. The passage of temperature and moisture fronts through a bed of wheat 8 m high when the air flow rate is 0.08 kg dry air/(s.m²) when aerated with ambient air that has a dry bulb temperature of 20°C and a relative humidity of 50%. The initial moisture content and temperature of the wheat are 11% (wet basis) and 30°C respectively.
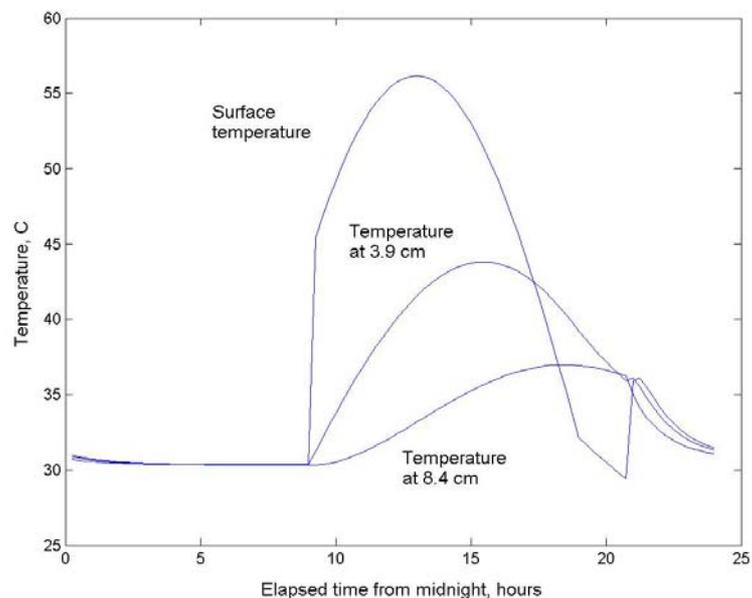
Figure 6. Temporal variations of the temperatures of wheat at the surface and at distances of 3.9cm and 8.4cm below the upper surface of the grain bulk before the passage of the cooling wave. All emissivities are assumed to be 0.9.

The fact that heated grains dry when they are cooled might be dubbed *desiccaeration*. It is possible that this process might be exploited in the recircaeration process considered in this paper. Figure 6 shows the diurnal temperature variations of grains at the upper surface, and 3.9 and 8.4 cm below the surface during the preliminary stages of aeration. All of the emissivities are assumed to be 0.9, a value chosen to highlight the process. In the case considered the air is deemed to flow until 9am when the aeration fan is turned off. Under the influence of solar radiation onto the roof the temperature of the upper surface of the grains rises quickly. When the fan is turned off during the day a temperature wave propagates by *thermal conduction* down through the grain and attenuates as it travels at a finite speed. Hence the times at which the maximum temperatures at the depths of 3.9 cm and 8.4cm occur later than the time the maximum temperature at the surface. These phenomena can be observed in Figure 6. The surface temperature falls rapidly when the solar radiation falls to zero, but it rises abruptly when the aeration fan is turned at 21 hours. This is because the upper surface is warmed by thermal energy stored beneath the surface of the bed. It can be observed that after about 3 hours of operation at the flow rate used in the numerical experiment, namely 0.008 kg/(s.m^2), the three temperatures assume almost equal and constant values until the aeration fan is again turned off and the upper surface is once more heated by solar radiation. An important feature of this behaviour is that at the air flow rate considered the high enthalpy air is forced out of the grain in a short time compared with the time the aeration system is in operation.
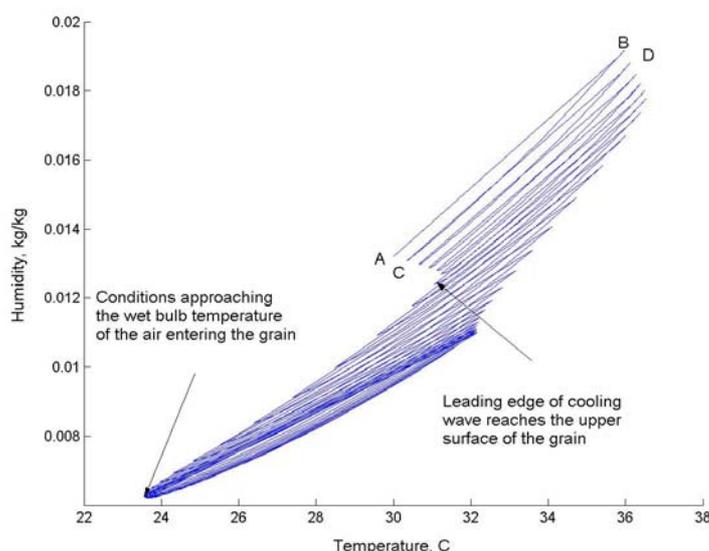

Figure 7. The process of desiccaeration of grain at the upper surface of the grain when the air inlet conditions are constant at 20⁰C and a relative humidity of 50%. All emissivities are assumed to be 0.9.

The process of desiccaeration in the upper region of the grain is illustrated in Figure 7. The grain has an initial temperature of 30⁰C and the humidity of the intergranular air is about 0.013 kg water/kg dry air shown as point A in Figure 7. During the day the grain at the upper surface heats up to about 36⁰C and the intergranular humidity increases to about 0.019 kg water/kg dry air because the equilibrium humidity increases with temperature as indicated by point B in Figure 7. When the aeration fan is turned on air from deeper inside the grain bulk with a temperature of about 30⁰C and a relative humidity of about 50% flows through the warm grain which then simultaneously cools and dries. Air leaves the grain bulk at point C in Figure 7. As one might expect points A and B lie close to the 21⁰C wet bulb temperature line which is the wet bulb temperature of the air within the grain bulk. After about the sixth cycle of operation the leading edge of the cooling wave begins to penetrate the upper surface of the grain and the grain at the surface cools further and dries until it appears to approach equilibrium conditions. The air entering the grain bulk has a wet bulb temperature of 14⁰C, and the air leaving the surface (after it has cooled) appears to equilibrate at the same wet bulb temperature as indicated in Figure 7. The progressive drying of the upper surface of the grains is shown explicitly in Figure 8. It can be seen that the moisture content of the wheat

falls from 12.36% (dry basis) to about 10.25% (dry basis) which is equivalent to a reduction in moisture content from 11% (wet basis) to 9.3% (wet basis).

The implications of the results portrayed in Figures 6, 7 and 8 are that recircaeration may result in improved aeration systems because the absolute humidity of air leaving the upper surface of the grains is likely to be lower than ambient humidity. Solar radiation may enhance the process of desiccaeration. If this air is cooled to a temperature approaching ambient temperature its enthalpy will be lower than ambient air hence it will be more useful for cooling bulk stored grains.
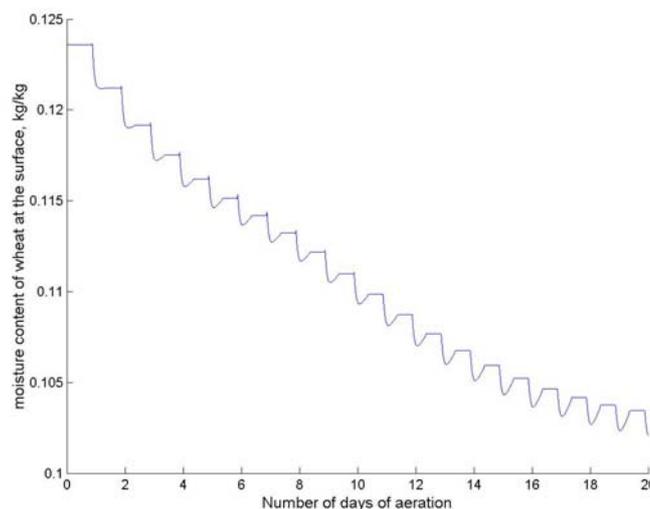
Figure 8. The decrease in the moisture content of wheat at the upper surface of a bulk of wheat initially with a moisture content 11% (wet basis) of aerated for 12 hours per day with air at a flow rate of 1 litre/(s.tonne) that has a temperature of 20ºC and a relative humidity of 50%. All emissivities are assumed to be 0.9.

5.2   Recircaeration as a practical option

The above results show that the absolute humidity of air leaving aerated grain bulks may be lower than that of ambient air. Hence, if air leaving the grain is cooled close to ambient temperature it is likely to have an enthalpy lower than that of ambient air and lower grain temperature can be attained. We shall now use our mathematical analysis to explore if this supposition is valid.

5.2.1 Thermodynamic aspects

Initially we shall explore how wheat that has a moisture content of 11% dry basis and a temperature of 30ºC is aerated with ambient air. Figure 9 shows the temperature profiles at intervals of five days for a total of 100 days of ambient aeration. It can be seen that half the grain bed has still to cool to less than about 27ºC. From an ecological point of view the wet bulb temperature is more significant and the profiles are plotted in Figure 10 and as would be expected they are close to 19.5ºC, the mean wet-bulb temperature of the air entering the grains. However, when the air is cooled according to equation 11 and readmitted to the grain the dry bulb temperature of the grain is reduced to about 23.3ºC and the wet bulb temperature of the intergranular air is about 15.7ºC as can be seen from Figures 11 and 12. Figure 9 highlights the influence of thermal conductivity on the profiles of the dry bulb temperature along the grain bed. This dispersive effect is evident in the vicinities of the air inlet and the upper surface of the grains.
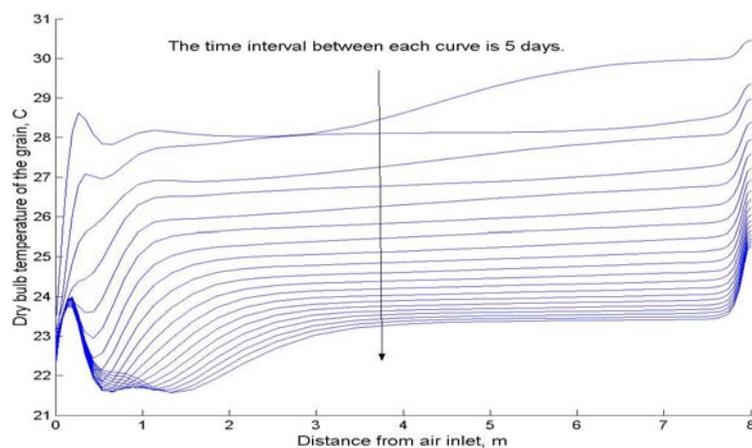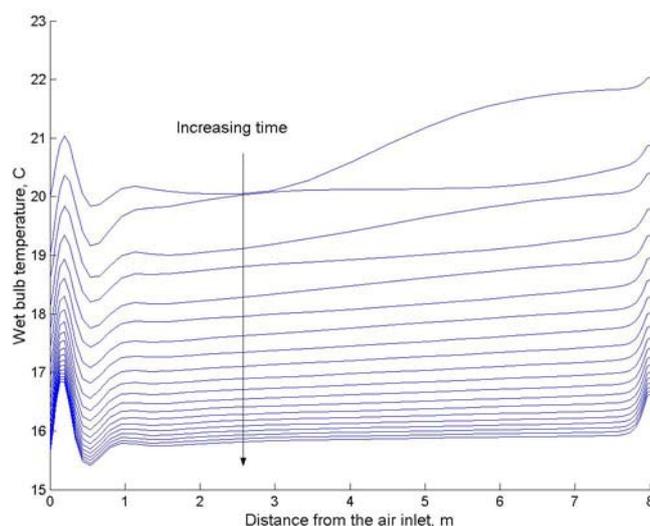
5.2.1.1 Effects of air flow rate
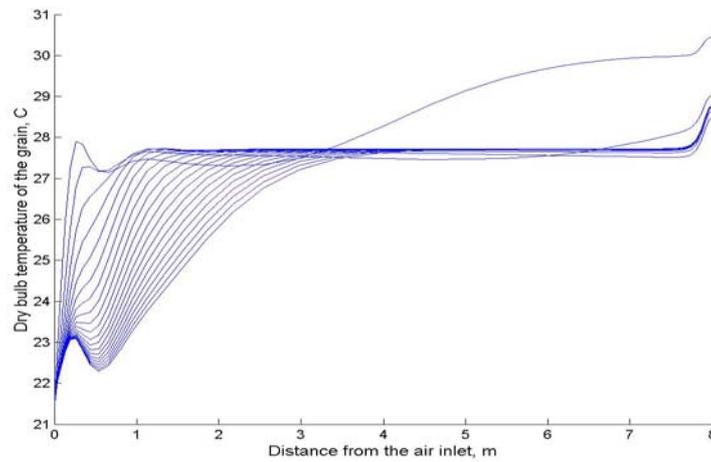
Figure 9. Dry bulb temperature profiles at intervals of five days in a bulk of wheat with an initial moisture content of 11% aerated with ambient air for a total of 100 days.
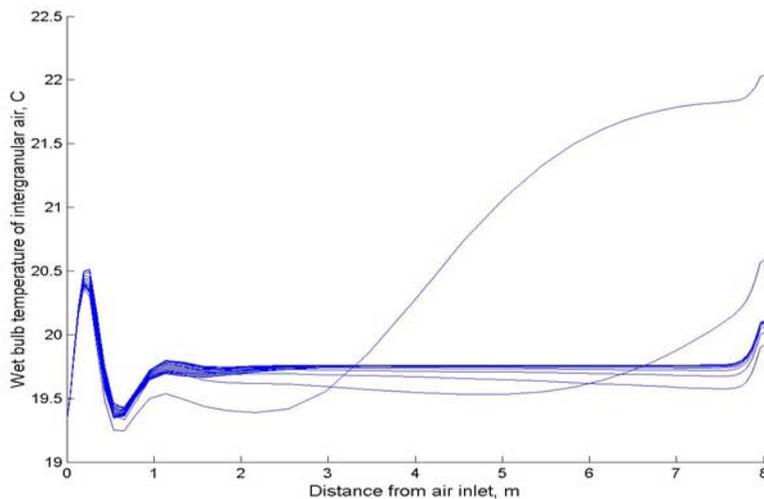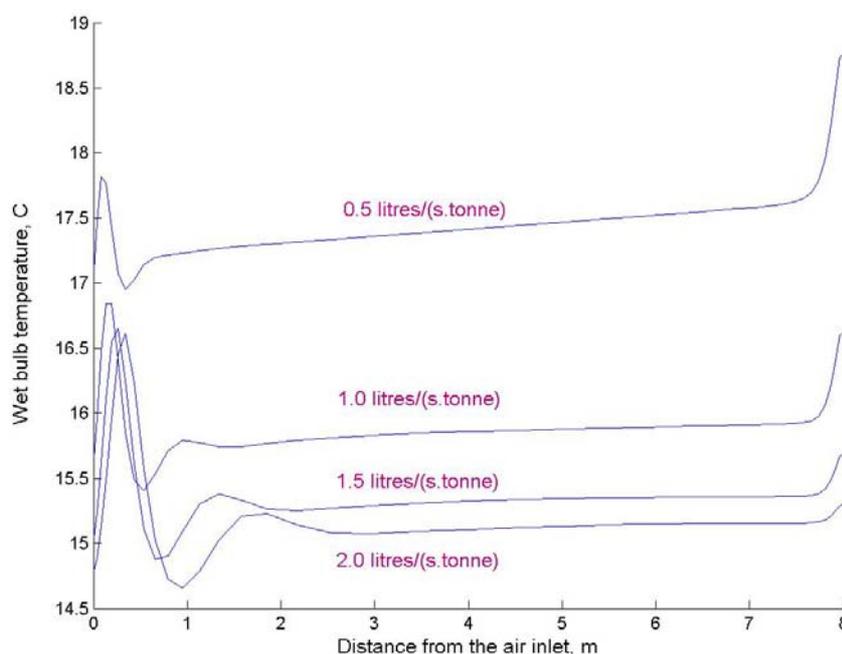

Figure 10. Wet bulb temperature profiles at intervals of five days in a bulk of wheat with an initial moisture content of 11% aerated with ambient air for a total of 100 days.

Figure 11. The dry bulb temperature profiles at intervals of five days in a bulk of wheat with an initial moisture content of 11% when the air leaving the upper surface of the grain is cooled and recirculated.
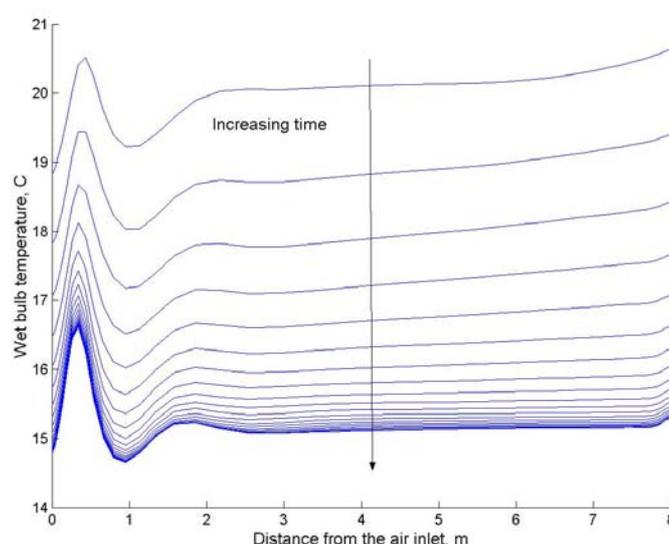

Figure 12. The wet bulb temperature profiles at intervals of five days in a bulk of wheat with an initial moisture content of 11% when the air leaving the upper surface of the grain is recirculated.

Figure 13. Profiles of wet bulb temperatures along the length of the grain bed after it has been recircaerated with nominal air flow rates of 0.5, 1.0, 1.5 and 2.0 litres per second per tonne of grain. The total elapsed time is 100 days.

Thus far we have considered the system operating with an air flow rate of nominally 1 litre/(s.tonne). We shall now investigate the effects of air flow rate on the intergranular wet-bulb temperature in an 8m tall silo. We shall show only the results for recircaeration as the

wet bulb temperature of grain aerated with ambient air is largely independent of flow rate. The nominal air flow rates considered are 0.5, 1.0,1.5 and 2.0 litres/(s.tonne) and the profiles of the wet bulb temperatures along the bed after 100 hours of recircaeration are shown in Figure 13. The rates at which the moisture and temperature fronts traverse the grain bulk are proportional to the air flow rate hence the benefits of recirculating cool air leaving the upper surface of the grain bulk become apparent more quickly at higher flow rates. Temperature profiles in a bulk of grain aerated with an air flow rate of 2 litres/(s.tonne) are shown in Figure 14, and by comparing these results with those portrayed in Figure 12 cooling is more rapid and deeper when the air flow rate is higher. The question arises as to whether the deeper cooling when the air flow rate is 2 litres/(s.tonne) occurs simply because more cooling waves have traversed the grain. In an attempt to answer this question the simulation was repeated with the air flow rate being 1 litres/(s.tonne) but for 200 days. It was observed that the final temperature profile resulted in temperatures that are intermediate between flow rates of 1 litres/(s.tonne) and 1.5 litres/(s.tonne) after 100 days of recircaeration. This result indicates that is it not only the passage of cooling waves that is important, but more heat is expelled from the upper surface of the grain when the air flow rate is higher.

Figure 14. The development of profiles of the wet bulb temperature in beds of wheat recircaerated with an air flow rate of 2 litres per second per tonne of grain.

5.2.2 Insect population dynamics

5.2.2.1 *Rhyzopertha dominica*

One of the principal reasons for adopting recircaeration is to improve the storability of food grains. It has been noted that the rates at which insect populations increase in stored grains are sensitive to the wet bulb temperature of the intergranular air, and to moderately high dry bulb temperatures, i.e. above the so-called supra-optimal temperature, which is about 35ºC. Figure 15 shows that when ambient air is used to aerate the 11% moisture content grain the increase in population of *R. dominica* is about 750 fold over a period of 100 days, and the population peaks at around 40,000 near the upper surface of the grains where conditions for their breeding are close to being optimal. When recircaeration is applied the population increase is typically 300 fold and the population peaks at about 4,000 fold, an order of magnitude less than in the case of ambient aeration. As can be seen from Figure 16 the potential of recircaeration to control the lesser grain borer, *R. dominica*, in wheat with a moisture content of 11% appears to be significant.   At the initial wet bulb temperature of the intergranular air, namely 21.84ºC, the population of *R. dominica* would increase about 7,155-fold over a period of 100 days. This again underscores the benefits of recircaeration that

results in a 300 to 500-fold increase in numbers. Figure 17 shows that increasing the air flow rate has a profoundly beneficial effect on controlling populations of *R. dominica*.

5.2.2.2 *Sitophilus oryzae*

The rice weevil *S. oryzae*, is better adapted to cooler climates than the lesser grain borer, *R. dominica*, but it is less able to tolerate aridity hence its prevalence in the more humid grain
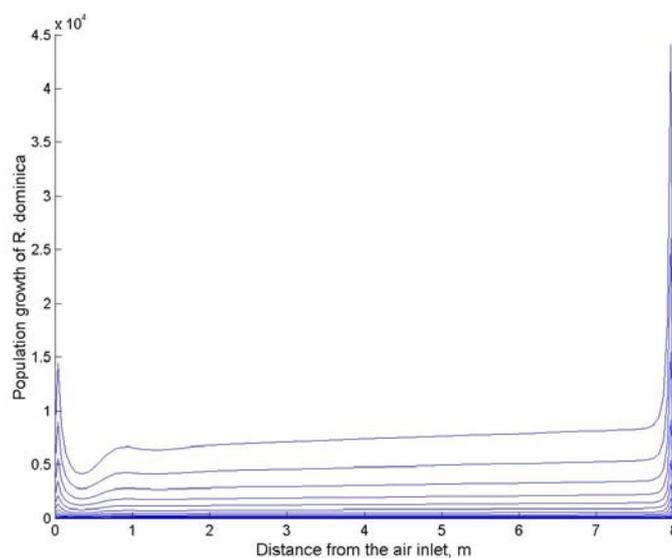

Figure 15. The population multiples of *R. dominica* at intervals of five days for a total of 100 days in 11% moisture content grain, initially at 30ºC, and aerated with ambient air.
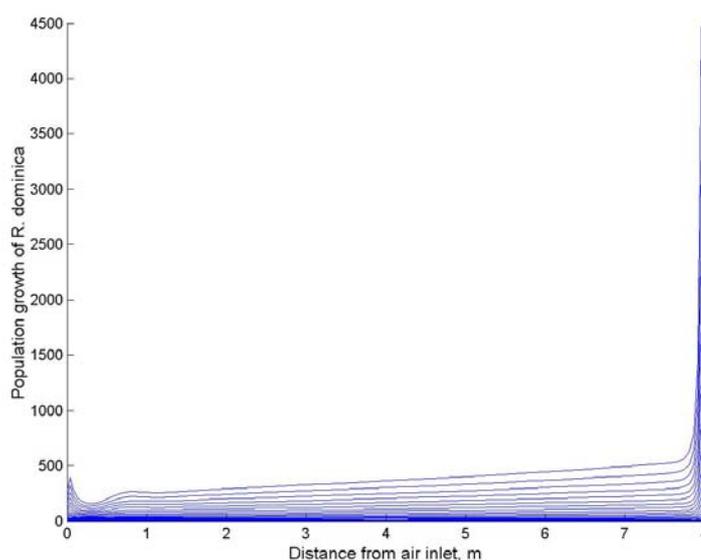

Figure 16. The population multiples of *R. dominica* at intervals of five days for a total of 100 days in 11% moisture content grain, initially at 30ºC, and aerated using the process of recircaeration.
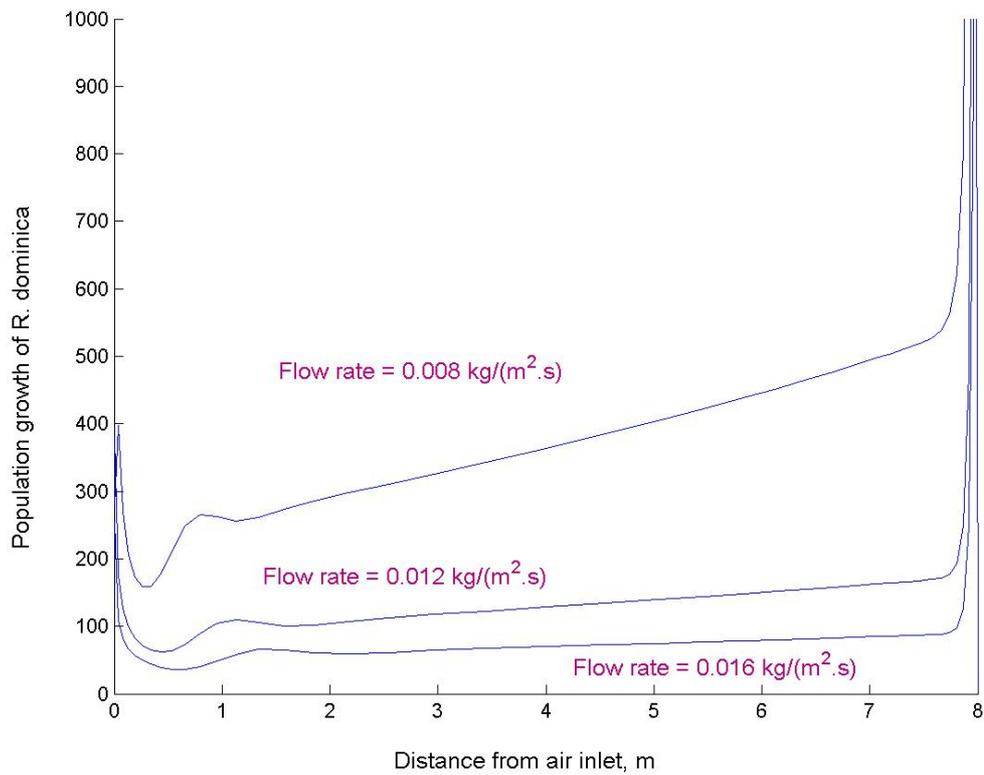
Figure 17. A comparison of the rates of population increase of *R. dominica* when 11% moisture content grain is recircaerated at flow rates equivalent to 1, 1.5 and 2 litres/(s.tonne).
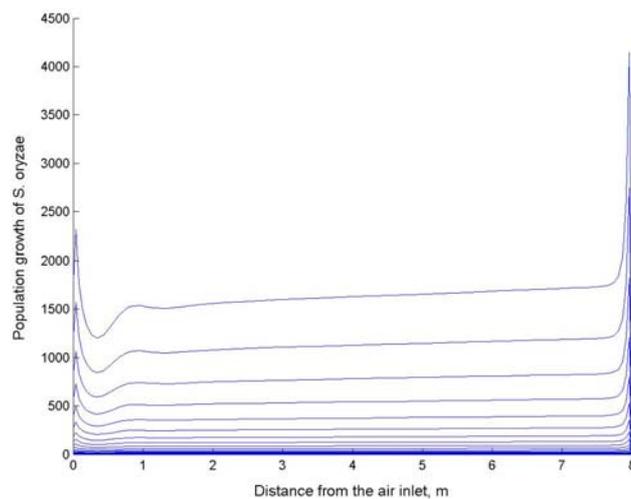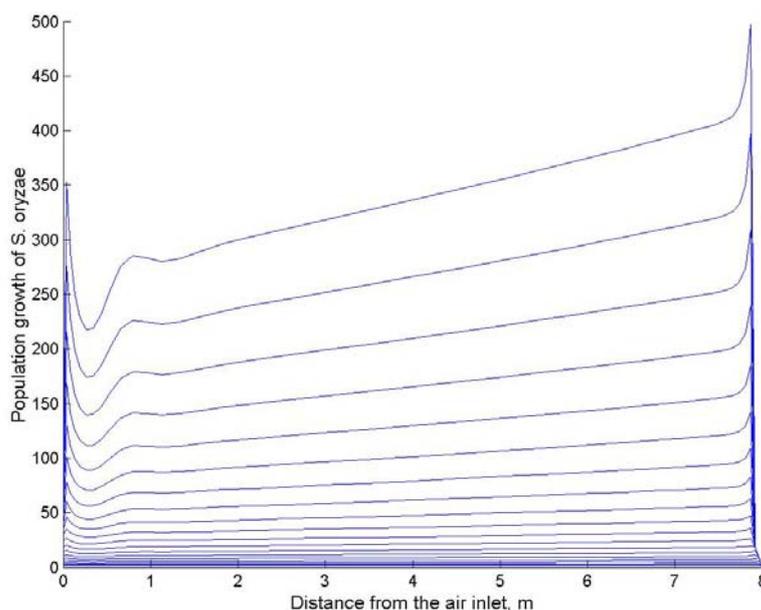

Figure 18. The population multiples of *S. oryzae* at intervals of five days for a total of 100 days in 11% moisture content grain, initially at 30⁰C, and aerated with ambient air.

Figure 19. The population multiples of *S. oryzae* at intervals of five days for a total of 100 days in 11% moisture content grain, initially at 30⁰C, and aerated using the process of recircaeration.

growing regions of Australia. In wheat with a moisture content of 11% and a temperature of 30⁰C (corresponding to an intergranular wet bulb temperature of about 21.84⁰C) a population of *S. oryzae* would increase 6400-fold. It can be seen from Figure 18 that aeration of wheat with ambient air reduces this number to typically 1500-fold except at the top of the grain bulk where the population increase increases about 4000-fold.   Figure 19 indicates that recircaeration might be expected to further reduce the population increase to about 350-fold. This result again indicates that recircaeration may bring about an order of magnitude reduction in insect populations.

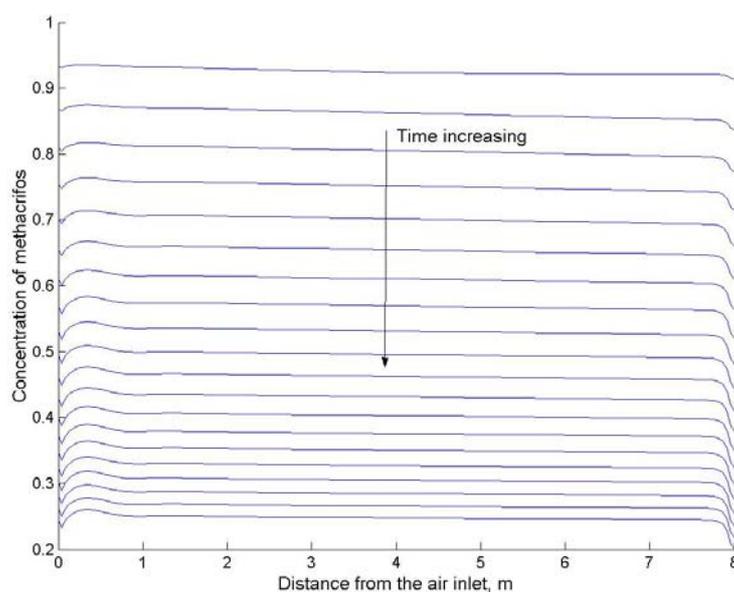## 5.2.3.   The rate of decay of pesticides

It is clear that in the climates under consideration pest insects can proliferate in wheat even when it is aerated or recircaerated. Chemical pesticides might be a useful adjunct to these grain cooling processes and here we shall consider the effects of aeration and recircaeration on the persistence of two contact chemicals, namely methacrifos and bioresmethrin. These two were chosen because they have different rates of decay. Methacrifos has a half-life of 7 weeks on grain with an intergranular wet bulb temperature of 20⁰C, whereas bioresmethrin has the somewhat longer half-life of 24 weeks. Desmarchelier (1979a,b) defines both of these chemicals as being labile because their half-lives are less then six months on freshly harvested grains with moisture contents and temperatures that are typical of those in Australia.

5.2.3.1 Methacrifos

After 100 days on grains that have a moisture content of 11% and a dry bulb temperature of 30⁰C the concentration of methacrifos would be about 17% of its initial value. Figure 20 shows that were the grain to be aerated the concentration would be typically 25%, falling to about 20% at the upper surface. When the grain is recircaerated the concentration of methacrifos falls to about 30% and 25% at the upper surface as can be seen from Figure 21..
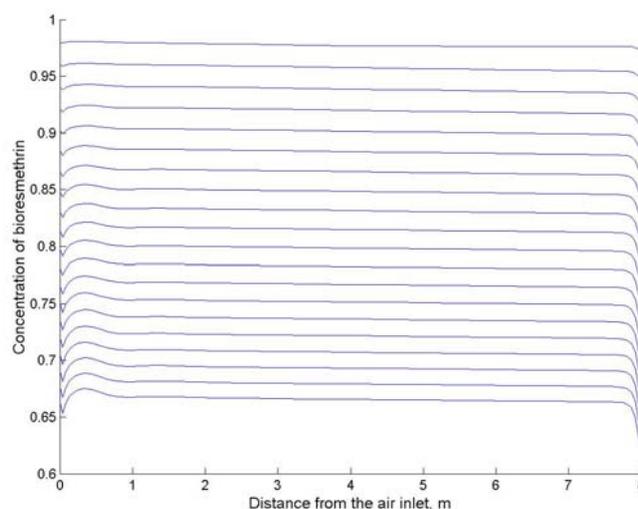
5.2.3.1 Bioresmethrin

Bioresmethrin is more persistent than methacrifos and over the short term aeration has less effect on the level of residues on grains than is the case with methacrifos. However, in the longer term aeration continues to be beneficial in prolonging the life of bioresmethrin. In grains in which the intergranular wet bulb temperature is 21.84ºC (i.e. 11% moisture content

Figure 20. **The rate of decay of the pesticide methacrifos on grain initially with a temperature of 30°C and with a moisture content of 11% (wet basis) when aerated with ambient air with an air flow rate of 0.008 kg/(s.m^2).**
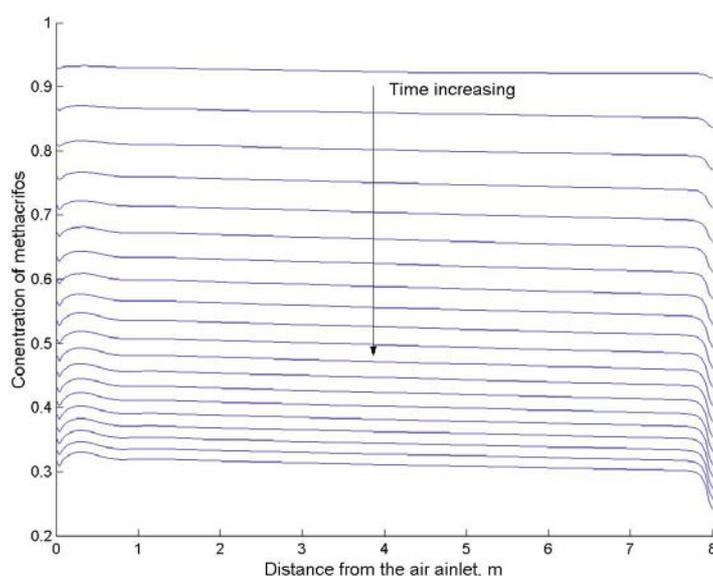
Figure 21. **The rate of decay of the pesticide methacrifos on grain initially with a temperature of 30°C and with a moisture content of 11% (wet basis) when recircaerated with an air flow rate of 0.008 kg/(s.m^2).**

Figure 22.   The rate of decay of the pesticide bioresmethrin on grain initially with a temperature of 30°C and with a moisture content of 11% (wet basis) when aerated with ambient air with an air flow rate of 0.008 kg/(s.m^2).
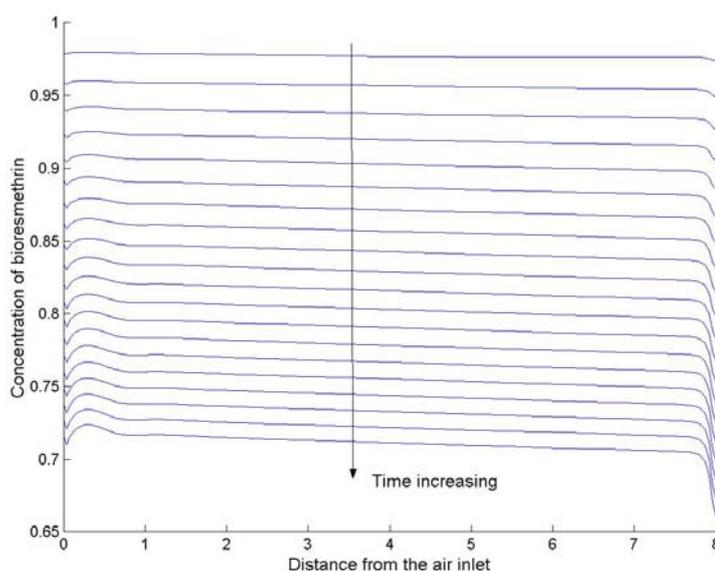

Figure 23.   The rate of decay of the pesticide bioresmethrin on grain initially with a temperature of 30°C and with a moisture content of 11% (wet basis) when recircaerated with an air flow rate of 0.008 kg/(s.m^2).

(wet basis) at a temperature of 30°C) after 100 days the concentration as a percent of the initial concentration is about 62%. This compares with values of about 66% and 72% in aerated and recircaerated grains respectively as indicated in Figures 22 and 23.. As well as the generally low rate of decay of bioresmethrin on grains a reason for the small difference in concentrations of pesticide on the aerated and recircaerated grain is that cooling by recircaeration occurs in waves and implied by Figure 5a. It takes approximately 200 hours of aeration before a cooling wave passes completely through the grain and for the recirculated air to have its full impact on further cooling.

6.   DISCUSSION

An objective of this work is to investigate mathematically the possibility of removing heat from a bulk of grains by cooling air leaving its upper surface and re-admitting the cool, relatively dry air into the grains. It was hypothesized that solar energy could be used to dry the upper region of a bulk of grains by a process of desiccaeration. When cooler air arising from deeper in the grain bulk flows through this dry grain its temperature rises above that of the atmosphere and there exists the possibility that the grain could be reduced in temperature below that of ambient.

The mathematical analysis indicates that a bulk of grains with a moisture content of 11% would be cooled from 30°C to a dry bulb temperature of typically 28°C; this corresponds to a wet bulb temperature of about 19.75°C. In the recircaeration mode investigated in this paper the grains cool to a typical dry bulb temperature of 23.5°C, and the wet bulb temperature is less than 16°C throughout most of the grain bulk.

The lower wet bulb temperatures in recircaerated grain affect the stored grain ecosystem in a generally positive manner. For example the ratios at which populations of *R. Dominica* increase in grains that are aerated with ambient or recirculated air are about 700 an 400 respectively. At the upper surface of the grains the reduction is more dramatic, namely from about 45,000 to 4,500. Similar order of magnitude reductions are also obtained for *S. oryzae*. However, insect populations at the surface of grain are not well controlled whether the grains have been aerated or recircaerated. In these cases it may be worthwhile treating the surface with an inert dust that damages insects' cuticles and causes them to dehydrate.

Chemical pesticides are still used to control insect pests and it is essential to adopt protocols for their use that slows the rate at which insects become resistant to them. Desmarchelier (1988) points out that cooling grains slows the rate at which insect populations grow and this reduces pressure on insects to develop resistance. We have noted that cooling also reduces the rate at which pesticides decay; a corollary of this is that cooling increases the time that pesticides remain effective. The results obtained in this study indicate that ambient aeration and recircaeration both slow the rate of decay of pesticides, and that recircaeration is the slightly more effective treatment.

It is clear that recircaeration is more effective than ambient aeration under the climatic conditions considered. This is because the stored grains act as a desiccant and this supports the first hypothesis posited in this paper. The second hypothesis is that solar energy combined with aeration dries out the upper layer of grain and this enables grains to be cooled to lower temperatures. Although the research reported in this paper indicates that the upper layer of grain does indeed dry as a result of solar energy it is not possible to state for certain that this phenomenon offers a net benefit. Further research on the effects of grain moisture content, air flow rates and emissivities needs to be carried out. It is also important that the findings of this paper be validated, at least qualitatively.

7.   CONCLUSIONS

The climatic conditions in many grain growing areas in Australia and around the world render ambient aeration unsuitable for protecting grains from insect pests. The principal reason for this is that the wet bulb temperature if too high. In this paper the hypothesis that the wet bulb temperature of air used to aerate grain can be reduced by coolinfg air leaving the upper surface of an aerated grain bulk and re-admittining the cooled air to the silo. A second hypothesis has been tests, namely that solar energy heats the upper surface of the grains and when air flows through this region of grain the grain dries by a process dubbed desiccaeration. When air flow through this region of dry grain its humidity is reduced by making it more suitable for aeration.

A simple mathematical model has been formulated to capture some of the main features of recircaeration. It indicates that:

i.   The upper surface of the bulk of grains does become dry as a result of its being heated by solar energy, but the effect of this on the cooling of grain is difficult to

discern because it is confounded by the grain bulk absorbing more heat. Further work is required.

ii. The wet bulb temperature of the intergranular air is reduced from about 19.5°C under ambient aeration to about 15°C when initially 11% moisture content grain is recircaerated in the climate studied.

iii. The air flow per unit horizontal area of the silo appears to be important as it determines how quickly the heat that accumulates during the day is expelled and cool dry air is recirculated.

iv. The factors by which the insect species *Rhyzopertha dominica* increase are reduced from about 750 with ambient aeration to less that 100 when recircaerated with an air flow rate of 0.016 kg/(s.m^2). Multiplication rates are also much reduced at the upper surface of the grain bulk, but a complementary insect control measure such as the use of inert dusts must be implemented in this region of the grain.

v. Recircaeration appears to reduce the concentration of pesticides that must be applied to bulks of grains, but not by a commercially significant amount.

It is recommended that more detailed mathematical analyses and field experiments be carried out to assess the role that solar energy might play in the effectiveness of recircaeration.

8.   NOMENCLATURE

A, B, C	Constants in the Chung-Pfost equation
c_a	Specific heat of dry air, J/(kg.°C)
c_g	Specific heat of dry grain, J/(kg.°C)
c_w	Specific heat liquid water, J/(kg.°C)
C^t	Concentration of pesticide at time t
dt	Increment of time, s
f_a	Air flow rate, kg/(s.m^2)
h_o	Heat transfer coefficient, W/(m^2.°C)
h_s	Differential heat of wetting, J/kg water
h_v	Latent heat of vaporisation of water, J/kg
k_{eff}	Effective thermal conductivity of grain, W/(m.°C)
k_p	A pesticide-specific constant, 1/°C
k_{Sp}	Species-specific constant in equation **, 1/(°C.s)
N_{Sp}^t	Number of insects of species, *Sp*, after a time, t
p	Vapour pressure of water, Pa
p_{atm}	Atmospheric pressure, Pa
p_{sat}	Saturation vapour pressure of water, Pa
Q_{solar}	Intensity of solar radiation, W/ m^2
r	Relative humidity
t	Time, s
$t_{1/2}$	Half-life of pesticide, s
$t_{1/2}^o$	Half-life of pesticide under standard conditions, s
t_h	Time of day past midnight, h
T	Temperature, °C
T_{amb}	Ambient temperature, °C
T_{amp}	Amplitude of diurnal temperature change, °C
T_{in}	Temperature of air entering the grain bulk, °C
T_g	Temperature of the upper surface of the grain bulkgrain bulk, °C
T_{mean}	Mean temperature of ambient air, °C
T_s	Temperature of the silo roof, °C
T_{sky}	Temperature of the sky, °C
T_{Sn}	An insect species-specific wet bulb temperature, °C
T_w	Wet bulb temperature of the intergranular air, °C
w	Humidity of air, kg/kg

W   Moisture content of grain, kg/kg
x Distance measured from the air inlet, m

Greek symbols

ε Void fraction of the bed of grains

ε_g Emissivity of grains

ε_i Emissivity of inner surface of the silo roof

ε_o Emissivity of outer surface of the silo roof

ρ_a Density of dry air, kg/ m^3

ρ_b Bulk density, kg/ m^3

σ Stefan-Boltzmann constant, W/(m^2.K^4)

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