DISINFESTATION OF GRAIN WITH HEATED AIR

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Abstract

This paper is concerned with a preliminary comparison of the operation, performance and cost of three types of process equipment which have been used to disinfest grain using heated air, namely the fluid bed, the spouted bed and the pneumatic conveyor.

Firstly, the state of the art for each system is described, and this is followed by a qualitative and quantitative assessment of the applicability of each based on parameters such as simplicity, reliability, ease of operation, thermal efficiency, throughput and operation costs. The suitability of each system for the associated processes of grain cooling, drying, cleaning and conditioning is also discussed.

From the viewpoint of ease of grain cooling, application to grain drying and cost of operation the fluid and spouted bed systems are preferable to the pneumatic conveying system, and for large grain throughputs and use of existing technology the fluid-bed technique appears best. Where larger grains are to be handled at smaller throughputs the spouted-bed system is attractive. For smaller grain flow rates where the separation of dust, chaff and husk from grain is undesirable the pneumatic conveyor system is appropriate.

Areas in which further work is needed to effect a complete comparison of these systems are mentioned.

Introduction

Australian scientists have long been interested in non-chemical methods of controlling insect pests in grain. These methods are needed because of concern over resistance to pesticides, customer reaction to the use of chemicals on food, and the possible dangers to operators when handling poisonous substances. One such method is the disinfestation of grain by heating it in a stream of hot air. The aim of the process is to heat the grain uniformly and provide dosages of heat that kill all stages of insect life within the grain without affecting its quality.

For continuous-flow applications, a grain temperature of 65°C has proved effective for control of Rhyzopertha dominica (F.) (Evans et al., 1983a), the most heat-tolerant of the common grain insects (Dermott and Evans, 1978). At a grain temperature of 65°C, no deterioration in the quality of 12% m.c. (w.b.) wheat has been observed (Dermott and Evans, 1978; Ghaly and Taylor, 1982; Ghaly and van der

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Touw, 1982). It has also been shown that complete disinfestation can be obtained at grain temperatures below 65°C, provided that a suitable holding period before cooling is allowed (Dzhorogyan, 1957a,b; Evans and Dermott, 1981).

Three types of grain heating process equipment using hot air have been assessed in Australia, namely the fluid bed, the spouted bed and the pneumatic conveyor. A commercial-scale continuous-flow fluidized-bed plant capable of disinfesting up to 200 tonnes of wheat per hour (200 t/h) has been installed at a grain terminal in central Victoria, and it has operated successfully (Evans et al., 1984). The use of spouted beds and pneumatic conveyors has so far been limited to pilot-scale rigs (Claflin et al., 1984; Sutherland et al., 1986, respectively), but they both offer considerable potential for commercial application. Elsewhere, Lim et al. (1978), Fleurat-Lessard (1980) and Vardell and Tilton (1981a,b) have demonstrated the effectiveness of hot air heating for grain disinfestation in fluidized beds. Dzhorogyan (1957a,b) and Fleurat-Lessard (1980) have also evaluated the use of convective heating in pneumatic conveyors for disinfesting grain.

This paper aims to compare the advantages and disadvantages of each of the three heating systems with regard to insect mortality, grain quality, thermal efficiency, grain dispersion, uniformity of heating, ease of integration into existing grain handling facilities and cost. An assessment is also to be made of the performances of the systems for the associated processes of grain cooling, drying, cleaning and conditioning.

Grain Heating Systems

Fluid Bed

Pilot Scale

The use of hot air heating in a fluidized bed to disinfest wheat was first studied in Australia by Dermott and Evans (1978). Their work established that, depending on heating periods, grain temperatures of 59-65°C were sufficient to kill all stages of the common grain insects in 14% m.c. (w.b.) wheat in a 10 kg capacity batch fluidized bed, and also that *R. dominica* was the most heat tolerant of the species treated. Dough characteristics and baking properties were not affected by the treatments required to disinfest the grain.

Further work with another small, batch-operated fluidized bed (Evans, 1981; Evans and Dermott, 1981) examined the effects of changes in inlet air temperature, bed depth, exposure time and final grain temperature on insect mortality. It confirmed that complete insect mortality is almost instantaneous for grain temperatures of 62-65°C, but that lower temperatures can be used provided that the grain is held for suitable periods before cooling.

Grain temperatures of 65°C or higher consistently provided complete kills of *R. dominica* in trials of a 0.5 t/h continuous-flow fluid-bed system (Evans et al., 1983a). The effects of particle dispersion in the continuous-flow bed were examined by adding baffles to the bed. However, it was found that dispersion, which gives rise to variations in residence time, did not significantly influence either maximal grain temperature or insect mortality. A fluid-bed cooler using water sprays was also incorporated into this system, and as well as providing adequate cooling of the grain, it had the ability to return to the grain the small amount of moisture removed by the heating process.

Commercial Scale

To determine problems of scale-up, to obtain realistic cost data, and to illustrate how such equipment could be integrated into the grain handling system, a nominal 50 t/h plant, designed and built by Niro Atomizer Pty. Ltd., was installed at the Grain Elevators Board sub-terminal at Dunolly in central Victoria in 1982. The plant, its operation and a series of experiments to evaluate its performance are described by Evans et al. (1983b, 1984) and Thorpe et al. (1984). Details of its instrumentation and a mathematical model describing the process are provided respectively by Thorpe *et al*. (1982) and Thorpe (1986).

Trials with grain flow rates up to 200 t/h have yielded complete kills of *R. dominica* when grain temperatures of 65-70°C are achieved with air flow rates ranging from 2.1 to 2.4 kg $s^{-1}m^{-2}$ and mean grain residence times of from 2.0 to 4.5 min. Rigorous evaluation by the Bread Research Institute, Barrett Burston Limited and Quantum Limited has shown no deleterious influence on the germination and functional properties of wheat, barley and oats (11-13% m.c.). It appears that inlet air temperatures as high as 250°C can be used to heat grain to 65-70°C without such properties being influenced. These trials showed further that the average 0.1% m.c.(w.b.) loss caused by the heating process could be replaced by the addition of water during the cooling process to give no net change in grain moisture content.

The total capital cost of the plant, including the provision of services was A$0.4 million in 1982. Operating costs depend on the grain throughput; for operation at 150 t/h, the energy required to treat each tonne of wheat was 1.13 kWh of electricity and 26.6 kWh (96 MJ) of gas. On the basis of 7 cents per kWh (7 c/kWh) for electricity and 0.7 cents per MJ (0.7 c/MJ) for LP gas, the total energy cost was 75 c/t. If natural gas could be used (0.5 c/MJ) then the energy cost would be reduced to 56 c/t.

The only problem experienced with this plant was the entrainment of husk and chaff in the heating-air recirculation duct (installed for the purpose of heat recovery), which led to a large number of the holes in the distributor plate becoming blocked and, hence, inadequate fluidization of the grain and large temperature gradients within the bed. This problem was eliminated by the addition of a cyclone in the recirculation duct. Under commercial conditions the entrained husk and straw could be returned to the grain stream if desired.

By modifying the operating conditions, the Dunolly plant can be used as a very effective grain drier. Thorpe and Evans (1983) predict that wheat flowing at 50 t/h can be dried from 14 to 12% m.c.(w.b.) with an inlet air temperature of 165°C and a maximum grain temperature of 70°C.

Fluid-bed treatment offers the following advantages:

(1) Rapid heat transfer (grain heating times < 60 s).

(2) Good mixing and temperature control which ensure uniform treatment of all particles.

(3) Simple and rugged construction and operational stability making it suitable for use in grain handling systems.

(4) Potential for high throughputs (> 500 t/h) with few engineering problems.

(5) Ease of grain cooling in the same plant.

(6) Adjustment of product moisture content, i.e. conditioning or drying.

(7) Separation of chaff and husk from grain, i.e. cleaning.

Possible disadvantages of the continuous-flow fluid-bed grain heating technique are:

(1) At high air velocities a significant amount of the fluidizing air can by-pass the grain in the form of bubbles (Botterill, 1975; Dermott and Evans, 1978), leading to a reduction in the efficacy of the heat transfer process. Accordingly, the lowest air velocity that gives good fluidization should be used.

(2) The grain heating rate is limited by the fluidizing air velocity which, for good fluidization, is typically two to three times the minimum fluidization velocity of 1 m/s for wheat. However, heating surfaces could be inserted in the grain bed to increase the rate of heat transfer.

(3) There is some particle dispersion leading to a distribution of residence times and uneven heat treatment. Levenspiel (1962) states that such dispersion decreases the effectiveness of heat transfer. However, the ideal plug flow of grain can be approached by reducing the air velocity, increasing the length of the fluidized bed or inserting baffles. Evans et al., (1983a) have shown that dispersion does not significantly affect the disinfestation process when such baffles are used.

(4) Some energy is wasted in pumping air through a distributor plate that requires a pressure drop equivalent to that through the bed of grain to ensure uniform fluidization. This may account for up to 10% of the total energy cost for the heating process.

(5) Recirculation of heating air without adequate cleaning can block holes in the distributor plate and lead to uneven fluidization. Installation of a cyclone or bag filter can eliminate this problem. In any case, such recirculation may

not be worthwhile when most of the sensible heat is removed from the heating air during fluidization (Ginzburg and Rezchikov, 1966).

(6) The separation of dust, husk and chaff from grains is unavoidable, and if they are to be returned to the grain stream so as to avoid a net loss in weight, an additional disinfestation process for this material is required.

Spouted Bed

The disinfestation of wheat by heating in a spouted bed, which is a special form of fluid bed, has been studied by Claflin and Fane (1981, 1983, 1984), Claflin et al., (1984), Claflin (1985) and Claflin et al., (1986). Spouted beds are well suited to particles greater than 1 mm in diameter, and they have been used successfully for grain drying (e.g. Mathur and Epstein, 1974; Khoe and van Brakel, 1980).

Studies with a 0.3 m diameter 16 kg capacity batch-operated spouted bed have shown that 100% kills of R. dominica can be achieved with maximal grain temperatures of 60-66°C. A draft tube inserted in the spouted bed controls the particle movement and gives more even heat treatment although thermal efficiency is somewhat lower. Under certain conditions, porous draft tubes offer advantages in terms of air distribution and pressure drop over solid-wall draft tubes. A mathematical model has been developed that describes the thermodynamics of the heating process in a spouted bed (Claflin and Fane, 1984).

Compared with a fluid bed, a spouted bed can offer more regular particle movement, lower air velocities, lower operating pressures (typically 70% of those in a fluid bed) and potentially better thermal economy (Mathur and Epstein, 1974). A major difficulty with spouted beds is the scaling up to large solids throughputs. Claflin et al., (1984) suggest that operating costs for the spouted-bed disinfestation of wheat are likely to be similar to those for fluid-bed disinfestation. The problem of blockage of the air distributor with entrained debris encountered in the fluid-bed system with recirculation of uncleaned air should not occur in the spouted-bed system with relatively large air inlet spouts. The merits and demerits of spouted and fluidized beds have also been discussed by Bakker-Arkema et al., (1978) with similar findings.

Design considerations suggest that a multi-spouted system with draft tubes would be necessary to approach plug flow and to handle commercial grain throughputs. It is estimated that a bed with seven cells, each 1 metre square, in series, could have a throughput of from 50 to 100 t/h depending upon inlet air temperature and air flow rate (Claflin et al., 1986). Greater throughputs, at the expense of extra complexity, could be achieved by operation with cells in parallel as well as in series (see Table III), and recycling the heating air would improve thermal efficiency. Spouted beds are also well suited to grain cooling, cleaning and conditioning. A particular attribute of the spouted bed is its ability to process the larger grains, such as maize, that are difficult to fluidize.

Pneumatic Conveyor

To assess the alternative system of heating grain in a pneumatic conveyor, a pilot-scale plant capable of treating up to 1 t/h of wheat has been tested (Sutherland et al., 1986). The system uses a 30 m long, 50 mm diameter steel conveying pipe, insulated with 50 mm of rockwool and supplied with heated air by a centrifugal fan and a liquefied-petroleum gas burner.

It has been found that with a grain residence time of only a few seconds in the pneumatic conveyor, 100% kill of R. dominica was obtained at an average grain temperature of 64°C in wheat of 13% m.c. (w.b.). For a grain temperature of 57°C, the mortality was 90%. When the grain was held for 30 seconds before cooling, complete kills occurred at 57°C but not at 54°C (96%). Germination tests indicated that heating had not harmed the wheat. A mathematical model, based on plug flow, has been developed which permits prediction of grain outlet temperature to within 1°C, and grain velocity and air pressure drop to within 5% of observed values (Sutherland et al., 1986).

The advantages of the pneumatic method are:

(1) Grain heating is very rapid (a few seconds).

(2) Grain heating time is not constrained by air velocity. Typically conveying velocities are ten times greater than fluidizing velocities.

(3) There is no dispersion or spread of grain residence times leading to uneven heat treatment.

(4) The system can be laid out either horizontally or vertically.

(5) Grain, chaff and dust are simultaneously conveyed and disinfested.

(6) Where desired a grain holding stage can easily be incorporated in the system.

The disadvantages of this technique are:

(1) Grain temperatures need longer than the conveying time to equilibrate (approx. 20 s); a grain holding stage may therefore be necessary.

(2) Grain temperatures are more difficult to measure and control than in fluid and spouted beds.

(3) Exit air temperatures are generally high, and unless recirculation is employed thermal efficiency could be low.

(4) Large grain throughputs (> 500 t/h) are not proven.

(5) Grain cooling needs a separate process.

(6) Grain drying and conditioning are difficult because of the short particle residence times.

(7) Almost no grain cleaning can be achieved.

Comparison of Operating Costs

Computer programs have been written which simulate the performance of each of the three grain heating systems considered. The program developed for the fluid-bed heating of wheat is based on a similar program for drying paddy rice (Sutherland, 1986), modified to include an approximate analysis of grain dispersion which assumes a Gaussian distribution of particle residence times. For the spouted bed and pneumatic conveyor wheat heating systems, programs were developed from the models mentioned above.

Results from runs of these programs are given in Tables I and II for the fluid bed, Table III for the spouted bed and Table IV for the pneumatic conveyor. A comparison of the three systems is given in Table V.

TABLE I. Estimated cost of heating in a fluid bed

Grain flow rate (t/h)	Inlet air temp. (°C)	Length (m)	Fan power (kW)	Heat input (MW)	Energy cost (c/t)
100	100	8.4	186	3.2	77
	300	2.6	58	2.3	47
	500	2.0	44	2.2	43
400	100	33.6	744	12.8	77
	300	10.4	232	9.2	47
	500	8.0	176	8.8	43

Notes:
1. 10 c/kWh for electricity
2. 0.5 c/MJ for natural gas
3. 70% fan efficiency
4. 20°C initial wheat temperature
5. 65°C final wheat temperature
6. 10°C inlet air dew-point temperature
7. 101.325 kPa atmospheric pressure
8. 12% (w.b.) initial wheat moisture content
9. No heat recovery
10. No heat losses
11. 100% thermal efficiency
12. 2 m width of bed
13. 0.2 m unfluidized bed height
14. 2.5 m/s inlet air velocity
15. Pressure drops through distributor plate and grain are equal

TABLE II. Estimated cost of cooling in a fluid bed

Grain flow rate (t/h)	Water flow rate (kg/s)	Length (m)	Fan power (kW)	Electricity cost (c/t)
100	0	10.7	237	24
	0.25	6.1	135	14
	0.5	2.1	47	5
400	0	42.8	948	24
	1.0	24.4	540	14
	2.0	8.4	188	5

Notes:
1. Parameters 1, 3, 6, 7, 10 to 15 as for Table I
2. 65°C initial wheat temperature
3. 30°C final wheat temperature
4. 20°C inlet air dry-bulb temperature
5. 15°C water temperature
6. No costs for water supply

TABLE III. Estimated cost of heating in a spouted bed

Grain flow rate (t/h)	Inlet air temp. (°C)	Number of cells		Air velocity (m/s)	Fan power (kW)	Heat input (MW)	Energy cost (c/t)
		series	parallel				
100	100	11	2	1.5	248	2.8	75
	300	3	2	1.1	53	2.1	43
	500	2	2	1.0	31	2.1	41
400	100	11	8	1.5	992	11.2	75
	300	3	8	1.1	212	8.4	43
	500	2	8	1.0	124	8.4	41

Notes:
1. Parameters 1 to 11 as for Table I
2. Each cell (1 m^2) handles a grain flow rate of 50 t/h

TABLE IV. Estimated cost of heating in a pneumatic conveyor

Grain flow rate (t/h)	Inlet air temp. (°C)	Length (m)	Fan power (kW)	Heat input (MW)	Energy cost (c/t)	Efficiency (%)
100	300	25.5	27	3.4	64	72
	500	8.6	14	4.3	80	53
400	300	100.0	396	10.6	58	93
	500	23.5	199	13.5	66	68

Notes:
1. Parameters 1 to 10 as for Table I
2. Diameter of pipe = 1.0 m (100 t/h), 1.25 m (400 t/h)
3. Inlet air velocity = 25 m/s (100 t/h), 50 m/s (400 t/h)
4. Conveying pipe is horizontal

TABLE V. Comparison of estimated heating costs in fluid bed, spouted bed and pneumatic conveyor systems (see Tables I, III and IV)

Grain flow rate (t/h)	Inlet air temp. (°C)	Energy cost (c/t) (as a proportion of fluid-bed cost)		
		Fluid bed	Spouted bed	Pneumatic conveyor
100	300	47	43	64
		(1)	(0.91)	(1.36)
	500	43	41	80
		(1)	(0.95)	(1.86)
400	300	47	43	58
		(1)	(0.91)	(1.23)
	500	43	41	66
		(1)	(0.95)	(1.53)

Tables I and III show that the energy costs (c/t) for the fluid bed and spouted bed heating systems, respectively, are independent of grain flow rate and are quite similar, being slightly lower for the spouted bed at each inlet air temperature considered (Table V). The grain bed areas, fan powers and heat inputs are proportional to grain flow rate at each temperature. The advantage of operating at 300°C instead of 100°C is obvious in terms of energy costs and size of equipment, but the small decrease in cost at 500°C compared with 300°C would not be worthwhile in commercial systems, because of the extra capital cost which would be involved in providing special heat resistant materials and insulation.

Varying the unfluidized bed height by $\pm$ 0.05 m from 0.20 m for a grain flow rate of 100 t/h and an inlet air temperature of 200°C, does not affect bed length and heat input but changes fan power by 25% (being proportional to bed pressure drop) and energy costs by less than 6%. Reducing the inlet air velocity to the fluid bed from 2.5 to 2.0 and 1.5 m/s increases bed area by 26 and 70% respectively, but does not significantly increase fan power, heat input or energy cost.

For the spouted-bed heating system (Table III) one cell of 1 m^2 area is needed for a grain flow rate of 50 t/h, so for a throughput of 400 t/h the system becomes too complex for practical purposes with eight cells in parallel being needed.

Predicted costs of grain cooling in a fluid bed are given in Table II. They are again independent of grain flow rate and vary from 24% of the total energy cost for an inlet air temperature of 100°C to 36% at 500°C for cooling with ambient air only. Where water is sprayed directly onto the grain at 0.5 kg/s per 100 t/h, cooling costs as a percentage of the total energy cost are reduced to 6% at 100°C and 10% at 500°C.

The heating costs for the pneumatic conveyor system (Tables IV and V) are substantially larger than those for the fluid bed and the spouted bed. The costs are not proportional to grain throughput as for the fluid and spouted beds but decrease with increasing throughput. For the pneumatic system the heat inputs are greater, and the fan powers are smaller at a grain flow rate of 100 t/h and larger at 400 t/h.

Predicted values of thermal efficiency varied from 53 to 93%, and energy costs could be reduced by heat recovery but at the expense of extra capital cost. The simulations used a pipe diameter of 1.0 m for a grain flow rate of 100 t/h and 1.25 m for 400 t/h. Using diameters of 0.75 and 1.0 m for 100 t/h (at 300°C) and 400 t/h respectively resulted in unreasonable conveyor lengths of greater than 100 m. For operation at 100 t/h and 500°C inlet air temperature, however, a more sensible conveyor length of 18.0 m is obtained for a pipe diameter of 0.75 m. This almost halves the heat input required thereby reducing the energy cost to 46 c/t, and increases the thermal efficiency to 93%. A large pneumatic conveying pipe (1.2 m in diameter and 24 m long) has been used in the U.S.S.R. as part of a recirculating grain drier with a throughput of 50 t/h (Rezchikov and Katkova, 1977).

To avoid grain choking in the conveying pipe the inlet air velocity of 25 m/s for a grain throughput of 100 t/h was increased to 50 m/s for 400 t/h. This may result in substantial damage to grain kernels by the conveying process at large throughputs. For a vertical pipe conveying 100 t/h of wheat with inlet air at 300 and 400°C, the heat inputs are unchanged, the pipe lengths increase by about 16%, the fan powers approximately double and the energy costs increase by less than 5% from those for horizontal conveying. For horizontal operation at 100 t/h and 300°C in a 1.0 m diameter pipe, increasing inlet air velocity from 25 to 30 m/s increases pipe length by 7%, fan power by 30%, heat input by 21% and energy cost by 22%.

Conclusions

Heat disinfestation is essentially a simple procedure. It requires only that all particles of a given batch of infested grain are heated to an appropriate lethal temperature-time combination. Although temperature is the more important variable, there is usually considerable flexibility in choosing a combination that will fall within the 'tolerance envelope' of the commodity to be treated and yet kill insects (Evans, this conference).

The investigations reviewed here show that heating in fluid beds, spouted beds and pneumatic conveyors is equally effective in entomological terms regardless of the system employed, and, furthermore, providing that appropriate treatment regimes are adopted, heating can probably be used to disinfest a wide range of cereals. Further work is needed, however, to define the heat tolerance of moist and large grains and of legumes and other non-cereal commodities.

Once the biological constraints imposed by the heat tolerance of the pests to be controlled and the commodity to be treated are defined, the question then becomes which of the heating techniques described offers the most cost effective solution to the problem to be tackled. Assessment of what is 'cost effective' will involve both qualitative (e.g. simplicity, reliability, ease of operation) and quantitative considerations (e.g. throughoutput, capital and operating cost). The findings of such assessments will vary from case to case but some preliminary generalisations can be made as follows:

(1) Each of the three heating techniques could handle several sizes of cereal grains and seeds, but the larger ones such as maize would be more suited to the spouted bed.

(2) Large grain throughputs (>500 t/h) can easily be handled in a fluid-bed system, but would be difficult to manage in a spouted bed or pneumatic conveyor.

(3) The vital process of grain cooling which follows heating is easily incorporated in a fluid-bed system and to a lesser extent in the spouted bed, but for the pneumatic conveyor a separate cooling process is required. This could be a fluid-bed cooler associated with a horizontal conveying pipe or a falling grain column air cross-flow cooler in conjunction with a vertical pipe (Sutherland et al., 1986). Large column coolers have been used in this way in grain driers in the U.S.S.R. (Rezchikov and Katkova, 1977), but only for a grain flow rate of 25 t/h per unit.

(4) The important associated process of grain drying is easily accommodated in a fluid or spouted bed but is difficult to achieve in a pneumatic conveyor.

(5) In the fluid-bed and spouted-bed systems dust, chaff and husk are separated from the grain stream, and a separate

disinfestation process is required for this material. For the pneumatic conveyor all the grain products are simultaneously conveyed and disinfested, and hence no grain cleaning is achieved.

(6) The estimated operating costs have been shown to be similar for the fluid-bed and spouted-bed systems, but significantly higher for the pneumatic conveying system which generally has lower thermal efficiencies.

(7) No attempt has been made in this paper to assess capital costs and a detailed comparison including all costs will be undertaken in the near future.

(8) Further work is needed to optimize the performance of each of the grain heating and cooling systems described. The effect of very high inlet air temperatures (approx. 500°C) on grain quality has also still to be determined.

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