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Disinfestation of grain using hot-air dryers: Killing hidden infestations of grain weevils without damaging germination

by

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ABSTRACT

This project aimed to provide recommendations on using hot-air dryers to disinfest grain as an alternative to OP admixture or fumigation. To do so, the most heat tolerant stages and species of insects were identified by oven heating of infested grain. A model of their mortality at elevated temperatures was integrated with existing models of germination loss, incorporated into a simulation of hot-air dryer operation and used to study the conditions needed for disinfestation. Based on information from these models, a practical-scale trial was undertaken.

Based on the heat mortality results, exposures of 15, 30, 45 and 60 minutes would be required to kill 99.9% of the most heat resistant stages of the grain weevil at grain temperatures of 52, 50, 48 and 46°C in malting barley at 12% moisture content.

A "window of opportunity" has been established within which disinfestation can be achieved without damage to grain, as judged by germination of malting barley. Grain temperatures 16-18°C above those listed above would be required to cause a fall of 1% in germination in the same exposure time. The temperature window is widest at low grain moisture and with barley of high initial germination. A practical test showed that the predictions of the model gave the desired result – disinfestation of the grain weevil without grain damage – except for a few locations where insects unexpectedly survived, indicating cool spots in the grain bed. Temperature differences in the dryer are large enough to make achieving a target temperature with a margin of error of + or – some 5°C, much more difficult.

Simulation of commonly used dryer types used in continuous flow has shown that, in principle, it is possible to achieve disinfestation of the grain weevil without grain damage in a dryer where the temperatures and airflows are constant and uniform. In a continuous-flow grain dryer, an air temperature of 80°C in combination with a particular residence time was predicted by a validated simulation model to kill 99.9% of *S. granarius* and to cause a reduction in germination of barley of less than 1%. For a given level of insect mortality, increasing the drying air temperature increased the grain throughput and reduced moisture loss and energy cost. Therefore the optimum treatment would be to use as high an air temperature as limits to germination loss allow. To get the temperature and transit time correct, the discharge rate and drying air temperature would have to be selected prior to the run, based on a guide for the type of dryer, the grain species and moisture content.

Energy costs at 80ºC were typically in the range 0.50 -1.00 £/t of input grain. Cost of lost weight were in the range 0.65£/t when starting from 11% moisture content to 3.26£/t when drying from 16%.

Selection of temperature and treatment time is not simple. Guidance for the appropriate combinations of inlet air temperature and temperature at the exhaust side will be needed for various designs of dryer and grain moisture levels.

The recommended air temperature and residence times would, therefore, enable disinfestation from most free-living species such as the saw-toothed grain beetle. Because feed wheat quality is much less critical and temperatures of 100-120°C for 3h and 1h respectively are permissible without quality loss, disinfestation of feed wheat from grain weevil is feasible without risk to feed grain quality.

Disinfestation of grain weevil in recirculating-batch dryers is expected to be more reliable than in continuous-flow. Further work is needed to find the best operating conditions for such dryers to achieve disinfestation.

SUMMARY

Introduction

With increasing pressure to avoid the use and minimise the choice of organophosphorus insecticides or fumigants, there is a need to find equivalently rapid non-chemical means of disinfesting grain. Heat disinfestation is a viable treatment and a successful pilot-scale disinfestation plant has been developed in Australia. Grain temperatures of 65°C kill the hardiest UK species (*S.granarius* larvae) in a few (2-3) minutes. Kill can be achieved at lower grain temperatures with longer exposure time and is also influenced by the moisture content of the grain. Other common free-living UK species, such as the saw-toothed grain beetle are considerably easier to kill by heating, so disinfestation using heat is clearly possible (Table 1). In the UK, hot-air dryers are widely available but to date, no studies have been done on how they could be used for disinfestation.

Table 1. Published exposure times (minutes) required for 100% mortality in a range of grain beetles

Species	Temperature (^{o}C)				
	45	48	50	55	60
Rhyzopertha dominica	-	-	942	17	0.5
Sitophilus granarius	300	60	55	10	2
Sitophilus oryzae	120	-	120	-	16
Oryzaephilus surinamensis	-	-	3	1.4	0.4

A disinfestation heat treatment must not reduce the grain quality for its end use. Safe drying temperatures for milling wheat and malting barley vary according to the moisture content; the higher the moisture content the lower the safe grain temperature, and while prolonged exposure to 65°C will cause loss of grain viability (germination) in damp grain, dry grain is considerably less susceptible to heat damage. Therefore there is a need to define accurately the range of treatment conditions that will kill insects but not harm grain, and to investigate how to operate a hot air dryer to achieve those conditions with as much of a safety margin as possible.

The overall approach comprised six steps:-

1. Determine what combinations of temperature and time kills the most heat tolerant UK insect species
2. Develop an insect mortality model
3. Consider the results alongside the existing data on how viability of malting barley is reduced by temperature and time, and determine if the opportunity for disinfestation without grain damage exists.

4. Modify a proven computer simulation, that predicts grain temperature and moisture inside heated air dryers, to calculate the effect of the grain conditions on insect mortality, as well as malting barley viability
5. Validate the predictions of the model in a practical test using a full-scale dryer
6. Use the simulations to explore how best to disinfest grain without damage to its quality in a heated air dryer

Determination of the most heat-tolerant stage of *Sitophilus granarius* and tolerance of this stage to a range of temperatures.

The objective of these laboratory based experiments was to first find the most heat tolerant stage of *S.granarius* and then to use that stage to find the mortality caused by exposure to temperatures from 45 – 60°C over a range of time intervals. This would produce a range temperature/exposure time relationships that could be used to develop the model for use with the dryer. This model would then be used to predict the mortality of the insects resulting from conditions in the dryer.

To determine the hardiest stage of grain weevil, two temperatures were assessed: 55 and 57.5^{o}C. Known aged cultures of each stage of the life cycle were set up by placing adults on wheat (15% m. c.) in a shallow layer which optimised the conditions for oviposition. The adults were left on for a set period (4 to 7 days) at 25^{o}C and 70% r.h. depending on the stage required. They were then removed from the grain by sieving.

Preliminary experiments to determine the hardiest stage were carried out in a fan-assisted oven. After treatment, the samples were placed in glass jars for incubation at 25^{o}C and 60% r.h. Mortality was determined by comparing numbers of adults emerging from the heated samples with numbers emerging from untreated samples. The preliminary tests showed that the larva IV and pupa were the most heat tolerant stages (Table 2) so these were chosen for the main tests.

Table 2. Mean warm-up times , exposure times and % mortality for all juvenile stages of *Sitophilus granarius* at 55°C for assessment of most tolerant stage

	Stage				
	Egg	Larva I	Larva II/III	Larva IV	Pupa
Mean control emergence	122	136	416	334	321
Mean Warm-up Time (mins., secs.)	2.41	2.44	3.17	6.26	3.23
Time (mins.)	Mortality (%)				
1.15	99.07	94.94	97.1	86.38	79.25
1.46	100	98.83	98.96	97.39	72.33
2.30	100	100	100	98.26	88.18
3.32	100	100	100	98.26	93.66
5.00	100	100	100	100	95.1
7.04	100	100	100	100	100
10.00	100	100	100	100	100

To provide the data for the disinfestation model, the insects were exposed in the oven at six temperatures: 45, 48, 50, 55, 57.5 and 60°C for seven time periods at each temperature. It was decided to try and shorten the warm-up times to obtain more constant temperatures for input into the mortality model by doing treatments in vacuumed plastic bags in a water bath, a technique that had been effectively used for testing the effect of temperature on the germination of malting barley. The time to kill 50% (LD50) or 99% (LD99) of insects were estimated by a probability analysis (probit).

Table 3. The treatment temperatures, their mean warm-up and the LT_{50} and LT_{99} achieved after exposure of Larva IV/Pupa of *Sitophilus granarius* in a fan-assisted oven

Temperature (°C)	Mean warm-up (min.sec)	LT_{50} (hour.min)	LT_{99}
45	2.10	2.52	78.53
48	2.06	0.28	2.33
50	1.54	0.07	0.51
55	2.25	0.01	0.06
57.5	1.46	0.00 *	0.01
60	2.05	43 secs **	

* < 1 minute

**100% mortality

Table 4. The treatment temperatures, their mean warm-up and the LT_{50} and LT_{99} achieved after exposure of larva IV/ Pupa of *Sitophilus granarius* in vacuumed sealed bags in a water bath

Temperature	Mean warm-up	LT_{50}	LT_{99}
(^{o}C)	(min.sec)	(hour.min)	
45	1.10	1.09	3.25
48	1.30	0.20	1.58
50	0.52	0.05	0.52
55	1.00	38 secs *	
57.5	1.40	1 sec *	
60	1.45	1 sec *	

* 100% mortality

Insects took longer to die at the same temperatures in the oven than in the water bath, probably because they were denied the survival benefit of evaporative cooling. For this reason and because the oven represented a situation closer to the reality of a grain dryer, the oven results were used as a basis for the new mortality model to interact with the existing models of dryer operation and germination loss. The oven experiments suggested exposure times to achieve complete mortality of 3h, 1h, 10 minutes and 3 minutes for temperatures of 48, 50, 55 and 57.5°C respectively.

Development of an insect mortality model and the opportunity for thermal disinfestation

For each oven temperature, tables of values of exposure time and insect mortality (normally the mean of three values) were constructed. Probit analysis was used to produce a model which expressed insect death rate as a function of grain temperature. The grain temperature was the mean temperature recorded during the exposure period.

Using a criterion of a mortality of 99.9 % as a satisfactory level of disinfestation then an exposure time of about 30 min at 50°C would be required (Table 5). Exposure to a grain temperature of 55°C for a few minutes would be expected to be lethal to the grain weevil. The values in Table 5 are slightly different from the oven experiment presented above because different probability methods were used.

Table 5. Exposure times in minutes for different levels of grain temperature and insect mortality

Grain temperature (°C)	Mortality		
	50%	99.0%	99.9%
46	110.5	266.5	311.9
48	29.9	72.2	84.4
50	9.8	23.8	27.8
52	3.7	9.0	10.6
54	1.6	3.8	4.5
56	0.7	1.8	2.1

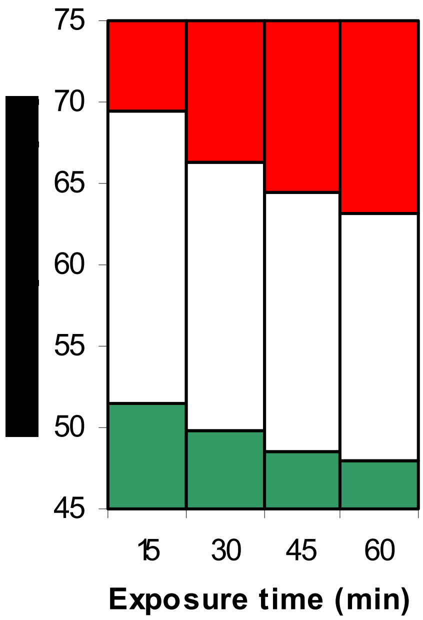
Further simulations examined the effect of initial germination on exposure time for a one percent loss in grain germination. The simulations were carried out for initial germinations of 99%, 98%, 97% and 96% for grain temperatures of 55ºC, 60ºC and 65ºC and moisture contents of 12% w.b., 14% w.b. and 16% w.b.

For an exposure time of 15 min, constant temperatures of 51.4ºC would kill 99.9% of the grain weevils and 69.4ºC results in a germination loss of 1% from an initial value of 98% for barley at moisture content of 12 % w.b. The difference in these temperatures and therefore the "window of opportunity" is 18ºC (Fig. 1). The longer the exposure times, the lower is the grain temperature required for both insect kill and loss in germination. The window of opportunity reduces with increasing exposure time – the window is 15ºC for a 60 min exposure. For wheat the window is less, at about 12ºC, and is little influenced by exposure time. This is due to the higher moisture content (14% w.b.) and the resultant lower grain temperature for a 1% loss in germination.

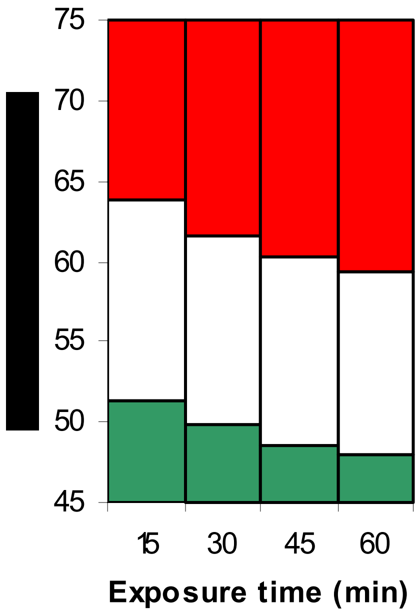
It is clear from the analysis that a temperature "window of opportunity" for thermal disinfestation is available, in which insect kill may be achieved without unacceptable loss of grain germination. Although a longer exposure time is required for disinfestation when grain temperature is lower, the window is hardly affected by the exposure time (Fig. 1).

Figure 1. Prediction by simulation of the "window of opportunity" (the central bar) for thermal disinfestation of grain that is all at the same temperature and moisture. Grain temperature to achieve 99.9% insect mortality (where lower and central bars meet) and to cause a one percent loss of germination (where central and upper bars meet) from an initial germination of 98% for different exposure times.

(a) Barley at 12% moisture content



(b) Wheat at 14% moisture content



Simulation of heated-air dryer operating conditions for disinfestation of grain

The mixed-flow dryer, a popular type of heated-air continuous-flow dryer in the UK, is designed to give a more uniform thermal treatment to the grain than the more simple design of the cross-flow dryer. In the cross-flow dryer a moving stream of grain is successively dried and cooled by air flowing at right angles to the stream. Simple cross-flow types consist of a single drying bed, preceding, and continuous with, a cooling bed. A proven model of drying developed by SRI was used that simulates accurately the temperature and moisture profiles and any loss of grain viability throughout a heated-air, continuous-flow dryer, of the mixed-flow or cross-flow design. Moisture content and temperature of grain and air are predicted as functions of drying time and position in the grain bed, and the resulting loss of germination is calculated.

The insect mortality model developed in this project was incorporated into both the mixed-flow and the cross-flow model. In this part of the work, simulations were carried out for the mixed-flow and cross-flow dryer types to investigate the effect of operating conditions in continuous-flow, one pass operation on the disinfestation and the impact on the other important factors listed above (Tables 6 & 7).

Table 6. Simulation output in relation to insect survival for a mixed-flow dryer with equal heating and cooling sections and a drying air temperature of 80ºC for barley and wheat.

(a) Barley at initial moisture content 12 % w.b.		Insect mortality			
		99.99 %	99.9 %	99%	90%
Throughput (t/h)		7.49	7.64	7.86	8.27
Residence time (min)		90.8	89.1	86.6	82.3
Moisture content (% w.b.)		10.68	10.71	10.75	10.82
Germination loss (%)		0.16	0.15	0.14	0.12
Grain temperature (°C)	Discharge	21.7	21.9	22.1	22.5
	Maximum	69.5	69.3	69.0	68.5
Energy cost (£/t)		0.51	0.50	0.49	0.46

Table 7. Simulation output in relation to insect survival for a mixed-flow dryer with a 9m^2 heating section, a 3m^2 cooling section and a drying air temperature of 80ºC.

(a) Barley at initial moisture content 12 % w.b.		Insect mortality			
		99.99 %	99.9 %	99%	90%
Throughput (t/h)		6.82	7.01	7.34	8.31
Residence time (min)		15.4	14.9	14.3	12.6
Moisture content (% w.b.)		10.76	10.80	10.87	11.05
Germination loss (%)		0.14	0.14	0.12	0.10
Grain temperature (°C)	Discharge	40.8	41.3	42.0	43.6
	Maximum	76.2	76.2	76.1	75.8
Energy cost (£/t)		0.68	0.66	0.63	0.56

As shown in Tables 6 and 7, an air temperature of 80 ^{o}C in combination with a particular residence time were predicted to kill 99.9% of *S. granarius* and to cause a reduction in germination of barley of less than 1%. The barley was assumed to have an initial m.c. of 12% wet basis and an initial germination of 98%.

For a given level of insect mortality, as drying air temperature was increased, throughput increased, moisture loss reduced and energy cost reduced. Therefore the optimum treatment would be to use as high an air temperature as limits to germination loss allow.

The two components of treatment cost were energy cost and the value of weight loss owing to drying. Energy costs at 80ºC were typically in the range 0.50 -1.00 £/t of input grain. Cost of lost weight were in the range 0.65 £/t when starting from 11 % moisture content to 3.26 £/t when drying from 16%.

From the simulation runs, disinfestation treatments were effective in both types of dryer when run in a continuous-flow, once-through operation. This supports the earlier work with a simple model that suggested disinfestation in dryers is possible without unacceptable damage to the germination. There were operational and cost benefits of using as high an air temperature as possible, limited by the risk of germination damage. Treatment became much slower and more costly as initial moisture content increased.

These results for mixed-flow are for specific dryer designs, with a given number of ducts and area of bed etc. Results are likely to be a little different of a larger or smaller dryer of the same design is used, but the influences of varying parameters will be similar.

Evaluation of the suitability of a full-scale, heated-air dryer for disinfestation of grain

The final experiment of this project was intended to validate the models on a practical scale using a mixed-flow dryer in recirculating-batch operation to allow controlled heating and monitoring of the grain batch. The dryer was filled with approximately 10 t of wheat which was recirculated as it was brought up to the required temperature for disinfestation, and then discharged into a holding bin. The treatment conditions, selected with the use of the insect mortality and barley viability models, aimed to achieve no detectable loss of viability and a 0.1 % survival of insects. Grain temperatures were measured at inlet and outlet of the dryer using thermocouples where some canisters of insect-infested wheat and malting barley samples were also placed to assess survival and grain viability respectively. In addition, bags of insects were dropped into the dryer as it was loaded and some of these were recovered as the grain discharged into the holding bin. Two experiments were carried out, the first to investigate a treatment using a relatively low temperature, 50°C, for a relatively long time, 30 min., the second a higher temperature, 55°C, for a shorter time, 15 min. The method used for the tests was adapted from the ISO 11520-1 “Agricultural grain driers – Determination of drying performance”.

There was a persistent temperature difference between the top and bottom of the dryer on the exhaust side (Table 8). This difference, which was largely caused by some of the batch being longer in the heating zone that the rest, meant that it was not possible to bring all the temperatures to the target at the same time. The difference between the inlet and exhaust sides, resulting from cooling and drying in the grain bed, effectively provided two different temperature environments to which the insects in canisters embedded in the dryer were exposed. In Run 1 this difference was about 13°C, and 10°C in Run 2.

Table 8. Measured maximum temperatures (^oC) from thermocouples in canisters on each side of dryer and their insect % mortality or germination. t = nominal exposure time.

Side	Canister Position & Content	Run 1 (t = 30 min)	% Insect mortality (I) or Germination (G)	Run 2 (t= 17.5 min)	% Insect mortality (I) or Germination (G)
Inlet	Top Insect (Row 3)	61.8	100 I	57.9	100 I
	Top barley (Row 3)	59.4	97 G	56.3	98.5 G
	Bottom Insect (Row 1)	62.3	100 I	56.2	100 I
	Bottom Barley (Row 1)	62.2	98 G	56.8	99 G
	Mean	**61.4**		**56.8**	
Exhaust	Top Insect (Row 4)	43.0	0 I	48.7	72 I
	Top Barley (Row 4)	44.0	99 G	49.1	97 G
	Bottom Insect (Row 1)	53.5	100 I	51.3	100 I
	Bottom Barley (Row 1)	51.1	98.5 G	52.3	97 G
	Mean	**47.9**		**50.4**	
Temperature difference between Inlet and Exhaust side means		13.5		6.4	

The calculated mortality of the weevil larvae was lower than or equal to the results from the canisters inserted in the inlet and exhaust of the dryer (Table 8), suggesting that the mortality model was predicting conservatively the likely effect on insects of the heating. This allows a certain margin of safety in predictions made with the model in thesimulations.

The comparison of measured and calculated grain viability confirmed the validity of the model, in that a loss of a fraction of a percent was predicted for the samples and the measured loss was not detectable at the level of the resolution of the germination test, i.e. 1% point, except for one sample on the inlet (hotter) side in Run 2 where a 1% point loss was recorded. This gives confidence that the model for viability loss was working well in this situation.

After Run 2, the grain was ventilated with the dryer fan and the cooling rate was 1.0^oC/min, so that a temperature of 20^oC was reached after a cooling period of 36 min.

It was clear from the test that in practice, conditions in a dryer are neither uniform or constant (e.g. air temperature may vary over the dryer plenum and also varies in time as the thermostat takes effect). The effect of these variations will be to narrow the window in which disinfestation without grain damage can be achieved. Other parameters, e.g. grain throughput, cannot be easily selected by the operator. Simulations show that the effectiveness of disinfestation in continuous-flow, once-through treatment is particularly sensitive to the grain residence time; the disinfestation is achieved by a high temperature exposure for a short time and if the time is only a little too short, disinfestation will be ineffective. Because residence time is not at all straightforward to set, it would be difficult to achieve the disinfestation effect reliably. Given this sensitivity and the lack of information on the operating conditions within the dryer, disinfestation for *S.granarius* using either type of dryer in continuous-flow, once-through mode will be very difficult to achieve reliably in practice.

In recirculating-batch operation, the thermal treatment would take place over a longer time and at a lower peak temperature, so the process would be less sensitive to fluctuations. It would also be more expensive in energy, lost weight and labour. Temperature of the grain, for controlling the disinfestation process, would be more easily determined by the dryer's instrumentation or by a low cost system that could be added. To firmly establish how to use a dryer in recirculating-batch mode for disinfestation, a model of this operation is needed. The basis of such a model exists, developed for studies on dryer control at SRI, but further work is needed to set it up and use it for recirculating-batch disinfestation.

Conclusions and recommendations

1. This project has identified the combinations of grain temperature and exposure time to that temperature that would enable grain to be disinfested from the most heat tolerant life stage of the most tolerant UK grain pest, the grain weevil.
2. A "window of opportunity" has been established within which disinfestation can be achieved without damage to grain, as judged by germination of malting barley. The window is widest at low grain moisture and with barley of high initial germination.
3. A practical test showed that the predictions of the model gave the desired result – disinfestation of the grain weevil without grain damage – except for a few locations where insects unexpectedly survived, indicating cool spots in the grain bed.
4. Simulation of commonly used dryer types used in continuous flow has shown that, in principle, it is possible to achieve disinfestation of the grain weevil without grain damage in a dryer where the temperatures and airflows are constant and uniform. The dryer settings needed to disinfest without damage, and how tolerant they are to uncertainties in the settings have been studied in detail.
5. In practice, however, disinfestation of grain weevil would be difficult to achieve reliably in continuous-flow treatment because of the considerable temperature variation within hot-air dryers and because grain throughput would have to be precisely set. The minimum temperatures must be high enough to guarantee disinfestation, the maximum temperatures must not be so high as to damage germination.
6. The recommended air temperature and residence times (Fig 1) would, however, enable disinfestation from most free-living species such as the saw-toothed grain beetle and, if the areas of minimum temperature could be located and monitored, the recommendations would prove suitable for disinfesting feed grain, even from grain weevils inside the grain.

7. Disinfestation of grain weevil in recirculating-batch dryers will be more reliable because the treatment would be at a lower temperature but for a longer time than in continuous-flow. Provided they have a high grain recirculation rate, the mixing will make settings less critical and grain temperature more uniform. Further work is needed to find the best operating conditions for such dryers to achieve disinfestation. An existing simulation model could be readily adapted for such work.

BACKGROUND

With increasing pressure to avoid the use and minimise the choice of organophosphorus insecticides or fumigants on potential foodstuffs due to concerns about residues and human health, there is a need to find equivalently rapid non-chemical means of disinfesting grain, particularly for organic use. Grain cleaning can effectively remove free-living insects and mites but the developing stages survive within the grain and emerge after treatment. Cleaning would thus need to be combined with another treatment in order for it to succeed. Heat disinfestation is a viable treatment and a successful pilot-scale disinfestation plant has been developed in Australia (Evans et al., 1984). As a result, there is considerable information in this context concerning the hardiest species and stage, and it would appear that grain temperatures of 65°C achieve complete mortality of the hardiest UK species (*S. granarius* larvae) in a few (2-3) minutes (Evans, 1987). Other common free-living UK species, such as the saw-toothed grain beetle are considerably easier to kill.

In Australia, purpose-built heat disinfestation is required as grain needs little drying, however in the UK, hot-air dryers are widely available, (all commercial stores and most farm stores had a dryer (Prickett 1992), and, to date, no thought has been given to their use for disinfestation. Costs of hot-air drying to remove moisture are usually quoted at about £1 per tonne, comparable with the costs of curative fumigation. However, costs of heat disinfestations are likely to be much lower as residence times in the dryer are likely to be shorter.

Although high grain temperatures can damage quality in damp grain, especially viability, most grain is intended for animal feed for which temperatures in excess of 100°C are permissible. For milling wheat and malting barley, safe drying temperatures vary according to the moisture content, the higher the moisture content the lower the safe grain temperature, and while prolonged exposure to 65°C will cause loss of grain viability in damp grain; dry grain is considerably less susceptible to heat damage. Temperatures to damage milling quality are generally higher and are therefore a less sensitive indicator of heat damage than germination. Baking quality is supposed to be unaffected below 70°C (Finney et al. 1962; Wasserman and Muhlbauer 1980) and if the glutenin fraction of wheat endosperm proteins is more sensitive than the gliadin fraction (Scofield et al 1983) but in wheat dried at 70-95C, the proportion of glutenins can increase and the proteins become insolubilised which can actually enhance breadmaking quality (Godon, 1988). The market level for malting barley germination is 98%, the market level for seed only 85% so malting barley appears a more demanding criterion. What is not immediately apparent is whether seed wheat is more sensitive than malting barley. However, the classic viability nomograms of Roberts and Roberts (1972) suggest that at 40°C, 15% mc, wheat takes 15 days to fall to 85% germination, the seed market requirement, while malting barley takes less than 10 days to fall to 98%, the malting market requirement. This again indicates that malting barley quality would be damaged more rapidly than wheat seed quality.

Recent work has shown that mortality can be achieved at lower grain temperatures and longer exposure time and is also influenced by the moisture content of the grain (Beckett et al, 1998). Therefore there is a need to define accurately the conditions that kill insects but do not harm grain, and how to operate a hot air dryer to achieve those conditions with as much of a safety margin as possible.

Proven models of drying can simulate accurately the temperature and moisture profiles and any loss of grain viability throughout a hot-air dryer (Bruce, 1984). By incorporating a simple model of how insect mortality depends on temperature, grain moisture content and exposure time into the simulation model, the operating conditions for successful decontamination can be efficiently explored, and the best approach determined. The heat disinfestation technique will be demonstrated in a commercial size dryer to validate the approach described. Further simulations for different dryer types will enable recommendations for the safe operation of hot-air dryers for decontamination to be made.

The objectives of the project were:-

- To identify the UK insect and/or mite species and stage most resistant to heat (including internal developers)
- To identify time/ temperature / moisture content combinations required to disinfest, using heat, grain at various moisture contents infested with this species, and to summarise the results as a mortality model
- To devise and validate thermal disinfestation /decontamination strategies using a hot-air dryer of the mixed-flow type, used on many UK farms
- To make recommendations for the operation of hot-air dryers for disinfestation

Part 1.
EXPERIMENTS TO FIND MOST HEAT-TOLERANT STAGE OF *SITOPHILUS GRANARIUS* AND SUBSEQUENT ASSESSMENT OF TOLERANCE OF THIS STAGE TO A RANGE OF TEMPERATURES

S. Conyers

Summary

The literature indicates that internally developing insects are the most resistant to heat and there was little published information on the heat resistance of the commonest UK, representative, the grain weevil. Initial tests exposing the developing stages in an oven at temperatures of 55 and 57.5°C, indicated that 4th instar larvae and pupae were the most resistant stages to heat so detailed observations concentrated on this age group. The developing insects were exposed to temperatures between 45 and 60°C both in an oven and also in a sealed bags in a water bath, the latter being used because of the quick heat-up times and the fact that no moisture loss occurred. Insects died slower at the same temperatures in the oven than in the water bath, probably because they were denied the survival benefit of evaporative cooling. For this reason and because the oven represented a situation closer to the reality of a grain dryer, the oven results were used as a basis for the new mortality model to interact with the existing models of dryer operation and germination loss. The oven experiments suggested exposure times to achieve complete mortality of 3h, 1h, 10 minutes and 3 minutes for temperatures of 48, 50, 55 and 57.5°C respectively.

Introduction

There have been several studies looking at the effect of temperature on different species of grain store insects and some of these are found in Table 1. The first three species have juvenile stages, which develop inside their food whereas the fourth, *Oryzaephilus surinamensis* L. (Saw-toothed grain beetle), is an external developer and needs only a fraction of the time of the internal developers to die at high temperatures. Therefore *Sitophilus granarius* L. (Grain Weevil) was chosen for these tests as it is the most heat-tolerant species of the common grain pests encountered in the UK. The results of Dzhorogyan (1955) represent the only published result for high temperature treatments with *S. granarius* and therefore this was used as the basis for the treatment times.

The objective of the project was to first find the most heat tolerant stage of *S. granarius* and then to use that stage to find the mortality caused by a range of temperatures from 45 – 60°C after exposure for a number of time intervals. This would produce a range temperature/exposure time relationships that could be used to develop the model for use with the dryer. This model would use the results from the oven tests to predict the mortality of the insects resulting from conditions in the dryer.

Materials and Methods

<u>The Insects</u>

Sitophilus granarius L. (Grain Weevil) was used for these tests and the first task was the selection of the most tolerant developmental stage. There was little published work on *S. granarius* with heat and therefore it was important that initial tests were run to assess the relative tolerances of the immature stages. Evidence from the literature for other insect species which developed internally, showed that the fourth instar was the most tolerant stage, however it was important to ensure that this was also the case for *S. granarius*.

Known aged cultures of each stage of the life cycle were set up by placing 500 adults on 500g of wheat (15% m.c.) in a plastic tank (190 mm wide x 280 mm long x 170 mm deep) so that the grain formed a shallow layer in the bottom. This optimised the conditions for oviposition. The adults were left on for a set period (4 to 7 days) at 25°C and 70% relative humidity (r.h.) depending on the stage required (Table 2). They were then removed from the grain by sieving (2.0 mm mesh). The grain was divided into two and each half was placed in a glass jar (75 mm wide x 150 mm high) and sealed by waxing a filter paper circle (No. 551, Schleicher and Schell GmbH., Dassel, Germany) to the top. The jars were replaced in the same conditions to incubate. At the same time as the tank was set up a 100g sample of grain was taken as a moisture sample. This was kept with the infested grain until it was time for testing.

<u>Preliminary oven tests to determine the most resistant stage</u>

Two temperatures were assessed: 55 and 57.5°C. The maximum time exposure for the weevils at each temperature was based on the work with ovens published by Dzhorogyan (1955) (Table 1). There were seven time intervals and each was √2 less than the previous treatment time, to give an even distribution of results.

The experiments were carried out in a 225 l fan-assisted oven (Model IPR225.XX1.5, Sanyo Gallenkamp plc., Loughborough, Leics., UK). This oven was in a controlled environment room set at 25°C and 60% r.h. For each oven test, the samples were divided in half and then divided into eight equal samples. This gave seven different treatment times and a control sample, each one comprising approximately 30 g. Using the two halves of each sample meant that two different temperatures could be run in succession once the oven was adjusted. As this was a preliminary experiment, there was only one replicate for each treatment time/temperature combination. A shelf midway up the oven (420 mm from the floor) was used and a position at the left front of the shelf gave the short time to the target temperature for the sample (The fan was positioned midway up the right hand wall). Rapid heating to the required temperature was an important requirement for the predictive modelling that was to be used with the laboratory results and the subsequent drier tests. Only one sample could be treated as heating times to a target temperature varied as much as five min between positions on the same shelf.

The sequence for the treatment of each sample was as follows: The oven temperature was set at 0.5°C below temperature required. This ensured a temperature that was a degree higher than the target temperature at the sample position. This meant that heating of the oven continued past the target temperature and ensured a faster heating time. The thermocouple (Type-T with a beaded tip and PTFE insulation (-50 to +250°C), with its tip embedded in a grain of wheat, was placed in the middle of a circular metal grid (200 mm diameter, mesh size 800 μm). The 30 g sample of infested wheat was spread, one grain thick, evenly over surface of the grid and around thermocouple grain. The temperature of the oven was ascertained prior to the input of the sample by a further Type-T thermocouple, which was attached to the oven shelf adjacent to the sample grid. The temperatures were recorded on a chart recorder (MobileCorder Model MV230, Yokogawa Martron Ltd., Wooburn Green, U.K.).

The oven door was closed as the stopwatch was started to record the time that the sample took to reach target temperature. Once the temperature was reached, the warm-up time was recorded and the removal time was noted by adding the treatment time for the sample to the warm-up time. The oven temperature was reduced to a degree below the temperature required to achieve the target temperature in the oven. The sample and the thermocouple were removed once treatment time was completed. The door of the oven was closed immediately afterwards to allow it to heat up to the required temperature in preparation for the next sample. The setting on the oven thermostat was also increased. The sample was spread one grain thick evenly on a metal grid with raised sides (200 mm diameter, mesh size 800 μm) and placed in the draught from a fan (Model 1062, Pifco, Taiwan). The thermocouple was also in the draught from the fan. The fan draft ensured that the sample cooled rapidly. The thermocouple indicated the cooling down time for the sample and also signalled the start of the next treatment cycle when the temperature reached that of the room, as long as the oven had reached its target temperature.

The samples were place in glass jars (50 mm wide x 65 mm high) with nylon mesh top for incubation at 25°C and 60% r.h. after treatment. Mortality was determined by comparing numbers of adults emerging from the heated samples with numbers emerging from untreated samples.

<u>Experiments to determine mortality of 4th instar larvae .</u>

The insects were exposed at six temperatures : 45, 48, 50, 55, 57.5 and 60°C for were seven time periods at each temperature. The longest time period was estimated from the initial testing and from the published results (Table 3). Larva IV and pupa were the most tolerant stages, with a similar level of susceptibility, so these were used for the more detailed tests over a larger range of temperatures. The cultures were set up in the same tanks but with 800 g of wheat and more initial adults than in the preliminary tests, 900, to ensure a high level of oviposition within the grains. The adults were left on for 11 days to ensure that there was an even representation from each of the stages during testing. The tanks were placed at 30^{o}C and 70% r.h. and these conditions were maintained once the adults were removed from the grain. It was placed in the same jars as the preliminary test but two extra were used to accommodate the increased quantity of grain. Similar conditions were used to incubate the samples to determine adult emergence after the grain had been treated in the oven. The increased temperature of 30°C rather than 25°C used in the preliminary tests, ensured that the insects developed faster and therefore the tests were completed in a shorter time.

After the preliminary tests, it was decided to try and shorten the warm-up times to obtain more constant temperatures for input into the mortality model. This meant doing treatments in vacuumed plastic bags in a water bath, a technique that had been effectively used for testing the affect of temperature on the germination of malting barley. The advantage of this method is that the grain was kept in one layer so that there was uniform heating of the grains and also the large volume of water in the bath kept the temperature constant allowing the grain to heat up faster than in the oven. It also meant that the moisture content of the wheat would remain the same throughout the treatment, which was an important requirement. It was decided to carry out the water bath tests with the oven tests in parallel, to act as a comparison and as a representation of the situation found in a grain dryer. To ensure comparability between the two methods, the same batch of infested grain was used for each technique at each temperature.

The 800 g batch of infested wheat was halved and each half was divided into 32 samples with the aid of a Boerner Divider (Burrows Equipment Co., Evaston, Illinois, U.S.A.). Each sample was approximately 12 g and was placed in a glass tube (255 mm wide x 75 mm high). Three replicates were used for each time/temperature combination for each temperature. Seven different time intervals were used for each temperature to ensure that there were sufficient data points for probit analysis. Three further replicates were used as controls. It was important that the warm up times for the three replicates for each time period/temperature were similar.

Oven Tests. The sequence for testing in the oven and the oven itself was the same as for the preliminary test. Each replicate was tested separately in the same manner with the only divergance from the preliminary test being the use of nylon mesh grid for placement of the sample on the oven shelf. The smaller mesh size (130 μm) meant that there was no loss of small grains. The only exception was at 45^{o}C where the three replicates were placed on the shelves at the same time. This was done because the treatment times were so long, with a maximum time of 5 hours, that the differences in warm-up time between shelves was not considered important. Two ovens of the same make were used to ensure the testing was completed in two days. Three separate nylon mesh grids were used in the three areas of the oven shelf that had the fastest warm-up times. Only one thermocouple was used and that was placed on the mesh with the fastest warm-up time.

Water Bath Tests. These were carried out in a water bath (300 mm wide x 550 mm long x 180 mm deep) with a circulation propeller (Grant Instruments Ltd., Cambridge, U.K.). The water bath temperature was set to the required temperature using a similar grain embedded thermocouple as for the oven tests. However in this case the thermocouple was in a grain inside a thin polyethylene bag (150 mm x 150 mm), which was heat-sealed top and bottom using a foot-operated impulse heat sealer (Element length 340 mm, Model 1300, Hulme-Martin Ltd., Woking, Surrey). Each bag contained 12 g of wheat, which surrounded the embedded grain in a single layer. A slit was cut in the bag to allow entry to the thermocouple and the hole was sealed with silicone mastic.

The plastic bag was partially vacuumed to the grain by the use of a suction pump (Model SM166 17, Sartorius Gmbd., Goettingen, Germany). This acted through a ball valve, which was attached to the bag before it was heat-sealed. A cork borer was used to make a tape-reinforced hole in the bag. The valve opening was pushed through the hole and a nut was attached to the end and screwed tight with a spanner. This arrangement meant that the partial vacuum could be reapplied and the set up used to give heating times for each temperature test. Three such set-ups with thermocouples were made and an average temperature measurement taken on each occasion. The temperatures were recorded on a chart recorder (Hybrid recorder Model HR2300 and MobileCorder Model MV230, Yokogawa Martron Ltd., Wooburn Green, U.K.).

The sequence for the treatment of each sample was as follows: The water bath was set to the required temperature with a thermocouple-inserted vacuumed bag. The three-thermocouple bag set-ups were then used to give an average warm-up time for the temperature that had been set. This warm-up time was used for the test samples. Each 12 g sample was placed in a single layer in a pre-sealed bag with only a 20 mm hole left in one corner. The bag was partially vacuumed by placed a tube from the vacuum pump through the hole in the bag. The pump was turned on and once the partial vacuum was achieved the bag was heat-sealed. If the vacuum failed the sample was transferred to a new bag and the process was repeated. Bulldog clips were attached to one edge of the bag and this was dropped into the water bath along with the other two replicates whilst the stopwatch was started to monitor the warm-up time. The treatment time was then added to the warm up time and the total noted for the removal time. Further sets of three bags were added to the water bath for other time intervals as this did not affect the temperature of the bath.

Once the heat treatment was complete, the three replicates were removed and hung from a rack in the stream of a fan (Model 1062, Pifco, Taiwan) to give a rapid cool down of the samples. Once they had reached room temperature the bag was opened. Each sample was placed in a glass tube (255 mm wide x 75 mm high) at a similar temperature to the oven treatments and was monitored regularly for adult emergence.

An extra set of three control samples was used to test the effect of sealing the grain in a partially vacuumed plastic bag. This was done for the maximum time interval for the temperature to be tested.

Statistical analysis

For each temperature, the mortality data was plotted against each time interval using a probit computer analysis (Version 7a Central Science Laboratory, York UK). This produced a straight line relationship between time and mortality, when both are converted by Log_{10} for the former and by probits for the latter, which allowed the prediction of the exposure time required to achieve a certain level of mortality, the lethal time (LT). In this case the LT for 50% (LT_{50}) and 99% (LT_{99}) *for S. granarius* were used. The goodness of fit for the relationship is shown by the closeness of the dotted lines (95% confidence limits) either side of the straight line relationship.

Moisture content

The moisture contents (mc) of the samples were taken before and after treatment and determined according to ISO 712, by drying in a ventilated oven at 130°C for 2h. The intention was to compare the mc of grain exposed in the oven and in the water bath in order to ascertain the effect of mc on insect survival.

Results and Discussion

The preliminary tests showed that the larva IV and pupa were the most heat tolerant stages so these were chosen for the main tests. The published times for survival of grain weevils (Dzorogyan, 1955) were longer than the times which had achieved 100% mortality in these tests and therefore the highest time interval was lowered for the main tests, except at 45^{o}C, as this was likely to require a long exposure time.

The heating profiles of the samples of grain subjected to each of the oven temperatures are very similar (Fig.1) with a slight over-shoot after the target temperature was reached. Warm-up and cool-down periods showed more rapid transitions at the higher temperatures as shown by the steeper profiles. Generally they have all fulfilled the requirements of the criteria for the model with rapid warming and cooling and the maintenance of a constant target temperature over the treatment period. The water bath achieved more rapid warm-up times than the oven tests as shown in Figs. 2 and 3.

The oven tests produced a range of lines for survival against temperature (Fig. 4, Table 4) within 95% confidence limits , except at the two temperature extremes. For 60^{o}C there was 100% mortality with only 45 seconds after the warm-up period. It was not possible to do enough time intervals accurately below this time and this was compounded by the variation in the warm-up time. At the other end of the scale, the 45^{o}C result must be viewed with caution. The treatment of all three replicates together for each exposure time except for the two shortest time intervals did have an effect on the mortality. There was much higher mortality at the hottest position and three separate samples at this position would probably have given a result for LT_{99} closer to 5 and half hours. A comparison between the results for the oven tests and the published results Dzhoroygan (1955) have shown a reduction in time at the higher temperatures, 55 and 60°C but there was agreement at 50°C and the temperatures below this required much longer exposures in the present study.

The water bath method of determining mortality gave even higher mortality than the oven method (Fig. 5, Table 5). Complete mortality was achieved by a much shorter time period and, because of the rapid rate of kill resulting from the water bath technique, lines could not be produced for 55, 57.5 and 60°C. Exposure in the water bath at 50°C produced a similar time to the oven and therefore the published result but the exposure times for complete mortality at 45 and 48°C were appreciably shorter than the oven's results.

It is probable that the differences in weevil survival were related to the behaviour of moisture in the two techniques. Moisture could not be lost from the sealed bags so mc stayed the same using the water bath throughout the treatment (Table 6) and this aided quick heat penetration. In contrast, moisture loss accompanied heating in the oven and evaporative cooling is an important mechanism that aids insect survival at high temperature. The water bath's temperature was also more constant and able to produce a faster warm-up time than the oven . Another factor is oxygen. It is an essential part of respiration whose functions are limited and finally cease at high temperatures. The bags have a finite supply of oxygen and this may be a further reason why there is the difference between the techniques. Overall it was concluded that the temperature/treatment times from the oven tests provided a better basis for estimating the treatment times needed in the dryer.

Table 1. Oviposition period and age of each developmental stage of *Sitophilus granarius* at treatment

Developmental Stage	Oviposition period (Days)	Treatment age (Days)
Egg	4	1 - 5
Larva I	4	6 - 10
Larva II/III	6	12 - 18
Larva IV	6	21 - 27
Pupa	7	28 - 35

Table 2. Published exposure times (minutes) required for 100% mortality in a range of grain beetles

	Temperature (^{o}C)				
Species	45	48	50	55	60
Rhyzopertha dominica a	-	-	942	17	0.5
Sitophilus granarius b	300	60	55	10	2
Sitophilus oryzae c	120	-	120	-	16
Oryzaephilus surinamensis d	-	-	3	1.4	0.4

a Beckett and Morton (2003)

b Dzhorogyan (1955)

c Tsuchiya and Kosaka (1943)

d Obretenchev (1983)

Table 3. Mean warm-up times, exposure times and % mortality for all juvenile stages of *Sitophilus granarius* at 55 and 57.5°C for assessment of most tolerant stage

		Stage				
		Egg	Larva I	Larva II/III	Larva IV	Pupa
Temperature (°C)	Mean control emergence	122	136	416	334	321
55	Mean Warm-up Time (min.sec.)	2.41	2.44	3.17	6.26	3.23
	Time (min.sec.)					
	1.15	99.07	94.94	97.1	86.38	79.25
	1.46	100	98.83	98.96	97.39	72.33
	2.30	100	100	100	98.26	88.18
	3.32	100	100	100	98.26	93.66
	5.00	100	100	100	100	95.1
	7.04	100	100	100	100	100
	10.00	100	100	100	100	100
57.5	Mean control emergence	99	166	371	348	291
	Mean Warm-up Time	3.22	4.09	4.88	7.06	4.30
	Time (min.sec.)					
	0.30	100	100	100	99.71	78.69
	0.42	100	100	99.38	100	79.23
	1.00	100	100	99.18	95.39	91.26
	1.25	100	100	100	100	99.45
	2.00	100	100	100	100	99.73
	2.50	100	100	100	100	100
	4.00	100	100	100	100	99.73

Table 4. The treatment temperatures, their mean warm-up and the LT_{50} and LT_{99} achieved after exposure of Larva IV/Pupa of *Sitophilus granarius* in a fan-assisted oven

Temperature	Mean warm-up	LT_{50}	LT_{99}
(°C)	(mins.)	(hrs.)	
45	2.10	2.52	78.53
48	2.06	0.28	2.33
50	1.54	0.07	0.51
55	2.25	0.01	0.06
57.5	1.46	0.00	0.01
60	2.05	43 secs *	

* 100% mortality

Table 5. The treatment temperatures, their mean warm-up and the LT_{50} and LT_{99} achieved after exposure of larva IV/ Pupa of *Sitophilus granarius* in vacuumed sealed bags in a water bath

Temperature	Mean warm-up	LT_{50}	LT_{99}
(°C)	(mins.)	(hrs.)	
45	1.10	1.09	3.25
48	1.30	0.20	1.58
50	0.52	0.05	0.52
55	1.00	38 secs *	
57.5	1.40	1 sec *	
60	1.45	1 sec *	

* 100% mortality

Table 6. A comparison of the mean moisture content loss due to oven and water bath treatment

Temperature (°C)	Treatment	Time (min.sec)	Mean MC (%)	MC Loss (%)
50	Water bath	62.00	12.88	0.02
	Control	-	12.90	
50	Oven	62.00	11.49	2.4
	Control	-	13.89	
55	Oven	8.00	13.30	0.37
	Control	-	13.67	
55	Water bath	12.00	12.83	0.2
	Control	-	13.07	
60	Oven	5.15	12.75	0.61
	Control	-	13.36	

Figure 1. The change in temperature of infested grain after placement in a fan-assisted oven

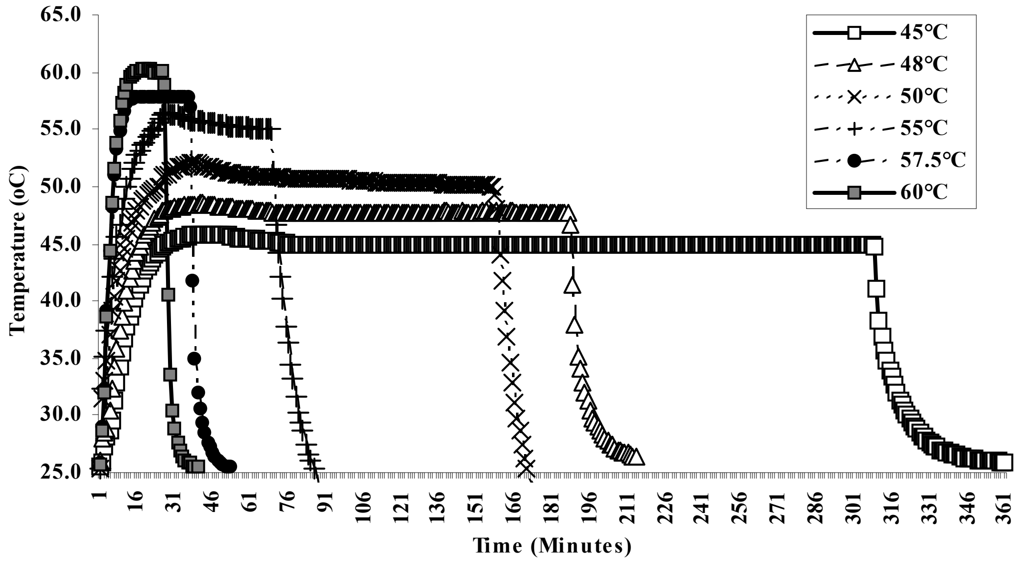


Figure 2. The change in temperature of infested grain after placement in a fan-assisted oven or water bath at 45, 48 or 50^{o}C

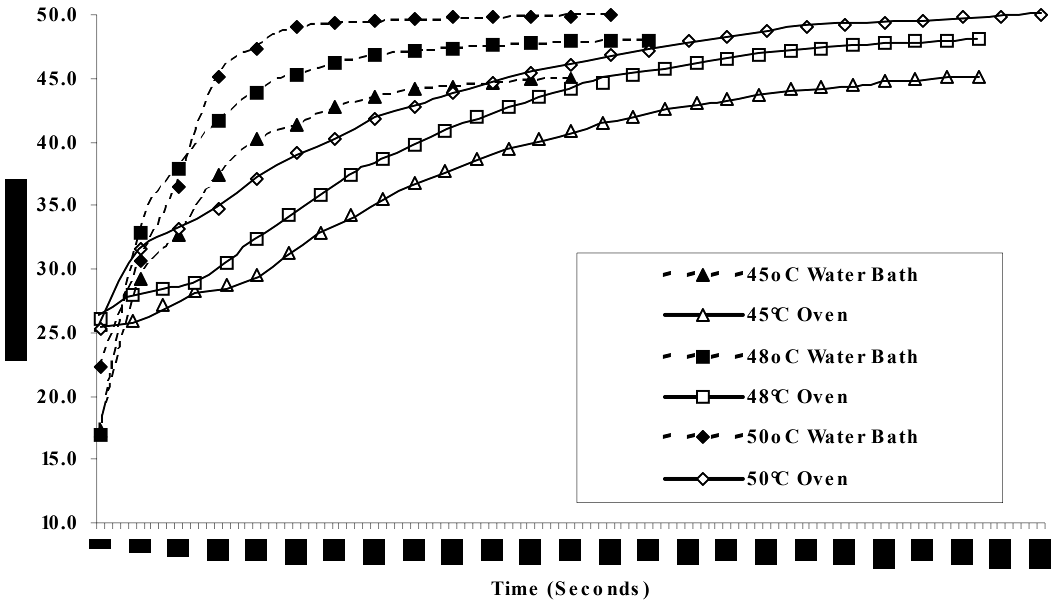


Figure 3. The change in temperature of infested grain after placement in a fan-assisted oven or water bath at 55, 57.5 or 60^{o}C

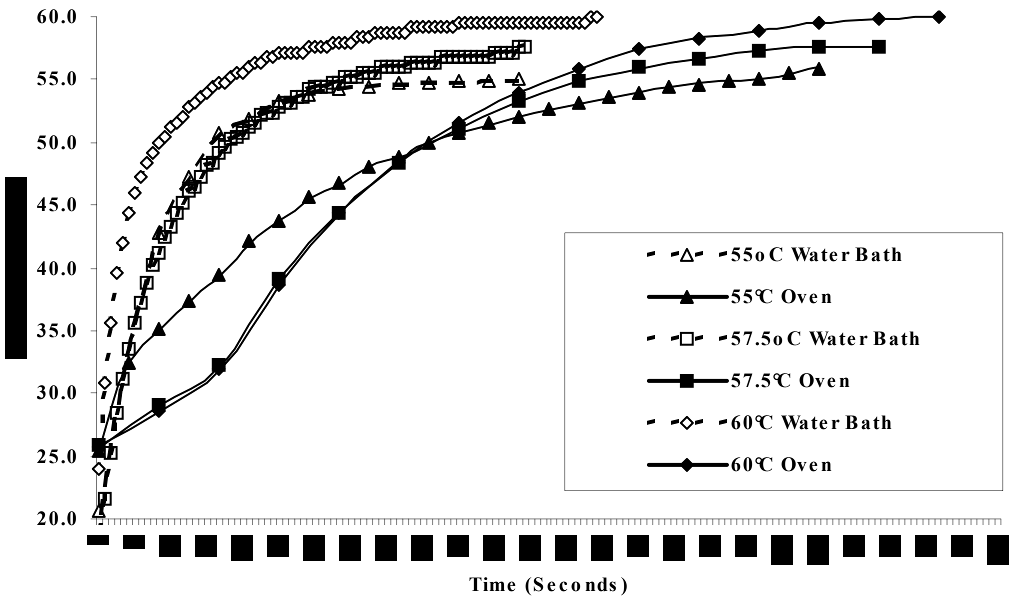


Figure 4. Probit analysis of the mortality of *Sitophilus granarius* (Larva IV/Pupa) after exposure at various time intervals to a range of temperatures in a fan-assisted oven

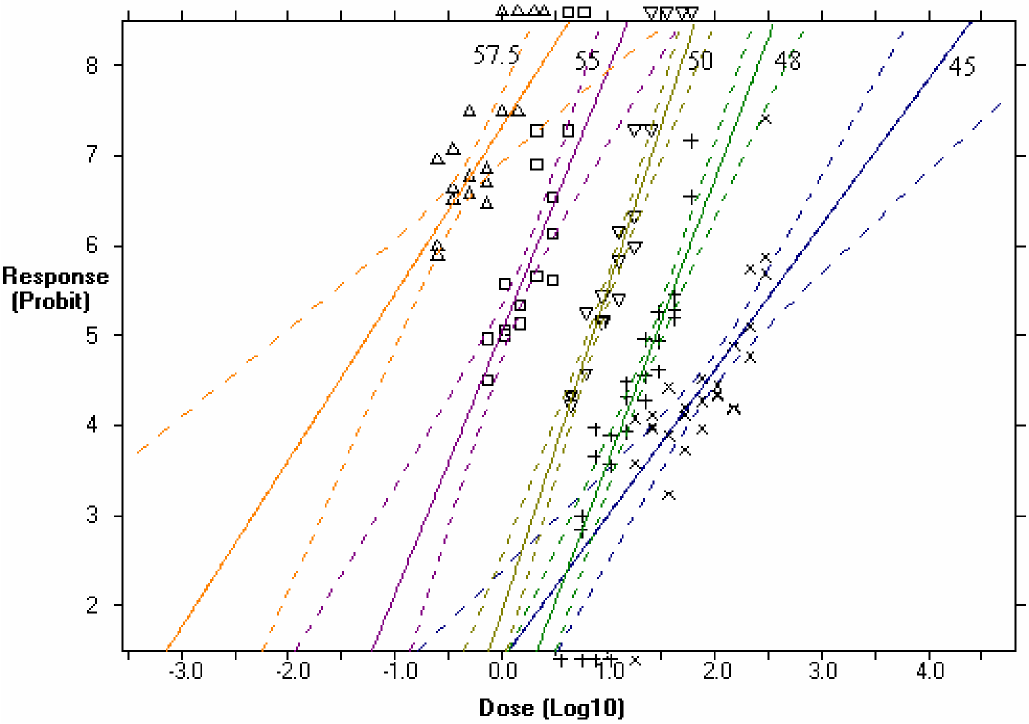
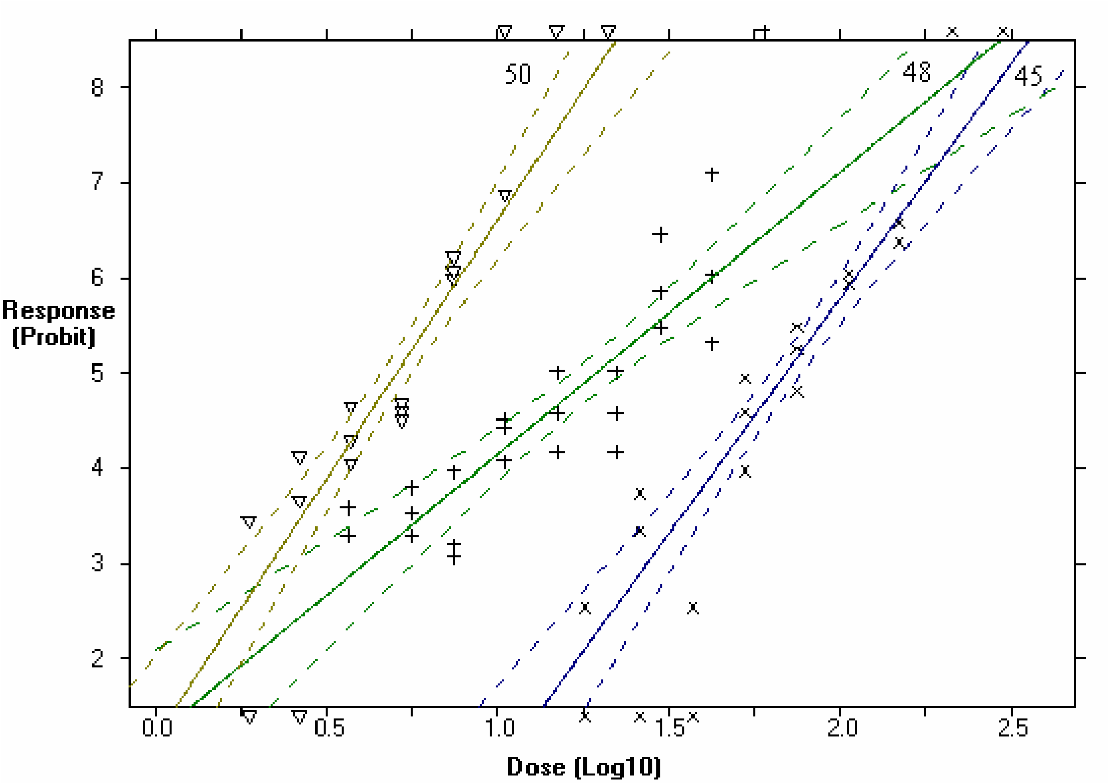


Figure 5. Probit analysis of the mortality of *Sitophilus granarius* (Larva IV/Pupa) after exposure in vacuumed plastic bags for various time intervals to a range of temperatures in a water bath



Part 2

DEVELOPMENT OF AN INSECT MORTALITY MODEL AND THE OPPORTUNITY FOR THERMAL DISINFESTATION OF GRAIN

P J C Hamer, D M Bruce, R P White

Summary

In order to provide guidance on the operating conditions of hot air dryers to disinfest grain, a model is needed to describe mortality of grain weevils (*Sitophilus granarius*) in relation to time and grain temperature. The same probit analysis used for predicting the effect of the loss of seed viability was used and based on the assumption that mortality has a statistically "normal" distribution with time at constant temperature. Data from the oven experiments (Part 1 of this report) were used to develop the model which assumed a linear death rate, defined as the reciprocal of the standard deviation. The standard deviation was related to grain temperature by a power series. A naturally occurring mortality of 6.5% was determined by regression.

The insect mortality model was used to predict grain temperature required to kill the grain weevil (at its most tolerant stage) and an existing germination model was used to predict the grain temperature for a small acceptable level of loss in germination at two moisture contents and at several initial levels of grain viability. This "window of opportunity" for thermal disinfestation was 18ºC for barley at 12% moisture content and reduced to 12ºC for wheat at 14% moisture content when the germination for both barley and wheat were initially at 98% and a 1% loss of germination was acceptable. The heat treatment technique for disinfestation is most likely to be successful for high quality grain of low moisture content.

Introduction

The concept of using hot-air dryers to disinfest grain involves raising grain temperature to cause mortality to the most tolerant UK insect species without a loss of grain viability. In order to provide guidance on the operating conditions of hot air dryers for this purpose, a mortality model needs to be developed and incorporated into proven dryer simulation models. These simulation models accurately calculate the temperature and moisture profiles throughout a hot-air dryer and will thus allow us to identify conditions to minimise loss of grain viability throughout a hot-air dryer.

Predictions of the effect of the loss of seed viability during heated air drying are based on an assumption that seed death has a statistically "normal" distribution with time at constant temperature and moisture content (Roberts, 1960). Germination percentages are represented as probabilities, which, when transformed to equivalent values of the standardised normal deviate or 'probit', have a linear death rate defined by the reciprocal of the standard deviation (the symbol σ identifies the standard deviation) (Nellist, 1981). For cereal the standard deviation is related to grain temperature and grain moisture content (Ellis & Roberts, 1980). An explanation of probit analysis in relation to predicting cereal quality is presented by Nellist & Bruce (1987).

The extent of the loss of grain viability depends on the initial quality of the grain, the temperature and moisture content of the grain and the time of exposure (Nellist, 1981). The conditions inside a hot-air dryer during operation are complex because of the time taken to warm the grain, cooling due to evaporation, the effect of temperature and moisture fronts passing through the bulk, and so on. Temperature, moisture and exposure time are varying simultaneously and their effects on variability are complex. Insects with or inside grain will also experience the same complex interactions. The proven probit approach to predicting grain viability has been used by Beckett and Morton (2003) and Beckett et al. (1988) to predict mortality levels at given grain temperature for different heat soak and heat shock treatment of *Rhyzopertha dominica* (F.), the lesser grain borer.

Probit analysis is used here to develop an insect mortality model for grain weevils for use in hot-air dryer simulation models. The models are used to predict grain temperature required to kill the grain weevil for different times of exposure and to predict the grain temperature for a small acceptable level of loss in germination. The difference in grain temperature between the loss in germination and killing the insects can be termed the "window of opportunity" and is here determined for different exposure times and grain moisture contents.

The objectives of this module of the project were:-

- To develop a model to describe mortality of grain weevils (*Sitophilus granarius*) in relation to time and grain temperature.
- To identify, by simulation, a "window of opportunity" for thermal disinfestation of grain without affecting quality.

Insect mortality model

Approach

The probit method of analysing insect mortality requires a knowledge of the death rate, assumed linear in the probit method, at a lethal temperature and the initial death rate of the insects at the start of exposure to a lethal temperature. Lethal 'nominal' temperatures of 45°C, 48°C, 50°C and 55°C held constant in an oven (Part 1) were used to obtain data for the most tolerant stage of the grain weevil (*Sitophilus granarius*) to enable the model to be developed.

On exposure to the heated oven, grain took time to heat up (warming phase) to a plateau and then, when removed from the oven, followed a cooling phase. The warming phase was typically of the order of 2 minutes and there was no clearly defined point in time when the plateau was reached. Therefore time at which exposure to the fixed temperature started was difficult to determine. This was of a concern because some insect death would occur prior to the starting point for the timing of exposure. The problem was most acute at the higher oven temperatures when exposure times of only a few minutes were sufficient to kill the insects because some insect death would occur prior to the starting point for the timing of exposure.

The time to start the timing of exposure was therefore taken as the time when the temperature rose by 90% from the ambient (typically about 25°C) to the target exposure temperature. For example if the target temperature was 45°C, the start of timing of exposure would occur when the temperature reached 43°C (the calculation is 25+(45-25)x90/100).

For each oven temperature tables of values of exposure time and insect mortality (normally the mean of three values) were constructed. Probit analysis, carried out using the statistical package GENSTAT (Payne et al., 1987), then provided estimates of a constant and the death rate as the reciprocal of the standard deviation (i.e. 1/σ) (Table 1). The grain temperature was the mean temperature recorded during the exposure period.

The constant varies with the starting time of exposure and represents the initial mortality (in the same way that the initial germination needs to be specified for seed viability). The parameter 1/σ is unaffected by the timing of the exposure and therefore any inaccuracy in determining the initial exposure time is unimportant in determining the standard deviation sigma, σ.

The standard deviation (σ, min) was related to temperature (T, °C) using a power equation of the form:

$$\sigma = a(T - T_b)^b \qquad (1)$$

where T_b (°C) is the temperature below which insect mortality is unaffected by a heat treatment and a and b are constants. Fitted values of T_b = 35.4°C, a = 3872 x 10^6, b = -7.556 accounted for 99.9% for the variation.

The following approach was adopted in order to determine a value for the naturally occurring mortality of insects not receiving the heat treatment (at this stage of development). This will now be referred to as the ‘control’ mortality. For each of the four treatment temperatures, the time profile of insect mortality was predicted from the time the samples were placed in the oven using the records of grain temperature, by calculating the standard deviation, σ, (eqn 1) for a control mortality of 3%. (Note for grain temperatures less than T_c = 35.4°C a very large value of σ was used). Measured mortalities were compared with prediction by regression with the line fitted through the origin and normalised so at the start of the heat treatment the mortality of the insects (M, %) when compared to the control was zero:

$$M = 100(1 - P / P_c) \qquad (2)$$

where P is the probability of survival at the time of the observation and P_c is the probability of the control (untreated) insects surviving. (P_c = 0.97 or 97% for the case being considered of control mortality of 3%). The slope of the fitted line was found to be 0.936.

This exercise was repeated for control mortalities of 5%, 10% and 15% and produced slopes of 0.981, 1.042 and 1.079. By fitting a line through the slopes, the control mortality for a slope of 1.0 was determined to be 6.5%. This value was used in the model for the initial mortality of insects not receiving the heat treatment, i.e. the control mortality.

Results

Figure 1 compares the model prediction of mortality with measurement. Note that the graph presents the accuracy of the model in relation to the measurements used to develop the model. An independent set of data would be needed to validate the model.

Table 2 presents the mortality in relation to grain temperature and exposure time. Using a criterion of a mortality of 99.9 % as a satisfactory level of disinfestation then an exposure time of about 30 min at 50°C would be required. Exposure to a grain temperature of 55°C for a few minutes would be expected to be lethal to the grain weevil.

Window of opportunity

Approach

The 'probit' germination model is based on relating the standard deviation, σ, to the moisture content, (M, % wet basis) and grain temperature (T_g, °C). For barley, *Hordeum vulgare* L. 'Proctor', Ellis & Roberts (1980) related the logarithm of σ (min) by a multiple linear regression of the form:

$$\ln(\sigma) = a_0 + a_1 \ln(M) + a_2 T + a_3 T^2$$

The coefficients were: a_0 = 30.26 (when the standard deviation units are in minutes), a_1 = -5.896, a_2 = -0.0921 and a_3 = -0.000986.

Nellist & Bruce (1987) obtained similar data for winter wheat, *Triticum aestivum* L. 'Maris Hobbit' and derived the coefficients: $a_0 = 40.29$, $a_1 = -5.896$, $a_2 = -0.3178$ and $a_3 = 0.0$.

Simulations for barley and wheat were carried out for an initial grain quality with germination of 98% assuming constant grain temperature and moisture content. The simulations were carried out for grain temperatures in the range 55°C to 65°C in 1°C steps and moisture contents 12 %, 14 % and 16 % on a wet basis (w.b.).

Further simulations examined the effect of initial germination on exposure time for a one percent loss in grain viability. The simulations were carried out for initial germinations of 99%, 98%, 97% and 96% for grain temperatures of 55ºC, 60ºC and 65ºC and moisture contents of 12% w.b., 14% w.b. and 16% w.b.

The grain temperature required to achieve an insect mortality of 99.9% was simulated for exposure times of 15, 30, 45 and 60 minutes. The grain temperature required for a loss in germination of one percent from an initial germination of 98% was simulated assuming moisture contents of 12% w.b. to represent stored barley and 14% w.b. to represent stored wheat for the same exposure times. The "window of opportunity" was taken as the difference in grain temperature between the insect mortality simulations and the germination simulations.

Results

The simulations (Figure 2 and Table 2) show that at lower temperatures barley is more susceptible to quality losses than wheat but less susceptible at higher temperatures. For an increase in temperature from 55ºC to 65ºC the exposure time for a one percent loss in viability is much less for barley (by a factor of about 8) than for wheat (factor about 25).

The moisture content also has a major influence on the exposure time for a loss in grain quality. For a one percent loss in both barley and wheat germination, the exposure time is about 2.5 and 5.5 times less when the moisture content is 14% w.b. and 16% w.b. instead of 12% w.b.

The initial germination has a major influence on the loss germination due to exposure of high temperature. For example the exposure time for a one percent loss in germination is about twice as long at an initial germination of 99% compared to an initial value of 97%.

For an exposure time of 15 min, constant temperatures of 51.4ºC kill 99.9% of the grain weevils and 69.4ºC results in a germination loss of 1% from an initial value of 98% for barley at moisture content of 12 % w.b.(Fig. 2a). The difference in these temperatures and therefore the "window of opportunity" is 18ºC (Fig.3). The longer the exposure times, the lower the grain temperature required for both insect kill and loss in germination. The window of opportunity reduces with increasing exposure time – the window is 15ºC for a 60 min exposure.

For wheat the window is less, at about 12ºC, and is little influenced by exposure time. This is due to the higher moisture content (14% w.b.) and the resultant lower grain temperature for a 1% loss in germination.

Discussion & conclusions

The insect mortality model is based on the same probit method used for the germination model. The insect death rate is the reciprocal of the standard deviation (σ) which was well related to temperature by a power series (eq. 1). The power series provided estimates of the rapid reduction of exposure times for insect mortality in relation to grain temperature (Table 2).

The model, presented in this report, did not take into account any possible effects of grain moisture on insect mortality. Beckett et al. (1998) studied the effects of both grain temperature and moisture content on the mortality of *R. dominica* and *Sitophilus oryzae* L. (Rice Weevil). The effects on insect mortality of grain moisture content (within the range suitable for stored grain) are small compared to the temperature effects, and in general all stages survive longer at a given temperature as grain moisture increases.

There are statistical methods to take account of the fact that the number of insects exposed to a treatment can not be observed directly (Wadley's problem) (Finney, 1971). However the mortality model did not use the normal Wadley's algorithm as there were insufficient control samples. The derived value for the control mortality of 6.5% is similar to published values. Research on *S. oryzae* showed that natural mortality in the first instar was 3.5% at 80% r.h. (Howe, 1952). 90% of mortality in juvenile phase occurs in the 1st instar and if conditions are favourable after this, survival is virtually 100% (Birch, 1945). The controls from the present work were at 70% so the control mortality may have been higher though *S. granarius* can tolerate drier conditions than *S. oryzae* (Howe, 1952).

It is clear from the analysis that a temperature "window of opportunity" is available, in which disinfestation of insects may be achieved without unacceptable loss of grain germination. Although a longer exposure time is required for disinfestation when grain temperature is lower, the window is hardly affected by the exposure time (Fig. 3).

The technique of thermal disinfestation is most likely to be successful for:

(a) grain of low moisture content because of its lower sensitivity of dry grain to exposure to high temperature.
(b) high quality grain, because the loss of grain viability due to temperature depends largely on the initial viability (Table 1).

Table 1. The estimate of parameters by probit analysis on insect mortality of *Sitophilus granarius* from oven heating tests in relation to measured grain temperature. The figures in brackets are the standard errors.

Grain temperature (°C)	Constant	1/σ
45.1	-1.348 (0.092)	0.007272 (0.000616)
48.0	-1.871 (0.185)	0.05746 (0.00645)
50.0	-1.256 (0.115)	0.1503 (0.0106)
55.0	-1.025 (0.292)	0.655 (0.118)

Table 2. Exposure times in minutes for different levels of grain temperature and insect mortality

Grain temperature	Mortality		
(°C)	50%	99.0%	99.9%
46	110.5	266.5	311.9
48	29.9	72.2	84.4
50	9.8	23.8	27.8
52	3.7	9.0	10.6
54	1.6	3.8	4.5
56	0.7	1.8	2.1

Table 3. The exposure time for reductions in viability of 1% for different initial viability at different constant grain temperature and constant grain moisture content (*M,C.*).

Initial germination (%)	*M.C.*(%, w.b.)	Exposure time (min)					
		Barley temperature			Wheat temperature		
		55°C	60°C	65°C	55°C	60°C	65°C
99	12	524	188	64	954	195	40
	14	211	76	26	385	78	16
	16	96	34	12	175	36	7
98	12	333	119	40	606	124	25
	14	134	48	16	244	50	10
	16	61	22	7	111	23	5
97	12	251	90	30	456	93	19
	14	101	36	12	184	38	8
	16	46	16	6	84	17	3
96	12	204	73	25	371	76	15
	14	82	29	10	150	31	6
	16	37	13	5	68	14	3

Figure 1. Model prediction of insect mortality compared to measurement for a control mortality of 6.5%. The fitted line accounted for 94.9% of the variation.

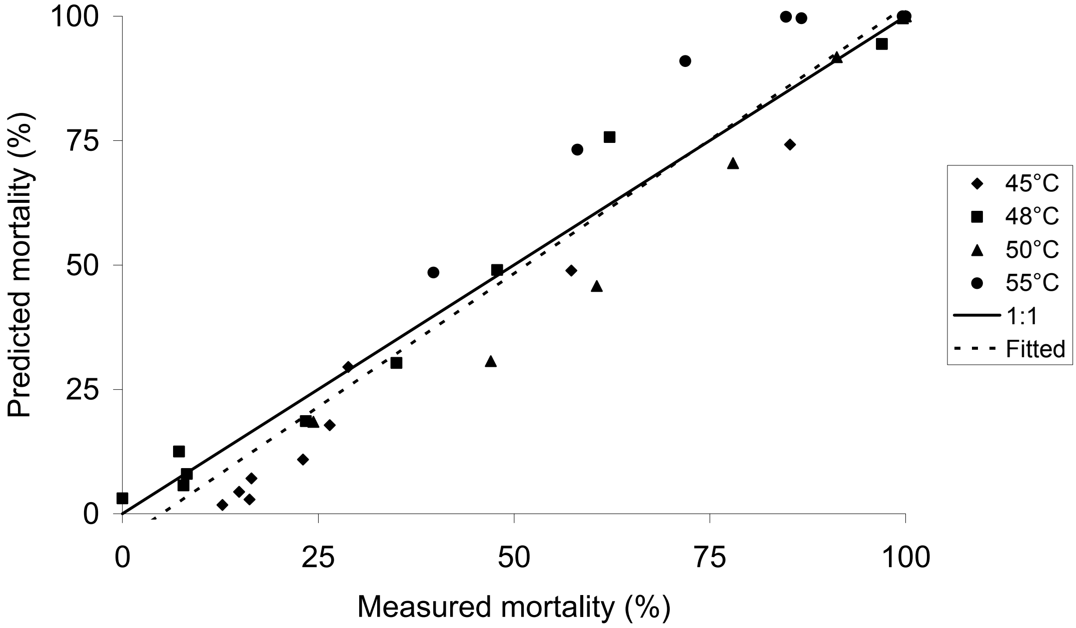
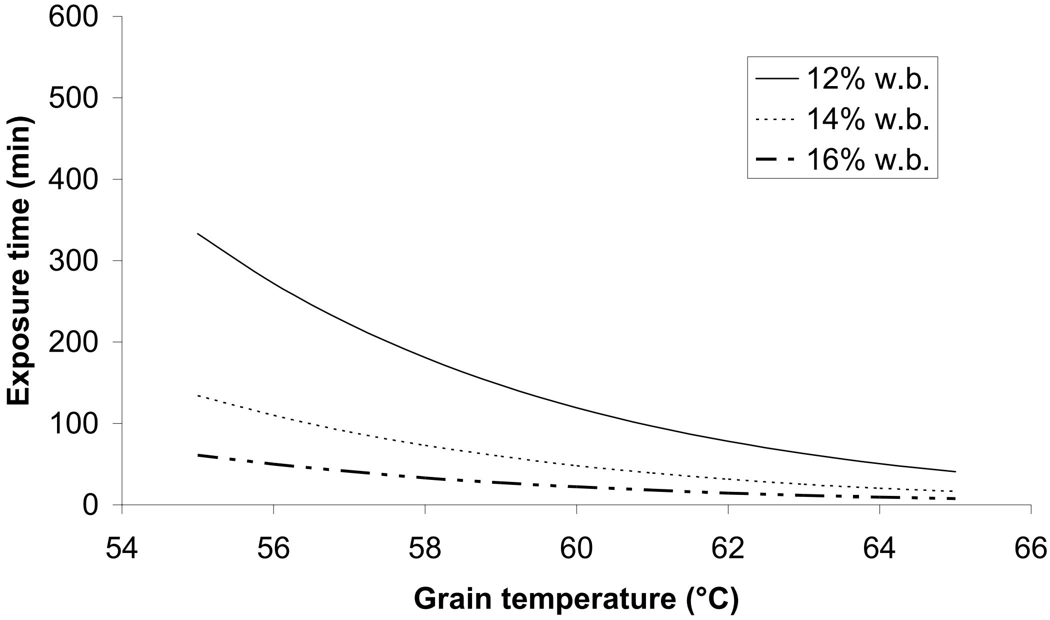


Figure 2. Prediction, by simulation, of exposure time to reduce viability of (a) barley and (b) wheat from 98% to 97% in relation to constant grain temperature and constant moisture content.

(a) Barley



(b) wheat

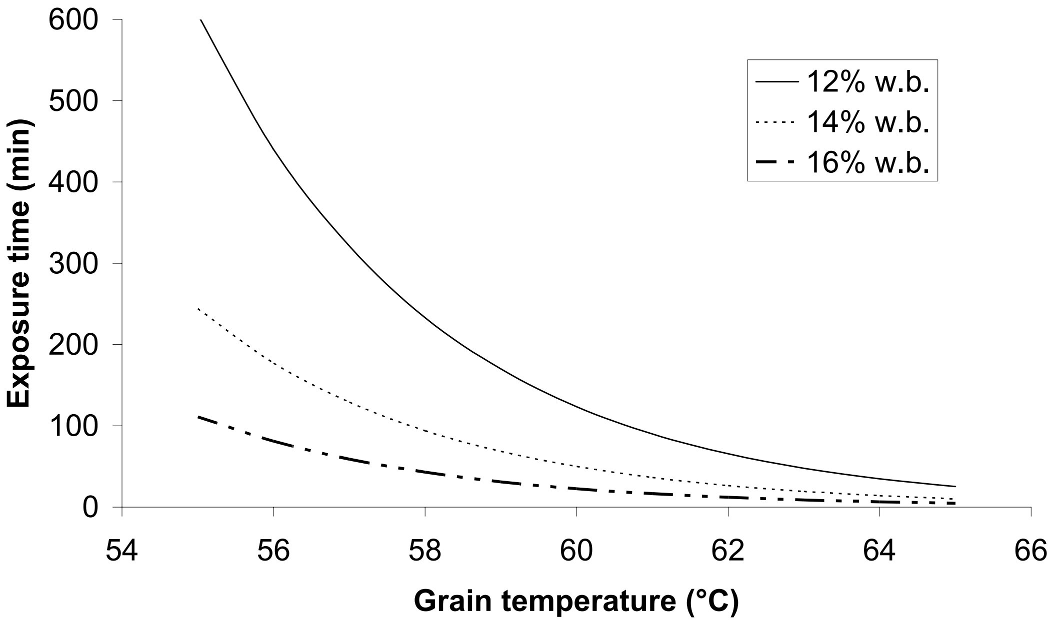
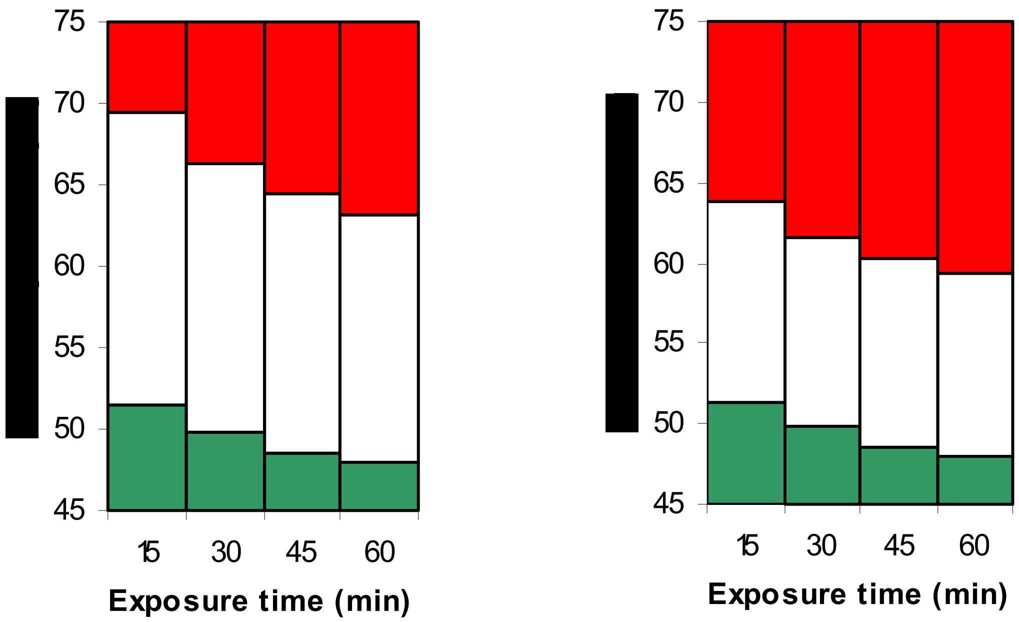


Figure 3. Prediction, by simulation, of the "window of opportunity" (the unmarked area) as the difference in grain temperature to achieve 99.9% insect mortality (lower area) and a one percent loss of germination (upper area) from an initial germination of 98% for different exposure times.

(a) Barley

(b) Wheat



Part 3.

SIMULATION OF HEATED-AIR DRYER OPERATING CONDITIONS FOR DISINFESTATION OF GRAIN

P J C Hamer, D M Bruce

Summary

The simulation models of mixed-flow and cross-flow dryers operating at steady state were modified to include the insect mortality model developed in this project. The performance of such dryers for thermal disinfestation was explored by running the models with particular initial conditions of air and grain. To make comparison of the performance straightforward, operating conditions were chosen to arrive at a set of conditions with the same insect mortality, 99.9%. The results also make it possible to examine how sensitive is the desired result to parameters which may not be well controlled.

Thermal disinfestation is possible with both types of dryer, though the window of possible conditions is narrower in cross-flow. The analysis from which this conclusion is drawn is the clear, steady conditions of the simulation models. However, analysis of the sensitivity of the disinfestation to various parameters raises concerns. In practical situations, some parameters *e.g.* air temperature, vary in time or with location, whilst others, *e.g.* throughput, are not simple to set. The sensitivity of the disinfestation effect to throughput in particular, but also to temperature, means that realistic deviations from the ideal values could render the disinfestation ineffective. If the dryers were used in recirculating-batch operation, it is probable that disinfestation would be achieved more robustly. A small further study would be needed to confirm this and to specify suitable operating conditions.

Introduction

There is a need to define accurately the conditions that kill insects but do not harm grain and then to operate a heated-air dryer to achieve the conditions with as much a safety margin as possible. The objective of finding operating conditions by which to disinfest grain by heating without severely affected grain viability can best be met by using a validated simulation model. Other important aspects that need to be considered when using a heat treatment to disinfest grain include:

- the loss in moisture content and hence weight of the grain
- the temperature of the grain for subsequent storage
- the cost of the treatment

Proven models of drying can simulate accurately the temperature and moisture profiles and any loss of grain viability throughout a heated-air dryer. The basis of computer simulation of heated-air drying of grain is well described by Giner et al. (1998). Moisture content and temperature of grain and air are predicted as functions of drying time and position in the grain bed using a mathematical model which is based on differential equations derived from mass and energy balances for the grain and air. The model requires mass transfer and heat transfer coefficients and the physical and thermal properties of grain and air and equilibrium relationships. The simulation model also contains routines that predict the loss of germination in relation to the moisture content and temperature of the grain.

The mixed-flow dryer, a popular type of heated-air continuous-flow dryer in the UK, is designed to give a more uniform thermal treatment to the grain than the more simple design of the cross-flow dryer. Mixed-flow dryers have rows of ducts through which air is supplied to and removed from the moving grain bed. A two-dimensional model better represents the air and grain flows in the vicinity of the ducts and hence gives better predictions of grain temperature than a simpler one-dimensional model of Bruce (1984). Good prediction of grain temperature is important for the germination loss model. The two–dimensional model for the simulation of a mixed-flow grain drying used in this study is that of Giner et al. (1998), developed at SRI. The ability of the model to predict the overall drying performance, the moisture and temperature profiles in the drying bed during drying experiments on a laboratory scale has been established (Giner and Bruce, 1998).

In the cross-flow dryer a moving stream of grain is successively dried and cooled by air flowing at right angles to the stream. Simple cross-flow types consist of a single drying bed, preceding, and continuous with, a cooling bed. A validated computer model of a cross-flow grain dryer simulates the performance and enables operating conditions to be studied (Nellist, 1987).

The insect mortality model developed in this project (Part 2 of this report) has been incorporated into both the two-dimensional mixed-flow model and the cross-flow model. In this part of the work, simulations are carried out for the mixed-flow and cross-flow dryer types to investigate the effect of operating conditions in continuous-flow, one pass operation on the disinfestation and the impact on the other important factors listed above. The objectives of this module were:-

- To devise, by simulation, thermal disinfestation / decontamination strategies using a hot-air dryer of the mixed-flow type used on many UK farms
- To investigate, by simulation, operating conditions of the other commonly used dryer type, cross-flow, for thermal disinfestation
- To make recommendations on the operation of heated-air dryers for disinfestation

Mixed flow dryer

Materials & methods

Measurements of the size, distribution and number of air inlet and exhaust ducts of the dryer at CSL were used to represent a typical mixed-flow dryer (Table 1), which is the Law-Denis dryer, with a natural gas burner, used for the full scale trial (Part 4 of this report).

In normal operation as a continuous flow dryer, the inlet plenum is divided so that some of the rows of ducts allow cool air to enter to cool the grain. The CSL dryer has eight rows of inlet ducts. Simulations were carried out assuming (a) six rows were used for heating and two for cooling (ratio heating: cooling of 3:1) and (b) four rows of heating and four for cooling (ratio 1:1).

Grain bulk density of 642.6 kg/m^3, (Nellist, 1987) and reference ambient conditions of air temperature, 15°C, relative humidity, 80%, and barometric pressure, 101.325 kPa, (used as a basis for calculating test results in the appropriate British Standard (BS 3986: 1998) were assumed. These values will be referred to as the 'standard' conditions.

The heated air mass flow (b) was estimated from measurements of fuel consumption (F) during a heating period (t), average drying air temperature (θ_d) and the average ambient temperature (θ_a):

$$b = FH/(Ac_{pa}(\theta_d - \theta_a)) \qquad (1)$$

where A is the area of the ducts calculated from the number of inlet ducts (8), the height of a cross flow section (0.1 m), the depth of the dryer (2.0 m) and the number of slices through the dryer (12); H is the net calorific value of fuel (for natural gas H = 39.6 MJ/m^3: www.dti.gov.uk/energy/inform/calvalues.pdf) and c_{pa} is the specific heat of air at constant pressure [c_{pa} = *1.01 kJ/(kgK)]*. The gas usage was 81.2 m^3 during a t= 2 hour period in Run 2 of the validation test (Part 4 of this repiort), the average drying temperature was θ_d= 80°C and the ambient temperature was θ_a = 16°C. The heated air mass flow rate was calculated to be b=21.41 kg/min/m^2.

The simulations involved specifying the initial and final moisture content of the grain and solving the differential equations in the model to predict throughput for a specified drying air temperature. The model prediction of insect mortality was noted and the simulation rerun a number of times with a modified target moisture content until the model prediction of insect mortality was 99.9%, i.e. insect survival of 0.1%.

A series of simulations was carried out to represent treatment of wheat assumed to be at an initial moisture content of 14% wet basis (w.b.). Coefficients for the germination model were those given for wheat by Nellist and Bruce (1987). A similar series of simulations was carried out to represent barley with an initial moisture content of 12% w.b. and coefficients for the germination model by Ellis & Roberts (1980). For both the wheat and barley, series of simulations were conducted with drying air temperatures in the range 55°C to 100°C in 5°C steps. The initial germination prior to disinfestation was assumed to be 98%. The cost of heating the air was calculated using eq 1 where θ_d was the drying air temperature and θ_a = 15°C the 'standard' ambient air temperature. A gas price of 1.37p/kWh was assumed (www.mwen.org.uk/energy_conversion.htm). The power of the electrical components was 14.6 kW (Law-Denis Engineering Ltd.) and the cost of electricity 5p/kWh.

Further simulations investigated the impact of initial moisture content on operating conditions to disinfest grain. The safety margin of operation was investigated by determining the conditions for various levels of insect mortality.

Results & discussion

Figures 1 to 4 all relate to treatment conditions that cause a 99.9% mortality of the insects. In all four graphs of each figure, drying air temperature is the independent variable. The top left graph shows how the throughput and residence time change with drying air temperature. Top right shows the moisture loss and germination loss, where the initial value is 98%. The lower left graph shows the maximum grain temperature reached anywhere in the dryer and the temperature of grain discharged from the cooling section, with ambient temperature shown for comparison. The lower right bar chart shows energy cost, in which the costs of electricity for the electrical components and of gas for air heating are stacked.

The simulations for wheat with a dryer having a heating to cooling ratio of 3:1 (Fig. 1) indicate benefits in operating the dryer at higher temperatures. The benefits include increased throughput and hence lower residence time, smaller losses of grain moisture and lower energy costs. Of course, too high a temperature results in an unacceptable increase in germination loss and increases the temperature of grain at discharge. Operating with a drying air temperature of 80ºC is predicted to result in negligible loss in germination. However the grain discharge temperature is rather high at 30.5ºC.

When the heating and cooling sections are of equal size and a drying air temperature of 80ºC the discharge temperature is more acceptable at 19.1ºC (Fig. 2). The germination loss remains negligible and additional benefits are smaller loss in moisture content and lower operating costs. The margin of safety if air temperature exceeds 80ºC for any reason is less.

The results for the simulations for barley (initial moisture content 12% w.b.) are similar to wheat (initial moisture content 14% w.b.) except that the moisture content of the discharge grain as the drying air temperature increases when the heating and cooling sections are of equal size (Figs. 3 & 4).

Whereas Figures 1 and 2 relate to wheat at initial moisture of 14% w.b., Table 2a explores the effect of varying the initial moisture content of wheat/ barley on the main results. The dryer has equal heating and cooling sections. As initial moisture increases, disinfestation becomes more problematic: throughput reduces (and hence residence time increases), the loss in moisture content increases and the germination loss increases. Energy costs also increase. To limit germination loss to the value achieved at 12% initial moisture content, drying temperature must be reduced if the grain for treatment has a high moisture content. This situation is explored in Table 2b which shows how the drying air temperature must be reduced by some 8ºC for each % point increase in initial moisture to avoid increasing damage to grain germination. The throughput is greatly decreased, and the costs increased as a result of increased initial moisture.

Table 3 explores the effect on the throughput of (a) barley and (b) wheat of setting various insect survival rates. The simulations indicate very small safety margins. An increase in throughput of 6.6% for barley and 8.5% for wheat increases the insect survival from an acceptable level of 0.1% to a very unacceptable level of 10%. This is a consequence of the disinfestation effect taking place in a short time at a high temperature. A small reduction in residence time has a significant effect on survival.

Recirculation of air, i.e. using air from the exhaust of the cooling section reheating it and using it for the drying section, made no difference to the output except that it reduced the specific heat consumption and hence the energy costs.

Cross flow dryer

Materials & methods

For simulation purposes, the design of a simple cross-flow dryer can be expressed in terms of bed depth, the areas of the drying and cooling sections and airflows in these sections (Nellist, 1987). The simulations were conducted at the standard conditions for a typical commercial dryer of 12 m^2 bed area and a bed depth of 0.2 m, with a drying to cooling ratio of 3:1 (i.e. bed areas of 9 m^2 and 3 m^2) and the mass rate of airflow fixed at 30 $kg/min.m^2$ for both the drying and cooling areas. The simulations represented wheat with an initial moisture content of 14% w.b. and barley at 12% w.b. and the fuel prices were the same as for the mixed-flow dryer simulations.

In the same way as the mixed-flow dryer, simulations investigated the impact of the ratio of heating to cooling bed areas, bed depth and the initial moisture content on operating conditions to disinfest grain. The safety margin of operation was investigated by determining the conditions for various levels of insect mortality.

Results & discussion

The format of Figures 5 and 6 are the same as for the mixed-flow dryer simulations (Figs. 1 to 4) and the benefits of operating the dryer at higher temperatures are the same. For comparable heating /cooling ratios (compare Fig. 1 with Fig. 5 for wheat and Fig. 3 with Fig. 6 for barley) the residence time of the cross-flow dryer is longer than the mixed-flow dryer and the treatment cost is more. Furthermore a lower drying air temperature is needed in avoid germination losses.

A cross flow dryer has a cool, air-exhaust side, where the insects may most easily survive, and a hot air-inlet side where the grain germination will be most affected. To ensure a given level of insect mortality, the bed will need to reach a higher temperature than in a mixed-flow dryer at the same air temperature so that its cooler side is lethal. However this leads to greater loss in germination.

Table 4 explores the effect of varying the initial moisture content of wheat and barley on the main results. As initial moisture content increases, the throughput decreases, the germination losses increase, discharge temperature reduces and energy costs increase.

Table 5 explores the influence of the proportions of the heating and cooling areas on the main results. As the proportion of the heating section of the dryer increases the throughput increases but any change in the moisture content of the grain at discharge is relatively small and the germination losses are the same. As would be expected the temperature of the grain at discharge decreases with increasing area of cooling bed. With a bed ratio of 1.4 (7 m^2 heating / 5 m^2 cooling) the temperature of the grain at discharge is less than 20ºC.

Table 6 explores the influence of bed depth on the main results for two heating /cooling bed sizes. As bed depth increases, the throughput decreases even though the residence time increases considerably. (This would be expected as the volume of material in the dryer increases in proportion to the bed depth). The moisture content decreases considerably with increasing bed depth and the germination losses become unacceptably high. For the same heating /cooling areas, the discharge temperatures are low but at the larger heating area (Table 6b) the grain discharge temperature is over 38ºC at 0.1 m bed depth and decreases with increasing bed depth. The energy costs are similar at 0.1 m and 0.2 m bed depth but then increase with increasing bed depth.

Table 7 explores the effect on the throughput of barley (Table 7a) and wheat (Table 7b) of setting various insect survival rates. As with the mixed-flow dryer, the simulations indicate very small safety margins. An increase in throughput of about 10% increases the insect survival from an acceptable level of 0.1% to a very unacceptable level of 10%.

Conclusions

Simulation runs

1. From the simulation runs, disinfestation treatments were effective in both types of dryer when run in a continuous-flow, once-through operation. This supports the earlier work with a simple model (Part 2 of

this report) that suggested disinfestations in dryers are possible without unacceptable damage to the germination. There were operational and cost benefits of using as high an air temperature as possible, limited by the risk of germination damage. Treatment became much slower and more costly as initial moisture content increased.

2. These results for mixed-flow and cross-flow were calculated for specific dryer designs, with a given number of ducts and area of bed etc. Results are likely to be a little different of a larger or smaller dryer of the same design is used, but the influences of varying the parameters will be similar.
3. An air temperature of 80 ^{o}C in combination with a particular residence time were predicted to kill 99.9% of *S. granarius* and to cause a reduction in germination of barley of less than 1%. The barley was assumed to have an initial m.c. of 12% wet basis and an initial germination of 98%.
4. The temperature of discharged grain depended on the proportion of the dryer used for cooling. Treatment conditions that allowed in-bin cooling were certainly possible.
5. As drying air temperature was increased for a given level of insect mortality, throughput increased, moisture loss reduced and energy cost reduced. Therefore the optimum treatment would be to use as high an air temperature as limits to germination loss allow.
6. The two components of treatment cost were energy cost and the value of weight loss owing to drying. Energy costs at 80ºC were typically in the range 0.50 -1.00 £/t of input grain. Cost of lost weight were in the range 0.65£/t when starting from 11 % moisture content to 3.26£/t when drying from 16%.

Practice

7. These results for mixed-flow are for specific dryer designs, with a given number of ducts and area of bed etc. Results are likely to be a little different of a larger or smaller dryer of the same design is used, but the influences of varying parameters will be similar.
8. In practice conditions in a dryer are neither uniform or constant (e.g. air temperature may vary over the dryer plenum and also varies in time as the thermostat takes effect). Other parameters, e.g. grain throughput, cannot be easily selected by the operator. The effect of these variations will be to narrow the window in which disinfestation without grain damage can be achieved. From the results, Tables 3 and 7, the effectiveness of disinfestation in continuous-flow, once-through treatment is particularly sensitive to the grain residence time. Because residence time is not at all straightforward to set, it would be difficult to achieve the disinfestation effect reliably.
9. **Given this sensitivity and the lack of information on the operating conditions within the dryer , disinfestation for *S. granarius* using either type of dryer in continuous-flow, once-through mode will be very difficult to achieve reliably in practice**.
10. In recirculating-batch operation, the thermal treatment would take place over a longer time and at a lower peak temperature, and would be more expensive in energy, lost weight and labour. From the principles already understood, such a treatment would be effective and sensitivity to dryer settings is expected to be less but it would be slower and result in greater moisture loss. Temperature of the grain,

for controlling the disinfestation process, would be more easily determined by the dryer's instrumentation or by a low cost system that could be added. To firmly establish how to use a dryer in recirculating-batch mode for disinfestation, a model of this operation is needed. The basis of such a model exists, developed for studies on dryer control at SRI, but further work is needed to set it up and use it for recirculating-batch disinfestation.

Table 1. The dimensions to specify the CSL dryer for the two dimensional mixed-flow model

Number of rows of inlet (and outlet) ducts	8	Height of dryer	4.2 m
Total width of dryer	2.39 m	Depth of dryer	2.0 m
Perpendicular distance between centre of input and output ducts	0.2 m	Vertical distance between adjacent inlet (or outlet) ducts	0.51 m
Vertical distance from top of the dryer to first inlet	0.28 m	Vertical distance from top of the dryer to first outlet	0.04 m
Average width of duct opening	0.2 m	Cross-sectional area of ducts	0.2 m^2

Table 2. Simulation output in relation to initial moisture content for a mixed-flow dryer with equal heating and cooling sections and (a) drying air temperature of 80ºC and (b) drying temperature to achieve disinfestation and the same germination loss as for the shaded column of (a).

(a) Drying air temperature 80ºC		Initial moisture content, % w.b.					
		11	12	13	14	15	16
Throughput (t/h)		9.85	7.64	6.51	5.49	4.63	3.95
Residence time (min)		76.0	89.1	105.7	126.9	152.2	180.6
Moisture content (% w.b.)		10.17	10.71	11.15	11.48	11.72	11.89
Germination loss (%)	Barley	0.09	0.15	0.26	0.43	0.73	1.22
	Wheat	0.30	0.45	0.68	0.92	1.04	1.61
Grain temperature (°C)	Discharge	23.9	21.9	20.3	19.1	18.5	18.1
	Maximum	69.3	69.3	69.6	70.2	71.1	72.0
Energy cost (£/t)		0.39	0.50	0.59	0.69	0.82	0.97

(b) Barley germination loss of 0.15% (see shaded area table 2a)		Initial moisture content, % w.b.			
		11	12	13	14
Drying air temperature		87	80	72	63
Throughput (t/h)		10.22	7.64	4.89	2.40
Residence time (min)		65.8	89.1	140.9	290.2
Moisture content (% w.b.)		10.14	10.71	11.05	11.13
Grain temperature (°C)	Discharge	25.9	21.9	19.0	18.5
	Maximum	70.9	69.3	65.6	60.7
Energy cost (£/t)		0.41	0.50	0.70	1.25

Table 3. Simulation output in relation to insect survival for a mixed-flow dryer with equal heating and cooling sections and a drying air temperature of 80ºC for barley, Table 3(a) and wheat, Table 3(b).

(a) Barley at initial moisture content 12 % w.b.		Insect mortality			
		99.99 %	99.9 %	99%	90%
Throughput (t/h)		7.49	7.64	7.86	8.27
Residence time (min)		90.8	89.1	86.6	82.3
Moisture content (% w.b.)		10.68	10.71	10.75	10.82
Germination loss (%)		0.16	0.15	0.14	0.12
Grain temperature (°C)	Discharge	21.7	21.9	22.1	22.5
	Maximum	69.5	69.3	69.0	68.5
Energy cost (£/t)		0.51	0.50	0.49	0.46

(b) Wheat at initial moisture content 14 % w.b.		Insect mortality			
		99.99 %	99.9 %	99%	90%
Throughput (t/h)		5.35	5.49	5.68	6.07
Residence time (min)		130.2	126.9	122.5	114.8
Moisture content (% w.b.)		11.43	11.48	11.56	11.71
Germination loss (%)		1.02	0.92	0.80	0.62
Grain temperature (°C)	Discharge	19.1	19.1	19.2	19.4
	Maximum	70.5	70.2	69.8	69.1
Energy cost (£/t)		0.71	0.69	0.67	0.63

Table 4. Simulation output in relation to initial moisture content for a cross-flow dryer with a 0.2 m bed depth, a 9 m^2 heating section, a 3 m^2 cooling section and a drying air temperature of 80ºC.

Variable		Initial moisture content, % w.b.					
		11	12	13	14	15	16
Throughput (t/h)		7.90	7.01	6.10	5.19	4.35	3.62
Residence time (min)		13.2	14.9	17.4	20.7	25.0	30.4
Moisture content (% w.b.)		10.16	10.80	11.34	11.76	12.03	12.15
Germination loss (%)	Barley	0.09	0.14	0.20	0.30	0.44	0.63
	Wheat	0.30	0.45	0.68	1.04	1.61	2.46
Grain temperature (°C)	Discharge	43.8	41.3	37.9	34.1	30.0	25.8
	Maximum	76.5	76.2	76.0	75.9	76.1	76.5
Energy cost (£/t)		0.59	0.66	0.76	0.89	1.06	1.28

Table 5. Effect of proportions of heating and cooling. Drying air temperature 80ºC, bed depth 0.2 m and initial moisture content 14%.

Variable		Heating / cooling bed sizes (m^2)					
		4/8	5/7	6/6	7/5	8/4	9/3
Throughput (t/h)		2.31	2.89	3.46	4.04	4.62	5.19
Residence time (min)		46.6	37.2	31.2	26.7	23.3	20.7
Moisture content (% w.b.)		12.04	11.91	11.84	11.78	11.76	11.77
Germination loss (%)	Wheat	1.04	1.04	1.04	1.04	1.03	1.04
Grain temperature (°C)	Discharge	16.3	16.4	17.1	19.8	25.6	34.1
	Maximum	75.9	75.9	75.9	75.9	75.9	75.9
Energy cost (£/t)		1.03	0.98	0.95	0.92	0.90	0.89

Table 6. The influence of bed depth. Drying air temperature 80ºC and initial moisture content of 14 % w.b.

(a) Drying bed 6 m^2 / cooling bed 6 m^2		Bed depth (m)			
		0.1	0.2	0.3	0.4
Throughput (t/h)		3.41	3.46	3.04	2.73
Residence time (min)		15.8	31.2	53.1	79.0
Moisture content (% w.b.)		12.58	11.84	11.07	10.48
Germination loss (%)	Wheat	0.41	1.04	1.94	3.07
Grain temperature (°C)	Discharge	18.8	17.1	17.0	17.6
	Maximum	74.2	75.9	77.5	78.7
Energy cost (£/t)		0.90	0.95	1.15	1.35

(b) Drying bed 9 m^2 / cooling 3 m^2		Bed depth (m)			
		0.1	0.2	0.3	0.4
Throughput (t/h)		5.11	5.19	4.56	4.09
Residence time (min)		10.5	20.7	35.4	52.6
Moisture content (% w.b.)		12.56	11.77	10.88	10.16
Germination loss (%)	Wheat	0.41	1.04	1.94	3.06
Grain temperature (°C)	Discharge	38.4	34.1	29.3	26.1
	Maximum	74.2	75.9	77.8	78.7
Energy cost (£/t)		0.86	0.89	1.06	1.23

Table 7. Simulation output in relation to insect survival for a mixed-flow dryer with a $9m^2$ heating section, a $3m^2$ cooling section and a drying air temperature of 80ºC.

(a) Barley at initial moisture content 12 % w.b.		Insect mortality			
		99.99 %	99.9 %	99 %	90 %
Throughput (t/h)		6.82	7.01	7.34	8.31
Residence time (min)		15.4	14.9	14.3	12.6
Moisture content (% w.b.)		10.76	10.80	10.87	11.05
Germination loss (%)		0.14	0.14	0.12	0.10
Grain temperature (°C)	Discharge	40.8	41.3	42.0	43.6
	Maximum	76.2	76.2	76.1	75.8
Energy cost (£/t)		0.68	0.66	0.63	0.56

(b) Wheat at initial moisture content 14 % w.b.		Insect mortality			
		99.99 %	99.9 %	99 %	90 %
Throughput (t/h)		5.00	5.19	5.53	6.51
Residence time (min)		21.5	20.7	19.4	16.5
Moisture content (% w.b.)		11.67	11.76	11.92	12.28
Germination loss (%)		1.12	1.04	0.91	0.63
Grain temperature (°C)	Discharge	33.4	34.1	35.3	38.0
	Maximum	76.1	75.9	75.8	75.3
Energy cost (£/t)		0.92	0.89	0.84	0.71

Figure 1. Wheat in a mixed-flow dryer - heat/cool ratio 3:1. Simulations of (a) throughput and residence time, (b) moisture content and residence time after treatment (c) grain temperature at discharge relative to ambient temperature and the maximum grain temperature in the bed and (d) the energy cost of disinfestations in relation to the drying air temperature

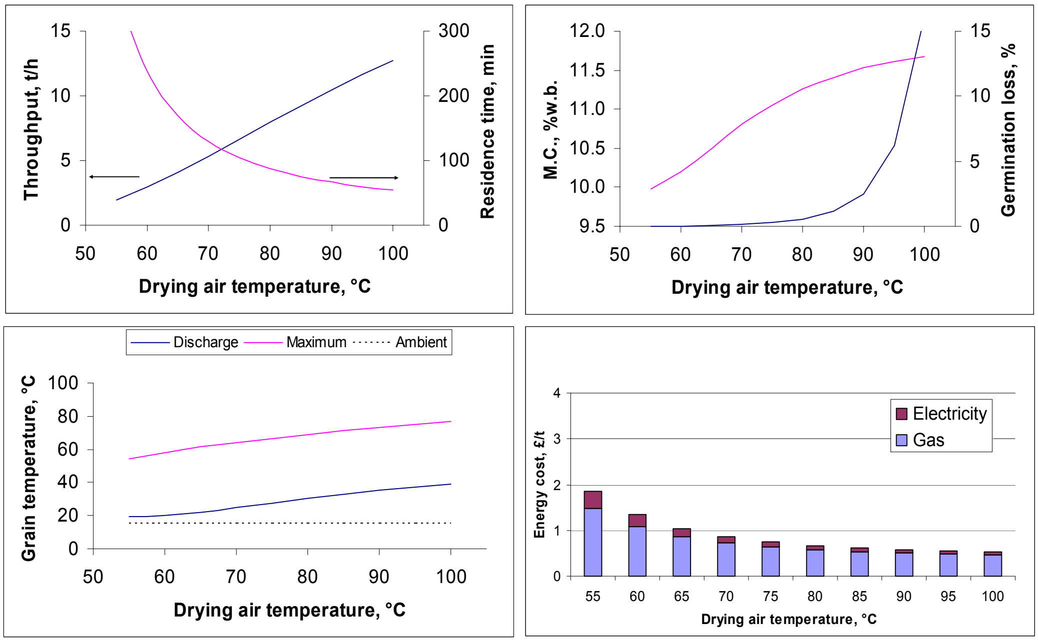


Figure 2. Wheat in a mixed-flow dryer - heat/cool ratio 1:1. Simulations of (a) throughput and residence time, (b) moisture content and residence time after treatment (c) grain temperature at discharge relative to ambient temperature and the maximum grain temperature in the bed and (d) the energy cost of disinfestations in relation to the drying air temperature

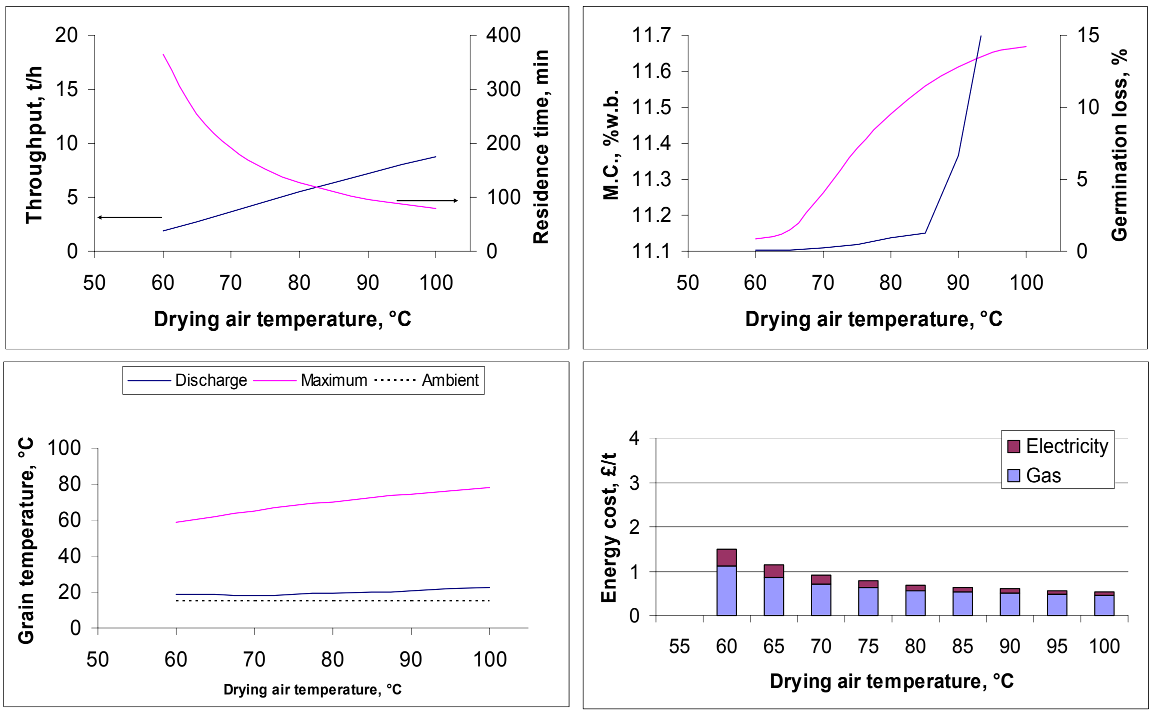


Figure 3. Barley in a mixed-flow dryer - heat/cool ratio 3:1. Simulations of (a) throughput and residence time, (b) moisture content and residence time after treatment (c) grain temperature at discharge relative to ambient temperature and the maximum grain temperature in the bed and (d) the energy cost of disinfestations in relation to the drying air temperature

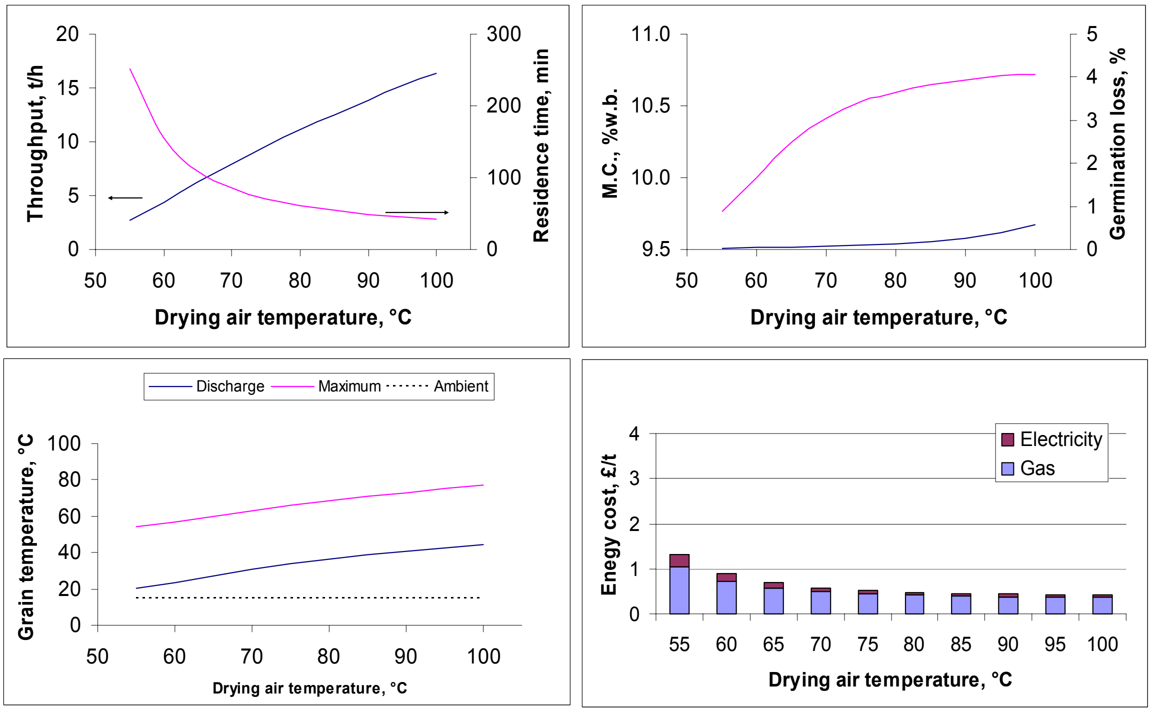


Figure 4. Barley in a mixed-flow dryer - heat/cool ratio 1:1. Simulations of (a) throughput and residence time, (b) moisture content and residence time after treatment (c) grain temperature at discharge relative to ambient temperature and the maximum grain temperature in the bed and (d) the energy cost of disinfestations in relation to the drying air temperature

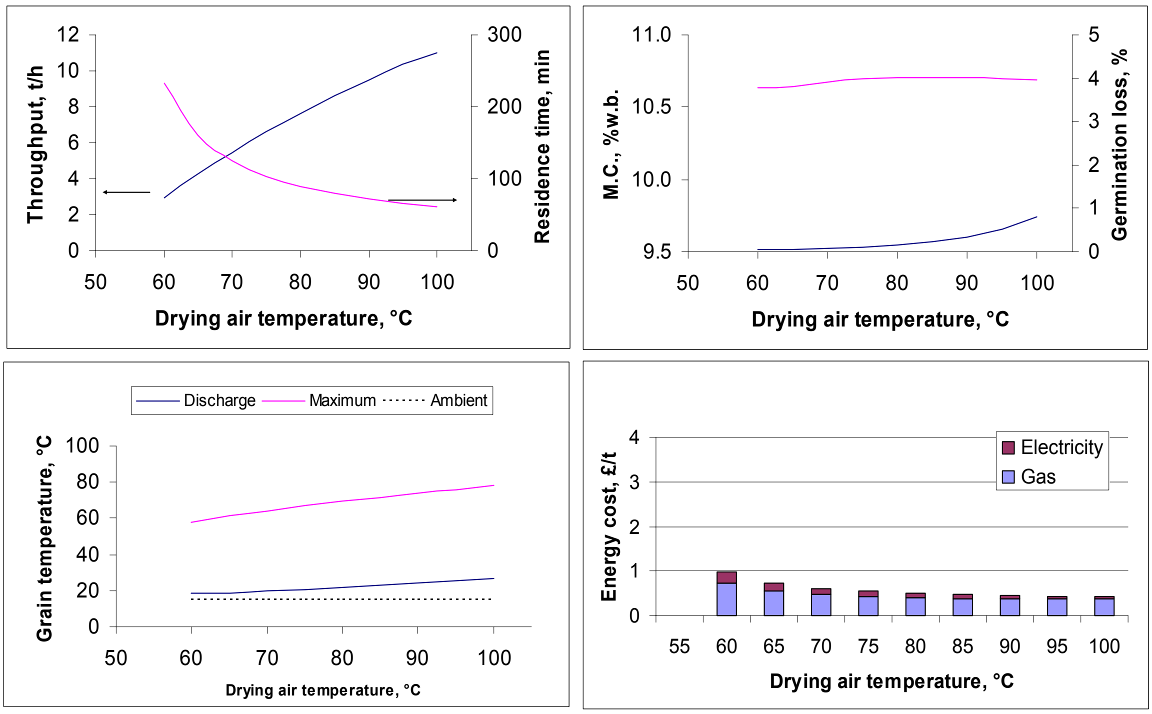


Figure 5. Wheat in a cross-flow dryer - heat/cool ratio 3:1 & bed depth 0.2 m. Simulations of (a) throughput and residence time, (b) moisture content and residence time after treatment (c) grain temperature at discharge relative to ambient temperature and the maximum grain temperature in the bed and (d) the energy cost of disinfestations in relation to the drying air temperature

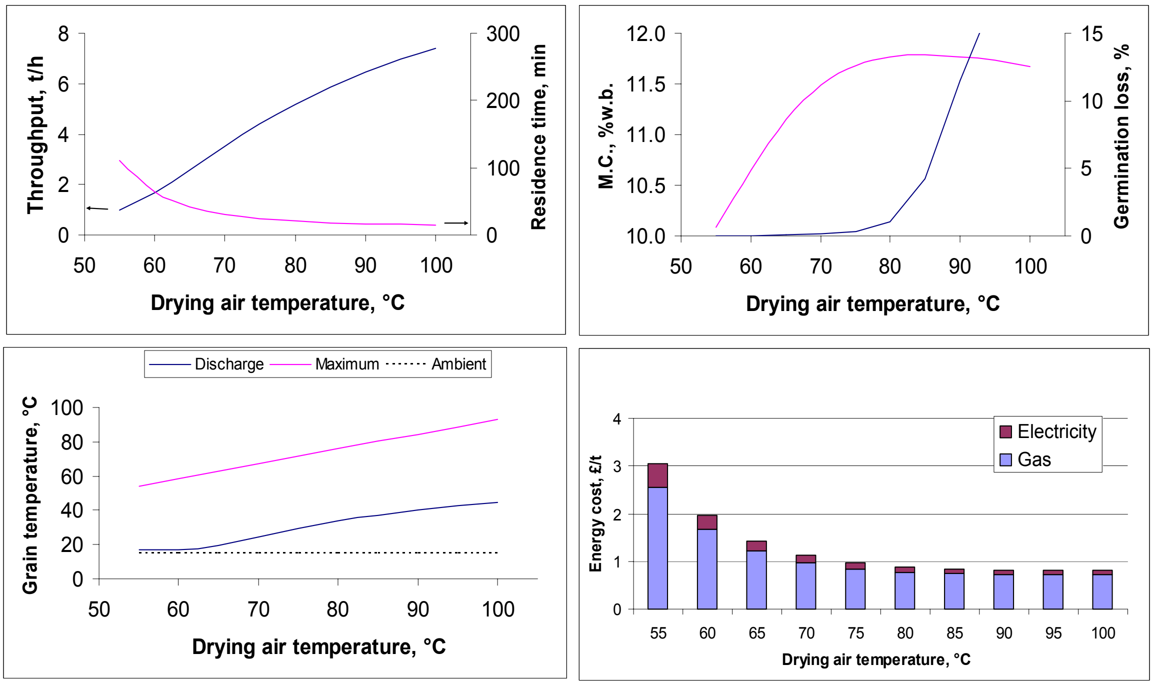
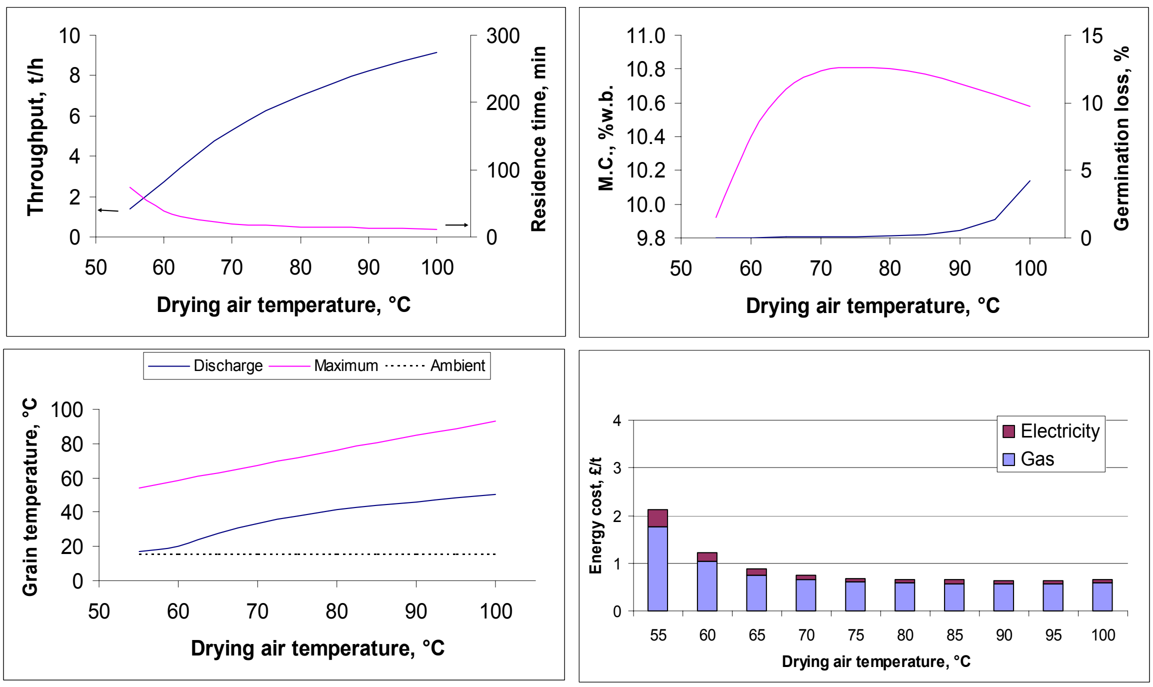


Figure 6. Barley in a cross-flow dryer - heat/cool ratio 3:1 & bed depth 0.2 m. Simulations of (a) throughput and residence time, (b) moisture content and residence time after treatment (c) grain temperature at discharge relative to ambient temperature and the maximum grain temperature in the bed and (d) the energy cost of disinfestations in relation to the drying air temperature



Part 4.

EVALUATION OF THE SUITABILITY OF A FULL-SCALE, HEATED-AIR DRYER FOR DISINFESTATION OF GRAIN

D M Bruce, P J C Hamer, D J Wilkinson, S Conyers, D M Armitage

Summary

Previous experiments had modelled the times required to disinfest grain from the hardiest stage of the hardiest insect, the 4th instar larva of the grain weevil, without deleterious effects on the most sensitive measurement of quality, germination. This experiment was intended to validate the models on a practical scale in recirculating batch operation to allow controlled heating and monitoring of the grain batch.

The batch dryer was filled with approximately 10 t of wheat, brought up to the required temperature for disinfestation as it was recirculated, and then discharged into a holding bin. The treatment conditions, selected with the use of the insect mortality and barley viability models, aimed to achieve no detectable loss of viability and a 0.1 % survival of insects. Grain temperatures were measured at inlet and outlet of the drier using thermocouples where some canisters of insect-infested wheat and malting barley samples were also placed to assess survival and grain viability respectively. In addition, bags of insects were dropped into the drier as it was loaded and some of these were recovered as the grain discharged into the holding bin. Two experiments were carried out, the first to investigate a treatment using a relatively low temperature, 50^{o}C, for a relatively long time, 30 min., the second a higher temperature, 55^{o}C, for a shorter time, 15 min.

Grain viability loss was not detectable and insect mortality was well predicted, although conservative, i.e. mortality was higher than predicted. However, there were differences between exhaust and inlet temperatures of over 13°C in the first run and 6° C in the second. This also meant that complete insect mortality was not achieved. Further practical tests based on the germination and mortality models would be required to perfect the treatment for the experimental set-up. In practice it would be difficult to deliver an effective disinfestation treatment against grain weevils for individual dryers because sufficient temperature monitoring is not usually present.

Introduction

Simulation models already exist of two types of dryer, mixed-flow and cross-flow, which incorporated a model of how grain viability was affected by temperatures and moisture changes experienced by grain during the drying process. For this project, a new model has been developed, to predict the mortality of the insects resulting from conditions in the dryer. This model, based on data generated in the project, was incorporated in the two simulations. Indications from the modelling work were that it was feasible to heat the grain in the dryer so as to cause a very high level of mortality of insects and a very low level of reduction in grain viability.

A test using a full-scale mixed-flow dryer, of a type used on UK farms, was required to provide evidence on a practical scale of the efficacy of thermal disinfestation, temperature and moisture data for use with the simulation models and practical experience in the operation of a drying system for disinfestation. The objectives were (a) enable experimental results and predictions from a simulation to be compared, thus validating the simulation model before further investigations were undertaken, and (b) to gain practical experience in, and data from, using a full-scale dryer for disinfestation

The aim, was to heat the whole batch of grain to a target temperature. In principle this could be achieved in one of two ways, either in one pass through the dryer using the machine in continuous-flow mode so that each part of the grain passed in turn through the same heating and cooling treatment, or by heating the grain in a batch with recirculation followed by cooling and discharge, so that all the grain was heated, and then cooled. The batch approach test method was decided on because of several factors; (a) batch heating would allow the temperature to be increased gradually to the target and thus made the experiment more controllable, (b) recirculation of grain during heating would be expected to give a more even temperature of grain and hence a more effective treatment, (c) the hot batch allowed good control of exposure of the instrumented canisters of grain, described below, (d) by treating grain in a batch, all the grain could be subjected to the treatment, whereas in continuous flow, the initial material might not be fully disinfested and, (e) cooling of grain in the dryer could be continued for as long as necessary following treatment.

Methods and materials

Experimental plan

The batch dryer was filled with approximately 10 t of wheat, brought up to the required temperature for disinfestation and then discharged into a holding bin. Grain temperatures were measured at inlet and outlet of the drier using thermocouples where some insect canisters and barley samples were also placed to assess survival and grain viability respectively. In addition, bags of insects were dropped into the drier as it was loaded and some of these were recovered as the grain discharged into the holding bin.

Two experiments were carried out, the first to investigate a treatment using a relatively low temperature, 50^{o}C for a relatively long time, 30 min., the second a higher temperature, 55^{o}C, for a shorter time, 15 min. These conditions were chosen as the simulation had shown these would achieve disinfestation while not damaging germination.

The method used for the tests was adapted from the ISO 11520-1 "Agricultural grain driers – Determination of drying performance". Adaptation was needed because the purpose of the test was not simply to determine the drying performance.

Material.

Cleaned wheat at an initial moisture content of approximately 16% wet basis was used for these experiments.

Drying system.

The dryer was a Law-Denis dryer of the mixed-flow type, of holding capacity approximately 12t, fed via conveyors and elevators from a holding bin, and fitted with a gas-fired burner to heat the air. Air was moved by a fan on the exhaust side of the dryer, and thus drawn through the dryer.

The air inlet plenum allowed access to eight rows of ducts in six columns. In normal operation as a continuous flow dryer, the inlet plenum would be divided so that some rows of ducts allowed ambient air to enter to cool the grain after the heating zone. For this test, these doors were adjusted to their lowest position so that the whole plenum was supplied with heated air. On the exhaust side, there were eight rows of ducts in five columns, plus a half duct at the end of each row, from which exhaust air flowed into the exhaust plenum.

Grain discharge rate, and hence the flow rate of grain through the dryer, was controlled by the rate of discharge of grain from the bottom of the dryer. Instrumentation on the dryer included 'inlet air temperature', which was measured by sensors in the air entering the 2nd row of ducts from the top of the inlet air plenum, and 'grain temperature', which was the temperature of air exhausting from a duct on the 3rd row of ducts from the bottom.

Moisture content.

Five samples of wheat were taken at equidistant depths from the holding bins before loading the drier and their moisture determined by drying at 130°C for 2h in a ventilated oven according to ISO 712. The moisture content of barley samples for the viability tests was determined by the same method.

Insect mortality.

Wheat grain infested with *Sitophilus granarius* (IV instar larvae and pupae), the most heat-tolerant species of UK insect storage pests, was produced by CSL as described in Part 1 of this report, and packaged into two forms. Bags (60 x 60 mm) of polyester mesh (475 aperture) each containing some 10g of wheat were designed to be carried through the conveyers and canisters (15 mm diameter x 100mm length) made of metal mesh containing a similar amount were intended for insertion into grain via the exhaust and inlet of the drier. Fifty bags and 30 canisters filled with infested wheat were used for each of the two experimental runs.

Grain viability.

Thirty canisters filled with malting barley (11g, Variety 'Optic') were also used for each of the two runs. The germinative energy test carried out on the barley samples 10 days after each run based on IOBRecommended Methods. One hundred grains were divided between two filter papers in a Petri dish with 4 ml of water added. Germinating grains were removed at 24, 48 and 72 h, at which point the test finished. It was done at 15°C rather than 20°C as as this reflected the temperature experienced by the germinating grains at the end of steeping. A further test was done four weeks latter to ensure that there was no delayed effect of the heating treatment on the germinative energy of the barley.

Temperature and relative humidity

Type T thermocouples (copper-constantan) were used. The data logger and thermocouples were calibrated by placing the thermocouple junctions in a heated block with a reference sensor. All were with 0.5°C of the reference temperature.

To measure temperatures of air in the grain bed, thermocouples were installed about 10 cm into the grain bed and about 10 cm along each of 4 ducts on the inlet and four ducts on the exhaust faces of the dryer. Two thermocouples were near the top of the dryer and two near the bottom. The temperature of air entering the dryer burner and in the exhaust plenum was also recorded.

The temperature of the air in the canisters was recorded by installing thermocouples in four of the paired canisters containing barley and four containing infested wheat.

Sensors for r.h. were installed in the exhaust plenum and in ambient conditions near the dryer inlet.

Temperature and relative humidities were recorded using a Campbell data logger and summary data displayed on a laptop computer during the experiment.

Experimental details

Run 1. The objective was to raise the grain temperature in the dryer to 50°C. The dryer was filled with wheat, during which the 50 insect bags were added, 10 at each of five stages (10 min apart). Dryer fan and burner were started and the dryer and system were set to circulate grain from dryer outlet back to the inlet. Demanded air temperature was set to 70°C. Various problems, described later, were experienced which increased the time taken to heat up the grain in the dryer. Drying air temperature was ultimately raised to 100°C to achieve the required grain temperature.

When the grain was judged to be sufficiently hot, the fan and burner and grain discharge were all turned off, and the access doors to the two plenums opened. Thirty pairs of canisters (one each of infested wheat and malting barley) were inserted into the grain bed through the duct apertures, 15 on each of the inlet and exhaust sides, in positions in the lowest 3 rows on the inlet side and lowest four rows on the exhaust side that could be reached quickly and safely. The plenum doors were closed and the canisters were allowed to remain in place for a period of 30 min, after which they were removed and cooled. The grain was then discharged into the holding bin through a sieve device to retrieve the insect bags from the grain flow, which were also cooled.

The heated grain was then re-loaded into the dryer, during which the 50 insect bags for Run 2 were added as before. Grain was left in the dryer overnight during which time the temperatures were recorded to measure the rate of cooling of grain in the unventilated dryer, which represented a long duration ‘steeping’ treatment.

Run 2. Target grain temperature in the dryer was 55°C, 5°C higher than Run 1. It became clear that there were differences in temperature between locations in the dryer during Run 1, such that the thermocouples in grain near the inlet side were generally hotter than those on the exhaust side. So effectively two different treatments were being delivered, depending on which side of the dryer was considered. The procedure for Run 2 was as for Run 1, except for the following. To allow for the observed lower temperatures observed on the exhaust side the time for which the canisters were left in the grain bed was increased from the planned time of 10 min. to approximately 16 min. This treatment was selected to increase the disinfesting effect on the cooler side of the dryer and to examine whether the treatment on the hotter side gave acceptably low loss in viability

After the canisters had been retrieved, the fan was turned on to cool the grain in the dryer while temperature recording continued so as to determine the rate of cooling of grain in the fully ventilated dryer. Discharge to the bin and retrieval of insect bags followed this cooling.

Results and discussion

<u>Temperature of grain.</u>

In Figs 1-4, thermocouple locations in the legend indicate the row of ducts in which each was located, where row 1 is the lowest exhaust or inlet duct, and in this dryer 8 was the uppermost. Left or Right are defined looking at the face from the plenum. All eight thermocouples were positioned in the penultimate aperture in their row. The temperature from the four thermocouples on the exhaust side of the dryer was taken as the best estimate of grain temperature because as the air exhausts from the grain bed, the temperature of air and grain are likely to be close. Significant cooling of grain occurred during its passage through the elevators and conveyors. During Run 1, the temperatures from the four thermocouples were tracked and it was clear that the target of 50°C would be reached only if the hot air temperature were raised significantly. This was done in several steps until 100°C was achieved, at which temperature the rate of rise of exhaust temperature was sufficient for the target to be achievable. The burner cut out on several occasions as a result of grain accumulating in the hopper beneath the dryer, so the rate of discharge of grain had to be reduced to avoid this fault.

There were persistent temperature differences between the top and bottom of the dryer, on both the inlet and exhaust sides (Figs. 1-4). These differences varied with time as the temperature of the grain increased. They also varied depending on how long the grain had been exposed to heating. Thus for Run 2, in Fig 3 at 75-80 min, the grain near the sensors at the top was still cold because it had been in the dryer reservoir and not yet been exposed to heating. The temperature difference between top and bottom of the dryer was exaggerated by cooling owing to the relatively slow rate of grain recirculation of which the grain handling system was capable.

During Run 1, in the period when the canisters were embedded in the grain, (Figs 1 and 2 between times 342 and 372 min,) the temperature of the thermocouples in the grain on the inlet side were not constant but on the exhaust side were 4^{o}C lower at the top than at the bottom. During Run 2 the differences were consistently 10^{o}C higher on the inlet side and 8^{o}C lower on the exhaust side (see Figs 3 and 4 between times 120-150 min). This difference, which was a consequence of the fact that some of the batch had been longer in the heating zone that the rest, meant that it was not possible to bring all the temperatures to the target at the same time. So in Run 1 the dryer was stopped when the exhaust temperatures reached about 52^{o}C at the bottom and 48^{o}C at the top. Indicated 'grain temperature' on the dryer panel was 50^{o}C at this point. Canisters were inserted near the bottom of the dryer, so the difference between the inlet and exhaust side effectively provided two different temperature environments for the canisters. In Run 1 this difference was about 13^{o}C, and 10^{o}C in Run 2.

The temperature records from thermocouples in the canisters were used as inputs to the insect mortality and germination loss models to calculate the expected effects of the treatment received by the canisters. The most important elements of the experimental data are given in Table 1.

Insect survival at inlet and exhaust.

There was considerable variation in weevil mortality, depending on the position of the canisters (Table 2). In the first run, approximately 90% of the developing weevils died in the 12 canisters on the inlet side and 10 out of 12 canisters were successfully disinfested. In contrast, only 58% died on the outlet side with 7/15 canisters being disinfested. In the second run, even less were killed with 70% dying on the inlet side, 8/12 canisters being disinfested and only 40% on the exhaust side with just 2/15 canisters being completely devoid of insects.

During Run 1, on the inlet side, there was complete control for the top and bottom with the only survivors found at the mid section in the side ducts. Of these, the side closest to the wall of the building, showed a reduction in numbers of adults of 75%, when compared to the control. For the exhaust side, complete control was only achieved in the middle of the top row. For the top and the bottom zones, numbers similar to the control, and therefore experiencing little mortality, were only found at the edges with the mid ducts having no emergence. For the middle bottom row there was emergence in all three ducts though the mid and wall side duct showed a 48% reduction in adult numbers whereas the other side was the same as the control.

For Run 2, with the higher temperature but shorter exposure, there was more adult emergence throughout the test zones. For the inlet side there were no rows with complete mortality as for each row, the end ducts adjacent to the open space of the building gave similar emergence to the control. For the mid zone this extended to the next duct as well. On the exhaust side there were only four canisters that had no emergence: the middle of the top row, the open side of the middle top row and the two middle positions for the bottom row. Of those with emergence it was the ducts at the side that showed no effect from the exposure but with this run there was more emergence from the samples in the mid ducts in the top three rows.

When the results from the runs are compared to the temperature profiles it is possible to see why there is a difference in emergence. The temperature profiles of the two runs while the canisters were in the grain are shown in Figures 5-8. The main difference was the exposure time to the final temperature – in Run 1 the canisters arrived at a temperature in balance with their surrounding. In Run 2, even though more time was allowed for heating than had been planned, the canisters were still increasing in temperature at removal time. The reduced exposure time allowed more survival for Run 2. The higher level of emergence for the exhaust side was due to the lower temperatures, obvious in Figs 5-8, temperatures which were probably further reduced in the side ducts especially on the side of the drier adjacent to the void of the building.

It should be born in mind that the estimate of mortality achieved by this method was conservative as the canisters were not subject to elevated temperatures during the heating up period or during the cooling down period.

Insect survival in the grain stream.

The mortality of insects in the bags in the grain stream was greater than in the canisters (Table 3). In this case, in Run 1 about 90% of insects died in bags recovered from the grain stream entering the holding bin and complete mortality occurred in 4 of the 8 bags recovered. In Run 2, about 97% of weevil larvae died and 15 out of the 17 recovered bags had no live insects in them. The same trend is seen in the bags recovered from the conveyer. About 68% of insects died in bags recovered from Run 1, and 12 of the 31 had no living insects while about 95% were killed in Run 2 and 17 of the 19 bags were successfully disinfested.

The insect bags were small and flexible so that they would move with the grain. However it was not clear that all received the treatment intended as only 23% were collected at the point of discharge into the output bin after Run 1 and 53% after Run 2 (Table 2). The retrieval rate for the latter run was improved by removing a blockage at the bottom of the drier formed by an accumulation of tea bags. From previous experience, the insect bags could become caught in the handling system and might not have been exposed with the grain. This can be seen by the numbers found within the conveying system. These were mainly in the conveyor that connected the top of the conveyor with the conveyor that fed the drier. Results for these had to be interpreted with particular care.

In Run 2, the insect bags were left within grain at 45°C overnight. This temperature had dropped to between 25 – 35°C by the morning. If the drop in temperature was linear this would mean 0.6°C/h and that the temperature was at 44°C or above for 1.5 h . There are no results in the literature for the grain weevil but the rice weevil required 8 hours at 44°C, 12 h at 43°C and 17 h at 42°C for 50% mortality at each temperature (Beckett et al, 1998). Therefore if mortality is proportional to the exposure time, the cumulative total may be 15% . The rice weevil is certainly more tolerant than the grain weevil so the mortality of the latter may be higher. However the initial drop in temperature would have been quicker than estimated, especially at the periphery which would suggest that mortality during this ‘steeping’ period would not have exceeded 20%.

Moisture content

The slow heating of the grain during the first run resulted in a moisture loss of about 4% from the experimental grain (Table 4) but only 1.5% from the barley in the canisters while the equivalent losses in the second run were 1.8% and 1.9% in both cases.

Prediction of insect mortality and barley viability.

The calculated mortality of the weevil larvae was lower than or equal to the results from the canisters inserted in the inlet and exhaust of the dryer (Table 5), suggesting that the mortality model was predicting conservatively the likely effect on insects of the heating. This allows a certain margin of safety in predictions made with the model in later simulations.

The comparison of measured and calculated grain viability (Table 6) confirmed the validity of the model, in that a loss of a fraction of a percent was predicted for the samples and the measured loss was not detectable at the level of the resolution of the germination test, i.e. 1% point, except for one sample on the inlet (hotter) side in Run 2 where a 1% point loss was recorded. This gives confidence that the model for viability loss was working well in this situation.

Cooling rates.

Cooling rates of the grain were recorded after Run 1 overnight with no fan when the cooling rate was approximately 0.82^{o}C/h (Fig. 5). After Run 2, the grain was ventilated with the dryer fan (Fig 6 and the cooling rate was 1.0^{o}C/min, so that a temperature of 20^{o}C was reached after a cooling period of 36 min.

Practical aspects of disinfesting grain in a heated air dryer

Temperature settings.

The objective of heat disinfestation is to achieve a grain temperature that achieves insect kill but does not damage seed viability. Dryers generally have a "grain temperature" indicator, provided by a temperature sensor mounted in the exhaust airstream. A sensor in the exhaust stream will generally read close to the temperature of grain at that location in the dryer, and so could potentially be useful. However, the temperature in other locations may be significantly different, and also the sensor may not be sufficiently accurate. To illustrate the differences between locations in the trial, temperature differences between the bottom of the exhaust side (where the dryer's "grain temperature" sensor is located) and the top of the same side were about 6 ^{o}C for Run 2 , the bottom being hotter. These differences are large enough to make achieving a target temperature with a margin of error of + or – some 5^{o}C, much more difficult.

In Run 1 of the trial, a heated air temperature approaching 100^{o}C was used to achieve the required target grain temperature of 50^{o}C, as indicated on the thermocouples in the grain bed, within a reasonable time. Using a lower air temperature would mean a longer time would be needed to raise the grain temperature, and too low a temperature would not achieve a suitable treatment. A higher inlet air temperature would heat the grain faster which would reduce treatment cost per batch. However, the danger of overheating grain on the (probably hotter) inlet side of the dryer would increase. This means that selection of temperature and treatment time is not simple. Guidance for the appropriate combinations of inlet air temperature and temperature at the exhaust side will be needed for various designs of dryer and grain moisture levels.

Batch vs. continuous.

In the trial the dryer was used in batch mode, which allowed the heating time to be chosen simply by heating until a guide temperature, previously calculated with the aid of simulation, was reached. It also allowed substantial cooling to be achieved before grain was discharged. However, if a large quantity of grain needs treatment, batch operation has a lower throughput of grain and uses energy less efficiently than a continuous flow treatment. If the dryer were used in continuous flow, the heat treatment would need to be achieved in one pass. To get the temperature and transit time correct, the discharge rate and drying air temperature would have to be selected prior to the run based on a guide for the type of dryer, the grain species and moisture content. Also, cooling would probably not be adequate, owing to the short residence in cooling section provided by most types of dryer, so cooling after treatment would be essential.

Costs

The costs of the disinfestation process arise from the cost of the energy used and, depending on the requirements of the market, loss of saleable weight of the grain owing to moisture loss during treatment. Costs of labour and depreciation of equipment are specific to individual enterprises and have not been estimated. The energy and lost weight costs are estimated below for Run 1. Run 2 started with already warmed grain so was not representative. A run time of 4 h has been estimated for Run 1, to allow for 2 h of stoppages.

At 146.4 m^3, the gas used represented 5797 MJ, and at 39.6 MJ/ m^3 for the net calorific value of gas and 1.37p/kWh, the gas cost was £22.03. Electricity at 5p/kWh for a 4 h run cost £2.92, so the total energy cost was £24.95. For Run 1, the moisture change was 16.0 to 11.8% wet basis, giving a weight loss of 0.48 t for a 10 t batch, so at a nominal value of £70/t the lost weight cost was £33.6. The grain was relatively high in the range appropriate for disinfestation. For Run 2 moisture change was much less, from 11.8 to 10.0 % wet basis, because in this run the moisture was low for disinfestation. Run 2 gave a weight loss of 0.19 t for a 9.5 t batch so the lost weight cost was £13.3. Taking the mean of both runs, the lost weight cost averaged at £23.5. Total cost of energy and lost weight for the 10 t batch was then £48.45, so the cost per tonne of grain before treatment was £4.85.

Figure 1. Run 1: Air temperatures in grain bed near dryer air inlet

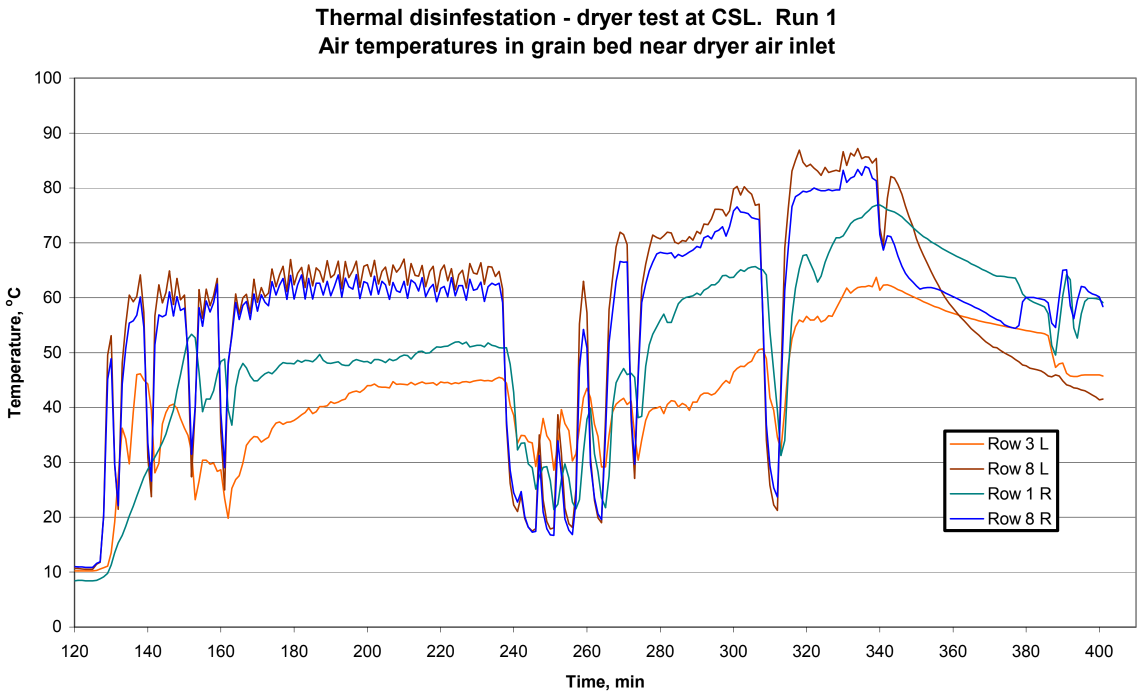


Figure 2 Run 2: Air temperatures in grain bed near dryer air exhaust.

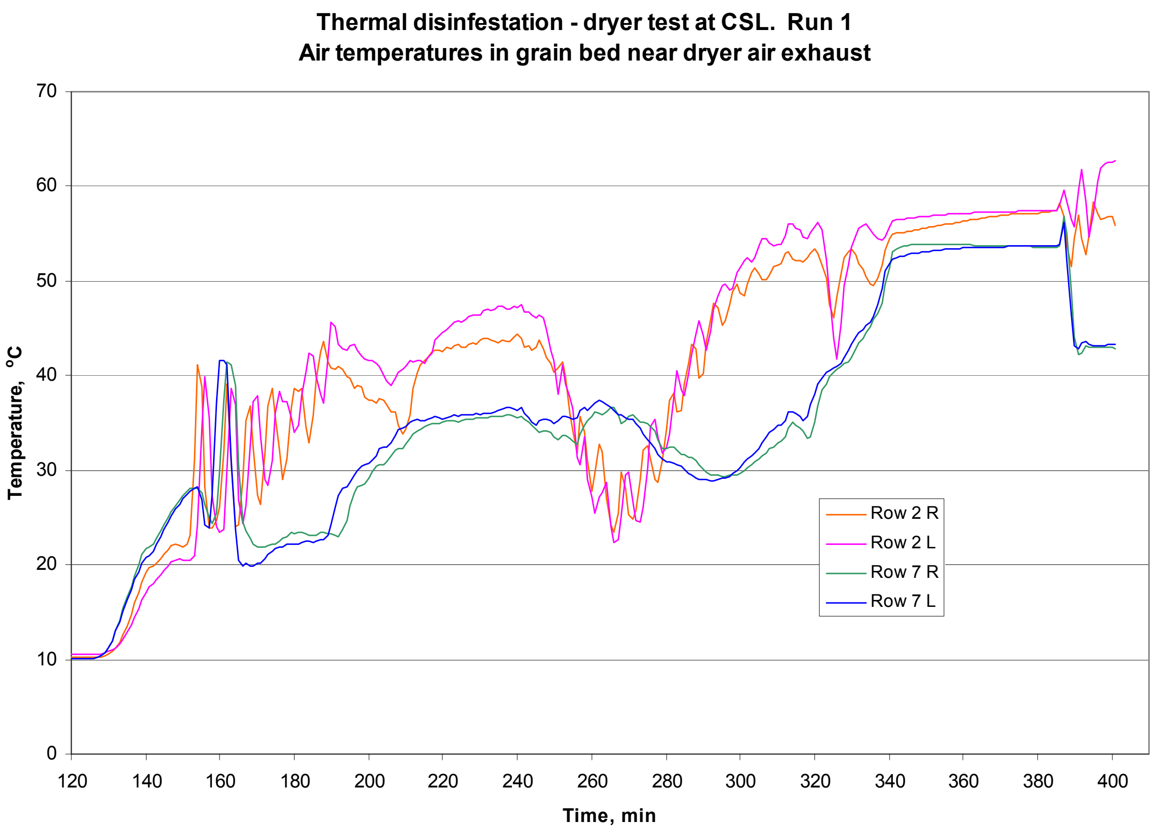


Figure 3. Run 2: Air temperatures in grain bed near dryer air inlet

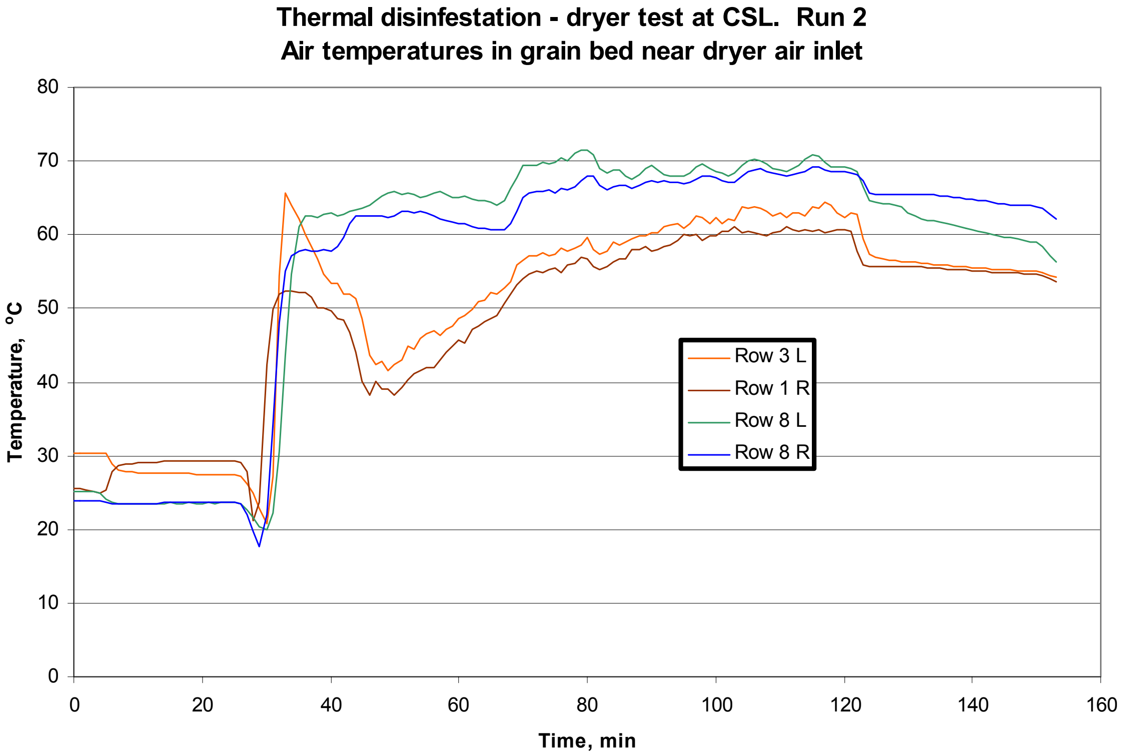


Figure 4. Run 2: Air temperatures in grain bed near dryer air exhaust

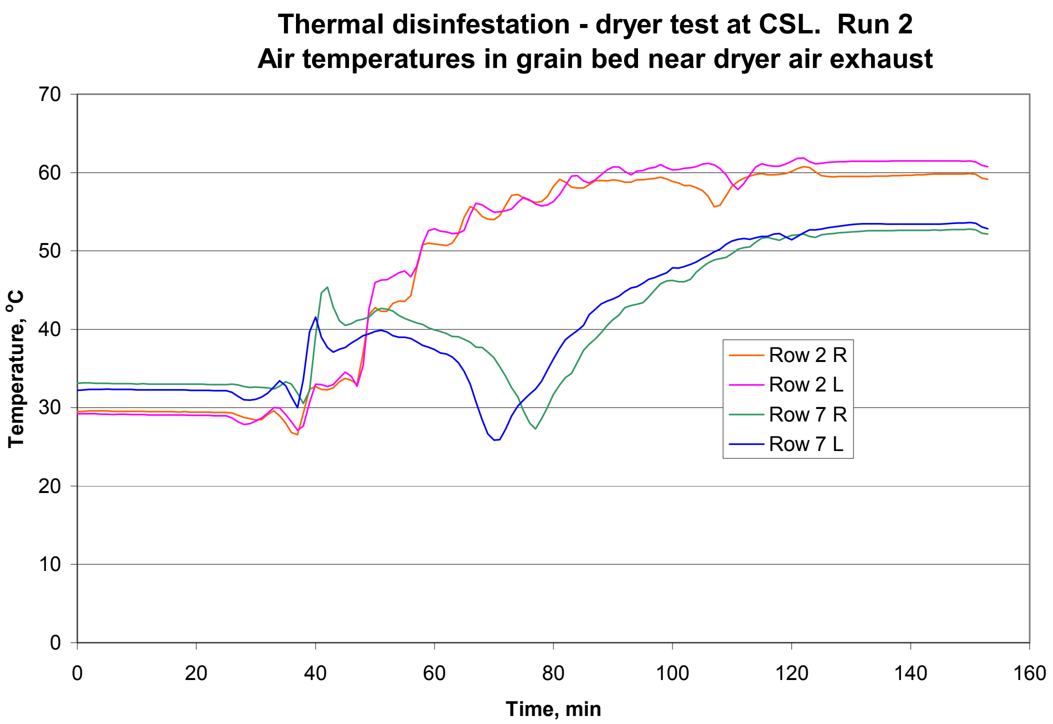


Figure 5. Run1**.** Heating of canisters of infested wheat

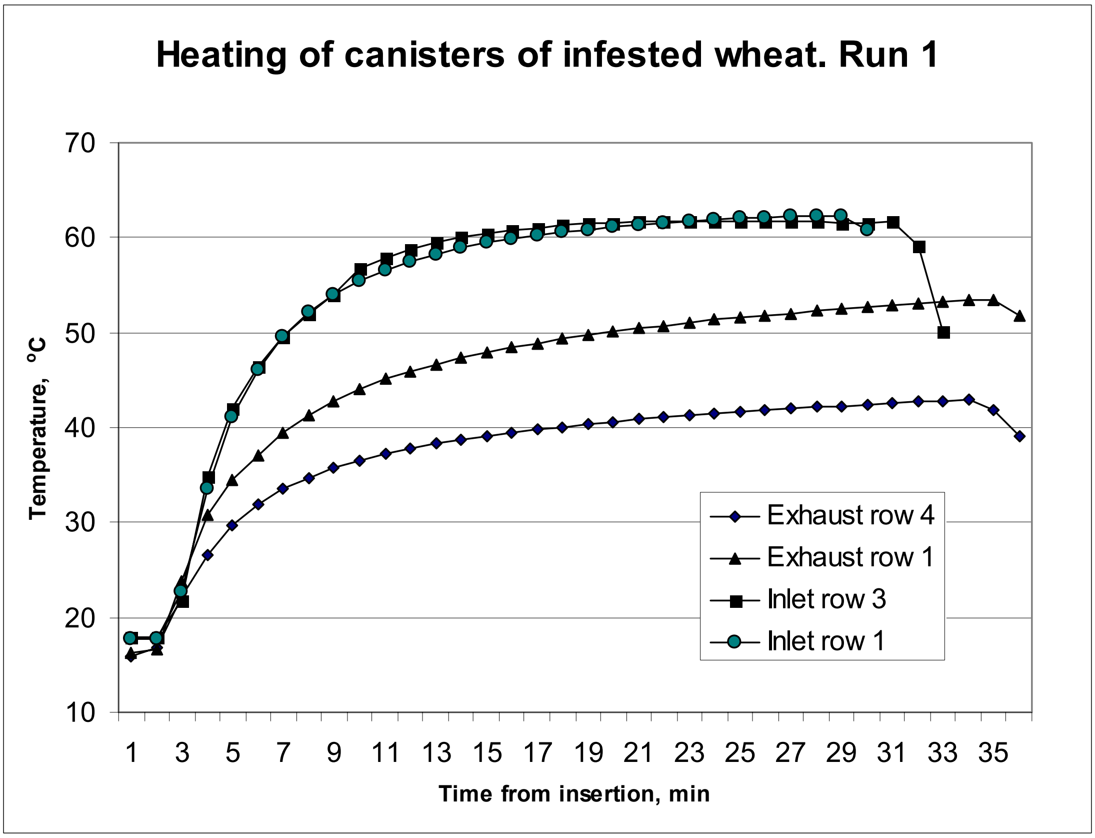


Figure 6. Run 1. Heating of canisters of malting barley

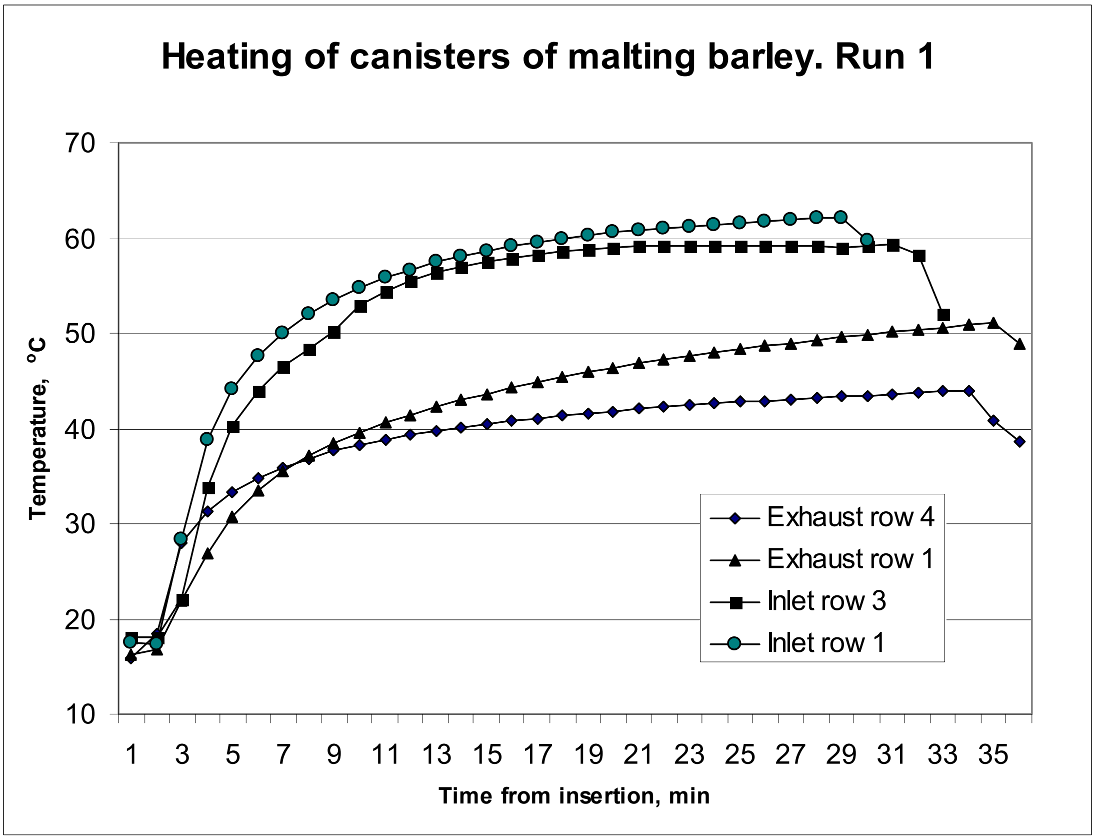


Figure 7. Run 2. Heating of canisters of infested wheat.

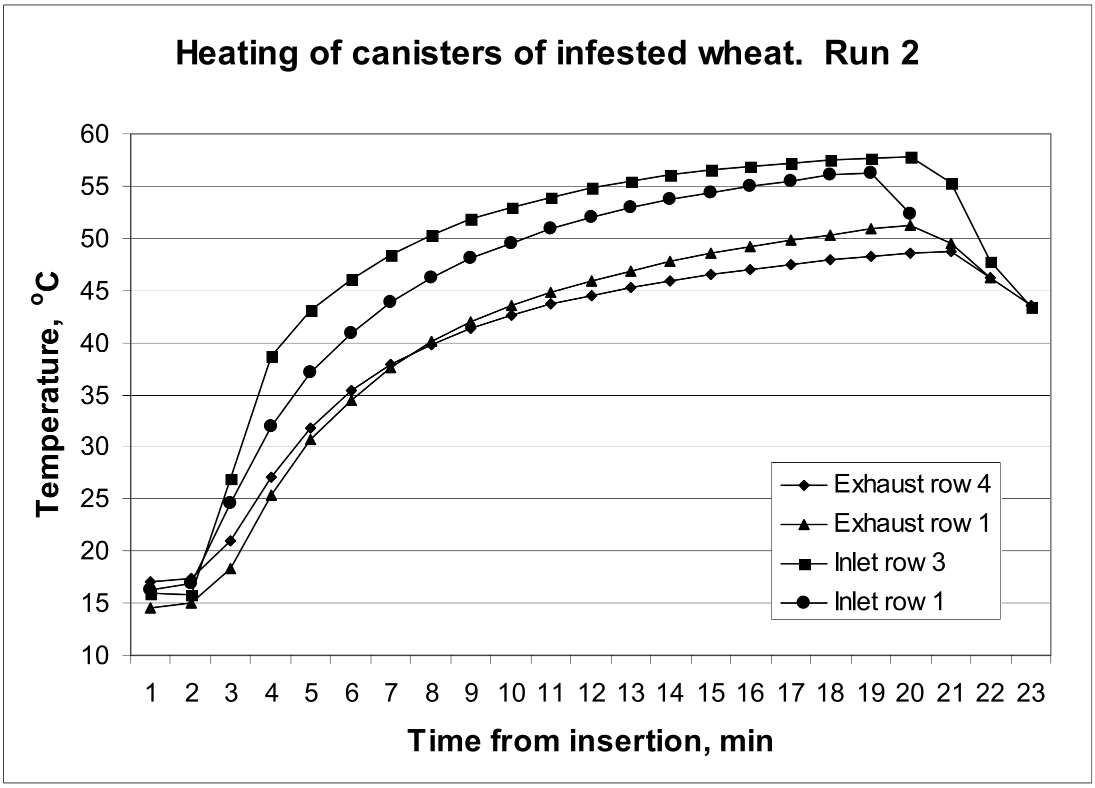


Figure 8. Run 2. Heating of canisters of malting barley

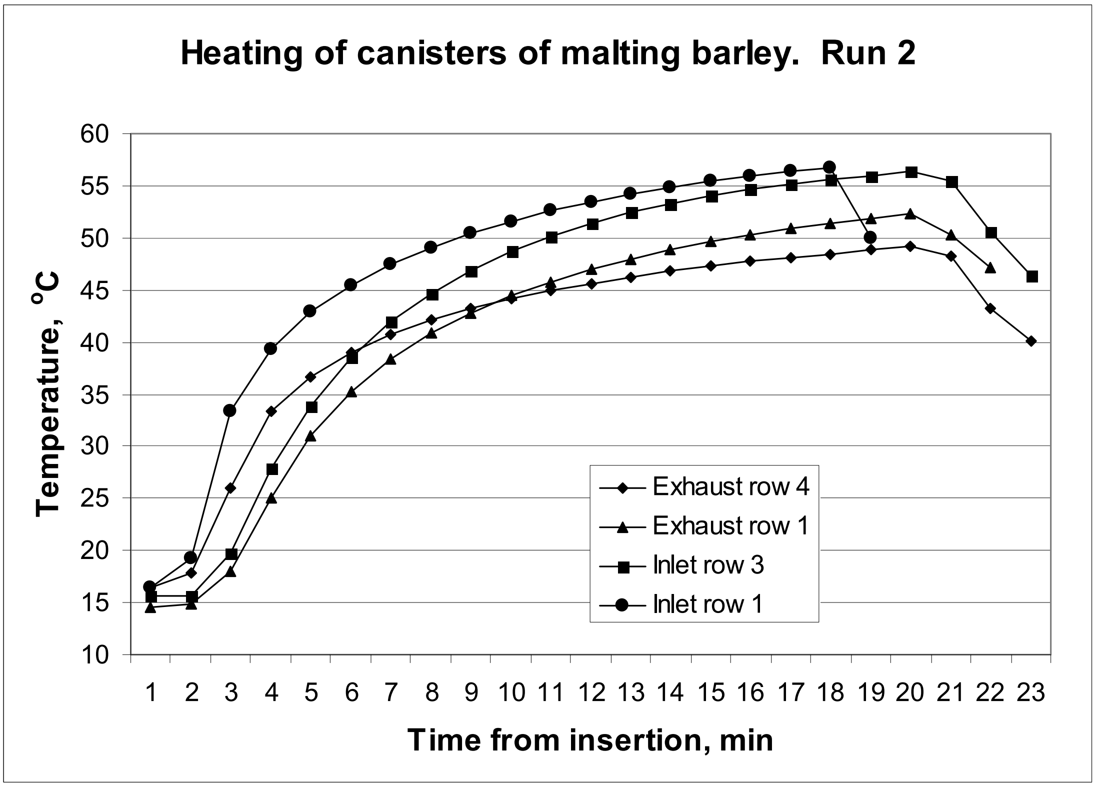


Figure 9. Cooling of grain between Run 1 and 2, with no fan assistance.

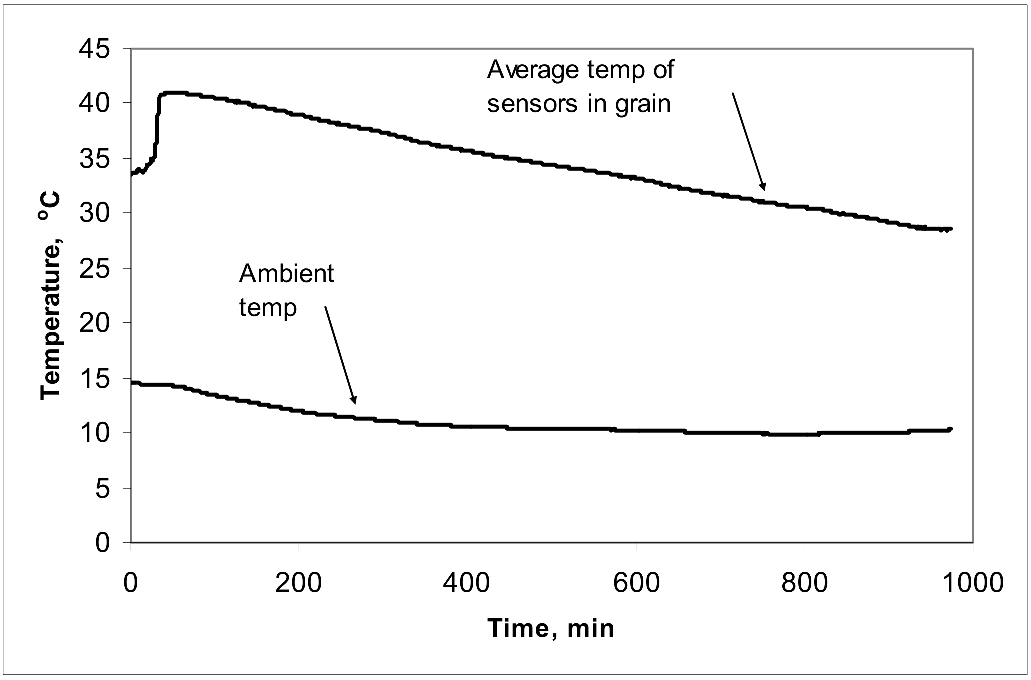


Figure 10. Cooling of grain after Run 2, with fan assistance.

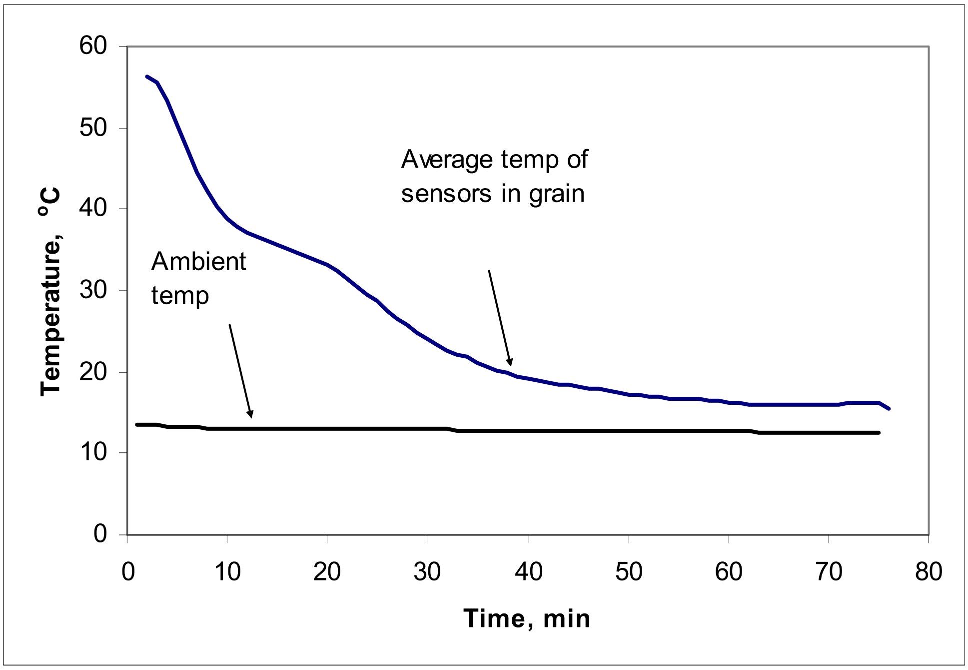


Table 1. Measured maximum temperatures (^oC) from thermocouples in canisters on each side of dryer and their insect % survival or germination.

Side	Canister Position & Content	Run 1 (t = 30 min)	% Insect mortality (I) or Germination (G)	Run 2 (t= 17.5 min)	% Insect mortality (I) or Germination (G)
Inlet	Top Insect (Row 3)	61.8	100 I	57.9	100 I
	Top barley (Row 3)	59.4	97 G	56.3	98.5 G
	Bottom Insect (Row 1)	62.3	100 I	56.2	100 I
	Bottom Barley (Row 1)	62.2	98 G	56.8	99 G
	Mean	**61.4**		**56.8**	
Exhaust	Top Insect (Row 4)	43.0	0 I	48.7	27 I
	Top Barley (Row 4)	44.0	99 G	49.1	97 G
	Bottom Insect (Row 1)	53.5	100 I	51.3	100 I
	Bottom Barley (Row 1)	51.1	98.5 G	52.3	97 G
	Mean	**47.9**		**50.4**	
Temperature difference between Inlet and Exhaust side means		13.5		6.4	

Table 2. Proportion of *S.granarius* larvae killed, numbers developing and no of samples disinfested during hot-air batch drying of 10 t of wheat.

			Run					
			1	2	1	2	1	2
Position (Row)	Location	No. of canisters	Mean % mortality		Mean Numbers		Canisters disinfested	
Inlet								
1	Left	2	100	100	0	0	2/2	2/2
	Right	2	100	50	0	33	2/2	1/2
2	Left	2	88	100	8	0	1/2	2/2
	Right	2	50	17	24.5	45	1/2	0/2
3	Left	2	100	100	0	0	2/2	2/2
	Right	2	100	50	0	24.5	2/2	1/2
Mean % mortality or No.s			90	70	4.3	13.7		
Exhaust								
1	Left	2	82	36	11.5	37	1/2	0/2
	Right	3	33	33	45	48.5	1/3	0/3
2	Left	2	100	50	0	19.5	2/2	0/2
	Right	1	100	34	0	35	1/1	0/1
3	Left	2	21.5	40	53.5	42.5	0/2	0/2
	Right	1	52	0	31	48	0/1	0/1
4	Left	3	76	81	15.7	10	2/3	2/3
	Right	1	0	49	62	27	0/1	0/1
Mean % mortality or No.s			58	40	27.0	29.0		
Control Nos.					64.6	53.4		

Table 3. The proportion of insect bags retrieved, insect mortality in them, bags in which all insects died and percentage of bags with damaged grain at each location after each run.

		Bin Sieve		Conveyor	
Results	Run	1	2	1	2
Retrieval (%) (No.s)		16 (8/50)	34 (17/50)	62 (31/50)	38 (19/50)
Mortality (%) Range		89.8 (69.0 – 100)	96.5 (56.9 – 100)	68.3 (0 – 100)	94.9 (43.8 – 100)
Bags with complete mortality		4/8	15/17	12/31	17/19
Damage (%) (Nos)		7.7 (3/39)	16.7 (6/36)	12.8 (5/39)	11.1 (4/36)

Table 4. Grain moisture changes during the two runs. (Moisture, in % wet basis, was determined by ISO 712)

Material	Initial moisture	Moisture after Run 1	Moisture after Run 2	Loss of moisture in Run 1	Loss of moisture in Run 2
Wheat	16.0	11.8	10.0	4.2	1.8
Barley	15.0	13.5	13.1	1.5	1.9

Table 5. Comparison of insect mortality in the canisters with calculated mortality based on the model devised by this project.

Side	Row	Run 1		Run 2	
		Measured mortality, %	Calculated mortality, %	Measured mortality, %	Calculated mortality, %
Exhaust	4	21.2	0.1	34.3	7.3
Exhaust	1	100	100	100	37.3
Inlet	3	100	100	100	100
Inlet	1	100	100	100	100

Table 6. Measured and calculated viability loss.

Side	Row	Run 1		Run 2	
		Measured viability loss*, %	Calculated viability loss, %	Measured viability loss*, %	Calculated viability loss, %
Exhaust	4	0	0.01	0	0.35
Exhaust	1	0	0.02	0	0.38
Inlet	3	1	0.18	0	0.42
Inlet	1	0	0.25	0	0.41

*Where a zero value is tabulated, measured viability equalled or exceeded the control value.

CONCLUSIONS AND RECOMMENDATIONS

1. This project has identified the combinations of grain temperature and exposure time to that temperature that would enable grain to be disinfested from the most heat tolerant life stage of the most tolerant UK grain pest, the grain weevil, *S. granarius*. Based on the heat mortality results, exposures of 15, 30, 45 and 60 minutes would be required to kill 99.9% of the most heat resistant stages of the grain weevil at grain temperatures of 52, 50, 48 and 46°C in malting barley at 12% mc.

2. A "window of opportunity" has been established within which disinfestation can be achieved without damage to grain, as judged by germination of malting barley. Grain temperatures 16-18°C above those listed above would be required to cause a fall by 1% in germination in the same exposure time. The temperature window is widest at low grain moisture and with barley of high initial germination.

3. A practical test showed that the predictions of the model gave the desired result – disinfestation of the grain weevil without grain damage – except for a few locations where insects unexpectedly survived, indicating cool spots in the grain bed.

4. Simulation of commonly used dryer types used in continuous flow has shown that, in principle, it is possible to achieve disinfestation of the grain weevil without grain damage in a dryer where the temperatures and airflows are constant and uniform. The dryer settings needed to disinfest without damage, and how tolerant they are to uncertainties in the settings have been studied in detail. In a continuous-flow grain dryer, an air temperature of 80 ^{o}C in combination with a particular residence time was predicted by a validated simulation model to kill 99.9% of *S. granarius* and to cause a reduction in germination of barley of less than 1%. For a given level of insect mortality, increasing the drying air temperature increased the grain throughput and reduced moisture loss and energy cost. Therefore the optimum treatment would be to use as high an air temperature as limits to germination loss allow. To get the temperature and transit time correct, the discharge rate and drying air temperature would have to be selected prior to the run, based on a guide for the type of dryer, the grain species and moisture content.

5. The two components of treatment cost are energy cost and the value of weight loss owing to drying. Energy costs at 80ºC were typically in the range 0.50 -1.00 £/t of input grain. Cost of lost weight were in the range 0.65£/t when starting from 11 % moisture content to 3.26£/t when drying from 16%. Batch operation has a lower throughput of grain and uses energy less efficiently than a continuous flow treatment, which is important if a large quantity of grain needs treatment.

6. The objective of heat disinfestation is to achieve a grain temperature that achieves insect kill but does not damage seed viability. In practice, however, disinfestation of grain weevil would be difficult to achieve reliably in continuous-flow treatment because of the considerable temperature variation within hot-air dryers and because grain throughput would have to be precisely set. The minimum temperatures must be high enough to guarantee disinfestation, the maximum temperatures must not be so high as to damage germination. Dryers generally have a "grain temperature" indicator, provided by a temperature sensor mounted in the exhaust airstream. A sensor in the exhaust airstream will generally read close to the temperature of grain at that location in the dryer, and so could potentially be useful. However, the temperature in other locations may be significantly different, and also the sensor may not be sufficiently accurate. These differences are large enough to make achieving a target temperature with a margin of error of + or – some $5^{o}C$, much more difficult.

7. In Run 1 of the practical trial, a heated air temperature approaching $100^{o}C$ was used to achieve the required target grain temperature of $50^{o}C$, as indicated on temperature sensors installed in the grain bed, within a reasonable time. Using a lower air temperature would mean a longer time would be needed to raise the grain temperature, and too low a temperature would not achieve a suitable treatment. A higher inlet air temperature would heat the grain faster which would reduce treatment cost per batch. However, the danger of overheating grain on the (probably hotter) inlet side of the dryer would increase. This means that selection of temperature and treatment time is not simple. Guidance for the appropriate combinations of inlet air temperature and temperature at the exhaust side will be needed for various designs of dryer and grain moisture levels. Application of the principles outlined in this report will therefore depend on a greater knowledge of temperature variations within different types of dryer and accompanying improvements to the instrumentation within the dryers.

8. Treatment times to disinfest grain from insects that do not complete development within the grain, such as the saw-toothed grain beetle, are much shorter than times for developing grain weevils, usually by a factor of ten. The recommended air temperature and residence times would, therefore, enable disinfestation from most free-living species such as the saw-toothed grain beetle. If the areas of minimum temperature could be located and monitored, the recommendations would prove suitable for disinfesting feed grain, even from grain weevils inside the grain, because feed wheat quality is much less critical and temperatures of 100-120°C for 3h and 1h respectively are permissible without quality loss. In this case, our recommendations to kill weevil infestations could be followed without risk to feed grain quality.

9. Disinfestation of grain weevil in recirculating-batch dryers is expected to be more reliable than in continuous-flow because (a) the treatment would be at a lower temperature but for a longer time so dryer settings are less critical, (b) recirculation will achieve a more even treatment, reducing the effect of hot or cold zones, provided the dryer has a high grain recirculation rate, and (c) it will be possible to measure the grain temperature during the process and hence control the process to ensure the batch is treated effectively. Further work is needed to find the best operating conditions for such dryers to achieve disinfestation. An existing simulation model could be readily adapted for such work.

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