

REPORT FOR LINK PROJECT AFM87 - Modified atmospheres at raised temperature, an alternative to methyl bromide as a means of ensuring clean, pest-free, hygienic standards in food commodities

C H Bell¹, B B Harral², T J Wontner Smith¹, S T Conyers¹, K A Mills¹, S K Cardwell¹ and B E Llewelin¹

¹ *Central Science Laboratory, Sand Hutton, York YO41 1LZ*

² *Silsoe Research Institute, Wrest Park, Silsoe, Beds. MK45 4HS*

Executive Summary

The principal objective of this programme was to find a viable alternative to the commercially important fumigant methyl bromide, shortly to be restricted under the international Montreal Protocol agreement because of ozone depletion concerns, for dealing with infestation and hygiene problems on a range of durable food commodities produced overseas, notably raw cocoa, coffee, dried fruits, nuts, spices and rice. The loss of methyl bromide will remove a major safeguard for the maintenance of food hygiene, increasing the risk of spreading problems arising from the trading of crops and raw commodities throughout the industry. It is thus of vital importance to develop viable alternatives to methyl bromide. In the absence of alternatives, the only course of action would be to apply for a critical use exemption, but for this to be accepted by the Technical and Economic Assessment Panel of the UNEP Montreal Protocol, it would have to be shown that alternatives had been tried and had failed. The establishment of a sound technological base for an alternative control procedure would result in rapid adoption by industry provided that the changes necessary in commercial practice were economically feasible for the commodity concerned.

Of the various alternatives under investigation internationally, the one which appears most widely acceptable to the UK retail market and which is sufficiently advanced for further development in the immediate future, is treatment involving the use of modified atmospheres (MA). For each commodity this may require some reworking of industrial practice, and will also involve investment in providing a suitable generation source for the MA and a suitable container for treatments. The principal problem encountered in the trade is dealing with infestation or contamination at the point of receipt where time is of the essence. Of all factors rapid action was the reason for choosing methyl bromide as a mainstay for pest control. Even allowing for the fact that most of the commodities listed above are imported from warm climate regions, some enhancement of temperature will still be necessary to reduce the treatment times needed with MA applications. For these reasons the current programme investigated the requirements for modified atmosphere temperature combinations to achieve control in 24-48h treatments.

The current tests in an 0.5% oxygen atmosphere with 13% CO₂ gave the following order of tolerance: *Rhyzopertha dominica* > *Lasioderma serricornis* > *Sitophilus oryzae* > *Carpoglyphus lactis* > *Tribolium castaneum* > *Carpophilus dimidiatus* > *Stegobium paniceum* = *Ephestia cautella* > *Plodia interpunctella* = *E. elutella* = *Oryzaephilus mercator*. This reflects the order of tolerance to heat in the absence of MA but temperatures up to 5°C higher are required for control within 24 hours. In the low oxygen MA, the temperatures required for control within 24 hours ranged from 35°C for pests of cocoa, coffee and walnuts, to 44°C for *R. dominica*, a pest of rice.

The modelling studies in this project could not tackle the diversity of situations created by different commodity packaging and concentrated on commodities stored in bulk. Modelling did however enable the commodity moisture changes that take place during heating to be predicted and showed how these can be controlled. It also showed that the convective heating of bulk stored commodities is at least 10 times faster than the conductive heating of packaged commodities and confirmed that heating air should be recirculated to minimise the energy input and conserve moisture and volatile products. With the appropriate airflow and air humidity control, bulk commodities can be heated from 15°C to 45°C in less than 12 hours at a cost of about £1.20 per tonne. Cooling with ambient air is both rapid and simple as the air is always passing through a warmer commodity, preventing condensation. Provided the target temperature causes 100% insect mortality in 24 hours, and that suitable air heaters, humidifiers and controllers are available, the whole treatment can be completed within 48 hours.

The temperature differential between the extent to which the atmosphere can be heated, as determined by the upper limit tolerated by the commodity, and the target temperature for pest control, is a crucial factor in determining heating rates. The greater the difference between these temperatures, the better the prospects for engineering an economic treatment system. For most of the commodities included in this project the results of quality tests on treated samples revealed that a quite generous temperature margin was available, up to 15°C. As mentioned above the pests of rice were the most heat tolerant, requiring exposure at 44°C for control within 24 h, but fortunately rice proved to be the most heat tolerant commodity. For seasonings such as coriander and fennel the treatment window lay between 40 and 55°C while for cocoa, coffee and walnuts it lay between 35 and 50°C. For dried fruit such as apricots, however, the window was only between 38 and 45°C. This coupled with the considerable difficulties for achieving any enhancement over temperature transfer by conduction for the packed commodity by using convection systems makes it very unlikely that a raised temperature MA treatment method can be made sufficiently effective for this commodity.

The packaging of products proved to be the major criterion for success of the treatments in the modified freight container. Following initial tests on the rate of conduction heating in small parcels of each of the seven commodities, trials were conducted on a full container load, on pallets, of 10 tonnes of bagged cocoa, and on two partial loads, 5 tonnes of bagged rice and 4 tonnes of boxed walnuts. With the recirculating atmosphere creating a convectional heating system in the container, a very different result was obtained in the heating rates of bagged cocoa and rice than in the small scale tests on heat conduction, with the cocoa reaching 35°C within 24 h and 40°C in 48 h while half the quantity of rice failed to reach 40°C after 4 days of heating. This was of concern for rice as the target temperature for pest control is much higher than for other commodities. The smaller grain size of the bagged rice undoubtedly restricted the movement of gas. The result in cooler conditions with boxed walnuts indicated that a more powerful heating system would be required to enable treatments within a 24 hour

period but the fact that the temperature rise showed no sign of levelling off after the 48 h test run indicated that heat transfer through the boxes, though slow, was effective. The results indicated that boxed dried apricots would be unlikely to heat sufficiently to enable a treatment within a manageable time period, especially when taking into account the higher target temperature.

In conclusion a more powerful air circulation system than that provided by the 350W fan installed in the container would be needed for the successful treatment of bagged coffee, cocoa, coriander or fennel, or boxed walnuts, within a 48-hour period when ambient temperatures are below 20°C, though the extent to which increased air flow can speed heat transfer would require some further investigation. For bagged rice and boxed dried apricots, the heated container does not appear to provide a solution and for rice, as for most commodities, the ability to treat in bulk, preferably in silos, offers the best solution. For coffee and cocoa this would offer the prospect of using heat alone, target temperatures for pests of these commodities being less than 45°C.

1. RESPONSE OF INSECTS TO WARM LOW OXYGEN ATMOSPHERES

3.1 Introduction

It has been established that MAs based on high carbon dioxide can achieve complete kill of a range of stored product pests within 24-48 h by raising the temperature to 38°C or above (Jay, 1986; Corinth and Reichmuth, 1995). A similar result can be expected with low oxygen atmospheres (Adler et al., 2000). With temperatures below 30°C, however, exposures of 2 or more weeks duration become necessary for control, depending on the species present (Annis, 1987). The energy costs of heating commodities are considerable and there is also a high likelihood that raised temperatures shorten shelf life or remove flavours. The principal pest species of each commodity were therefore selected to identify the minimum temperature that could achieve their control within a 24-h period in the presence of a low oxygen atmosphere that could be generated economically in practice by the combustion of propane.

1.2 Materials and Methods

After initial experiments to confirm the level of oxygen required for full efficacy, the modified atmosphere (MA) of 0.5% oxygen, 13% carbon dioxide and a balance of nitrogen was tested at a range of raised temperatures at 70% rh to find the temperature which gave complete mortality within 24 h for all stages of each species.

1.2.1 Modified atmosphere generation

The MA, based on the product of propane combustion, was for experimental purposes generated by a gas blender (Signal Instrument Co. Ltd., Camberley, Surrey) which mixed compressed air, carbon dioxide and nitrogen to give the correct mixture. This was checked using an oxygen meter (Servomex 570A, Crowborough, Sussex) and a carbon dioxide meter (Anagas CD 95, Environmental Instruments, Leamington Spa, Warwickshire). This check was made at the outlet of the blender. The gas output was split into three and passed to three flow meters. The lines from these were fed into a 225 l incubator (Prime Series, Sanyo Gallenkamp plc, Monarch Way, Belton Park, Loughborough, Leics).

Each line then passed to an rh generation system. This consisted of a 100 ml measuring cylinder containing an 80 ml mixture of 42 ml glycerol and 38 ml distilled water which gave an rh of 70% (Johnson, 1940). The inlet tube passed to the bottom of the cylinder and the atmosphere bubbled up through the solution. The outlet tube was flush with the bottom of the rubber bung which sealed the cylinder. The outlet tube from each cylinder was connected to a 6-L capacity glass desiccator (220 mm diameter x 250 mm height) where the exposure took place with one time interval per desiccator. The MA was added at a rate of 500 ml/min to bring the atmosphere down to the required level within half an hour and was then maintained by a flow of 100 ml/min. The oxygen and carbon dioxide levels were monitored on the exhaust from the desiccators outside the incubator.

A further similar desiccator was set up for all exposure times at the same temperature but without the MA. The rh in this chamber was maintained at 70% with a potassium hydroxide solution.

A temperature of 40°C and 70% rh was used as the starting point for assessment of tolerance. The temperature was then increased or decreased by 2°C depending on whether there was any survival. 35°C was chosen as the minimum temperature as this is below the upper limit for the complete development of most of the candidate species. Initially, time intervals of 16, 24 and 48 h were used.

1.2.2 Preparation of known age developmental stages

The age of the different stages of each species used are detailed in Table 1 and the rearing foods in Table 2. The procedures followed for tests are then given for each species.

Table 1. Age of all stages of the candidate species when tested to assess their tolerance to 0.5% oxygen and 13% carbon dioxide in nitrogen

Stage	Treatment age range (Days*)			
	Egg	Larvae	Pupae	Adult
<i>Carpoglyphus lactis</i>	1 - 3		NA	
<i>Carpophilus dimidiatus</i>	1 - 3	14 - 18	20 - 23	4 - 8
<i>Ephestia cautella</i>	1 - 3	28 - 32	34 - 37	2 - 6
<i>E. elutella</i>	1 - 3	36 - 40	44 - 48	2 - 6
<i>Lasioderma serricorne</i>	1 - 3	32 - 36	40 - 42	2 - 6
<i>Oryzaephilus mercator</i>	1 - 3	18 - 21	23 - 25	7 - 14
<i>Plodia interpunctella</i>	1 - 3	28 - 32	43 - 37	2 - 6
<i>Rhyzopertha dominica</i>	1 - 3	24 - 27	30 - 33	7 - 14
<i>Sitophilus oryzae</i>	1 - 3	18 - 22	25 - 27	7 - 14
<i>Stegobium paniceum</i>	1 - 3	27 - 31	33 - 36	2 - 6
<i>Tribolium castaneum</i>	1 - 3	34 - 38	41 - 45	7 - 14

* - For eggs, larvae and pupae this is the time from hatch at 25°C and 70% rh except *R. dominica* where data is for 30°C and 70% rh. For adults this is the time from emergence.

Table 2. Culture Foods for the test species

Species	Food
<i>Carpoglyphus lactis</i>	Yeast and Wheat germ (3:1)
<i>Carpophilus dimidiatus</i>	Rolled Oats and Yeast (10:1)
<i>Ephestia cautella</i>	Wheat Feed, Yeast and Glycerol (10:1:2)
<i>E. elutella</i>	Wheat Feed, Yeast and Glycerol (10:1:2)
<i>Lasioderma serricorne</i>	Wheat Feed and Yeast (10:1)
<i>Oryzaephilus mercator</i>	Wheat Feed, Rolled Oats and Yeast (5:5:1)
<i>Plodia interpunctella</i>	Wheat Feed, Yeast and Glycerol (10:1:2)
<i>Rhyzopertha dominica</i>	Whole Wheat Grain
<i>Sitophilus oryzae</i>	Whole Wheat Grain
<i>Stegobium paniceum</i>	Wheat Feed and Yeast (10:1)
<i>Tribolium castaneum</i>	Whole Wheat Flour and Yeast (20:1)

1.2.2.1 Mites - *Carpoglyphus lactis*

The mite was reared on a mixture of yeast and wheat germ (3:1) in 50 ml flasks at 20°C and 80% rh. To obtain eggs of a known age cultures were passed through sieves of 250, 180 and 150 µm to remove all eggs and juvenile stages. Just the fraction above the 250 µm and below 150 µm was kept and this was placed in a fresh flask together with some extra food which had passed through a 150 µm sieve. After two days eggs were collected by passing the culture media through a 250, 180 and 150 µm sieves. The two larger mesh sieves were used to contain the mobile stages.

The eggs were collected from the top of the 150 µm sieve. This fraction was then spread out over a glass petri dish (100 mm diameter) and the eggs were removed singly using a single-hair paint brush (00). They were transferred to a well (10 mm diameter) in a perspex strip (140 mm length x 20 mm width) which contained four of these. The floor of each well was a piece of black card held in place with wood glue. Thirty eggs were placed in each well. The wells were covered with a glass microscope slide which was secured with metal clips. One strip was used for each treatment which included exposure to the test temperature without the MA and one strip was kept as a control. This was placed in a glass desiccator (220 mm diameter x 250 mm height) on a mesh grid over a potassium hydroxide solution giving an atmospheric humidity of 80%. This was placed in an environmentally-controlled room at 25°C. Treated cells were placed in the same desiccator after completion of the exposure period.

Mobile stages from the 180 and 250 sieves were combined and tested in single well (35 mm diameter) perspex cells (70 mm x 70 mm). The bottom was covered with a piece of black card held in place by wood glue. A portion of culture was added to each cell which was then covered with glass secured with four clips. Three cells were set up for each treatment time with a further three for control which was placed under similar conditions as for the egg controls.

1.2.2.2 External feeding beetles - *Carpophilus dimidiatus*, *Lasioderma serricorne*, *Oryzaephilus mercator*, *Stegobium paniceum* and *Tribolium castaneum*

A mixture of whole wheat flour and yeast (20:1) was passed through a sieve of 180 µm. A 1 cm layer of this food was placed in the bottom of a glass dish (140 mm diameter x 70 mm height). 200 adults were added and the dish was then covered with nylon mesh. The adults were left for three or four days at 25°C and 70% rh and a light regime of 15 hours light and 9 hours dark. The adults and the eggs were then removed by passing the contents of the dish through 250 and 180 µm sieves respectively.

For egg treatments these were placed on V-shaped pieces of photographic paper for counting. The required amount, usually 30 eggs, was then brushed out on to the surface of culture food (10 ml) (Table 2) in glass tubes (25 mm diameter x 75 mm height) with nylon mesh tops. Three tubes were used for each treatment with three for the controls which were kept at 25°C and 70% rh. The treated tubes were returned to these conditions.

For testing later developmental stages eggs were placed on the surface of culture food (Table 2) in glass jars (90 mm diameter x 140 mm height) with a nylon mesh top. When they

reached the required stage they were counted out in batches of 30 and tested in a similar manner as the eggs.

1.2.2.3 Internal feeding beetles - Rhyzopertha dominica and Sitophilus oryzae

350g of whole wheat, conditioned at 25°C and 70% rh, was placed in the bottom of a plastic tank (26 cm length x 16 cm width x 16 cm height). Fluon was placed in a 3 cm band around the top of the tank to prevent escape by the adults. 400 to 600 adults were introduced to lay eggs and the tank was covered with nylon mesh. The adults were left on for three or four days at 25°C and 70% rh for *S. oryzae* or at 30°C and 70% rh for *R. dominica*. The wheat was then treated in 10 g portions in glass tubes (25 mm diameter x 75 mm height) with nylon mesh tops if the egg stage was required or incubated further at 25°C and 70% rh for *S. oryzae* or at 30°C and 70% rh for *R. dominica* in glass jars (90 mm diameter x 140 mm height) for the correct length of time for the other stages. The same quantities of wheat and glass tubes were used to treat the other stages. Three tubes were used for each treatment with three for the controls which were kept at 25°C and 70% rh for *S. oryzae* or at 30°C and 70% rh for *R. dominica*. The treated tubes were returned to these conditions.

1.2.2.4 Moths - Ephestia cautella, E. elutella and P. interpunctella

Day old adults were removed from culture jars by adding carbon dioxide to the atmosphere in the jar. The adults were placed in a plastic sieve (120 mm diameter). A glass dish (90 mm diameter x 55 mm height) with a piece of damp cotton wool taped to its bottom was then inverted over the unconscious adults and held in place on the sieve with tape. The sieve was then placed in a glass dish (140 mm diameter x 70 mm height). The adults were left for three days at 25°C and 70% rh and a light regime of 15 hours light and 9 hours dark. The eggs were then removed from the bottom of the glass dish.

For testing later developmental stages, batches of 30 eggs were placed in glass jars (60 mm diameter x 60 mm height) half-filled with culture medium. The larvae, pupae were then treated in these jars. Because of their high sensitivity and short longevity, adult moths were not tested.

1.2.3 Choice of experimental material and conditions

After initial testing at 40°C the temperature was either decreased or increased in 2°C increments dependent on whether there was survival at 24 h with the MA. This initial temperature also helped with some species in the identification of their most tolerant stage, which was then used for continued testing. If no difference was apparent between two or more stages then the stage that was easiest to produce was selected (Table 3). Data for exposures with temperature alone and in combination with the MA were tabulated.

Table 3. Selected stage for further selection and final Probit testing

Species	Stage
<i>Carpoglyphus lactis</i>	Egg
<i>Carpophylus dimidiatus</i>	IV instar Larvae
<i>Ephestia cautella</i>	Egg
<i>E. elutella</i>	Egg
<i>Lasioderma serricorne</i>	Egg
<i>Oryzaephilus mercator</i>	IV instar Larvae
<i>Plodia interpunctella</i>	Egg
<i>Rhyzopertha dominica</i>	IV instar Larvae and Pupae
<i>Sitophilus oryzae</i>	IV instar Larvae
<i>Stegobium paniceum</i>	Egg
<i>Tribolium castaneum</i>	IV instar Larvae

1.2.4 Analysis of results and Probit tests

Once a temperature had been found where there was no survival at 24h then tests were started to estimate the lethal time which killed 50% of individuals tested (LT₅₀) and the lethal time to kill 99% (LT₉₉) of the individuals tested. A similar method of MA generation and humidification was used as for the initial testing. The exposures took place in similar sized (6 litre) desiccators. Seven time intervals were used with the longest being between 20 and 24 h and the others decreasing stepwise by a factor of about $\sqrt{2}$. Three replicates of 30 individuals were tested at each time interval. Testing was carried out on food in glass tubes (25 mm diameter x 75 mm height) with nylon mesh placed over the top as in the initial tests. All the equipment was kept at the testing temperature in a controlled environment room. At temperatures of 40 and above the MA monitoring instruments were kept in a separate room connected by a nylon pipe (3.2 mm diameter) as this was above their operating temperatures. There were 3 sets of tubes kept at 25°C and 70% rh to act as controls. Counts of the results of the MA exposure were left until there was adult emergence. The counts were then done and were then entered into a Probit computer program. This has a correction for control mortality (Abbott, 19). It also calculates the LT₅₀ and LT₉₉ values together with all the statistics supporting the results.

1.3 Results

3.1.1 Initial testing for each species

The test results revealed wide differences between species in tolerance, some being controlled within 24 h by temperatures as low as 35°C while one species (*R. dominica*) showed a very small survival after 24 h at 44°C (Tables 4-14).

Table 4. Mortality of *Carpoglyphus lactis* in response to temperature and to temperature with 0.5% oxygen and 13% carbon dioxide in nitrogen (MA) at 70% rh

Stage	Time	Temperature (°C)					
		36		38		40	
			+ MA		+ MA		+ MA
Egg	Control*	✓		✓		✓	
	16			✓	✓	✓	X
	24	✓	✓	✓	X	✓	X
	48	✓	X	✓	X	X	X
Mobile Stages	Control*			✓		✓	
	16			✓	X	✓	X
	24			✓	X	✓	X
	48			X	X	X	X

* 25°C and 70% rh

✓ Survival

X 100% mortality

Table 5. Mortality (%) of *Carpophylus dimidiatus* in response to temperature and to temperature with 0.5% oxygen and 13% carbon dioxide in nitrogen (MA) at 70% rh

Stage	Time	Temperature (°C)					
		34		36		40	
		+ MA		+ MA		+ MA	
Egg	Control ^a (Number*)					20.8 (30)	
	16					100	100
	24					100	100
	48					100	100
Larva	Control ^a (Number*)	0.0 (30)		6.6 (30)		15.6 (30)	
	16	0.0	11.1	1.3	95.3	60.5	100
	24	0.0	17.8	4.8	100	84.1	100
	48	-	-	-	-	100	100
Pupa	Control ^a (Number*)					0.0 (30)	
	16					61.1	100
	24					93.3	100
	48					100	100
Adult	Control ^a (Number*)			7.4 (30)		0.0 (20)	
	16			0.0	100	88.9	100
	24			1.7	100	100	100
	48			0.0	100	100	100

^a 25°C and 70% rh

* Number of individuals tested per replicate, 3 replicates used

- Not tested

Table 6. Mortality (%) of *Ephestia cautella* in response to temperature and to temperature with 0.5% oxygen and 13% carbon dioxide in nitrogen (MA) at 70% rh

Stage	Time	Temperature (°C)					
		34		36		38	
			+ MA		+ MA		+ MA
Egg	Control ^a (Number*)	3.3 (20)		20.0 (20)		20.0 (20)	
	16	35.9	100	38.1	100	66.6	100
	24	30.7	100	45.9	100	95.9	100
	48	-	-	63.9	100	100	100
Larva	Control ^a (Number*)			0.0 (20)			
	16			11.7	100		
	24			8.3	100		
	48			-	-		
Pupa	Control ^a (Number*)			0.0 (15)		0.0 (15)	
	16			0.0	100	0.0	100
	24			0.0	100	0.0	100
	48			-	-	0.0	100

^a 25°C and 70% rh

* Number of individuals tested per replicate, 3 replicates used

- Not tested

Table 7. Mortality (%) of *Ephestia elutella* in response to temperature and to temperature with 0.5% oxygen and 13% carbon dioxide in nitrogen (MA) at 70% rh

		Temperature (°C)							
		34		36		38		40	
		+ MA		+ MA		+ MA		+ MA	
Stage	Time								
Egg	Control ^a (Number*)	6.7 (20)		6.7 (20)		21.7(3)		1.1 (30)	
	16	14.3	100	42.9	100	40.4	100	66.4	100
	24	25.0	100	75.0	100	65.3	100	-	-
	48	-	-	-	-	-	-	-	-
Larva	Control ^a (Number*)			7.5 (20)		0.0 (40)			
	16			-	-	0.0	100		
	24			10.8	100	0.0	100		
	48			-	-	0.0	100		
Pupa	Control ^a (Number*)					0.0 (15)			
	16					0.0	100		
	24					0.0	100		
	48					-	-		

^a 25°C and 70% rh

* Number of individuals tested per replicate, 3 replicates used

- Not tested

Table 8. Mortality (%) of *Lasioderma serricorne* in response to temperature and to temperature with 0.5% oxygen and 13% carbon dioxide in nitrogen (MA) at 70% rh

Stage	Time	Temperature (°C)					
		36		38		40	
			+ MA		+ MA		+ MA
Egg	Control ^a (Number*)	17.8 (30)		17.8 (30)		7.5 (30)	
	16	5.4	47.3	33.8	60.8	23.1	60.2
	24	13.5	64.8	39.2	81.0	79.6	100
	48	-	-	-	-	100	100
Larva	Control ^a (Number*)	12.2 (20)		12.2 (20)		7.8 (30)	
	16	0.0	77.2	20.3	58.2	0.0	92.7
	24	3.2	92.4	31.7	96.2	0.0	100
	48	-	-	-	-	0.0	100
Pupa	Control ^a (Number*)			6.6 (30)			
	16			8.4	100		
	24			0.0	100		
	48			-	-		
Adult	Control ^a (Number*)					3.0 (30)	
	16					2.1	100
	24					3.1	100
	48					35.8	100

^a 25°C and 70% rh

* Number of individuals tested per replicate, 3 replicates used

- Not tested

Table 9. Mortality (%) of *Oryzaephilus mercator* in response to temperature and to temperature with 0.5% oxygen and 13% carbon dioxide in nitrogen (MA) at 70% rh

Stage	Time	Temperature (°C)							
		34		36		38		40	
		+ MA		+ MA		+ MA		+ MA	
Egg	Control ^a (Number*)			13.3 (30)		8.9 (30)		3.3 (30)	
	16			9.0	100	13.4	100	49.4	100
	24			11.6	100	15.8	100	96.6	100
	48			-	-	-	-	100	100
Larva	Control ^a (Number*)	0.0 (30)		0.0 (30)		1.8 (30)		16.7 (20)	
	16	0.0	100	0.0	100	18.5	100	31.9	100
	24	0.0	100	1.2	100	16.3	100	32.0	100
	48	-	-	-	-	-	-	-	-
Adult	Control ^a (Number*)			11.4 (30)		2.2 (30)		1.9 (30)	
	16			0.0	100	0.0	100	0.0	100
	24			0.0	100	-	-	7.2	100
	48			-	-	-	-	75.6	100

^a 25°C and 70% rh

* Number of individuals tested per replicate, 3 replicates used

- Not tested

Table 10. Mortality (%) of *Plodia interpunctella* in response to temperature and to temperature with 0.5% oxygen and 13% carbon dioxide in nitrogen (MA) at 70% rh

Stage	Time	Temperature (°C)							
		34		36		38		40	
		+ MA		+ MA		+ MA		+ MA	
Egg	Control ^a (Number*)	24.4 (30)	24.4 (30)	24.4 (30)	24.4 (30)	13.3 (30)	13.3 (30)	14.4 (30)	14.4 (30)
	16	57.4	100	70.6	100	89.7	100	-	-
	24	47.1	100	88.2	100	98.7	100	88.3	100
	48	-	-	-	-	-	-	96.1	100
Pupa	Control ^a (Number*)					0.0 (30)	0.0 (30)		
	16					0.0	100		
	24					7.8	100		
	48					78.9	100		

^a 25°C and 70% rh

* Number of individuals tested per replicate, 3 replicates used

- Not tested

Table 11. Numbers emerging and percentage reduction (in parenthesis) of immature stages of *Rhyzopertha dominica* in response to temperature and to temperature with 0.5% oxygen and 13% carbon dioxide in nitrogen (MA) in 70% rh, and mortality (%) of adults, 3 replicates used throughout

		Temperature (°C)					
		40		42		44	
Stage	Exposure (h)	+ MA		+ MA		+ MA	
Egg	Control ^a	139.0					
	16	155.3(0.0)	2.7 (98.1)				
	24	171.3(0.0)	0.0 (100)				
	48	165.0(0.0)	0.0 (100)				
Larva	Control ^a	155.3		190.0		190.0	
	16	170.0 (0.0)	109.7(29.4)	179.7 (5.5)	44.0(76.9)	202.3(0.0)	6.3 (96.7)
	24	157.0(0.0)	47.3(69.5)	157.0(17.4)	0.0 (100)	158.3(16.8)	0.0 (100)
	48	145.3 (6.4)	0.0 (100)	-	-	-	-
Pupa	Control ^a	55.7		154.0		154.0	
	16	41.7 (25.1)	36.0(35.4)	109.7(28.8)	2.3 (98.5)	65.0 (57.8)	2.3 (98.5)
	24	50.7 (9.0)	12.3(77.9)	113.0(26.6)	0.7 (99.5)	70.7 (54.1)	1.0 (99.3)
	48	59.3 (0.0)	1.0 (98.2)	78.7 (48.9)	0.0 (100)	26.0 (83.1)	0.0 (100)
Adult	Control ^{a*}	9.6					
	16	3.8		98.4			
	24	3.8		100			
	48	9.0		100			

^a 25°C and 70% rh

* Number of individuals tested per replicate = 30

- Not tested

Table 12. Numbers emerging and percentage reduction (in parenthesis) of immature stages of *Sitophilus oryzae* in response to temperature and to temperature with 0.5% oxygen and 13% carbon dioxide in nitrogen (MA) in 70% rh, and mortality (%) of adults, 3 replicates used throughout

Stage	Time	Temperature (°C)					
		40		42		44	
			+ MA		+ MA		+ MA
Egg	Control ^a	246.7					
	16	55.7 (77.4)	0.0 (100)				
	24	0.0 (100)	0.0 (100)				
	48	0.0 (100)	0.0 (100)				
Larva	Control ^a	314.7		186.7		186.7	
	16	286.0(19.1)	92.7(71.5)	2 (98.9)	0.0 (100)	0.0 (100)	0.0 (100)
	24	197.0(37.4)	4.7 (98.5)	0.0 (100)	0.0 (100)	0.0 (100)	0.0 (100)
	48	7.3 (97.9)	0.0 (100)	0.0 (100)	0.0 (100)	0.0 (100)	0.0 (100)
Pupa	Control ^a	313.7		208.5		208.5	
	16	241.0(23.2)	0.3 (99.9)	26.3(87.4)	0.0 (100)	0.0 (100)	0.0 (100)
	24	119.0(62.1)	0.0 (100)	0.7 (99.7)	0.0 (100)	0.0 (100)	0.0 (100)
	48	0.0 (100)	0.0 (100)	0.0 (100)	0.0 (100)	0.0 (100)	0.0 (100)
Adult	Control ^{a*}	0.0					
	16	3.2	100				
	24	22.2	100				
	48	100	100				

^a 25°C and 70% rh

* Number of individuals tested per replicate = 30

Table 13. Mortality (%) of *Stegobium paniceum* in response to temperature and to temperature with 0.5% oxygen and 13% carbon dioxide in nitrogen (MA) at 70% rh

Stage	Time	Temperature (°C)					
		36		38		40	
		+ MA		+ MA		+ MA	
Egg	Control ^a (Number*)	1.1 (30)		1.1 (30)		3.3 (30)	
	16	36.0	100	73.0	100	42.5	100
	24	56.2	100	97.8	100	91.5	100
	48	-	-	-	-	98.9	100
Larva	Control ^a (Number*)	3.3 (30)		3.3 (30)		16.7 (30)	
	16	39.1	100	32.3	100	41.3	100
	24	31.1	100	39.1	100	64.4	100
	48	-	-	-	-	94.6	100
Pupa	Control ^a (Number*)					11.1 (30)	
	16					0.0	100
	24					13.7	100
	48					100	100
Adult	Control ^a (Number*)					1.1 (30)	
	16					69.7	100
	24					68	100
	48					100	100

^a 25°C and 70% rh

* Number of individuals tested per replicate, 3 replicates used

- Not tested

Table 14. Mortality (%) of *Tribolium castaneum* in response to temperature and to temperature with 0.5% oxygen and 13% carbon dioxide in nitrogen (MA) at 70% rh

Stage	Time	Temperature (°C)							
		34		36		38		40	
			+ MA		+ MA		+ MA		+ MA
Egg	Control ^a (Number*)	3.3 (30)		0.0 (30)				4.4 (30)	
	16	0.0	90.8	0.0	100			12.8	100
	24	1.2	100	1.1	100			23.2	100
	48	-	-	-	-			40.7	100
Larva	Control ^a (Number*)	0.0 (30)		0.0 (30)		0.0 (30)		0.0 (30)	
	16	-	-	0.0	100	0.0	100	0.0	97.1
	24	0.0	45.6	0.0	100	0.0	100	0.8	100
	48	-	-	-	-	0.0	100	0.0	100
Pupa	Control ^a (Number*)							3.4 (40)	
	16							1.9	100
	24							0.0	100
	48							4.3	100
Adult	Control ^a (Number*)			0.0 (30)		0.0 (30)		0.0 (30)	
	16			0.0	100	2.0	100	0.0	100
	24			0.0	100	-	-	1.1	100
	48			-	-	-	-	0.0	100

^a 25°C and 70% rh

* Number of individuals tested per replicate, 3 replicates used

- Not tested

1.3.2 Probit testing

More accurate predictions of the lengths of time required in the test MA at the temperatures identified as being effective for each species were then obtained by probit analysis (Tables 15-20). In these tests LD99 values ranging from 7.3 to 16.4 h were obtained at the various test temperatures.

Table 15. Time (Hours . minutes) required to give LD₅₀ and LD₉₉ for five species of stored product pests with a simulated burner gas atmosphere of 0.5% oxygen and 13% carbon dioxide (balance nitrogen) at 35°C and 70% rh

Species & Stage	Statistics		Slope (S.E.)	HF	<i>p</i> (D. F.)
	LD ₅₀ (95% Fiducial Limits)	LD ₉₉ (95% Fiducial Limits)			
<i>Ephestia cautella</i> Eggs	2.23 (2.08 - 2.38)	11.29 (9.19 - 15.20)	3.41 (0.30)	1.82	<0.001 (50)
<i>E. elutella</i> Eggs	2.57 (2.42 - 3.10)	7.29 (6.28 - 9.16)	5.75 (0.58)	1.89	0.002 (36)
<i>Oryzaephilus mercator</i> IV instar Larvae	3.52 (3.36 - 4.08)	7.56 (6.53 - 9.49)	7.44 (0.78)	2.46	0.001 (17)
<i>Plodia interpunctella</i> Eggs	0.53 (0.47 - 0.57)	8.12 (6.24 - 11.23)	2.39 (0.17)	1.0	0.066 (35)
<i>Stegobium paniceum</i> Eggs	3.22 (5.31 - 7.18)	10.13 (8.29 - 13.28)	4.82 (0.51)	1.0	0.646 (14)

S. E. - Standard Error of the slope
p - probability
D.F. - Degrees of Freedom

Table 16. Time (Hours . minutes) required to give LD₅₀ and LD₉₉ for *Carpophilus dimidiatus* and *Tribolium castaneum* with a simulated burner gas atmosphere of 0.5% oxygen and 13% carbon dioxide (balance nitrogen) at 36°C and 70% rh

Species & Stage	Statistics				
	LD ₅₀ (95% Fiducial Limits)	LD ₉₉ (95% Fiducial Limits)	Slope (S.E.)	HF	<i>p</i> (D. F.)
<i>Carpophilus dimidiatus</i> IV instar Larvae	5.23 (5.05 - 5.40)	10.14 (9.16 - 11.48)	8.35 (0.80)	1.0	0.232 (15)
<i>Tribolium castaneum</i> IV instar Larvae	4.49 (4.31 - 5.07)	13.10 (11.24 - 16.00)	5.32 (0.43)	1.0	0.365 (11)

S. E. - Standard Error of the slope

p - probability

D.F. - Degrees of Freedom

Table 17. Time (Hours . minutes) required to give LD₅₀ and LD₉₉ for the mite *Carpoglyphus lactis* with a simulated burner gas atmosphere of 0.5% oxygen and 13% carbon dioxide (balance nitrogen) at 40°C and 70% rh

Species & Stage	Statistics				
	LD ₅₀ (95% Fiducial Limits)	LD ₉₉ (95% Fiducial Limits)	Slope (S.E.)	HF	<i>p</i> (D. F.)
<i>Carpoglyphus lactis</i> Eggs	5.20 (4.41 - 5.56)	7.59 (7.04 - 9.42)	7.30 (0.96)	2.12	0.078 (7)

S. E. - Standard Error of the slope

p - probability

D.F. - Degrees of Freedom

Table 18. Time (Hours . minutes) required to give LD₅₀ and LD₉₉ for *Sitophilus oryzae* with a simulated burner gas atmosphere of 0.5% oxygen and 13% carbon dioxide (balance nitrogen) at 41°C and 70% rh

Species & Stage	Statistics				
	LD ₅₀ (95% Fiducial Limits)	LD ₉₉ (95% Fiducial Limits)	Slope (S.E.)	HF	<i>p</i> (D. F.)
<i>Sitophilus oryzae</i> IV instar Larvae	<u>Reared at 25°C</u>				
	6.47 (6.38 - 6.55)	9.44 (9.20 - 10.17)	14.80 (0.98)	11.53	<0.001 (25)
	<u>Reared at 30°C</u>				
	2.52 (2.34 - 3.08)	11.31 (9.45 - 14.28)	3.85 (0.30)	7.55	<0.001 (14)

S. E. - Standard Error of the slope

p - probability

D.F. - Degrees of Freedom

Table 19. Time (Hours . minutes) required to give LD₅₀ and LD₉₉ for *Lasioderma serricorne* with a simulated burner gas atmosphere of 0.5% oxygen and 13% carbon dioxide (balance nitrogen) at 42°C and 70% rh

Species & Stage	Statistics				
	LD ₅₀ (95% Fiducial Limits)	LD ₉₉ (95% Fiducial Limits)	Slope (S.E.)	HF	<i>p</i> (D. F.)
<i>Lasioderma serricorne</i> Eggs	3.55 (3.19 - 4.23)	16.35 (13.15 - 23.38)	3.71 (0.45)	1.0	0.298 (11)

S. E. - Standard Error of the slope

p - probability

D.F. - Degrees of Freedom

Table 20. Time (Hours . minutes) required to give LD₅₀ and LD₉₉ for *Rhyzopertha dominica* with a simulated burner gas atmosphere of 0.5% oxygen and 13% carbon dioxide (balance nitrogen) at 44°C and 70% rh

Species & Stage	Statistics				
	LD ₅₀ (95% Fiducial Limits)	LD ₉₉ (95% Fiducial Limits)	Slope (S.E.)	HF	<i>p</i> (D. F.)
<i>Rhyzopertha dominica</i> IV instar Larvae and Pupae	4.05 (3.46 - 4.21)	10.45 (9.23 - 13.03)	5.53 (0.51)	21.08	<0.001 (25)

S. E. - Standard Error of the slope

p - probability

D.F. - Degrees of Freedom

1.4 Discussion

Exposure to modified atmospheres based on low oxygen greatly enhanced the efficacy of heat in achieving control. In contrast to results with raised 10-15% CO₂ alone (Bell et al., 2003), the burner gas atmosphere containing comparable levels of CO₂ but with only 0.5% O₂ greatly reduced the time insects could survive at 35 - 45°C. The order of tolerance was similar to that for heat alone, namely *Rhyzopertha dominica* > *Lasioderma serricorne* > *Sitophilus oryzae* > *Carpoglyphus lactis* > *Tribolium castaneum* > *Carpophilus dimidiatus* > *Stegobium paniceum* = *Ephestia cautella* > *Plodia interpunctella* = *E. elutella* = *Oryzaephilus mercator*. The results obtained for insect mortality can be grouped to relate to each commodity (Tables 21-24). The commodity with the most tolerant pests to MA at raised temperature was rice (Table 21) while those with the least tolerant were coffee and cocoa (Table 24). Hence for rice the temperature required for disinfestation within 24 h was 44°C, for fennel and coriander and other herbs and spices it was 40°C (Table 22), for dried fruit and nuts it was 38°C (Table 23), and for coffee and cocoa it was 35°C (Table 24). Tables 21-24 recommend the minimum exposure time to be aimed for in achieving 100% kill of each species at these temperatures.

Table 21. The recommended exposure time (hours) required for complete mortality of all stages of three rice pests at 40, 42 or 44°C and 70% rh with or without a modified atmosphere (MA) of 0.5% oxygen, 13% carbon dioxide and 86.5% nitrogen

	<i>Tribolium castaneum</i> Rust-red flour beetle	<i>Sitophilus oryzae</i> Rice weevil	<i>Rhyzopertha dominica</i> Lesser grain borer
Temp. (°C) - or + MA			
40	>48	>48	>48
40 + MA	<16	48	>48
42	-	48	>48
42 + MA	-	16	48
44	-	-	>48
44 + MA	-	-	24

Table 22. The recommended exposure time (hours) required for complete mortality of all stages of four pests of herbs and spices at 35 to 40°C, 70% rh, with a modified atmosphere (MA) of 0.5% oxygen, 13% carbon dioxide and 86.5% nitrogen

	<i>Stegobium paniceum</i> Biscuit beetle	<i>Lasioderma serricorne</i> Cigarette beetle	<i>Oryzaephilus mercator</i> Merchant grain beetle	<i>Ephestia elutella</i> Warehouse moth
Temp. (°C) – or + MA				
35	-	-	>48	>48
35 + MA	-	-	10	10
36	>48	-	>48	>48
36 + MA	16	-	<16	<16
38	>48	>48	>48	>48
38 + MA	<16	48	<16	<16
40	>48	>48	>48	>48
40 + MA	<16	24	<16	<16

Table 23. The recommended exposure time (hours) required for complete mortality of all stages of six pests of dried fruit and nuts at 34 to 38°C, 70% rh, with a modified atmosphere (MA) of 0.5% oxygen, 13% carbon dioxide and 86.5% nitrogen

	<i>Tribolium castaneum</i> Rust-red flour beetle	<i>Carpophilus dimidiatus</i> Dried fruit beetle	<i>Carpoglyphus lactis</i> Dried fruit mite	<i>Ephestia cautella</i> Tropical warehouse moth	<i>Oryzaephilus mercator</i> Merchant grain beetle	<i>Plodia interpunctella</i> Indian-meal moth
Temp. (°C) – or + MA						
34	>48	>48	-	>48	>48	>48
34 + MA	24-48	48	-	16	<16	<16
35	>48	>48	-	>48	>48	>48
35 + MA	24	24	-	16	10	12
36	>48	>48	>48	>48	>48	>48
36 + MA	18	16	24-48	<16	<16	<16
38	>48	>48	>48	>48	>48	>48
38 + MA	<16	<16	24	<16	<16	<16

Table 24. The exposure time (hours) required for complete mortality of all stages of four pests of cocoa and coffee beans at 34 to 36°C, 70% rh, with a modified atmosphere (MA) of 0.5% oxygen, 13% carbon dioxide and 86.5% nitrogen

	<i>Ephestia cautella</i> Tropical warehouse moth	<i>Ephestia elutella</i> Warehouse moth	<i>Oryzaephilus mercator</i> Merchant grain beetle	<i>Tribolium castaneum</i> Rust-red flour beetle
Temp. (°C) – or + MA				
34	>48	-	>48	>48
34 + MA	<16	-	<16	24-48
35	>48	>48	>48	>48
35 + MA	16	10	10	16
36	>48	>48	>48	>48
36 + MA	<16	<16	<16	<16

2. MODELLING STUDIES

2.1 Summary

Modelling the gas flow and heat transfer requires knowledge of the physical and thermal properties of the gases and the commodity. The properties of the gases involved, nitrogen, carbon dioxide and oxygen, were taken from Bejan (1993), and diffusion coefficients from Bird *et al.* (1960). Computational modelling was then used to obtain a detailed view of the airflow within the commodity bulk under controlled conditions. This approach solves numerically the differential equations that describe heat and mass transfer, and predicts the air velocities, temperatures and pressures throughout the bulk and their variation with time. The commodity was modelled as a porous medium, with the appropriate physical and thermal properties.

The modelling showed that the convective heating of bulk stored commodities is at least 10 times faster than the conductive heating of packaged commodities. With the appropriate airflow and air humidity control, the model predicts that bulk commodities can be heated from 15°C to at least 45°C in less than 12 hours. Provided that an applied atmosphere at this temperature causes 100% insect mortality in 24 hours, the whole treatment can be completed in 48 hours.

2.2 Mathematical Modelling

Mathematical modelling is a powerful technique for investigating the behaviour of processes in which the parameters can take many different values. In this project there are several different heating conditions and a wide range of commodity properties. The model developed for stored commodities uses Computational Fluid Dynamics (CFD) techniques, and calculates air speeds, pressures and air temperatures throughout the store. In addition, the equations that describe heat and mass transfer between the air and the stored material are solved, giving the commodity temperature and moisture content and their variation with time.

Description of the Model

The CFD technique subdivides the store into cells in which the differential equations are solved numerically. The number of cells used depended on the layout being modelled, ranging from 2,000 to 125,000. The CFD software package CFX 4.3 (AEA Technology, 1999) was used to create the cells and solve the equations.

The commodity was treated as a porous medium with heat and moisture exchange between the commodity and the interstitial air, where the heat transfer coefficient was calculated from a correlation given by Boyce (1965). The floor and retaining walls of the store were assumed to be adiabatic, i.e. no heat transfer.

Moisture transfer has a profound effect on commodity heating because of the large amount of latent heat involved in the evaporation and condensation of water. It is important even when the change in moisture content is a fraction of one percent. To simulate moisture transfer the non-equilibrium model of Sun *et al.* (1995) has been included. Correlations describing the rate of moisture transfer and the heat of moisture desorption are not available

for many commodities so the relationships used in cereal drying simulations have been adopted.

The model allows time-dependent values to be calculated. In particular, the temperature distribution within the commodity bulk enables the volume of heated or cooled commodity to be calculated as a function of time. Time steps of up to 1.5 minutes were used, although steps as short as 6 seconds were necessary in some cases to maintain numerical stability.

2.2.2 Physical and thermal properties

Modelling the airflow and heat transfer in a commodity store requires physical and thermal properties of the solids and gases. Some of the required data is available in the literature but not all, therefore the complete range of physical and thermal properties has been measured. Bulk density, moisture content, porosity, permeability, specific heat and thermal conductivity have been obtained using standard methods, for cocoa, coffee, coriander, fennel, rice, walnut and dried apricot. The properties are given in Table 25. It is assumed that these are uniform and constant throughout the commodity within the operating range.

Table 25. Material properties used in the model

Commodity	m.c., % (w.b.)	Porosity	Bulk density, kg/m ³	Specific J/kg.°K	Thermal conductivity W/m.°K	Thermal diffusivity, m ² /h
Cocoa	6.5	0.56	520	1728	0.18	0.000721
Coffee	12.0	0.51	687	2031	0.15	0.000387
Coriander	11.0	0.769	269	2400	0.085	0.000474
Fennel	11.3	0.695	302	2330	0.086	0.00044
Rice	12.0	0.58	603	1800	0.126	0.000418
Walnut	4.5	0.604	407	1047	0.127	0.001073
Dried Apricot	24.5	0.209	882	1968	0.201	0.000417

An expression relating the pressure gradient in the commodity to the local air velocity was taken from ASAE D272.2 (1992). However, because the natural alignment of commodity kernels produces less resistance horizontally, a 70% difference in resistance between horizontal and vertical directions was assumed (Kumar and Muir, 1986).

2.2.3 Water sorption isotherms

Also known as Equilibrium-Relative Humidity curves, these curves relate the moisture content of the commodity to the relative humidity and temperature of the surrounding air. These data are used to calculate the moisture exchange between the commodity and the heating air. It is assumed that the rate of moisture loss from a product surrounded by air at a particular relative humidity and temperature is proportional to the difference between the product moisture and its equilibrium moisture. In the model the data are represented by an equation, which can take several forms. The following equations have been fitted and the best chosen on a least squares basis; the constants are given in Table 26. To simplify the calculations the same equations are used for both adsorption and desorption.

$$\text{Modified Henderson } r_h = 1 - \exp[-A(T + C).m^B]$$

Modified Halsey
$$r_h = \exp\left[\frac{-\exp(A + B.T)}{m^C}\right]$$

Modified Oswin
$$r_h = \frac{1}{\left(\frac{A + B.T}{m}\right)^C + 1}$$

Modified Chung-Pfost
$$r_h = \exp\left[\frac{-A \cdot \exp(-B.m)}{T + C}\right]$$

Where: r_h = Relative Humidity, decimal; T = Temperature, °C; and m = Moisture Content, % (d.b)

Table 26. Constants in Equilibrium-Relative Humidity equations

Commodity	Best fit equation	A	B	C
Cocoa	Halsey	4.218	-0.00904	2.469
Coffee	Oswin	11.340	-0.07143	2.4421
Coriander	Chung-Pfost	326.61	0.19323	56.4078
Fennel	Oswin	7.3354	-0.05051	1.5651
Rice	Henderson	1.9187×10^{-5}	2.4451	51.161
Walnut	Chung-Pfost	831.2	0.06391	104.86
Dried Apricot	Henderson*	-0.0701	0.8661	0.0

* Temperature not included

2.2.4 Conductive heating (Packaged commodities) versus Convective heating (Bulk commodities)

All the commodities can be stored in bags (e.g. cocoa, coffee, rice) or boxes (walnuts, dried apricots). A few are also stored in bulk (e.g. cocoa, rice). Heating can take place in two ways, convection and conduction. Convective heating depends on the volume of hot air flowing around individual beans, kernels, etc., hence the rate of heating can be increased by increasing the flow of hot air. Conductive heating depends on the pack size, the air temperature and the thermal diffusivity (Schneider, 1955), all of which are fixed for a given commodity. Commodities in boxes or impervious bags in which there is no air flow will be heated entirely by conduction, those in woven sacks will be heated by a combination of convection and conduction, while bulk commodities can be heated entirely by convection.

The computational modelling has not attempted to predict the heating rates of bagged and boxed products, for the following reasons:

- 3 The heating rates are limited by the commodity properties and will inevitably be slower than convective heating rates.
- 4 The porosity and heat transfer characteristics of the packaging materials are not known.

- 5 The air gaps between bags or boxes, which define the air flow and temperature distribution, are not known, and also make the model very complex and the analysis times extremely long.

2.2.5 Model validations

Time constraints have not allowed a full-scale heating trial of a bulk stored commodity to obtain data with which to compare and validate the model. However, the approach used and the equations incorporated into the model have been widely used over many years in studies of grain drying which have been extensively validated. Errors due to commodity property values have been minimised by measuring all the required properties using samples supplied by the industrial partners. Differences between model results and trials data are likely to be due to uncontrollable factors such as porosity and permeability variations in store, shrinkage during heating, dust, variation in weather conditions, etc.

2.2.5.1 Modified Atmosphere (MA) application

Trials in the converted container have shown that an airtight enclosure is necessary to achieve and maintain a low-oxygen atmosphere ($< 1\% \text{ O}_2$). Under these conditions the temperatures necessary for complete insect mortality are lower than those when heat alone is used. The predicted heating times for bagged and boxed commodities given in Table 3, assume that treatment takes place under a modified atmosphere in a sealed container. In the case of bulk stored products, past experience has shown that purging a bulk store and maintaining a low-oxygen atmosphere is not commercially practical. Leakage paths into a bulk store are always present despite careful attempts to seal all joints. Wind pressure and fluctuations in atmospheric pressure will drive ambient air, containing 22% oxygen, through these gaps. For this reason, the predicted heating times for bulk stores assume that heat alone is used to kill the insect pests and therefore a minimum temperature of 45°C is the target.

2.2.5.2 Insect mortality model

A simple model of insect mortality has been implemented in the heating model. The model uses data for the effect of temperature on *Sitophilus oryzae* from Bell and Armitage (1992) and Bell (this project), and the effect of relative humidity from Le Patourel (1986). However, its value is limited. It is clear from the shape of the relationship that mortality only becomes significant near the target temperature. Therefore, there will be a safety margin if we assume that the treatment does not begin until the point in the bulk with the longest heating time reaches the target temperature.

Model Predictions and Discussion

Commodities can be heated by conduction from contact with solids or liquids, by convection from air, or by radiation from a heat source or from a microwave generator. The current study considered heating only by conduction or convection.

2.3.1 Bagged and boxed commodities

If pure conduction is assumed then the time to heat to a given temperature can be calculated from the thermal diffusivity according to Schneider (1955). If each commodity is stacked in a cube of side equal to 1.2m – roughly a pallet load – then the predicted heating time is given in Table 27.

Table 27. Predicted heating time at the centre of a 1.2m cubic stack of bagged or boxed commodity, starting from 15°C and assuming conductive heating alone

Commodity	Maximum temperature, °C	Target commodity temperature, °C	Thermal diffusivity, m ² /h	Time to reach target, h
Cocoa	50	35	0.000721	100
Coffee	55	35	0.000387	167
Coriander	55	40	0.000474	167
Fennel	55	40	0.00044	180
Rice	55	44	0.000418	224
Walnut	50	38	0.001073	77
Dried Apricot	45	38	0.000417	233

In general, the predicted time given in Table 27 to reach the target temperature is longer than that measured in trials. That is because a 1.2m stack is not heated entirely by conduction, in reality some hot air is able to flow between the boxes or penetrate the bags - cocoa in hessian sacks is an example. The results suggest that the heating of bagged and boxed commodities will be more accurately studied experimentally than numerically.

Bulk commodities

Five commodities, cocoa, coffee, coriander, rice and dried apricots, out of the seven have been modelled assuming bulk storage and convective heating. Bulk fennel has not been modelled because it behaves in a similar manner to coriander. Bulk walnuts have not been included because they are invariably stored in boxes. Although dried apricots are also stored in boxes and are unlikely to be unpacked for treatment, they have been included to illustrate the behaviour of a commodity with extreme properties, namely high density and low porosity.

The simplest method of applying hot air to bulk stored material from a modelling point of view is to assume the store has a perforated floor and hot air at the maximum permitted temperature is injected through the floor. Then, assuming the stored material has a constant depth and uniform properties, only a small section of the store needs to be modelled because the airflow is unidirectional. In this case the model is two-dimensional, the run-times are short and different heating and cooling conditions can be explored. An alternative method of applying the hot air using pedestal aerators is described under the results for cocoa. Predictions have been obtained for one commodity only because the model is now three-dimensional and consequently the run-times are longer.

The predicted results for each commodity are now discussed in turn.

Cocoa

Information from cocoa users indicates that for practical reasons bulk cocoa is currently treated in 1000 tonne parcels with a depth of between 2.5 and 3 m. Figure 1 shows typical dimensions.

When air is supplied through a perforated floor the predicted results for heating and cooling bulk cocoa are shown in Figures 2 – 6. Figure 2 shows that if air at ambient temperature

(15°C) and 62% relative humidity is heated to 50°C and used to heat the cocoa then considerable drying will occur. This assumes that the air is not recirculated and hence its relative humidity as it enters the cocoa is always about 10%. Heating of the cocoa is also very slow because of the large amount of energy required to evaporate the moisture. Figure 3 shows the behaviour if the air is humidified to 70% r.h., the equilibrium value for cocoa at 50°C and 6.5% moisture content, before it enters the cocoa. The graphs of commodity temperature and moisture content show that the cocoa reaches 45°C in approximately 55 minutes, and drying is eliminated. However, the air relative humidity reaches saturation and a condensation front travels through the bulk for the first 25 minutes.

Figures 4 - 6 show behaviour during cooling, using air at 15°C and humidities of 62% r.h. (normal), 20% r.h. and 95% r.h., respectively. Cooling is a very simple process when ambient (15°C) air is used. Since the cold air is always passing through a warmer commodity there is no danger of condensation and there is no need to recirculate and humidify the air. The only effect of the two extreme humidity values, 20% and 95%, is to change the final cocoa moisture content.

In a practical system a low airflow rate is desirable to reduce the fan pressure. Although this increases the heating time it allows a smaller fan to be used. The heating air should also be recirculated, not only to minimise the energy input but also to conserve moisture and volatile products. Figure 7 shows the results assuming a lower airflow rate with recirculation. The airflow rate has been reduced from 6.7 m³/min per tonne to 0.8 m³/min per tonne, consequently the time to reach 45°C has increased from 55 minutes to 6.4 hours. However, the maximum power requirement is only 0.4 kW per tonne, compared with 4.8 kW per tonne at the higher airflow rate without recirculation. If the initial cocoa temperature is 25°C, instead of 15°C, the heating time is reduced from 6.4 hours to 3.4 hours.

Pedestal aerators are a possible alternative to a perforated floor as a means of applying the hot air. Each unit comprises a vertical duct connecting a 1m perforated section at the bottom to a fan at the top. The units are self-supporting and mobile so can be installed in an existing bulk store. Figure 8 shows 20 units in a 1000 tonne bulk store. Figure 9 shows the model of a section of the store containing a single pedestal aerator. Predictions of heating time for two store depths are shown in Figure 10. Note that the initial temperature of the cocoa is assumed to be 25°C, which is possible if the cocoa has recently arrived from origin. The natural path of the hot air is out through the top surface, hence the heating time is dictated by the temperature of the cocoa in the corners at floor level. Figure 10 shows that the greater depth has the shorter heating time because the higher vertical resistance forces more air into the corners which leads to a more rapid temperature rise. The shortest heating time using a pedestal aerator is now 4.2 hours compared with 3.4 hours using a perforated floor. The power requirement does not increase because the air is recirculated.

The results of modelling the heating of bulk cocoa are summarised in Table 28.

Fig. 1. Typical dimensions of a 1000 tonne bulk of cocoa

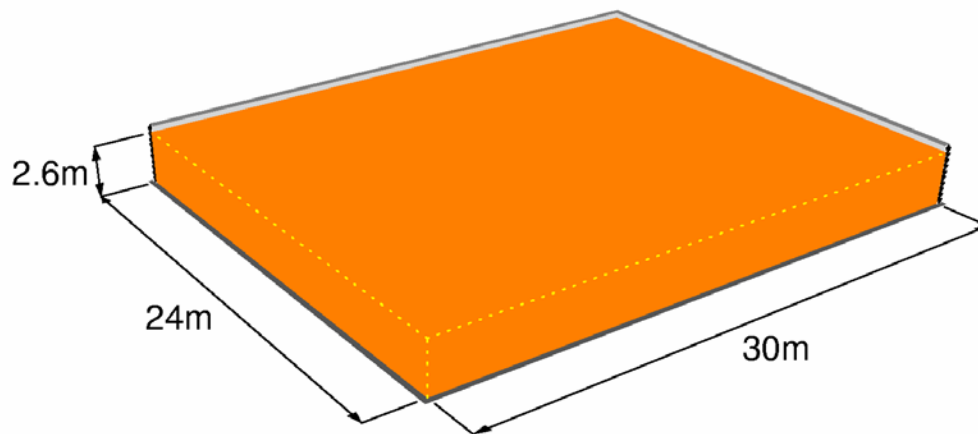


Fig.2. Bulk cocoa heating simulation, using 6.7 m³/min/tonne of air at 50°C, without humidification. Quantity: 1.5 tonnes; Depth of bed: 2 m; Initial temperature: 15°C; Initial moisture content: 6.5% (w.b.)

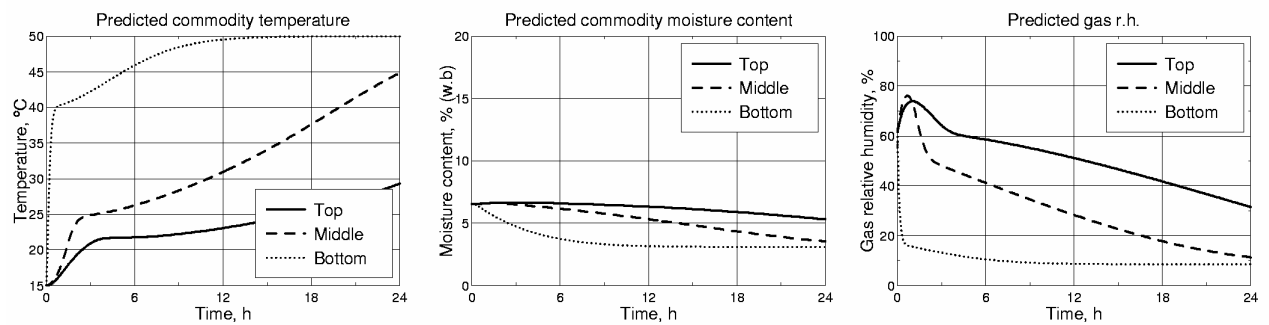


Fig. 3. Bulk cocoa heating simulation, using 6.7 m³/min/tonne of air at 50°C, humidified to 70% r.h. Quantity: 1.5 tonnes; Depth of bed: 2 m; Initial temperature: 15°C; Initial moisture content: 6.5% (w.b.)

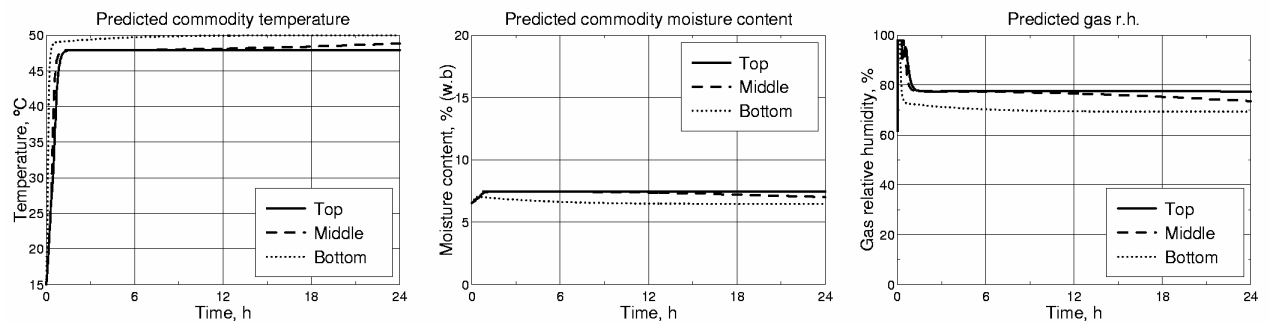


Fig. 4. Bulk cocoa cooling simulation, using $6.7 \text{ m}^3/\text{min}/\text{tonne}$ of air at 15°C and 62% r.h. Quantity: 1.5 tonnes; Depth of bed: 2 m; Initial temperature: 50°C ; Initial moisture content: 6.5% (w.b.)

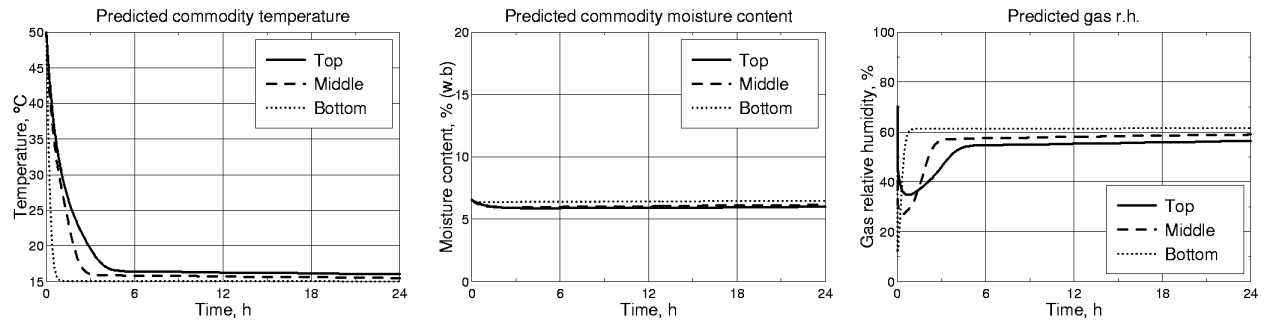


Fig. 5. Bulk cocoa cooling simulation, using $6.7 \text{ m}^3/\text{min}/\text{tonne}$ of air at 15°C and 20% r.h. Quantity: 1.5 tonnes; Depth of bed: 2 m; Initial temperature: 50°C ; Initial moisture content: 6.5% (w.b.)

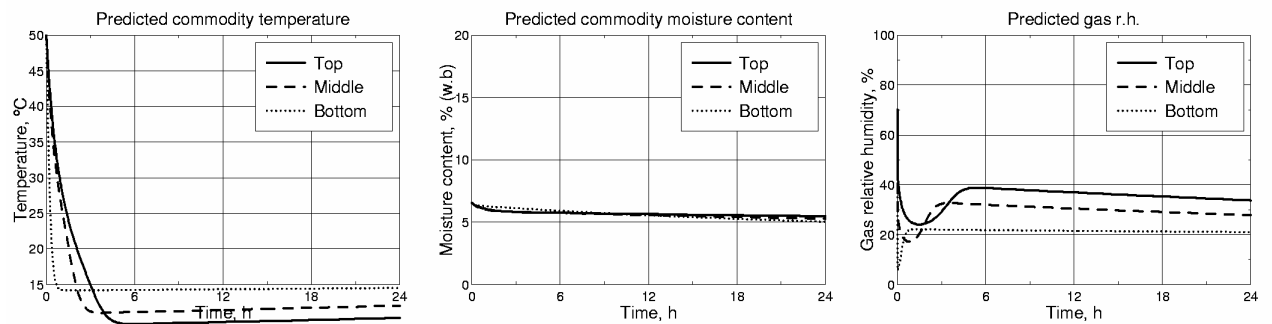


Fig. 6. Bulk cocoa cooling simulation, using $6.7 \text{ m}^3/\text{min}/\text{tonne}$ of air at 15°C and 95% r.h. Quantity: 1.5 tonnes; Depth of bed: 2 m; Initial temperature: 50°C ; Initial moisture content: 6.5% (w.b.)

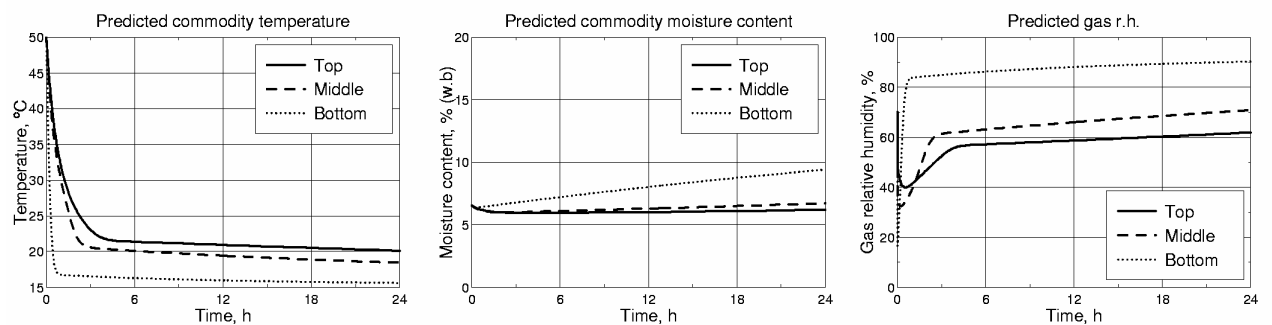


Fig. 7. Bulk cocoa heating simulation with air recirculation, using $0.8 \text{ m}^3/\text{min}/\text{tonne}$ of air at 50°C , humidified to 70% r.h. Quantity: 2.0 tonnes; Depth of bed: 2.7 m; Initial temperature: 15°C ; Initial moisture content: 6.5% (w.b.)

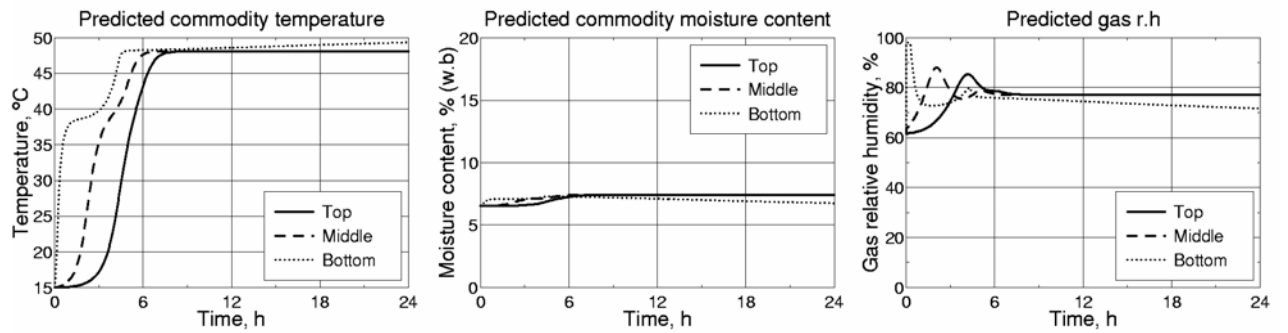


Fig. 8. 1000 tonnes of bulk stored cocoa with 20 pedestal aerators placed at 6m centres.

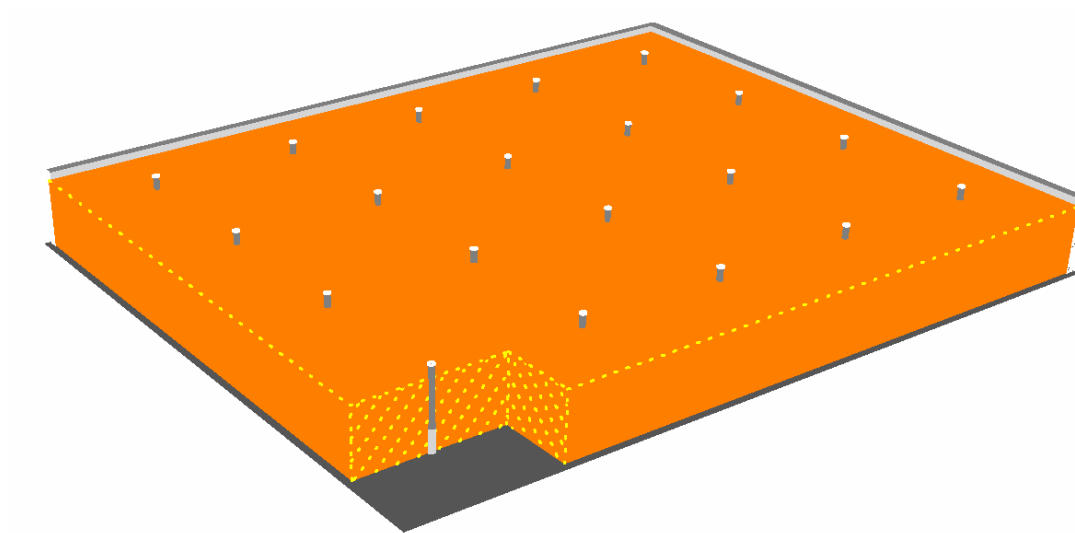


Fig. 9. Part of the computational grid surrounding each pedestal aerator.

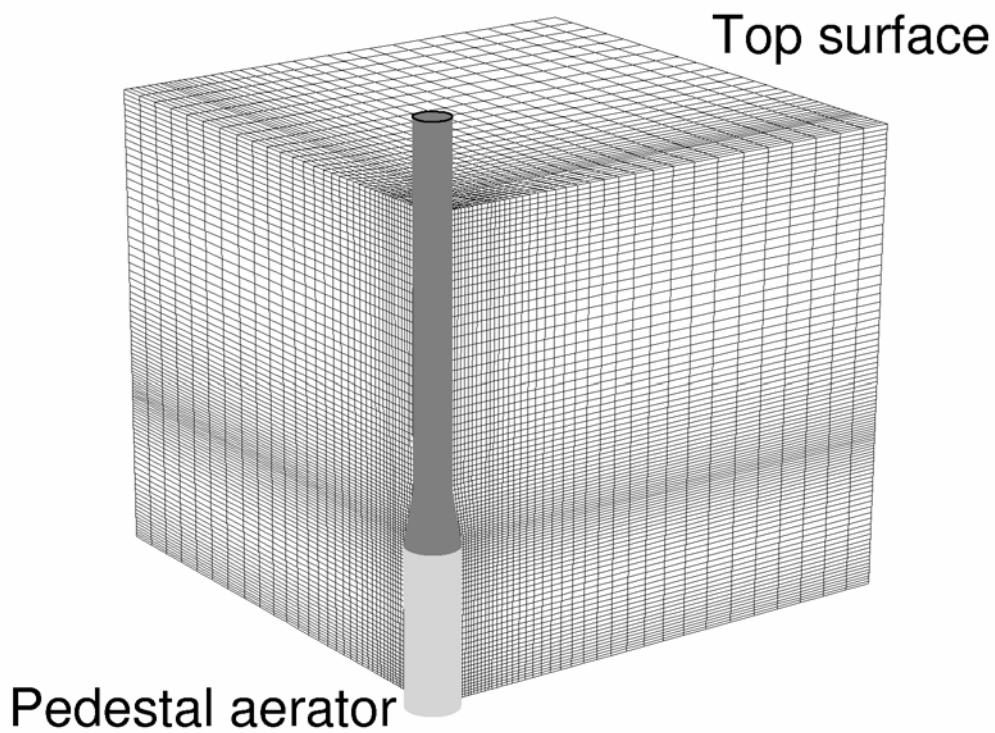


Fig. 10. The effect of bed depth on the predicted time taken to heat 50 tonnes of bulk stored cocoa.

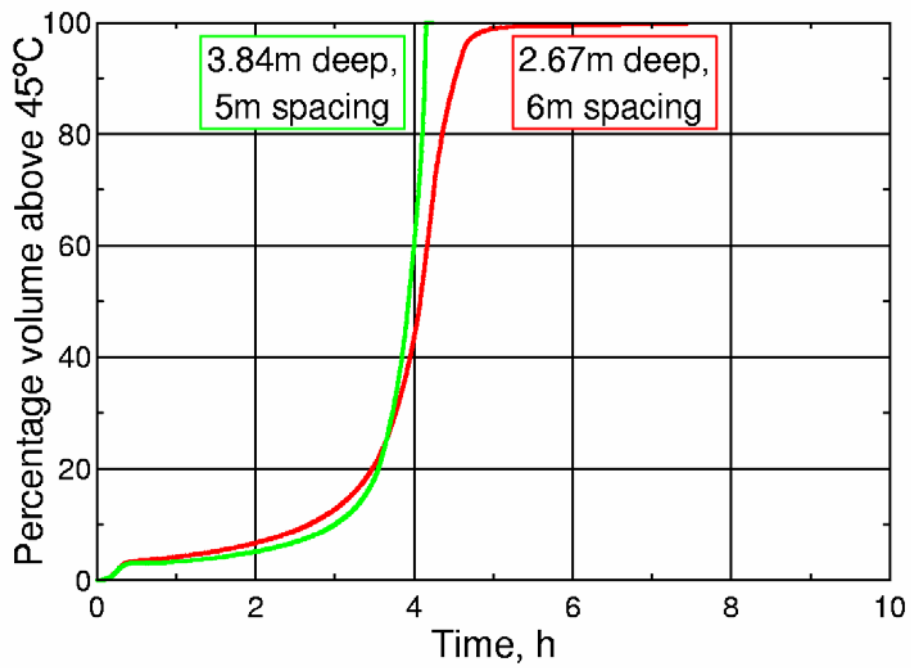


Table 28. Summary of predicted heating times and heating energy requirements for bulk cocoa

Air source	Cocoa depth, m	Airflow m ³ /min per tonne	Air re-circulation	Initial cocoa temperature, °C	Heating time to 45°C, h	Maximum energy, kW/tonne
Floor	2.0	6.7	No	15	0.9	4.8
Floor	2.7	0.8	Yes	15	6.4	0.4
Floor	2.7	0.8	Yes	25	3.4	0.4
Aerator	2.7	0.8	Yes	25	7.5	0.4
Aerator	3.8	0.8	Yes	25	4.2	0.4

2.3.2.2 Coffee

When air is supplied through a perforated floor the predicted results for heating and cooling bulk coffee are shown in Figures 11 – 15. Figure 11 shows that if air at ambient temperature (15°C) and 70% r.h. is heated to 50°C and used to heat the coffee then considerable drying will occur. This assumes that the air is not recirculated and hence its relative humidity as it enters the coffee is always about 10%. Heating of the coffee is also very slow because of the large amount of energy required to evaporate the moisture. Figure 12 shows the behaviour if the air is humidified to 70% r.h. before it enters the coffee. Drying is reduced and the bulk heats up to 45°C in 1.4 hours. However, the air relative humidity reaches saturation and a ‘condensation front’ travels through the bulk for the first 1.3 hours. Although any condensate will be quickly evaporated the effect on the commodity will need to be monitored.

Figures 13 - 15 show behaviour during cooling, using air at 15°C and humidities of 79% r.h. (normal), 20% r.h. and 95% r.h., respectively. Cooling is a very simple process when ambient (15°C) air is used. Since the cold air is always passing through a warmer commodity there is no danger of condensation and there is no need to recirculate and humidify the air. The only effect of the two extreme humidity values, 20% and 95%, is to change the final coffee moisture content.

In a practical system a low airflow rate is desirable to reduce the fan pressure. Although this increases the heating time it allows a smaller fan to be used. The heating air should also be recirculated, not only to minimise the energy input but also to conserve moisture and volatile products. Figure 16 shows the results assuming a lower airflow rate with recirculation. The airflow rate has been reduced from 5.1 m³/min per tonne to 0.8 m³/min per tonne, consequently the time to reach 45°C has increased from 1.4 hours to 11.6 hours. However, the maximum power requirement is only 0.4 kW per tonne, compared with 3.6 kW per tonne at the higher airflow rate without recirculation. If the initial bulk coffee temperature is 25°C, instead of 15°C, the heating time is reduced from 11.6 hours to 5.7 hours. The results of modelling the heating of bulk coffee are summarised in Table 29.

Fig. 11. Bulk coffee heating simulation, using 5.1 m³/min/tonne of air at 50°C, without humidification. Quantity: 2.0 tonnes; Depth of bed: 2 m; Initial temperature: 15°C; Initial moisture content: 15.1% (w.b.)

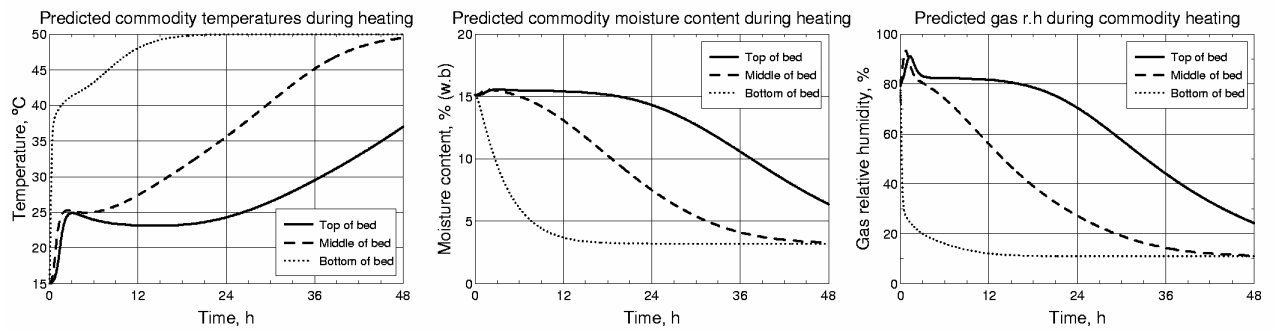


Fig.12. Bulk coffee heating simulation, using 5.1 m³/min/tonne of air at 50°C, humidified to 70% r.h. Quantity: 2.0 tonnes; Depth of bed: 2 m; Initial temperature: 15°C; Initial moisture content: 15.1% (w.b.)

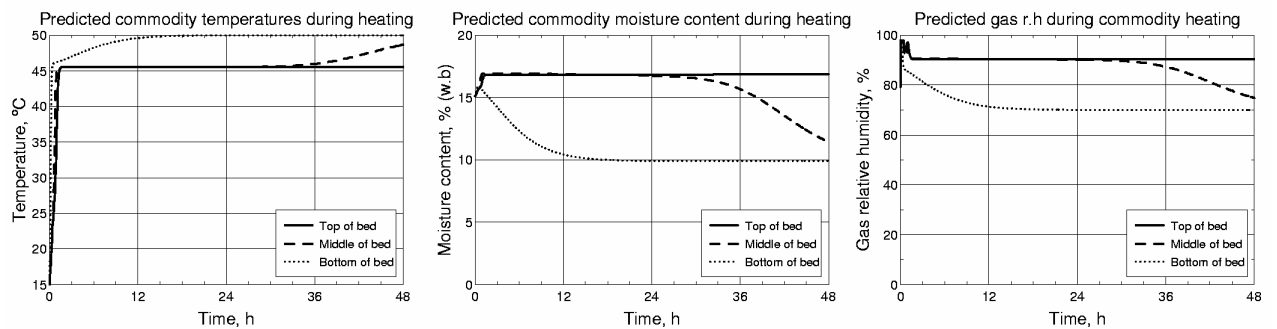


Fig. 13. Bulk coffee cooling simulation, using 5.1 m³/min/tonne of air at 15°C and 79% r.h. Quantity: 2.0 tonnes; Depth of bed: 2 m; Initial temperature: 50°C; Initial moisture content: 15.1% (w.b.)

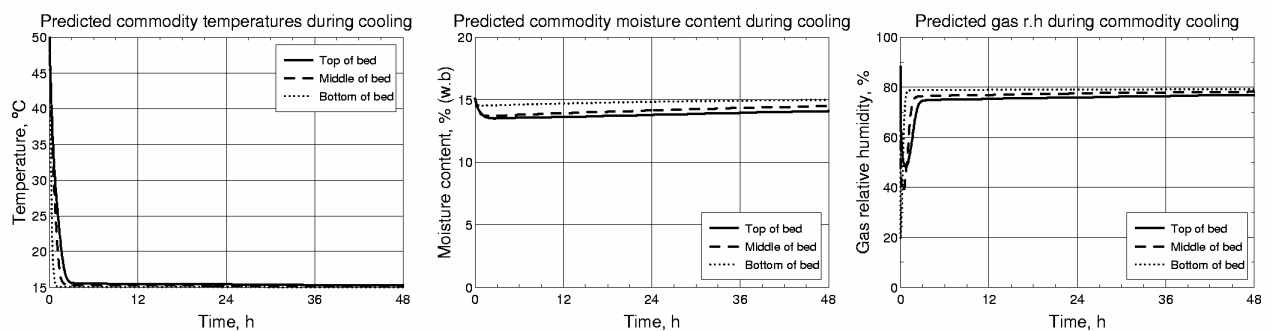


Fig. 14. Bulk coffee cooling simulation, using $5.1 \text{ m}^3/\text{min}/\text{tonne}$ of air at 15°C and 20% r.h. Quantity: 2.0 tonnes; Depth of bed: 2 m; Initial temperature: 50°C ; Initial moisture content: 15.1% (w.b.)

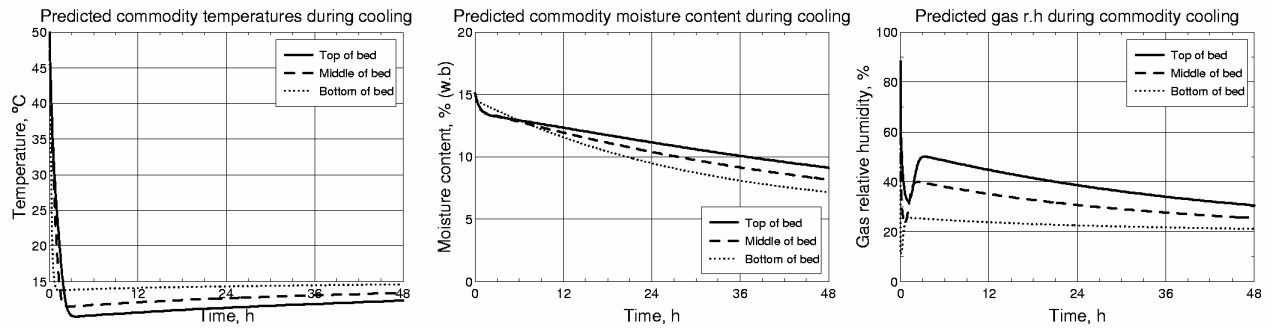


Fig. 15. Bulk coffee cooling simulation, using $5.1 \text{ m}^3/\text{min}/\text{tonne}$ of air at 15°C and 95% r.h. Quantity: 2.0 tonnes; Depth of bed: 2 m; Initial temperature: 50°C ; Initial moisture content: 15.1% (w.b.)

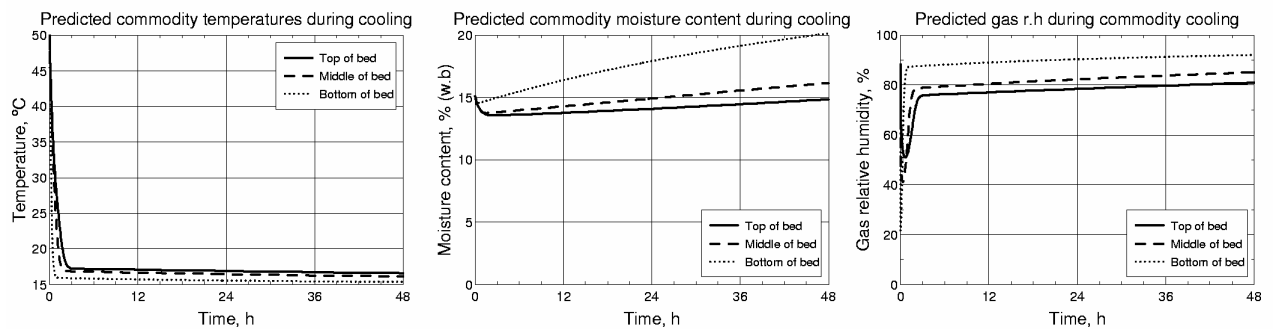


Fig. 16. Bulk coffee heating simulation with air recirculation, using $0.8 \text{ m}^3/\text{min}/\text{tonne}$ of air at 50°C , humidified to 70% r.h. Quantity: 2.9 tonnes; Depth of bed: 2.9 m; Initial temperature: 15°C ; Initial moisture content: 12.0% (w.b.)

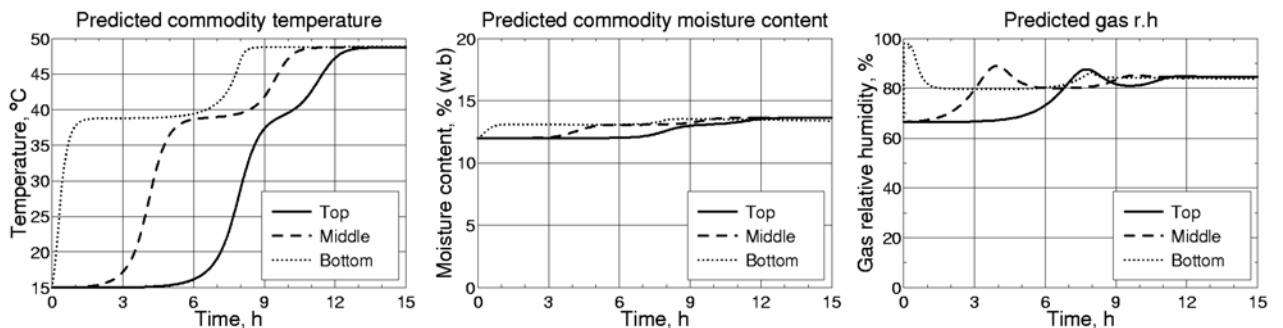


Table 29. Summary of predicted heating times and heating energy requirements for bulk coffee

Air source	Coffee depth, m	Airflow rate, m ³ /min per tonne	Air re-circulation	Initial coffee temperature, °C	Heating time to 45°C, h	Maximum energy, kW/tonne
Floor	2.0	5.1	No	15	1.4	3.6
Floor	2.9	0.8	Yes	15	11.6	0.4
Floor	2.9	0.8	Yes	25	5.7	0.4

2.3.2.3 Coriander

When air is supplied through a perforated floor the predicted results for heating and cooling bulk coriander are shown in Figures 17 – 21. Figure 17 shows that if air at ambient temperature (15°C) and 70% r.h. is heated to 50°C and used to heat the coriander then considerable drying will occur. This assumes that the air is not recirculated and hence its relative humidity as it enters the coriander is always about 10%. Heating of the coriander is also very slow because of the large amount of energy required to evaporate the moisture. Figure 18 shows the behaviour if the air is humidified to 70% r.h. before it enters the coriander. Drying is reduced and the bulk heats up to 45°C in 1.2 hours. However, the air relative humidity reaches saturation and a ‘condensation front’ travels through the bulk for the first 60 minutes. Although any condensate will be quickly evaporated the effect on the commodity will need to be monitored.

Figures 19 - 21 show behaviour during cooling, using air at 15°C and humidities of 59% r.h. (normal), 20% r.h. and 95% r.h., respectively. Cooling is a very simple process when ambient (15°C) air is used. Since the cold air is always passing through a warmer commodity there is no danger of condensation and there is no need to recirculate and humidify the air. The only effect of the two extreme humidity values, 20% and 95%, is to change the final coriander moisture content.

Fig.17. Bulk coriander heating simulation, using 12.9 m³/min/tonne of air at 50°C, without humidification. Quantity: 0.8 tonnes; Depth of bed: 2 m; Initial temperature: 15°C; Initial moisture content: 10.0% (w.b.)

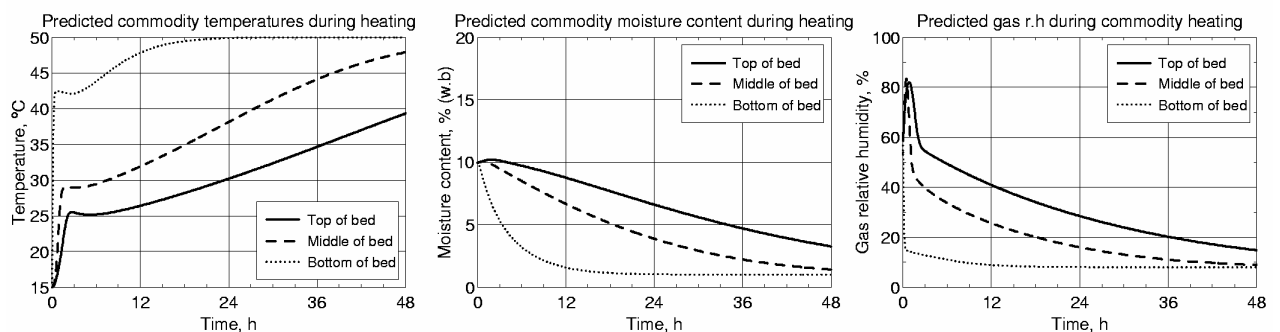


Fig.18. Bulk coriander heating simulation, using 12.9 m³/min/tonne of air at 50°C, humidified to 70% r.h. Quantity: 0.8 tonnes; Depth of bed: 2 m; Initial temperature: 15°C; Initial moisture content: 10.0% (w.b.)

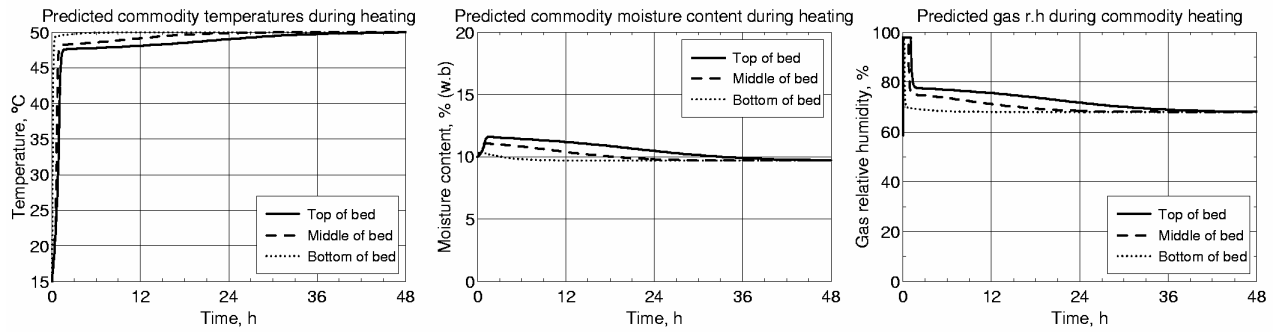


Fig. 19. Bulk coriander cooling simulation, using 12.9 m³/min/tonne of air at 15°C and 59% r.h. Quantity: 0.8 tonnes; Depth of bed: 2 m; Initial temperature: 50°C; Initial moisture content: 10.0% (w.b.)

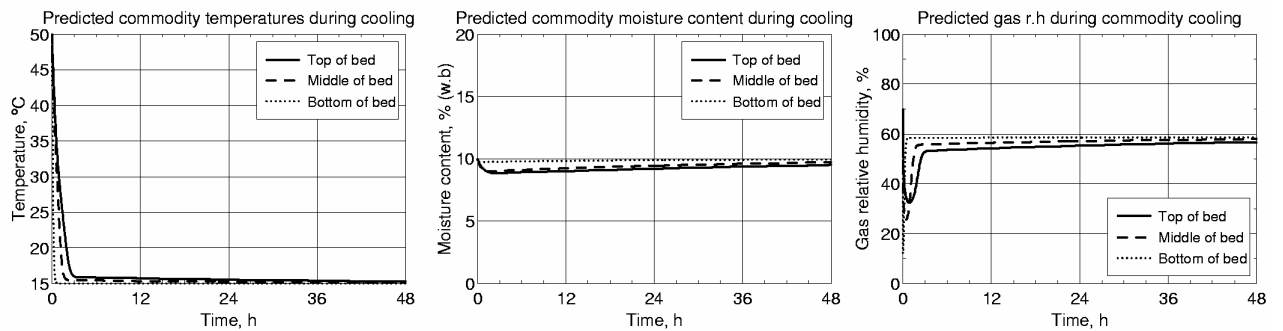


Fig. 20. Bulk coriander cooling simulation, using 12.9 m³/min/tonne of air at 15°C and 20% r.h. Quantity: 0.8 tonnes; Depth of bed: 2 m; Initial temperature: 50°C; Initial moisture content: 10.0% (w.b.)

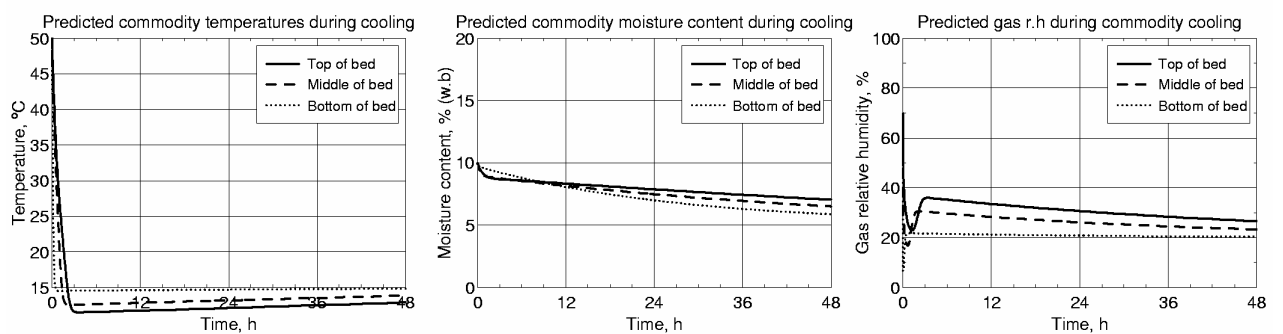
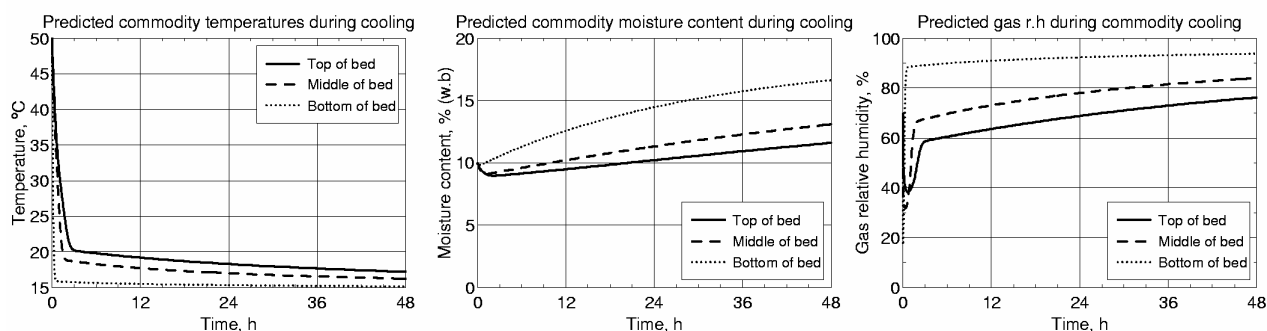


Fig. 21. Bulk coriander cooling simulation, using 12.9 m³/min/tonne of air at 15°C and 95% r.h. Quantity: 0.8 tonnes; Depth of bed: 2 m; Initial temperature: 50°C; Initial moisture content: 10.0% (w.b.)



2.3.2.4 Rice

Figure 22 shows the dimensions of 1000 tonnes of bulk stored rice. When air is supplied through a perforated floor the predicted results for heating and cooling are shown in Figures 23 – 27. Figure 23 shows that if air at ambient temperature (15°C) and 62% relative humidity is heated to 50°C and used to heat the rice then considerable drying will occur. This assumes that the air is not recirculated and hence its relative humidity as it enters the rice is always about 10%. Heating of the rice is also very slow because of the large amount of energy required to evaporate the moisture. Figure 24 shows the behaviour if the air is humidified to 68% r.h., the equilibrium value for rice at 50°C and 12% moisture content, before it enters the rice. The graphs of commodity temperature and moisture content show that the rice reaches 45°C in approximately 2.5 hours, and drying is reduced. However, the air relative humidity reaches saturation and a condensation front travels through the bulk for the first 2.2 hours.

Figures 25 - 27 show behaviour during cooling, using air at 15°C and humidities of 72% r.h. (normal), 20% r.h. and 95% r.h., respectively. Cooling is a very simple process when ambient (15°C) air is used. Since the cold air is always passing through a warmer commodity there is no danger of condensation and there is no need to recirculate and humidify the air. The only effect of the two extreme humidity values, 20% and 95%, is to change the final rice moisture content.

In a practical system a low airflow rate is desirable to reduce the fan pressure. Although this increases the heating time it allows a smaller fan to be used. The heating air should also be recirculated, not only to minimise the energy input but also to conserve moisture. Figure 28 shows the results assuming a lower airflow rate with recirculation. The airflow rate has been reduced from 5.8 m³/min per tonne to 0.8 m³/min per tonne, consequently the time to reach 45°C has increased from 2.5 hours to 10.2 hours. However, the maximum power requirement is only 0.4 kW per tonne, compared with 4.2 kW per tonne at the higher airflow rate without recirculation. If the initial rice temperature is 25°C, instead of 15°C, the heating time is reduced from 10.2 hours to 5.2 hours. The results of modelling the heating of bulk rice are summarised in Table 30.

Fig. 22. Typical dimensions of 1000 tonnes of bulk stored rice ready for fumigation.

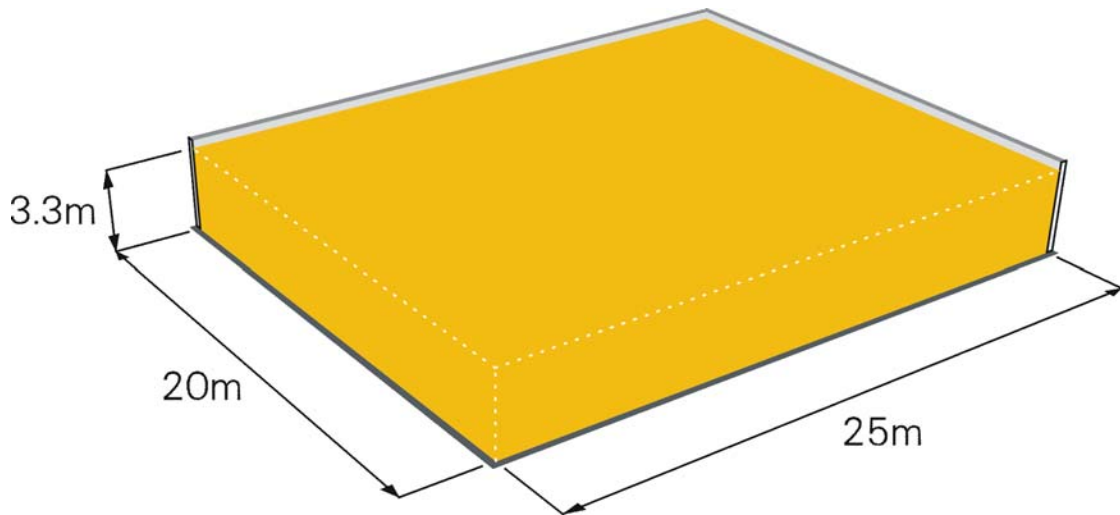


Fig. 23. Bulk rice heating simulation, using $5.8 \text{ m}^3/\text{min}/\text{tonne}$ of air at 50°C , without humidification. Quantity: 1.7 tonnes; Depth of bed: 2 m; Initial temperature: 15°C ; Initial moisture content: 14.5% (w.b.)

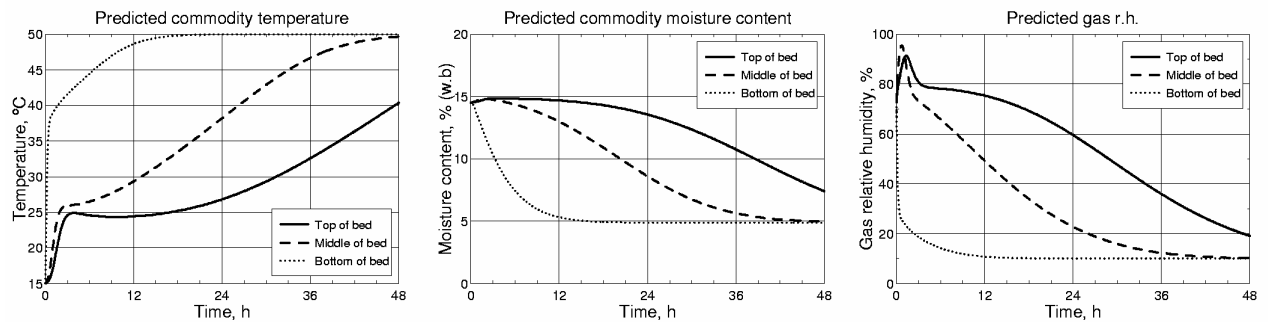


Fig. 24. Bulk rice heating simulation, using $5.8 \text{ m}^3/\text{min}/\text{tonne}$ of air at 50°C , humidified to 70% r.h. Quantity: 1.7 tonnes; Depth of bed: 2 m; Initial temperature: 15°C ; Initial moisture content: 14.5% (w.b.)

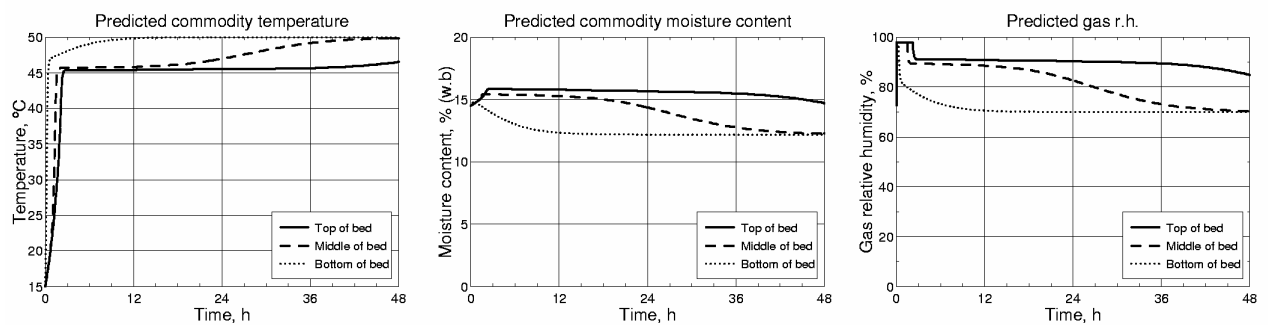


Fig. 25. Bulk rice cooling simulation, using 5.8 m³/min/tonne of air at 15°C and 62% r.h. Quantity: 1.7 tonnes; Depth of bed: 2 m; Initial temperature: 50°C; Initial moisture content: 14.5% (w.b.)

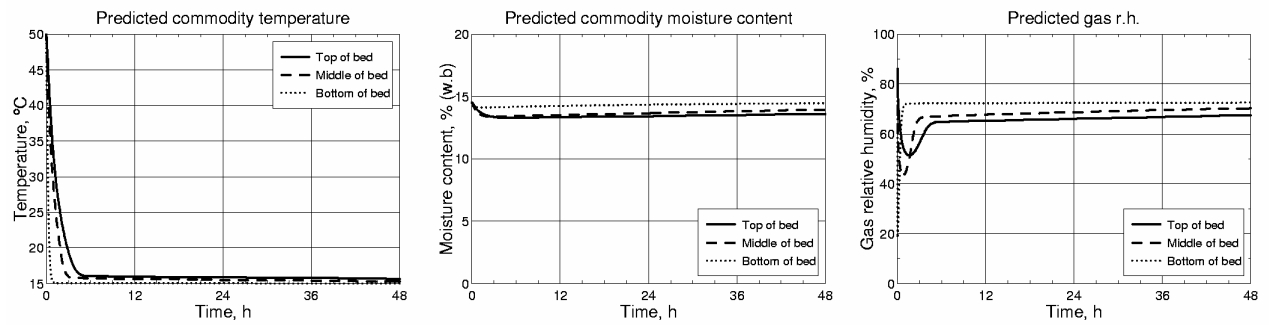


Fig. 26. Bulk rice cooling simulation, using 5.8 m³/min/tonne of air at 15°C and 20% r.h. Quantity: 1.7 tonnes; Depth of bed: 2 m; Initial temperature: 50°C; Initial moisture content: 14.5% (w.b.)

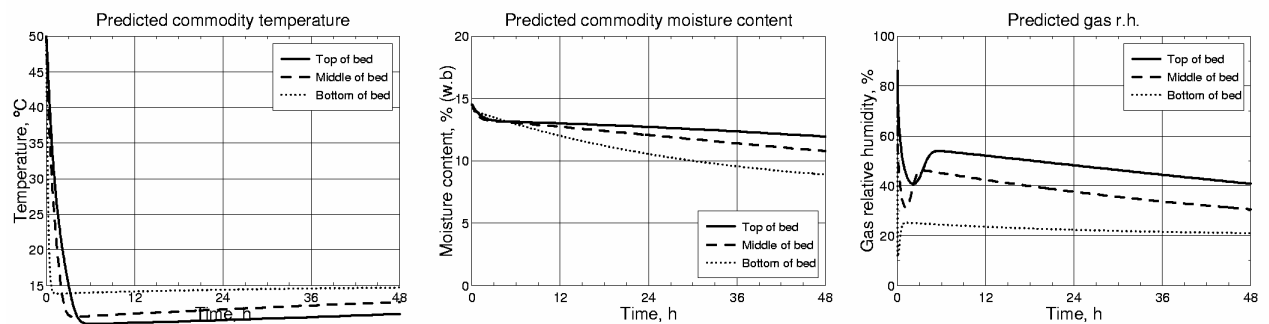


Fig. 27. Bulk rice cooling simulation, using 5.8 m³/min/tonne of air at 15°C and 95% r.h. Quantity: 1.7 tonnes; Depth of bed: 2 m; Initial temperature: 50°C; Initial moisture content: 14.5% (w.b.)

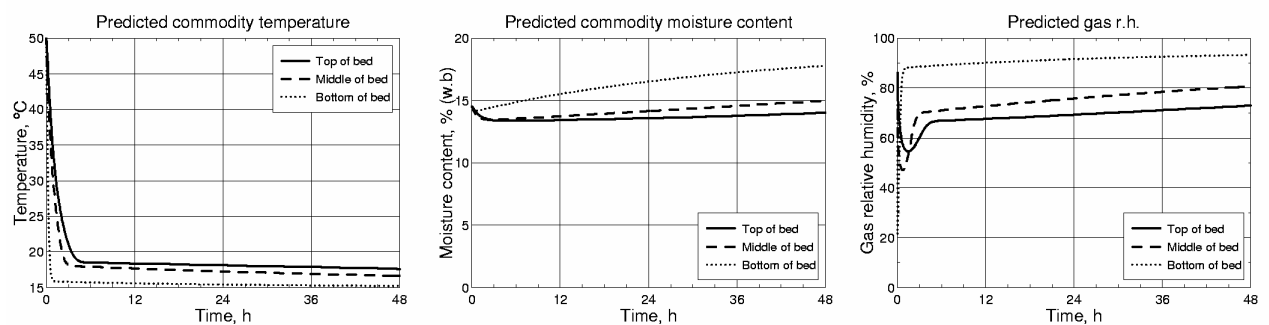


Fig. 28. Bulk rice heating simulation with air recirculation, using 0.8 m³/min/tonne of air at 50°C, humidified to 70% r.h. Quantity: 2.9 tonnes; Depth of bed: 3.3 m; Initial temperature: 15°C; Initial moisture content: 14.5% (w.b.)

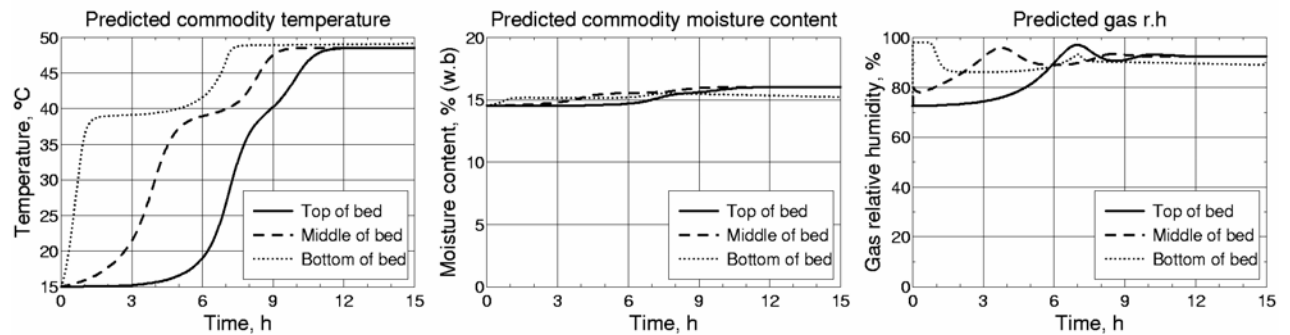


Table 30. Summary of predicted heating times and heating energy requirements for bulk rice

Air source	Coffee depth, m	Airflow m ³ /min per tonne	Air re-circulation	Initial coffee temperature, °C	Heating time to 45°C, h	Maximum energy, kW/tonne
Floor	2.0	5.8	No	15	2.5	4.2
Floor	3.3	0.8	Yes	15	10.2	0.4
Floor	3.3	0.8	Yes	25	5.2	0.4

2.3.2.5 Dried Apricots

Results for bulk dried apricots are shown in Figures 29 - 33. The Equilibrium-Relative Humidity relationships of dried fruit (prunes, sultanas, figs, apricots) are unusual in as much as they are independent of temperature between 5°C and 35°C. Unfortunately, the change in moisture content for a small change in relative humidity is also large, which makes the control of humidity just as important as it is for other commodities. Figure 29 shows the effects of heating without humidification, and Figure 30 shows the improvement when the air is humidified to 70% r.h. The graph of commodity temperature shows that the apricots reach 45°C in approximately 1.7 hours.

Figures 31 - 33 show behaviour during cooling, using air at 15°C and humidities of 74% r.h. (normal), 20% r.h. and 95% r.h., respectively. Cooling is a very simple process when ambient (15°C) air is used. Since the cold air is always passing through a warmer commodity there is no danger of condensation and there is no need to recirculate and humidify the air. The only effect of the two extreme humidity values, 20% and 95%, is to change the final apricot moisture content.

The major difference between heating and cooling bulk dried apricots and other commodities is the much greater pressure necessary to drive the heating air through the product. Estimated pressures are given in Table 31 below.

Fig. 29. Bulk dried apricots heating simulation, using $3.9 \text{ m}^3/\text{min}/\text{tonne}$ of air at 50°C , without humidification. Quantity: 2.5 tonnes; Depth of bed: 2 m; Initial temperature: 15°C ; Initial moisture content: 23.5% (w.b.)

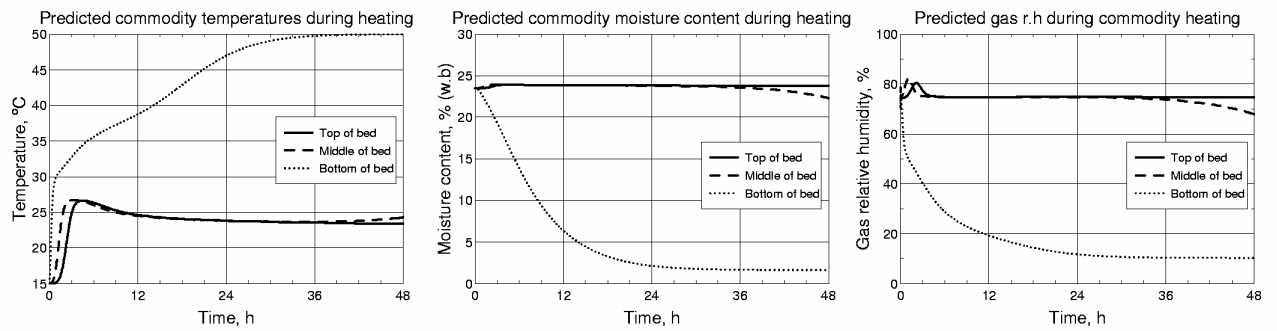


Fig. 30. Bulk dried apricots heating simulation, using $3.9 \text{ m}^3/\text{min}/\text{tonne}$ of air at 50°C , humidified to 70% r.h. Quantity: 2.5 tonnes; Depth of bed: 2 m; Initial temperature: 15°C ; Initial moisture content: 23.5% (w.b.)

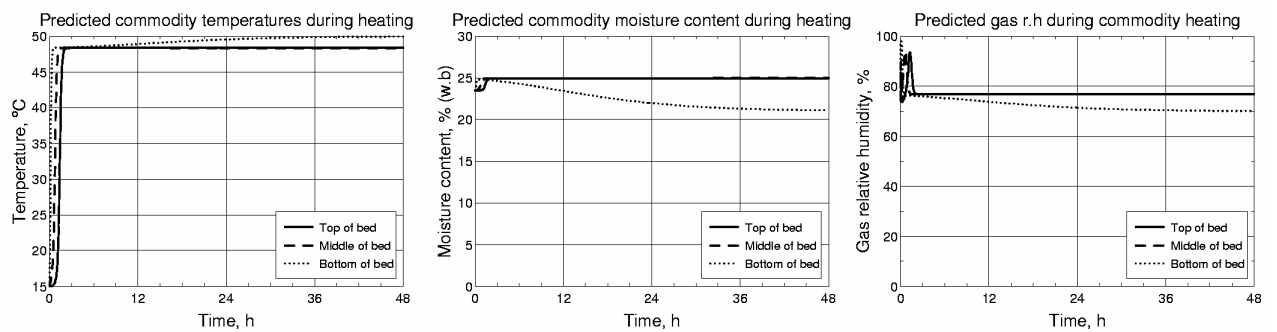


Fig. 31. Bulk dried apricots cooling simulation, using $3.9 \text{ m}^3/\text{min}/\text{tonne}$ of air at 15°C and 74% r.h. Quantity: 2.5 tonnes; Depth of bed: 2 m; Initial temperature: 50°C ; Initial moisture content: 23.5% (w.b.)

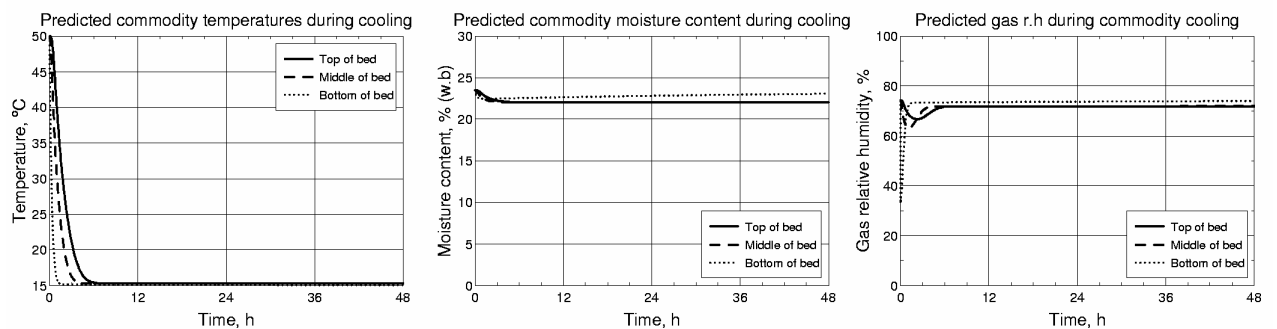


Fig. 32. Bulk dried apricots cooling simulation, using 3.9 m³/min/tonne of air at 15°C and 20% r.h. Quantity: 2.5 tonnes; Depth of bed: 2 m; Initial temperature: 50°C; Initial moisture content: 23.5% (w.b.)

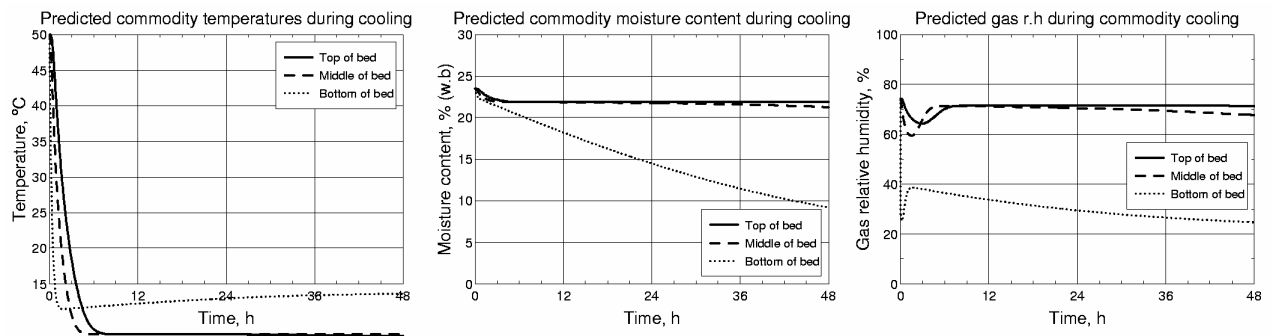
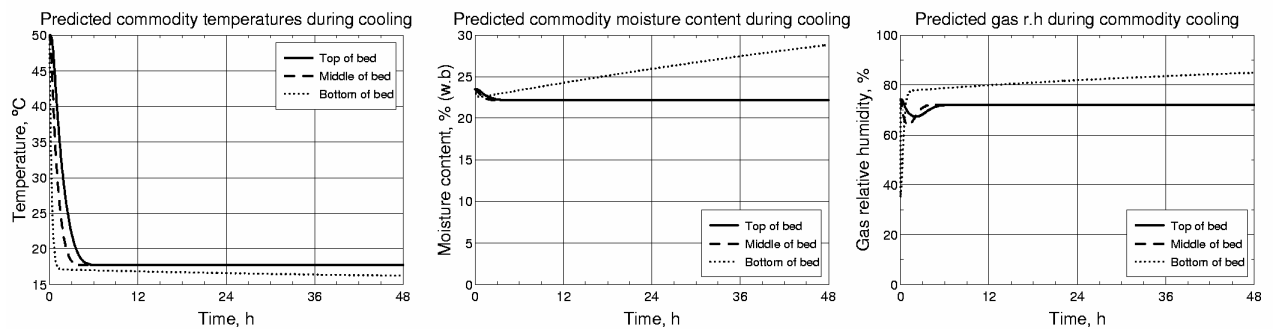


Fig. 33. Bulk dried apricots cooling simulation, using 3.9 m³/min/tonne of air at 15°C and 95% r.h. Quantity: 2.5 tonnes; Depth of bed: 2 m; Initial temperature: 50°C; Initial moisture content: 23.5% (w.b.)



2.3.3 Fan pressure

The results show that the heating time depends on the airflow rate through the commodity. To achieve a given airflow rate the fan must be capable of generating sufficient pressure to overcoming the resistance to flow in the commodity. Based on measured permeability values from each commodity Table 31 gives the estimated pressures required at the airflow rates used in the model.

Table 31. Estimated fan pressure at modelled airflow rates

Commodity	Air source	Commodity depth, m	Airflow rate, m ³ /min per tonne	Pressure, Pa
Cocoa	Floor	2.0	6.7	230
	Floor	2.7	0.8	15
	Aerator	2.7	0.8	15
	Aerator	3.8	0.8	55
Coffee	Floor	2.0	5.1	240
	Floor	2.9	0.8	25
Coriander	Floor	2.0	12.9	840
Rice	Floor	2.0	5.8	740
	Floor	3.3	0.8	200
Dried apricots(loose)	Floor	2.0	3.9	1000
Dried apricots(packed)	Floor	2.0	3.9	3300

2.3.4 Energy costs

An approximate energy cost per tonne of bulk commodity can be calculated assuming the following:

Specific heat of commodity:	2000 J/kg.°K
Commodity temperature rise (15°C – 45°C):	30°C
Cost of bulk propane gas:	£0.01/MJ
Efficiency of heating process, assuming the air is recirculated:	50%

The cost of heating 1 tonne of bulk commodity = $1000 \times 2000 \times 30 \times 0.01 \times 10^{-6} \times 2 = \text{£}1.20$

2.3.5 Equipment requirements

Irrespective of the air source, whether perforated floor or pedestal aerator, the air needs to be heated and its humidity controlled. Assuming the air is recirculated to conserve energy then the maximum power is required at the start of heating when there is the greatest difference between the hot air and the commodity temperature. The simulation results shown in Figures 7, 16 and 28 assume a power supply of 20 kW for each 50 tonnes of commodity.

In addition to the air heater, a humidifier is required. Ideally, this should use steam rather than a water spray so that the air stream is not cooled by the latent heat absorbed during evaporation.

Finally, automatic control is required of both air temperature and air humidity. The controller behaviour will need to reflect the commodity moisture content and its equilibrium-relative humidity characteristics in order to avoid drying and minimise condensation.

3.1 Conclusions from modelling studies

1. Modelling has enabled the heating of commodities in two store configurations to be studied relatively quickly and under controlled conditions.
2. Modelling has predicted the commodity moisture changes that take place during heating and shown how these can be controlled.
3. Modelling has shown that the convective heating of bulk stored commodities is at least 10 times faster than the conductive heating of packaged commodities.
4. The heating air should be recirculated to minimise the energy input and also conserve moisture and volatile products.
5. With the appropriate airflow and air humidity control, bulk commodities can be heated from 15°C to at least 45°C in less than 12 hours at a cost of about £1.20 per tonne.
6. Cooling with ambient air is both rapid and simple. Since the air is always passing through a warmer commodity there is no danger of condensation.
7. Provided the target temperature causes 100% insect mortality in 24 hours, the whole treatment can be completed in 48 hours.
8. Suitable air heaters, humidifiers and controllers are needed to make the system viable.

3. COMMODITY QUALITY TESTS

3.1 Introduction

For each commodity, the maximum temperature permissible for pest control is defined by the results of organoleptic and other quality tests which establish the size of the “window” which can be used for treatments without harming the product. Quality test results also help to further define the quantity of the commodity that can be treated by heat at one time, the higher the temperature rise that can be permitted and thus the greater the temperature range which can achieve control, the larger the possible batch size. Hence, the first step was to define the maximum allowable temperature for each commodity as dictated by quality effects. The programme commenced with ranging tests at 5°C temperature intervals for exposure periods of up to 4 or 6 days.

3.1 Methods

The evaluation of effects on commodities was undertaken by industry, using the standard quality tests performed upon receipt of a consignment. Aspects considered varied from commodity to commodity but included volatile oil levels and microbiological loading for spices, moisture content and mycotoxins for dried fruit and rancidity tests for nuts, in addition to running the appropriate organoleptic tests with the aid of sensory panels.

For the first series of tests samples were placed in sealed bags in incubators to avoid moisture loss during heating. In subsequent tests samples were held in desiccators and humidified atmospheres were fed in and out throughout exposures via ports in the desiccator lid. Temperatures were tested firstly up to 40 °C, and then up to 50 and 55 °C, the latter range to establish the maximum temperature to be aimed for in the design of forced atmosphere circulation systems.

3.1 Results

The difference in effect between the exposure of commodities in sealed plastic bags or in a humidified continuous low oxygen flow system at raised temperatures was not discernible in terms of quality loss for any of the commodities, including those for which the preservation of volatile constituents was a paramount objective. While a positive advantage for modified atmospheres over air could not be established statistically within the temperature range tested, there was no evidence of the MAs enhancing detrimental effects of any kind in any of the commodities. Results are given in full for each commodity in Tables 32-60 and are summarised in Table 61. Rice proved the most heat tolerant commodity, showing no adverse effects of any kind after 6 days at 55-56°C. Fennel and coriander seed could also tolerate exposure at 55°C well. For walnuts, coffee and cocoa the safe upper temperature was 50°C, while for dried apricots 45°C was the upper limit for a 4-day exposure.

3.3.1 Cocoa

Table 32. Cocoa - High Temperatures in Air - Test 1

Temperature (°C)	Exposure (days)	Sample	% Fat (on dry basis)	Free Fatty Acid (%)	Moisture (%)	Moisture in Shell (%)	Fat (OICC) (%)	Sensor y results
50	4	Original	58.7 ± 0.4	0.56 ± 0.09	6.9 ± 0.2	13.1 ± 0.2	2.4 ± 0.5	N. S.
50	4	Shelf life	58.0 ± 0.2	0.83 ± 0.05	6.4 ± 0.1	12.6 ± 0.4	1.9 ± 0.3	-
45	4	Original	58.6 ± 0.5	0.58 ± 0.07	7.0 ± 0.2	13.3 ± 0.5	2.4 ± 0.6	N. S.
45	4	Shelf life	57.9 ± 0.2	0.81 ± 0.09	6.6 ± 0.2	12.9 ± 0.2	2.4 ± 0.4	-
40	4	Original	58.9 ± 0.2	0.61 ± 0.05	6.9 ± 0.1	13.5 ± 0.4	2.0 ± 0.2	Sig
40	4	Shelf life	57.8 ± 0.2	0.78 ± 0.12	6.6 ± 0.2	12.9 ± 0.4	2.7 ± 1.5	-
35	4	Original	58.9 ± 0.3	0.56 ± 0.03	6.9 ± 0.1	13.7 ± 0.4	2.2 ± 0.5	Sig
35	4	Shelf life	58.0 ± 0.4	0.72 ± 0.07	6.7 ± 0.1	12.9 ± 0.3	2.7 ± 0.7	-
Control		Original	58.8 ± 0.3	0.58 ± 0.06	7.0 ± 0.2	13.3 ± 0.3	2.4 ± 0.5	
Control		Shelf life	58.0 ± 0.1	0.68 ± 0.06	6.4 ± 0.2	12.9 ± 0.3	1.6 ± 0.5	

Table 33. Cocoa in air - Test 2

Temperature (°C)	Exposure (days)	Sample	% Fat (on dry basis)	Free Fatty Acid (%)	Moisture (%)	Moisture in Shell (%)	Fat (OICC) (%)	Sensory results
50	6	Original	57.5 ± 0.1	0.96 ± 0.12	5.5 ± 0.2	11.9 ± 0.5	2.2 ± 0.2	N. S.
50	6	Shelf life	56.9 ± 0.5	1.06 ± 0.18	6.1 ± 0.1	11.9 ± 0.7	6.2 ± 3.6	N. S.
50	2	Original	57.5 ± 0.3	0.85 ± 0.05	5.8 ± 0.1	12.7 ± 0.3	2.3 ± 0.3	N. S.
50	2	Shelf life	57.5 ± 0.2	1.00 ± 0.06	6.3 ± 0.1	12.9 ± 0.1	2.3 ± 0.3	N. S.
45	6	Original	57.5 ± 0.2	0.95 ± 0.23	5.7 ± 0.2	12.4 ± 0.3	2.2 ± 0.2	N. S.
45	6	Shelf life	56.8 ± 0.3	1.08 ± 0.13	6.2 ± 0.1	12.1 ± 0.3	4.9 ± 1.2	N. S.
40	6	Original	57.5 ± 0.2	0.88 ± 0.13	5.8 ± 0.1	12.3 ± 0.4	2.9 ± 1.0	N. S.
40	6	Shelf life	57.0 ± 0.6	1.07 ± 0.18	6.2 ± 0.1	12.7 ± 0.3	3.9 ± 2.0	N. S.
40	2	Original	57.7 ± 0.1	0.98 ± 0.17	5.8 ± 0.2	12.6 ± 0.2	2.5 ± 0.4	N. S.
40	2	Shelf life	57.6 ± 0.3	1.03 ± 0.10	6.3 ± 0.2	12.8 ± 0.2	2.8 ± 0.5	N. S.
Control		Original	57.6 ± 0.2	0.87 ± 0.08	6.1 ± 0.1	12.8 ± 0.3	2.3 ± 0.7	
Control		Shelf life	57.2 ± 0.8	1.04 ± 0.11	6.4 ± 0.1	12.6 ± 0.5	4.5 ± 1.3	

Table 34. Cocoa in Nitrogen

Temperature (°C)	Exposure (days)	Sample	% Fat (on dry basis)	Free Fatty Acid (%)	Moisture (%)	Moisture in Shell (%)	Fat (OICC) (%)	Sensory results
50	7	Original	57.3 ± 0.3	0.94 ± 0.08	6.3 ± 0.2	12.5 ± 0.2	2.0 ± 0.2	N. S.
50	7	Shelf life	57.8 ± 0.5	1.11 ± 0.23	5.4 ± 0.2	12.2 ± 0.3	2.0 ± 0.6	N. S.
45	4	Original	57.4 ± 0.3	0.94 ± 0.06	6.4 ± 0.1	12.3 ± 0.3	2.0 ± 0.4	N. S.
45	4	Shelf life	57.8 ± 0.4	1.01 ± 0.10	5.5 ± 0.2	12.3 ± 0.5	2.1 ± 0.6	N. S.
40	4	Original	57.5 ± 0.4	0.94 ± 0.09	6.1 ± 0.04	12.0 ± 0.3	2.5 ± 1.1	N. S.
40	4	Shelf life	58.1 ± 0.2	1.12 ± 0.16	5.4 ± 0.2	12.0 ± 0.2	2.3 ± 0.8	N. S.
Control		Original	57.2 ± 0.2	0.92 ± 0.10	6.6 ± 0.2	12.8 ± 0.2	2.0 ± 0.3	
Control		Shelf life	57.7 ± 0.2	1.02 ± 0.09	5.6 ± 0.1	12.6 ± 0.3	1.8 ± 0.4	

Table 35. Cocoa in Burner Gas

Temperature (°C)	Exposure (days)	Sample	% Fat (on dry basis)	Free Fatty Acid (%)	Moisture (%)	Moisture in Shell (%)	Fat (OICC) (%)	Sensory results
50	6	Original	58.8 ± 0.2	0.70 ± 0.09	6.0 ± 0.2	12.6 ± 0.3	2.5 ± 0.4	N. S.
50	6	Shelf life	59.1 ± 0.2	0.73 ± 0.03	6.7 ± 0.2	13.2 ± 0.3	2.5 ± 0.4	N. S.
50	2	Original	58.6 ± 0.4	0.70 ± 0.14	6.6 ± 0.5	13.7 ± 0.7	2.2 ± 0.6	Sig
45	6	Original	58.8 ± 0.4	0.64 ± 0.05	6.4 ± 0.2	13.7 ± 0.3	2.2 ± 0.5	Sig
45	6	Shelf life	59.2 ± 0.2	0.72 ± 0.03	6.4 ± 0.2	13.0 ± 0.2	2.2 ± 0.5	N. S.
40	6	Original	58.8 ± 0.3	0.71 ± 0.08	6.2 ± 0.1	13.1 ± 0.4	2.5 ± 0.8	N. S.
40	6	Shelf life	59.2 ± 0.2	0.70 ± 0.04	6.3 ± 0.1	12.7 ± 0.5	2.4 ± 0.3	N. S.
40	2	Original	58.4 ± 0.4	0.63 ± 0.04	6.4 ± 0.2	13.4 ± 0.3	2.4 ± 0.3	Sig
Control		Original	59.0 ± 0.2	0.56 ± 0.03	6.4 ± 0.2	13.0 ± 0.5	2.1 ± 0.3	
Control		Shelf life	59.2 ± 0.2	0.67 ± 0.09	6.5 ± 0.1	13.5 ± 0.3	2.2 ± 0.4	

Table 36. Cocoa in carbon dioxide

Temperature (°C)	Exposure (days)	% Fat (on dry basis)	Free Fatty Acid (%)	Moisture (%)	Moisture in Shell (%)	Fat (OICC) (%)	Sensory results
50	6	59.1 ± 0.5	0.73 ± 0.07	5.7 ± 0.4	12.1 ± 0.7	2.4 ± 0.8	N. S.
50	2	59.1 ± 0.2	0.63 ± 0.04	5.3 ± 0.2	11.5 ± 0.6	2.1 ± 0.2	N. S.
45	6	59.0 ± 0.2	0.65 ± 0.10	6.2 ± 0.2	13.0 ± 0.4	2.3 ± 0.7	N. S.
40	6	59.0 ± 0.3	0.62 ± 0.07	6.2 ± 0.1	13.2 ± 0.4	2.1 ± 0.3	Sig
40	2	59.0 ± 0.2	0.68 ± 0.07	5.5 ± 0.1	12.1 ± 0.2	2.2 ± 0.8	N. S.
Control		58.9 ± 0.4	0.66 ± 0.06	5.5 ± 0.1	11.7 ± 0.2	1.9 ± 0.1	

Coffee

Table 37. Coffee in Air – Test 1

Temperature (°C)	Exposure (days)	Grade of original sample: 1 = full standard 5 = unacceptable	Grade of shelf life sample
40	6	1 ± 0	1 ± 0
40	4	1 ± 0	1 ± 0
40	2	1 ± 0	1 ± 0
30	4	1 ± 0	1 ± 0
30	2	1 ± 0	1 ± 0
Control		1 ± 0	1 ± 0

Table 38. Coffee in Air – Test 2

Temperature (°C)	Exposure (days)	Grade of original sample: 1 = full standard 5 = unacceptable	Grade of shelf life sample
55	4	1.6 ± 0.5	1.6 ± 0.9
55	2	1 ± 0	1.6 ± 0.5
50	6	1 ± 0	1.2 ± 0.4
50	4	1.4 ± 0.5	1.6 ± 0.9
50	2	1 ± 0	1.4 ± 0.9
Control		1 ± 0	1.6 ± 0.5

Table 39. Coffee in Nitrogen

Temperature (°C)	Exposure (days)	Grade of original sample: 1 = full standard 5 = unacceptable	Grade of shelf life sample
55	4	2.6 ± 0.5	n.a.
50	4	1.5 ± 0.5	n.a.
50	2	1.4 ± 0.5	n.a.
45	4	1.7 ± 0.4	n.a.
45	2	1.9 ± 0.2	n.a.
Control		1.4 ± 0.5	n.a.

Coriander

Table 40. Coriander in Air – Test 1

Temperature (°C)	Exposure (days)	Sample	Available Water (unit?)	Volatile oil	Enterobacteriaceae detected in number of samples indicated	Appearance	Flavour/ Aroma
40	4	Original	54.3 ± 8.3	0.4 ± 0	0 in 4	7.9 ± 0.5	6.2 ± 0.6
40	4	Shelf life	51.9 ± 1.1	0.27 ± 0.11	0 in 2	8.5 ± 0.6	7.7 ± 1.0
40	2	Original	58.1 ± 4.3	0.4 ± 0	2 in 4	7.3 ± 0.8	6.5 ± 0.8
40	2	Shelf life	52.2 ± 0.5	0.33 ± 0.12	n.a.	9.3 ± 0.3	7.5 ± 0.3
30	6	Original	59.5 ± 4.3	0.35 ± 0.10	1 in 4	8.5 ± 0.3	8.2 ± 0.6
30	6	Shelf life	52.5 ± 0.4	0.4 ± 0	0 in 2	8.8 ± 0.3	7.5 ± 1.1
30	4	Original	54.3 ± 3.8	0.4 ± 0	0 in 4	7.3 ± 0.9	5.9 ± 0.9
30	4	Shelf life	52.4 ± 1.6	0.33 ± 0.12	n.a.	8.8 ± 0.3	7.5 ± 1.1
30	2	Original	57.1 ± 2.9	0.4 ± 0	0 in 4	7.7 ± 0.7	6.7 ± 0.6
30	2	Shelf life	52.9 ± 2.1	0.33 ± 0.12	0 in 2	9.0 ± 0.4	8.2 ± 0.4
Control		Original	64.9 ± 1.3	0.4 ± 0	2 in 2	7.6 ± 0.1	6.3 ± 0.7
Control		Shelf life	51.9 ± 4.4	0.30 ± 0.14	0 in 1	8.7 ± 0.14	6.9 ± 0.6

Table 41. Coriander in Nitrogen

Temperature (°C)	Exposure (days)	Sample	Available Water (unit?)	Volatile oil	Enterobacteriaceae	Appearance	Flavour/ Aroma
55	2	Original	65.1 ± 8.3	1.2 ± 0	n.a.		
55	2	Shelf life	47.8 ± 0.4	0.38 ± 0.04	0 in 3	8.5 ± 0.3	8.2 ± 0.6
50	4	Original	69.6 ± 9.4	1.2 ± 0.04	0 in 4		
50	4	Shelf life	48.1 ± 1.4	0.38 ± 0.04	0 in 2	8.6 ± 0.3	7.9 ± 0.6
50	2	Original	61 ± 21	1.16 ± 0.05	0 in 5		
50	2	Shelf life	48.2 ± 0.7	0.37 ± 0.02	0 in 3	8.8 ± 0.2	8.8 ± 0.5
45	4	Original	74.6 ± 2.8	1.14 ± 0.05	0 in 5		
45	4	Shelf life	48.0 ± 0.6	0.38 ± 0.04	1 in 1	8.9 ± 0.4	8.6 ± 0.4
45	2	Original	76.5 ± 3.5	1.2 ± 0	0 in 4		
45	2	Shelf life	48.4 ± 0.5	0.42 ± 0.07	0 in 2	8.5 ± 0.5	8.5 ± 0.9
Control		Original	67.2 ± 8.0	1.18 ± 0.04	0 in 4		
Control		Shelf life	48.2 ± 0.8	0.37 ± 0.04	0 in 2	8.6 ± 0.2	8.3 ± 0.4

Table 42. Coriander in Burner Gas

Temperature (°C)	Exposure (days)	Sample	Available Water (unit?)	Volatile oil	Enterobacteriaceae	Appearance	Flavour/ Aroma
55	2	Original	46.9 ± 0.5	0.38 ± 0.04	3 in 5	8.5 ± 0.1	8.3 ± 0.4
55	2	Shelf life	51.8 ± 1.3	n.a.	n.a.	9.0 ± 0.5	8.5 ± 0.4
50	4	Original	47.4 ± 0.7	0.38 ± 0.08	4 in 5	8.3 ± 0.3	8.2 ± 0.4
50	4	Shelf life	53.1 ± 0.3	n.a.	n.a.	8.6 ± 0.2	8.5 ± 0.3
50	2	Original	46.7 ± 0.9	0.32 ± 0.04	4 in 5	8.6 ± 0.1	8.4 ± 0.5
50	2	Shelf life	52.1 ± 0.9	n.a.	n.a.	9.2 ± 0.3	8.8 ± 0.4
45	4	Original	47.0 ± 0.6	0.22 ± 0.13	4 in 5	8.4 ± 0.2	8.3 ± 0.4
45	4	Shelf life	52.1 ± 1.6	n.a.	n.a.	8.5 ± 0.3	8.6 ± 0.4
45	2	Original	47.3 ± 0.3	0.28 ± 0.11	5 in 5	8.4 ± 0.3	7.9 ± 0.3
45	2	Shelf life	52.4 ± 1.3	n.a.	n.a.	8.8 ± 0.3	8.6 ± 0.3
Control		Original	47.8 ± 0.8	0.34 ± 0.13	4 in 5	8.3 ± 0.3	8.0 ± 0.3
Control		Shelf life	52.1 ± 1.0	n.a.	n.a.	8.7 ± 0.6	8.7 ± 0.5

Table 43. Coriander in carbon dioxide

Temperature (°C)	Exposure (days)	Sample	Available Water (unit?)	Volatile oil	Appearance	Flavour/ Aroma
55	2	Original	47.4 ± 1.1	0.32 ± 0.08	8.7 ± 0.8	8.6 ± 0.5
50	4	Original	47.7 ± 0.7	0.30 ± 0.07	9.2 ± 0.3	8.8 ± 0.5
50	2	Original	48.2 ± 1.0	0.22 ± 0.13	8.9 ± 0.7	8.6 ± 0.2
45	4	Original	48.1 ± 1.3	0.32 ± 0.04	8.8 ± 0.5	8.4 ± 0.4
45	2	Original	47.9 ± 1.1	0.28 ± 0.08	8.6 ± 0.9	8.7 ± 0.4
Control		Original	48.1 ± 0.3	0.38 ± 0.09	8.9 ± 0.6	8.6 ± 0.4

Fennel

Table 44. Fennel in Air

Temperature (°C)	Exposure (days)	Sample	Available Water (unit?)	Volatile oil	Enterobacteriaceae	Appearance	Flavour/ Aroma
40	4	Original	54.6 ± 3.2	1.36 ± 0.09	1 in 5	8.0 ± 0.9	7.5 ± 1.0
40	4	Shelf life	52.6 ± 1.1	1.36 ± 0.09	0 in 1	9.0 ± 0.3	8.0 ± 0.9
40	2	Original	56.9 ± 3.7	1.4 ± 0	1 in 5	7.6 ± 0.5	6.8 ± 1.0
40	2	Shelf life	53.4 ± 0.9	2.0 ± 0.7	0 in 3	8.9 ± 0.1	8.2 ± 0.5
30	6	Original	55.9 ± 1.9	1.32 ± 0.18	4 in 5	8.0 ± 0.7	7.4 ± 0.3
30	6	Shelf life	53.4 ± 2.0	1.40 ± 0.14	0 in 1	8.7 ± 0.5	7.9 ± 0.7
30	4	Original	55.1 ± 3.3	1.36 ± 0.09	1 in 5	7.2 ± 1.6	6.9 ± 1.6
30	4	Shelf life	53.4 ± 1.6	1.36 ± 0.09	0 in 3	7.0 ± 2.4	6.6 ± 1.5
30	2	Original	57.7 ± 2.5	1.36 ± 0.09	2 in 5	7.7 ± 0.7	7.4 ± 0.5
30	2	Shelf life	54.4 ± 1.5	1.40 ± 0	0 in 4	9.0 ± 0.3	8.0 ± 0.4
Control		Original	56.3 ± 1.9	1.30 ± 0.14	0 in 1	5.5	6.0
Control		Shelf life	50.5	1.2	0 in 1	4.6	4.8

Table 45. Fennel in Nitrogen

Temperature (°C)	Exposure (days)	Sample	Available Water (unit?)	Volatile oil	Enterobacteriaceae	Appearance	Flavour/ Aroma
55	2	Original	66.1 ± 7.7	1.7 ± 0.2	0 in 3		
55	2	Shelf life	47.5 ± 0.6	1.4 ± 0.4	0 in 5	8.9 ± 0.2	8.0 ± 0.5
50	4	Original	65.1 ± 7.9	1.7 ± 0.1	1 in 3		
50	4	Shelf life	48.0 ± 0.1	2.0 ± 0.7	2 in 5	8.6 ± 0.6	7.8 ± 0.8
50	2	Original	69.3 ± 7.0	1.7 ± 0.1	0 in 3		
50	2	Shelf life	47.8 ± 0.4	1.7 ± 0.4	0 in 5	8.7 ± 0.3	8.0 ± 0.5
45	4	Original	68.4 ± 7.1	1.7 ± 0.1	0 in 3		
45	4	Shelf life	48.1 ± 0.2	2.1 ± 0.7	1 in 5	8.6 ± 0.4	7.6 ± 0.4
45	2	Original	64.7 ± 7.2	1.7 ± 0.1	0 in 3		
45	2	Shelf life	48.2 ± 0.3	1.6 ± 0.1	1 in 5	8.5 ± 0.4	7.8 ± 0.5
Control		Original	65.2 ± 8.2	1.7 ± 0.1	0 in 5		
Control		Shelf life	48.0 ± 0.1	2.0 ± 0.7	1 in 5	8.6 ± 0.6	7.8 ± 0.8

Table 46. Fennel in Burner Gas

Temperature (°C)	Exposure (days)	Sample	Available Water (unit?)	Volatile oil	Enterobacteriaceae	Appearance	Flavour/ Aroma
55	2	Original	47.2 ± 0.6	2.0 ± 0.3	0 in 5	8.3 ± 0.4	7.3 ± 0.5
55	2	Shelf life	50.4 ± 0.6			8.9 ± 0.5	8.4 ± 0.4
50	4	Original	45.8 ± 0.6	2.1 ± 0.5	0 in 5	8.7 ± 0.4	7.8 ± 0.4
50	4	Shelf life	50.8 ± 0.6			8.8 ± 0.6	8.3 ± 0.4
50	2	Original	46.9 ± 0.9	2.1 ± 0.3	1 in 5	8.4 ± 0.6	8.0 ± 0.3
50	2	Shelf life	49.8 ± 0.8			9.2 ± 0.2	8.6 ± 0.3
45	4	Original	46.9 ± 0.6	2.0 ± 0.3	0 in 5	8.7 ± 0.4	7.7 ± 0.4
45	4	Shelf life	50.9 ± 0.6			9.0 ± 0.6	8.7 ± 0.6
45	2	Original	46.4 ± 0.7	2.0 ± 0.5	3 in 5	8.7 ± 0.3	8.1 ± 0.9
45	2	Shelf life	50.5 ± 0.4			8.9 ± 0.2	8.5 ± 0.4
Control		Original	46.9 ± 1.3	1.8 ± 0.5	1 in 5	8.4 ± 0.7	7.5 ± 0.6
Control		Shelf life	51.1 ± 0.9			8.9 ± 0.2	8.4 ± 0.3

Table 47. Fennel in carbon dioxide

Temperature (°C)	Exposure (days)	Sample	Available Water (unit?)	Volatile oil	Appearance	Flavour/ Aroma
55	2	Original	46.3 ± 0.8	2.1 ± 0.1	9.0 ± 0.2	8.2 ± 0.6
50	4	Original	45.9 ± 0.8	2.2 ± 0.3	9.2 ± 0.3	8.8 ± 0.5
50	2	Original	46.4 ± 0.8	2.2 ± 0.2	8.9 ± 0.5	8.5 ± 0.4
45	4	Original	46.1 ± 0.5	2.3 ± 0.2	8.9 ± 0.6	8.6 ± 0.3
45	2	Original	45.9 ± 0.4	2.3 ± 0.2	9.1 ± 0.3	8.3 ± 0.6
Control		Original	45.9 ± 0.3	2.2 ± 0.2	9.1 ± 0.4	8.4 ± 0.6

Rice

Table 48. Rice in Air - First test

Temperature (°C)	Exposure (days)	Sample	Aerobic plate count (g)	Yeasts (g)	Moulds (%)	Bacillus cereus (g)	E.coli	Salmonella	Moisture (%)	Organoleptic Assessment
45	4	Original	43000 ± 15000	67 ± 115	53 ± 92	< 100	Absent	Absent	12.0 ± 0.1	Satisfactory
45	4	Shelf life	109000 ± 71000	< 10	33 ± 58	< 100	Absent	Absent	10.3 ± 0.2	Satisfactory
45	3	Original	53000 ± 29000	< 10	27 ± 46	< 100	Absent	Absent	12.2 ± 0.1	Satisfactory
45	2	Original	83000 ± 15000	37 ± 32	< 10	< 100	Absent	Absent	11.6 ± 0.0	Satisfactory
45	2	Shelf life	29000 ± 11000	< 10	< 10	< 100	Absent	Absent	10.6 ± 0.2	Satisfactory
35	4	Original	180000 ± 110000	20 ± 35	93 ± 101	< 100	Absent	Absent	12.0 ± 0.1	Satisfactory
35	4	Shelf life	31000 ± 7000	< 10	< 10	< 100	Absent	Absent	10.5 ± 0.2	Satisfactory
35	3	Shelf life	40000 ± 27000	< 10	< 10	< 100	Absent	Absent	11.2 ± 0.1	Satisfactory
35	2	Original	84000 ± 14000	113 ± 115	23 ± 40	< 100	Absent	Absent	11.7 ± 0.1	Satisfactory
35	2	Shelf life	52000 ± 25000	< 10	33 ± 58	< 100	Absent	Absent	10.7 ± 0.0	Satisfactory
Control		Original	190000 ± 21000	60 ± 17	500 ± 866	< 100	Absent	Absent	12.3 ± 0.1	Satisfactory
Control		Shelf life	190000 ± 200000	< 10	100 ± 173	< 100	Absent	Absent	10.8 ± 0.1	Satisfactory

Table 49. Rice in Air – Second test

Temperature (°C)	Exposure (days)	Sample	Aerobic plate count (g)	Yeasts (g)	Moulds (%)	Bacillus cereus (g)	E.coli	Salmonella	Moisture (%)	Organoleptic Assessment
55	6	Original	233 ± 115	< 10	< 10	< 100	Absent	Absent	12.1 ± 0.0	Satisfactory
55	4	Shelf life	33 ± 58	< 10	< 10	< 100	Absent	Absent	12.2 ± 0.1	Satisfactory
55	2	Original	233 ± 58	< 10	< 10	< 100	Absent	Absent	12.4 ± 0.0	Satisfactory
55	2	Shelf life	33 ± 58	< 10	< 10	< 100	Absent	Absent	12.4 ± 0.1	Satisfactory
50	4	Original	233 ± 58	< 10	< 10	< 100	Absent	Absent	12.4 ± 0.1	Satisfactory
50	2	Original	440 ± 225	< 10	< 10	< 100	Absent	Absent	12.6 ± 0.2	Satisfactory
Control		Original	1233 ± 1115	< 10	33 ± 58	< 100	Absent	Absent	12.8 ± 0.1	Satisfactory
Control		Shelf life	267 ± 58	< 10	< 10	< 100	Absent	Absent	12.8 ± 0.1	Satisfactory

Table 50. Rice in Nitrogen

Temperature (°C)	Exposure (days)	Sample	Aerobic plate count (g)	Yeasts (g)	Moulds (%)	Bacillus cereus (g)	E..coli	Salmonella	Moisture (%)	Organoleptic Assessment
55	4	Original	633 ± 351	< 10	< 10	< 100	Absent	Absent	10.2 ± 0.1	Satisfactory
55	4	Shelf life	300 ± 141	< 10	< 10	< 100	Absent	Absent	10.1 ± 0.1	Satisfactory
50	4	Original	367 ± 115	< 10	< 10	< 100	Absent	Absent	10.7 ± 0.0	Satisfactory
50	4	Shelf life	400 ± 141	< 10	< 10	< 100	Absent	Absent	10.5 ± 0.2	Satisfactory
50	2	Original	2333 ± 1443	67 ± 115	< 10	< 100	Absent	Absent	10.7 ± 0.1	Satisfactory
50	2	Shelf life	230 ± 170	< 10	< 10	< 100	Absent	Absent	10.5 ± 0.2	Satisfactory
45	4	Original	1333 ± 763	< 10	33 ± 58	< 100	Absent	Absent	10.6 ± 0.1	Satisfactory
45	4	Shelf life	250 ± 71	< 10	67 ± 58	< 100	Absent	Absent	10.3 ± 0.0	Satisfactory
45	2	Original	2633 ± 2950	< 10	< 10	< 100	Absent	Absent	10.7 ± 0.0	Satisfactory
45	2	Shelf life	325 ± 35	< 10	33 ± 58	< 100	Absent	Absent	10.3 ± 0.2	Satisfactory
Control		Original	1933 ± 603	< 10	67 ± 115	< 100	Absent	Absent	10.7 ± 0.1	Satisfactory
Control		Shelf life	533 ± 431	< 10	33 ± 58	< 100	Absent	Absent	10.5 ± 0.2	Satisfactory

Table 51. Rice in Burner Gas

Temperature (°C)	Exposure (days)	Sample	Aerobic plate count (g)	Yeasts (g)	Moulds (%)	Bacillus cereus (g)	E..coli	Salmonella	Moisture (%)	Organoleptic Assessment
55	4	Original	5833 ± 5408	< 10	< 10	< 100	Absent	Absent	9.4 ± 0.2	Satisfactory
55	4	Shelf life	2167 ± 1155	< 10	< 10	< 100	Absent	Absent	10.4 ± 0.1	Satisfactory
50	4	Original	4567 ± 2982	< 10	< 10	< 100	Absent	Absent	9.8 ± 0.3	Satisfactory
50	4	Shelf life	3233 ± 750	< 10	87 ± 150	< 100	Absent	Absent	10.5 ± 0.2	Satisfactory
50	2	Original	9000 ± 4583	< 10	550 ± 218	< 100	Absent	Absent	9.7 ± 0.1	Satisfactory
50	2	Shelf life	9333 ± 4725	< 10	40 ± 36	< 100	Absent	Absent	10.5 ± 0.1	Satisfactory
45	4	Original	12667 ± 3786	< 10	< 10	< 100	Absent	Absent	9.5 ± 0.3	Satisfactory
45	4	Shelf life	54000 ± 65848	< 10	133 ± 23	< 100	Absent	Absent	10.6 ± 0.3	Satisfactory
45	2	Original	11667 ± 3786	< 10	150 ± 50	< 100	Absent	Absent	9.7 ± 0.2	Satisfactory
45	2	Shelf life	16667 ± 2081	< 10	73 ± 40	< 100	Absent	Absent	10.7 ± 0.3	Satisfactory
Control		Original	24333 ± 10116	< 10	100 ± 0	< 100	Absent	Absent	9.9 ± 0.3	Satisfactory
Control		Shelf life	27000 ± 13000	< 10	23 ± 40	< 100	Absent	Absent	10.5 ± 0.1	Satisfactory

Table 52. Rice in carbon dioxide

Temperature (°C)	Exposure (days)	Sample	Aerobic plate count (g)	Yeasts (g)	Moulds (%)	Bacillus cereus (g)	E.coli	Salmonella	Moisture (%)	Organoleptic Assessment
50	4	Original	4500 ± 866	< 10	< 10	< 100	Absent	Absent	9.3 ± 0.1	Satisfactory
50	2	Shelf life	11833 ± 5838	< 10	33 ± 58	< 100	Absent	Absent	9.3 ± 0.1	Satisfactory
45	4	Original	12667 ± 3215	< 10	< 10	< 100	Absent	Absent	9.6 ± 0.1	Satisfactory
45	2	Shelf life	12133 ± 9626	< 10	243 ± 150	< 100	Absent	Absent	9.4 ± 0.1	Satisfactory
Control		Shelf life	20333 ± 7095	< 10	190 ± 95	< 100	Absent	Absent	9.3 ± 0.1	Satisfactory

Walnuts

Table 53. Walnuts in Air - First test

Temperature (°C)	Exposure (days)	Sample	Chemical Report			Microbiological Report				
			Moisture	FFA	PV	TVC	Coliforms	E. coli	Yeast	Mould
40	4	Original	2.84 ± 0.17	18.9 ± 1.6	0.86 ± 0.11	<1000	<10	<10	<1000	<1000
40	2	Original	2.96 ± 0.23	19.0 ± 2.9	0.81 ± 0.11	<1000	<10	<10	<1000	<1000
30	6	Original	3.00 ± 0.18	17.9 ± 2.6	1.18 ± 0.63	<1000	<10	<10	<1000	<1000
30	4	Original	2.80 ± 0.21	15.1 ± 4.3	0.98 ± 0.21	1000	<10	<10	<1000	<1000
30	2	Original	2.91 ± 0.18	18.4 ± 3.3	1.15 ± 0.40	<1000	<10	<10	<1000	<1000
Control		Original	2.90 ± 0.31	17.9 ± 3.6	0.85 ± 0.20	3000	<10	<10	<1000	<1000

Table 54. Walnuts in Nitrogen

Temperature (°C)	Exposure (days)	Sample	Chemical Report			Microbiological Report				
			Moisture	FFA	PV	TVC	Coliforms	E. coli	Yeast	Mould
55	2	Original	3.0 ± 0.3	0.85 ± 0.8	9.3 ± 4.4	1400	<10	<10	1700	400
50	4	Original	2.8 ± 0.3	0.93 ± 0.22	17.1 ± 5.4	800	<10	<10	<100	100
50	2	Original	3.1 ± 0.2	0.93 ± 0.10	15.2 ± 3.8	200	<10	<10	<100	100
45	4	Original	3.3 ± 0.2	0.88 ± 0.08	17.3 ± 1.8	2200	<10	<10	<100	100
45	2	Original	3.4 ± 0.1	0.82 ± 0.09	21.3 ± 4.9	800	<10	<10	<100	100
Control		Original	3.3 ± 0.3	0.95 ± 0.21	26.2 ± 4.8	<100	<10	<10	<100	100

Table 55. Walnuts in Burner Gas

Temperature (°C)	Exposure (days)	Sample	Chemical Report			Microbiological Report				
			Moisture	FFA	PV	TVC	Coliforms	E. coli	Yeast	Mould
55	2	Original	3.31 ± 0.11	0.99 ± 0.28	9.2 ± 1.0	300	<10	<10	<100	550
50	4	Original	3.38 ± 0.16	0.96 ± 0.16	11.4 ± 2.5	660	<10	<10	<100	1580
50	2	Original	3.48 ± 0.14	0.93 ± 0.14	15.4 ± 2.2	50	<10	<10	<100	<100
45	4	Original	3.39 ± 0.19	1.10 ± 0.20	15.6 ± 7.5	170	<10	<10	<100	200
45	2	Original	3.51 ± 0.05	1.01 ± 0.14	19.5 ± 3.9	80	<10	<10	600	100
Control		Original	3.87 ± 0.06	0.78 ± 0.04	19.7 ± 1.3	50	<10	<10	<100	<100

Table 56. Walnuts in carbon dioxide

Temperature (°C)	Exposure (days)	Sample	Chemical Report			Microbiological Report					Organoleptic Trial (% correct)
			Moisture	FFA	PV	TVC	Coliforms	E. coli	Yeast	Mould	
55	2	Original	3.45 ± 0.25	0.91 ± 0.08	7.7 ± 2.2	760	<10	<10	220	<100	48 (n=29)
50	4	Original	3.84 ± 0.22	0.99 ± 0.12	3.5 ± 0.9	260	<10	<10	400	<100	24 (n=29)
50	2	Original	3.64 ± 0.24	0.92 ± 0.14	9.3 ± 3.4	900	<10	<10	<100	<100	50 (n=12)
45	4	Original	3.87 ± 0.15	1.20 ± 0.41	6.3 ± 1.9	1120	<10	<10	460	<100	45 (n=29)
45	2	Original	3.72 ± 0.24	1.00 ± 0.17	7.2 ± 2.8	460	<10	<10	160	100	42 (n=12)
Control		Original	4.07 ± 0.10	0.88 ± 0.08	5.9 ± 0.3	470	<10	<10	130	300	

Apricots

Table 57. Apricots in Air – Test 1

Temperature (°C)	Exposure (days)	Sample	Chemical Report		Microbiological Report				
			Moisture	Sulphur dioxide	TVC	Coliforms	E. coli	Yeast	Mould
40	4	Original	27.6 ± 1.35	1468 ± 65	100	<10	<10	63000	<10
40	2	Original	26.9 ± 0.9	1472 ± 57	<100	<10	<10	50000	<10
30	6	Original	28.9 ± 1.7	1536 ± 112	<100	<10	<10	1500	<10
30	4	Original	29.5 ± 0.4	1564 ± 49	<100	<10	<10	<100	<10
30	2	Original	29.1 ± 0.6	1558 ± 73	<100	<10	<10	100	<10
Control		Original	28.9 ± 1.9	1580 ± 60	100	<10	<10	100	<10

Table 58. Apricots in Air – Test 2

Temperature (°C)	Exposure (days)	Sample	Chemical Report		Microbiological Report								
			Moisture	Sulphur dioxide	TVC	Coliforms	E. coli	Yeast	Mould	OSOMO Yeast			
50	4	Original	16.4 ± 0.4	812 ± 122	<100	<10	<10	<100	<100	<100	<100	<100	
50	4	Shelf Life	15.7 ± 1.6	1128 ± 120	<100	<10	<10	<100	<100	1200	<100	<100	
45	4	Original	17.2 ± 2.1	981 ± 27	<100	<10	<10	<100	<100	200	<100	<100	
45	4	Shelf Life	16.4 ± 0.2	1289 ± 50	<100	<10	<10	<100	<100	<100	<100	<100	
40	4	Original	17.6 ± 0.8	1066 ± 62	<100	<10	<10	3200	<100	7000	<100	<100	
40	4	Shelf Life	18.9 ± 1.8	1367 ± 119	<100	<10	<10	<100	<100	4500	<100	<100	
Control		Original	16.5 ± 1.4	1122 ± 249	<100	<10	<10	7000	<100	12000	<100	<100	
Control		Shelf life	16.5 ± 1.4	1473 ± 205	<100	<10	<10	<100	<100	40000	<100	<100	

Table 59. Apricots in Nitrogen

Temperature (°C)	Exposure (days)	Sample	Chemical Report		Microbiological Report							Organoleptic Trial (% correct)
			Moisture	Sulphur dioxide	TVC	Coliforms	E. coli	Yeast	Mould	OSOMO Yeast	OSOMO Mould	
50	4	Original										
50	4	Shelf Life	17.1 ± 0.5	1576 ± 253	<100	<10	<10	<100	<100	<100	<100	40 (n=25)
45	4	Original										
45	4	Shelf Life	17.3 ± 1.0	1591 ± 79	100	<10	<10	<100	<100	<100	<100	36 (n=25)
40	4	Original										
40	4	Shelf Life	16.7 ± 0.9	1700 ± 318	<100	<10	<10	<100	<100	<100	<100	48 (n=25)
Control		Original										
Control		Shelf life	15.9 ± 0.7	1597 ± 197	<100	<10	<10	<100	<100	<100	<100	

Table 60. Apricots in Burner Gas

Temperature (°C)	Exposure (days)	Sample	Chemical Report		Microbiological Report						Organoleptic Trial (% correct)	
			Moisture	Sulphur dioxide	TVC	Coliforms	E. coli	Yeast	Mould	OSOMO Yeast		OSOMO Mould
50	4	Original	16.1 ± 1.0	1729 ± 136	<100	<10	<10	<100	<100	<100	<100	
50	4	Shelf Life										
45	4	Original	17.0 ± 0.7	1667 ± 60	<100	<10	<10	<100	<100	<100	<100	25 (n=12)
45	4	Shelf Life										
40	4	Original	17.0 ± 0.7	1667 ± 60	<100	<10	<10	<100	<100	<100	<100	33 (n=12)
40	4	Shelf Life										
Control		Original	16.6 ± 0.6	1948 ± 148	<100	<10	<10	<100	<100	<100	<100	58 (n=12)
Control		Shelf life										

Table 61. Summary of results of tests at raised temperature in air or low oxygen on commodity quality

Commodity	Temperature limit (°C)
Cocoa	50
Coffee	50
Coriander	55
Fennel	55
Rice	55
Walnut	50
Dried apricot	45

3.4 Discussion

The temperature differential between the extent to which the atmosphere can be heated, as determined by the upper limit tolerated by the commodity, and the target temperature for pest control, is a crucial factor in determining heating rates. The greater the difference between these temperatures, the better the prospects for engineering an economic treatment system. For most of the commodities tested here there was a generous margin available, up to 15°C. The pests of rice were the most heat tolerant, requiring exposure at 44°C for control within 24 h (Table 21), but fortunately rice proved to be one of the most heat tolerant commodities (Table 61). Indeed some industry sources indicate that rice is unaffected by exposures to temperatures of 60°C or even higher, beyond the range of those tested here. For seasonings such as coriander and fennel there was a window between 40 and 55°C while for coffee and cocoa the window lay between 35 and 50°C. Walnuts also share this latter window because the most difficult to kill fruit and nut pest, the dried fruit mite *Carpoglyphus lactis* (Table 23) rarely occurs on tree nuts. Dried fruit such as apricots, however, have a narrower band of temperatures available (Table 61). This coupled with the considerable difficulties for achieving any enhancement over temperature transfer by conduction for the packed commodity by using convection systems makes it very unlikely that a raised temperature MA treatment method can be made sufficiently effective for this commodity.

4. TRIALS ON THE HEATING OF COMMODITIES

The purpose of this LINK project was to find a practical alternative to fumigation with methyl bromide and so tests were carried out on a small commercial scale to validate the parameters and principles emerging from the laboratory and modelling test programmes. The decision to use MA at raised temperatures was based on the industry wish for treatment times ideally to be no longer than two days. However, the treatment can only be effective if the commodity itself is heated throughout to the treatment temperature. The limiting factor for the total treatment time required for the technique to work effectively is the rate of heat transfer through the commodity rather than the time taken to achieve the low oxygen atmosphere throughout the treatment area using the high output propane burner.

4.1 Preliminary tests

Since little of the required commodity data is available in the literature the complete range of physical and thermal properties were measured at the outset of the project. Bulk density, moisture content, porosity, permeability, specific heat and thermal conductivity values were obtained, using standard methods, for cocoa (5 origins), coffee (5 origins), coriander, fennel, peanut, rice, walnut and dried apricot. The parameters for heating each commodity by convection in a fixed flow rate per tonne of commodity are shown in Table 62 below. The rate of heating of commodities will differ according to the heat source and hence the method of heating.

Table 62. Heating times and airflow resistance in various commodities

<i>Commodity</i>	Estimated* heating time to 35°C, hours	Estimated* air pressure per metre depth, Pa
Cocoa	5.5	90 – 115
Coffee	6	220 – 250
Coriander	8	325
Fennel	7.5	550
Peanut	5.5	150
Rice	3.5	675
Walnut	6.8	45
Dried apricot	6	1275 (loose) 4285 (packed)

* Assuming air at 35°C, start temperature 20°C and an air flow rate of 10 m³/min per tonne of commodity

To complement these findings preliminary tests concentrated on heating by conduction in incubators set up for testing of effects on product quality. Results from these tests revealed some notable differences between commodities in heating rates, with cocoa beans being the slowest to heat up while coffee, rice, fennel and coriander heated much more rapidly (Table 63).

Table 63. Times taken by small parcels of commodities to heat by conduction

Commodity	Quantity	Temp. rise (°C)	Time to target -5°C	Time to target -1°C
Cocoa	2.5 kg	20	4 h	7 h
Coffee	1 kg	10	25 min	75 min
		20	40 min	1 h 30 min
		30	60 min	2 h
Coriander	1 kg	10	10 min	60 min
		20	35 min	80 min
		25	60 min	2 h
		30	80 min	2 h 30 min
Fennel	1 kg	10	10 min	60 min
		20	30 min	70 min
		25	50 min	1 h 45 min
		30	65 min	2 h
Rice	750 g	15	20 min	75 min
		25	45 min	2 h
		35	60 min	2 h 30 min
Walnut	2 kg	10	15 min	2 h
		20	45 min	2 h 30 min
		30	100 min	4 h
Dried apricot	2.5 kg	10	1 h 45 min	4 h
		20	2 h 30 min	5 h 30 min

A subsequent test examined a commercially packaged 12.5 kg box of dried apricots in comparison with a similar quantity of cocoa beans in a light plastic container. Again the cocoa was slower to heat up. Over 24 hours were required for a temperature rise from seven to two degrees below the heating atmosphere temperature, as shown below:

Cocoa heating from -7 to -2 °C from target temperature:	24 h
Apricots heating from -7 to -2 °C “ “ “	14 h
“ “ “ -12 to -7 °C “ “ “	7 h

Hence apricots heated from -12 to -2 °C faster than cocoa from -7 to -2 °C. The reason for this may be because of the lower degree of contact between beans than for apricots, reducing the efficiency of heating by conduction. These heating times are very different from those presented in Table 27 for 1.2 m cubes of commodity, but here the cocoa was tested in a plastic sealed container and not in the typical hessian sack and the comparison was made on a commodity weight basis and not volume.

4.2 Larger scale trials

To improve upon heating rates by conduction alone, the larger scale trials were based on convectional heating by heated air/MA. The modelling studies provided some guidance on the flow rates of air required for the heating of a bulk of commodity (Tables 27 and 31).

4.2.1 Provision of the modified atmosphere for the trials

A self-cooled propane burning low oxygen atmosphere generator had been developed by CSL to hold loaded grain bins of up to 1000 tonnes capacity under an atmosphere of less than 1% oxygen. This machine was tested to gauge the range of temperatures and humidities it could deliver a low oxygen atmosphere without major engineering changes, based on the use of a dampening cover mounted over the heat exhaust fan and the alteration of air input rate. It was established that temperatures of between 10 and 15°C above ambient could readily be achieved in the product gas with accompanying humidity levels of 45 - 55% r.h. Moderate damping of the exhaust fan enabled the system to run without activation of the safety cut out on the coolant circuit. Ambient temperatures during the trial ranged from 16 to 19°C (Table 64).

Table 64. Output gas properties from the modified propane burner

Ambient temp. (°C)	Flow rate (litres/min)	% Oxygen	Gas temperature (°C)	Gas humidity (% r.h.)
16.6	264	1.2	27.6	55
16.8	254	1.4	27.4	55
16.8	157	0.4	27.1	53
17.2	157	0.3	27.4	54
18.5	123	1.3	31.8	49
17.0	124	1.3	31.7	46

4.2.1 Trials in a modified container

Recognising the difficulty likely to be encountered for some commodities such as rice and dried apricots, a freight container was purchased for the project and was modified to provide as far as was possible a uniform gas and temperature distribution. The seal on the container was improved to achieve a 15 second pressure decay half life. To achieve the transfer of heat most effectively, a system was installed to recirculate heated air and after some warming to inject MA generated by the propane burner into the circulation system. Heat was provided by electric heating elements (power 12 kW) over which a 0.35 kW airfoil fan recirculated the atmosphere within the container at a flow rate of up to 30 cubic metres per minute. A purpose-designed ventilated floor formed the source of heated air entering the main body of the container and making contact with the commodity. A thermostat control held the air temperature below the floor at 50°C. The container walls were insulated with polystyrene and fitted with aluminium cladding as the inner skin.

Trials were conducted on a full container load, on pallets, of 10 tonnes of bagged cocoa, and on two partial loads, 5 tonnes of bagged rice and 4 tonnes of boxed walnuts. The container was partitioned for the partial loads to maximalise air flow rates around the commodities.

4.2.1.1 Heating time results

For the fully loaded container with cocoa in sacks about 24 hours of 50°C air circulation were required for the centre position to heat to the 35°C target temperature (Fig. 34). Purging of the container atmosphere to below 1% oxygen required only 15 h, as measured in the trial with bagged rice (Fig. 35). The input to the container from the burner was 0.2 cubic meters per minute of MA containing 0.2% oxygen and 13% carbon dioxide. The heating of the rice, in spite of the smaller quantity in the container, was somewhat slower than for cocoa, the stack centre temperature levelling off at 38°C after about 30 hours (Fig. 36). Temperatures had still not reached 39°C after 4 days. In the test run with boxed walnuts (Fig. 37), about 48 h heating with circulating atmosphere at 45°C were required to reach the target temperature at the centre of the 4-tonne consignment, but ambient temperatures were about 10°C cooler when this trial was run and when this was taken into account the heating rate was more comparable to that of cocoa.

4.2.2.2 Tests on commodity cooling requirements

Calculations for the design of the cooling system to restore commodities to ambient temperatures after treatment and avoid drying the commodity showed that provided a strong airflow is applied to the commodity, only in extreme cases will any modification to air humidity be needed. Avoidance of extremely humid (>95%r.h.) or very dry (<25%r.h.) conditions will ensure that the moisture content change caused by the cooling process will be minimal. Hence the only design feature for the provision of cooling was the installation of a two-way venting valve on the air flow system to switch from internal to external air circulation. Following the treatment the commodity was cooled to ambient temperature in this way and after modelling studies showed no adverse effects such as moisture variation, by opening the door of the container.

4.2 Discussion

The use of heat alone for commodity disinfestation would entail reaching target temperatures close to the maximum tolerated by the commodity and in practical terms it would not be possible to kill pests throughout a consignment without damage to the peripheral parts of the stack. The most tolerant species to heat alone are *Rhyzopertha dominica* and *Lasioderma serricorne*, followed by *Sitophilus oryzae* and *Tribolium castaneum*, while pyralid moths and *Oryzaephilus* spp. are known to be more susceptible (Kirkpatrick and Tilton, 1972; Evans and Dermott, 1981; Fields, 1992). In the presence of a low oxygen modified atmosphere most of these differences in heat tolerance persist, but the temperatures required for control within 24 hours are reduced by about 5°C. In spite of the 15°C window this creates between the lower limit for insect control and the upper limit for commodity quality preservation, the packaging of products proved to be the major criterion for success of the treatments in the modified freight container.

With the recirculating atmosphere creating a convectional heating system in the container, a very different result was obtained in the heating rates of bagged cocoa and rice than in the incubator tests on heat conduction, with the cocoa reaching 35°C within 24 h and 40°C in 48 h

while half the quantity of rice failed to reach 40°C after 4 days of heating. This was of concern for rice as the target temperature for pest control is much higher than for other commodities. The smaller grain size of the bagged rice undoubtedly restricted the movement of gas. The result in cooler conditions with boxed walnuts indicated that a more powerful heating system would be required to enable treatments within a 24 hour period but the fact that the temperature rise showed no sign of levelling off after the 48 h test run indicated that heat transfer through the boxes, though slow, was effective. The results indicated that boxed dried apricots would be unlikely to heat sufficiently to enable a treatment within a manageable time period, especially when taking into account the higher target temperature.

In conclusion a more powerful air circulation system than that provided by the 350W fan installed in the container would be needed for the successful treatment of bagged coffee, cocoa, coriander or fennel, or boxed walnuts, within a 48-hour period when ambient temperatures are below 20°C, though the extent to which increased air flow can speed heat transfer would require some further investigation. For bagged rice and boxed dried apricots, the heated container does not appear to provide a solution and for rice, as for most commodities other than dried fruit and nuts, the ability to treat in bulk, preferably in silos, offers the best solution. For coffee and cocoa this would offer the prospect of using heat alone, target temperatures for pests of these commodities being less than 45°C.

Fig. 34. Change in temperature and relative humidity while heating bagged cocoa in the container

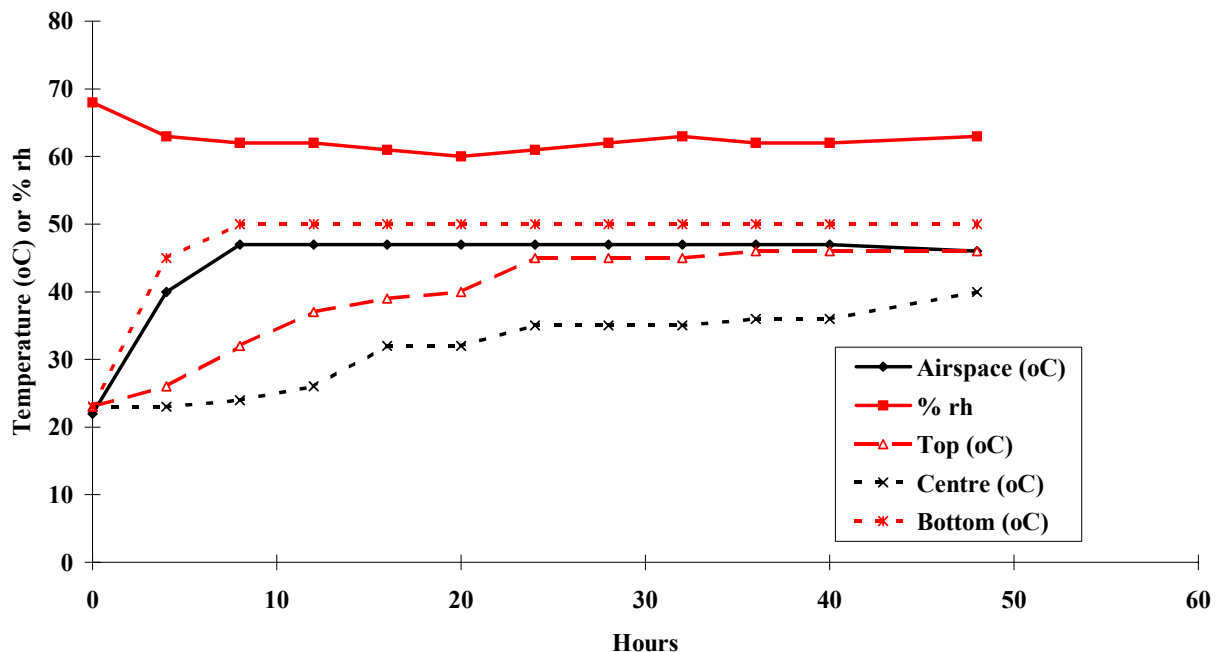


Fig. 35. Change in oxygen content, temperature and relative humidity in burner output and container headspace during trial with bagged rice

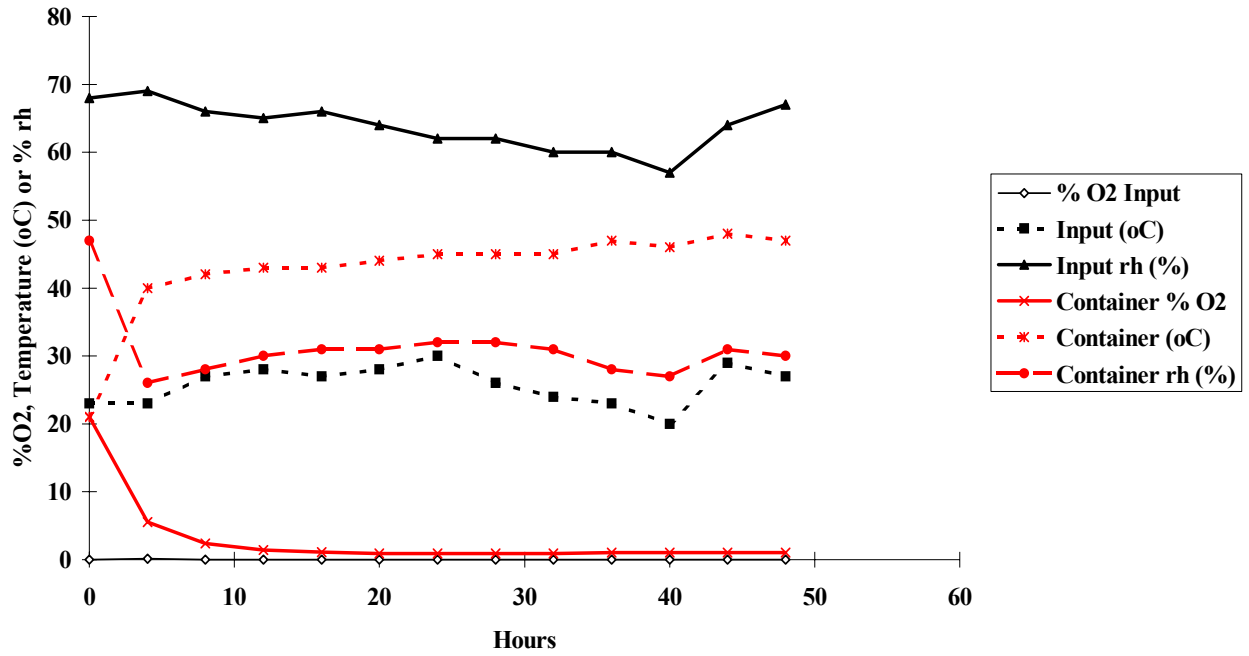


Fig. 36. Change in temperature and humidity while heating bagged rice in the container with burner gas

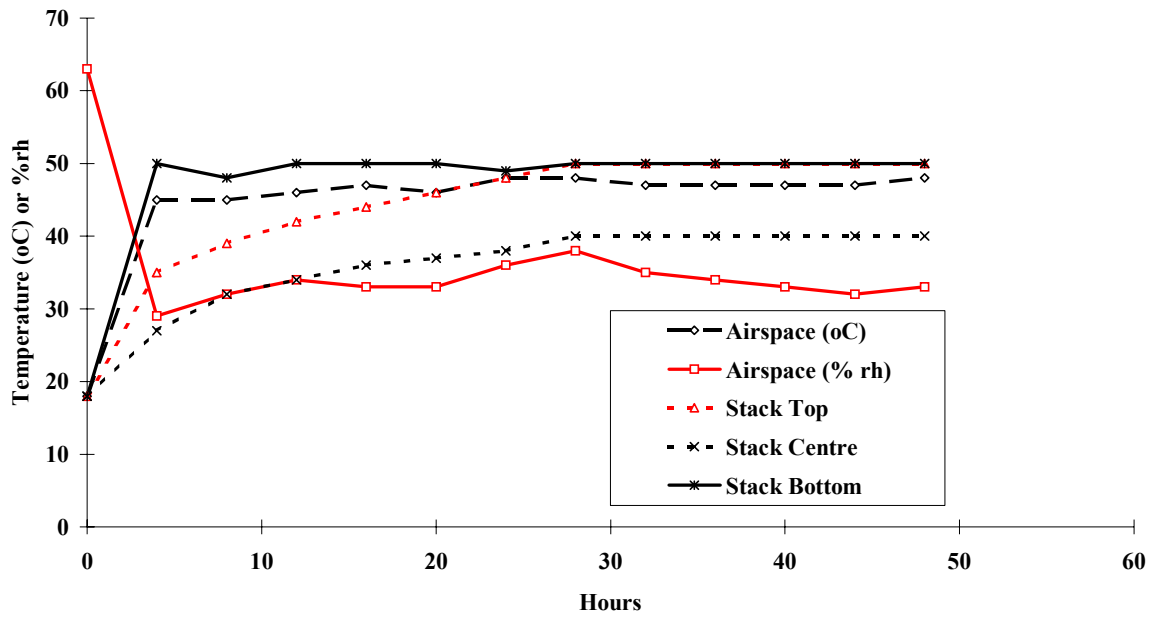
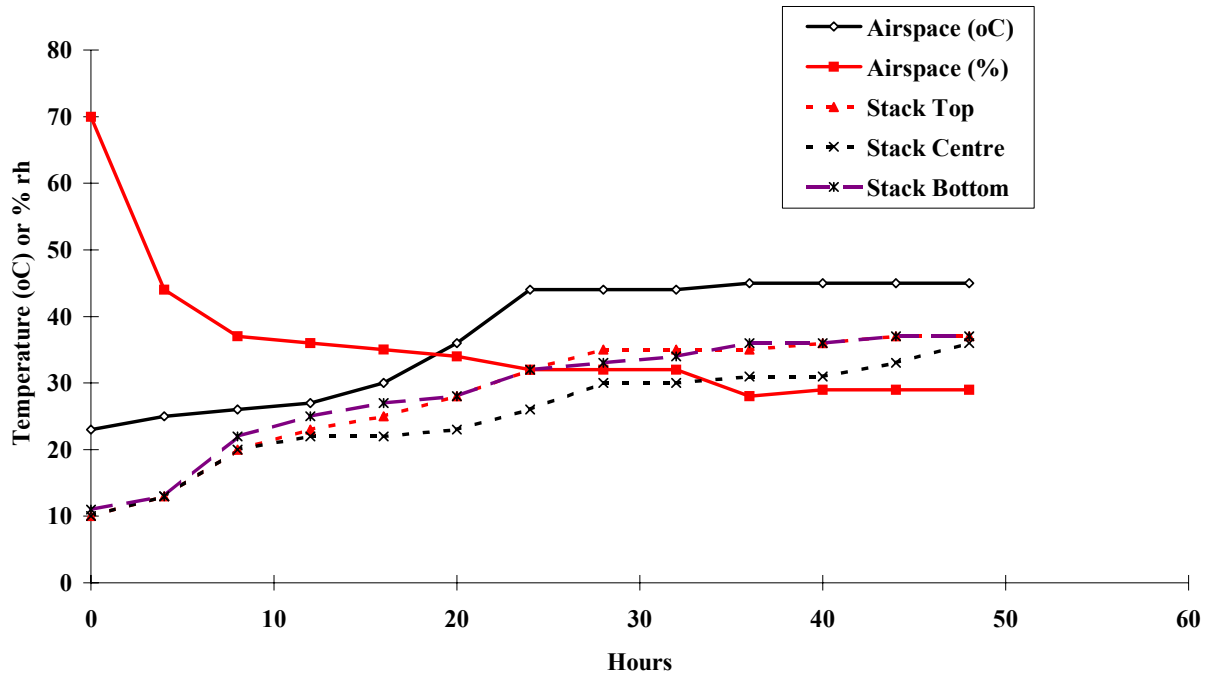


Fig. 37. Change in temperature and relative humidity (%) while heating boxed walnuts in the container



References

- Adler, C., Corinth, H-G. and Reichmuth, C. 2000. Modified atmospheres. In: Subramanyam, Bh., Hagstrum, D. W., (Eds), *Alternatives to pesticides in stored-product IPM*. Kluwer Academic Publishers, Boston, pp. 105-146.
- Annis, P.C. (1987) Toward rational controlled atmosphere dosage schedules: a review of current knowledge. In: Donahaye, E. and Navarro, S., eds., *Proceedings of the 4th International Working Conference on Stored-Product Protection*, 21-26 September, Tel Aviv, Israel, pp. 128-148.
- ASAE Standards (1992) Resistance to airflow of commodities, seeds, other agricultural products, and perforated metal sheets. D272.2.
- Bejan, A. (1993) *Heat Transfer*. John Wiley & Sons.
- Bell, C.H. and Armitage, D.M. (1992) *Alternative storage practices*. pp. 249-311 in: *Storage of Cereal Grains and their Products*, D.B.Sauer (ed.). American Association of Cereal Chemists, St Paul, MN.
- Bird, R.B., Stewart, W.E. and Lightfoot, E.N. (1960) *Transport Phenomena*. Wiley.
- Boyce, D.S. (1965) Commodity moisture and temperature changes with position and time during through drying. *Journal of Agricultural Engineering Research*, 10, 333-341.
- CFX4.3 (1999), AEA Technology, Harwell, Oxfordshire, UK.
- Corinth, H.G. and Reichmuth, C. (1995) Verfahren zum Entwesen von Gebauden [Method for disinfection of buildings]. European Patent, Kohlensaure-Werke Rud. Buse GmbH & Co., Tag der Veröffentlichung: 4th Jan 1995, Patent No. 0416255, 5 S.
- Evans, D.E. and Dermott, T. (1981) Dosage-mortality relationships for *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae) exposed to heat in a fluidised bed. *Journal of Stored Products Research* 17, 53-64.
- Fields, P.G. (1992) The control of stored product insects and mites with extreme temperatures. *Journal of Stored Products Research* 28, 89-118.
- Kirkpatrick, R. L. and Tilton, E.W. (1972) Infrared radiation to control adult stored-product Coleoptera. *Journal of the Georgia Entomological Society* 7, 73-75.
- Jay, E.G. (1986) Factors affecting the use of carbon dioxide for treating raw and processed agricultural products. GASGA Seminar on Fumigation Technology in Developing Countries. Tropical Development and Research Institute, London, pp 173-189.
- Kumar, A. and Muir, W.E. (1986) Airflow resistance of wheat and barley affected by airflow direction, filling method and dockage. *Transactions of the ASAE* 29, 1423-1426.
- Le Patourel, G.N.J. (1986) The effect of grain moisture content on the toxicity of a sorptive silica dust to four species of grain beetle. *Journal of Stored Products Research* 22, 63-69.
- Sun, Y., Pantelides, C.C. and Chalabi, Z.S. (1995) Mathematical modelling and simulation of near-ambient commodity drying. *Computers and Electronics in Agriculture* 13, 243-271.