# The performance of a novel grain cooling system

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*Abstract*

A particularly simple to construct thermally reactivated desiccant air conditioning system has been developed to cool farm-stored grains. It consists of a heat and mass exchanger that contains a desiccant that dries ambient air almost isothermally, an axial flow fan that removes the heat of sorption of the water on the desiccant during the grain cooling cycle, and a centrifugal fan that forces the air through the desiccant material and the stored grain The heat of sorption would normally be liberated inside the grain store, and this would limit the degree to which the grains would be cooled. A separate source of heat, such as a gas burner or solar collector, is required to reactivate the desiccant during the day. The system has no more moving parts than a conventional aeration system, save for an axial flow fan and a valve. The performance of the system was evaluated at three locations in Australia, namely Walla Walla and Moree in New South Wales and Warwick in Queensland during 1997 and 1998 A gas heater was used to regenerate the silica gel in the New South Wales experiments, and this was augmented by a solar air heater in the experiments carried out at Warwick. During the Walla Walla trial, the grain cooling system reduced the seed wet-bulb temperature of 104 tonnes triticale from 13.2℃ to 10.6℃, whereas during the Moree trial, the system reduced the seed wet-bulb temperature of 110 tonnes sorghum from 20.3℃ to 9.6℃ In the Queensland experiment the wet-bulb temperature of the intergranular air in a silo containing 50 tonnes of barley was reduced from 23.5℃ to 12.5℃ The electrical energy consumption of the system is about 1.25 kwh per tonne of grain cooled, and the coefficient of performance of the system based on electrical power input (energy supplied to the fans) is over 7

## Introduction

Contact chemical pesticides became widely used to control grain storage insects during the 1960s. However, insects rapidly developed resistance to chemical pesticides used to combat them, and it became necessary to develop more efficacious compounds to control them. Additionally, chemical residues in food grains have become a cause of concern to consumers. For these reasons physical methods of insect control are being investigated that are less likely to give rise to such severe resistance problems, and which leave stored grains completely free of chemical residues. One such non-chemical method of insect control is to cool grain by means of aeration, a process in which air with a suitably low wet-bulb temperature is forced through the stored grains. In many grain growing regions of the world, the heat content of the ambient air is too high to effect sufficient grain cooling to prevent the growth of insect populations. Mechanical refrigeration units may be used to reduce the heat content of ambient air, but such units are complicated to manufacture and expensive to use. Therefore, to meet the need of grain farmers and handlers to cool grains a simple and effective technology is sought that can reduce seed wet-bulb temperatures of bulk stored grains to close or below the threshold seed wet-bulb temperature below which insects cease to breed (Wilson and Desmarchelier, 1994). Thermally reactivated desiccant cooling technology could fulfil this requirement particularly well because the desiccant can be used to dry air during the night, and it can be reactivated during the day. The essence of the technology when it is applied to grain cooling is to reduce the enthalpy, or heat content, of ambient air by dehumidifying it as nearly isothermally as is practicable. It should be noted that the amount of desiccant required for grain cooling purposes is about 0.1% of the weight of grain that is to be cooled This is because the main purpose of the desiccant is to adsorb that small quantity of moisture in the air that would normally be absorbed by the stored grains during one nightly operation of the aeration system. This moisture is then driven off during the day as part of the reactivation cycle. The desiccant is not used to dry ambient air that is subsequently used to dry the mass of stored grains, as appears to have been the intention of Lal and Raman (1996) The desiccant is regenerated using ambient air that is heated using a gas burner, or a renewable source of energy such as solar

There is considerable interdisciplinary research presently being carried out on desiccant cooling systems, and much of the work carried out until 1992 has been summarised by Pesaran et al (1992) in a literature review that cites over 900 publications. The areas under investigation include the development of new desiccants that have an optimal sorption isotherm, *sensu* Collier and Cohen (1991), and desiccants that are not subject to performance degradation as a result of thermal cycling and air borne contaminants (Pesaran, 1993). The development of effective ways of binding desiccants to substrates to minimise parasitic power is also an area of active research (Anderson and Pesaran, 1991), and systems studies play an important role in exploring possible air conditioning systems and operating strategies (Thorpe, 1998). Desiccant solar air conditioning systems have been developed and evaluated under tropical conditions by Dupont et al. (1994 a,b).

Thorpe (1981) presented for the first time the concept of solar reactivated adsorbent bed system for cooling stored food grains. Experiments have indicated that by using the desiccant cooling system, grain temperatures up to 10℃ lower than those produced as a result of conventional ambient aeration can be achieved (Thorpe and Fricke, 1986; Ismail et al., 1991). However, this earlier work suggests that the performance of these devices can be improved if the desiccant beds were to better approach isothermality during the cooling cycle. In addition, the early desiccant cooling devices were not able to condition sufficiently high volume flow rates of air demanded by the Australian grain storage environment. To overcome these limitations the present study was initiated with following specific aims:

- To develop a thermally reactivated desiccant cooling system that is able to cool commercially useful volume flow rates of air to wet-bulb temperatures that are conducive to good grain storage.
- To investigate the possibility of using solar energy to heat the air used to regenerate the desiccant.
- To evaluate the field performance of the desiccant cooling system in order to establish its technical feasibility.

# A Thermally Regenerated Desiccant System for Cooling Stored Grains

## Principles of operation of the desiccant cooling system

It is noted above that the novel grain cooling system described in this paper reduces the enthalpy (and the wet-bulb temperature) of ambient air as a result of drying the air as nearly isothermally as practicable. This lower enthalpy air is far more efficacious in maintaining desirable properties of grains, such as baking quality in the case of wheat, and in reducing the propensity of insect populations to grow. The underlying air conditioning cycle exploited by the grain cooling device can be observed from the psychrometric chart (Figure 1). At night, cool ambient air with a high relative humidity, state 1, is compressed by the aeration fan to state 2. It is this air that would normally be used for ventilating grain in an ambient aeration system, but because of its high relative humidity it has a limited cooling capacity. The air is conditioned from state 2 to 3 by passing it through the novel desiccant cooling device. State 3 represents the state of the air leaving the desiccant cooling system, and it can be seen that the air has been dried almost isothermally as it passes through the device. The air may be further cooled from state 3 to 4 as it flows through the duct that connects the grain cooler to the silo. It is not necessary to thermally insulate the duct that leads from the cooling unit to the store that contains the grain that is being cooled. State 4 represents the air that is used to cool the grains. During the day ambient air at state 5 is first compressed by the aeration fan and then heated by an indirectly fired gas burner and/or a solar collector to state 6; it is this air that is used to reactivate the desiccant during the day. The warm humid air at state 7 is vented to atmosphere.

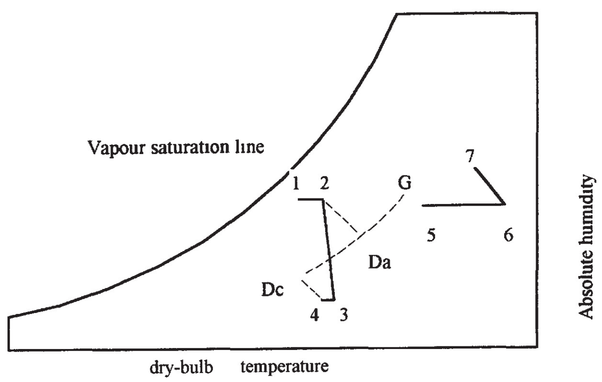


**Fig. 1.** Thermodynamic states of aeration air passing through the desiccant cooling device and the grain in the silo.

Figure 1 also shows the response of the stored grain in the silo to being cooled with either unconditioned ambient air or conditioned air from the desiccant device. In the untreated ambient aeration case, air at state 2 enters the grain, initially at state G, and a relatively fast cooling wave propagates along an $F_1$ line, as described by Banks (1972). The $F_1$ line lies practically along a constant grain moisture content line (Sutherland et al., 1971). A cooling wave propagates through the grain, its leading edge at state $D_a$ and its trailing edge at point 2. During much of the storage period the grain bulk is at the dwell-state, $D_a$, or along the line of almost constant enthalpy, $2 - D_a$. When the grain bulk is cooled with conditioned air leaving the desiccant cooling device at state 4 a similar grain cooling process occurs, but in this case the dwell state, $D_c$, is at a lower temperature and the grain moisture content is marginally less than the dwell state, $D_a$, in the ambient aeration case. During most of the storage period when the desiccant cooling system has been deployed, all of the grains will be cooler and drier than grain cooled by ambient aeration. The conditions achieved by aeration using conditioned air leaving the desiccant cooling system will be more hostile to insects and more conducive to grain preservation.

## Physical realisation of the air conditioning cycle

One of the key features of the design of the novel air conditioning cycle is the mechanism for attaining the nearly isothermal drying of ambient air. Essentially, the silica gel is contained in a series of narrow channels, as shown in Figure 2. Each channel is 1 cm wide. The ambient air to be conditioned is forced upwards through these channels, whence it is dried. As moisture is adsorbed by the silica gel, the heat of sorption is conducted, and to a certain extent dispersed by the flowing air, to the walls of the channels where it is removed by other streams of ambient air flowing horizontally through spaces between the channels containing the silica gel. The beds of silica gel are regenerated during the day by forcing through them air that is warm and has a low relative humidity. Heat loss through the sides of the channels is kept to a minimum during the reactivation cycle by not forcing air between them.

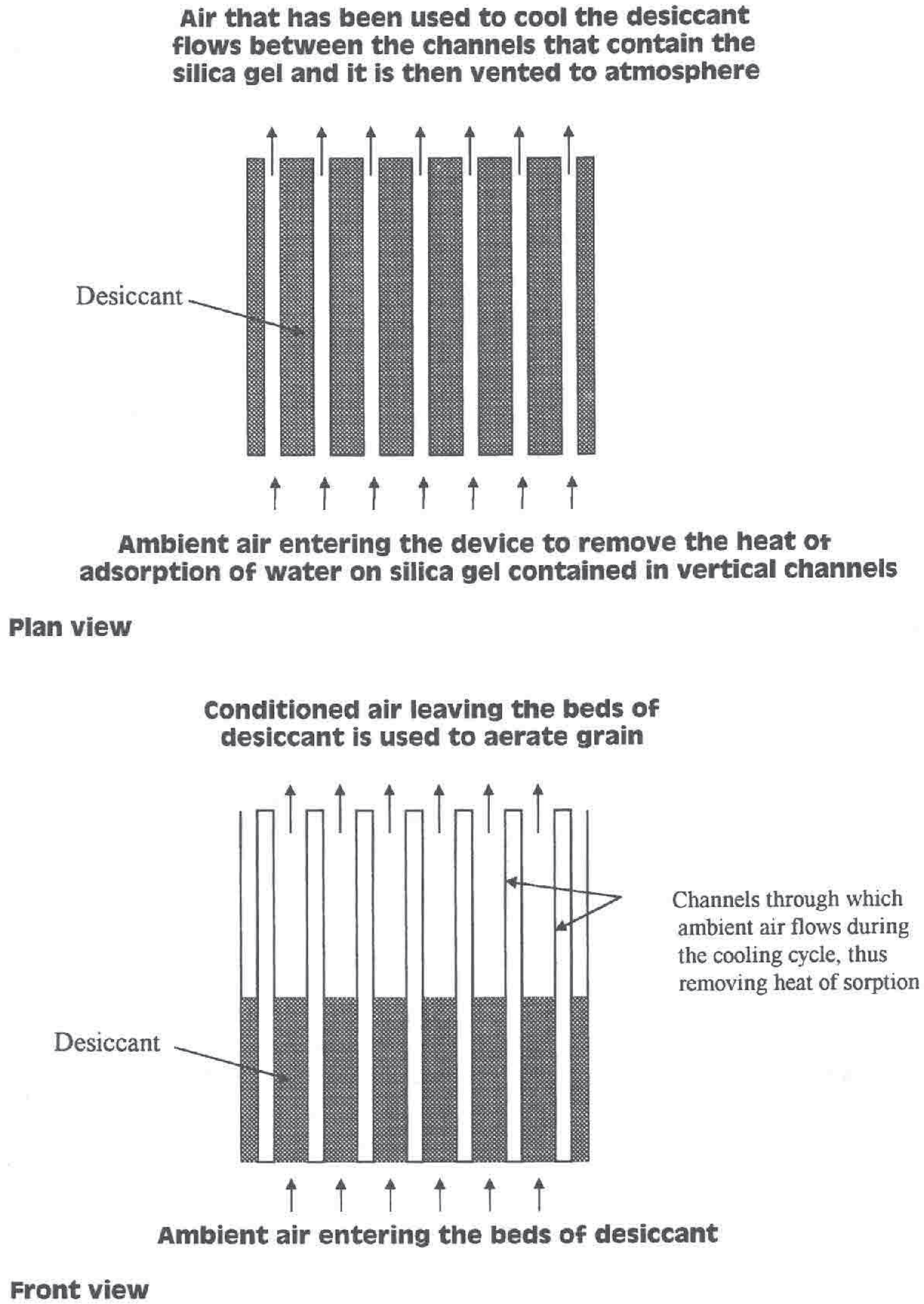


**Fig. 2.** Schematic of the plan and front view of the heat and mass exchanger.

The realisation of the entire system is shown in Figure 3. At night, a centrifugal fan compresses ambient air so that its temperature increases from temperature T1 to temperature T2 as it enters the main body of the cooling device. The ambient air to be used to aerate the grain is dried, and it is maintained close to ambient temperature by the secondary air, also at temperature T1, that is blown across the outside of the channels containing the silica gel. The air leaves the grain cooler with a temperature T3, and it may be cooled somewhat further to temperature T4 as it flows through the duct that connects the cooler and the grain silo. During the field experiments carried out at Walla Walla and Moree ambient air was heated by an indirect-fired gas burner before it was used to regenerate the silica gel A solar air heater was used to supply some of the energy to regenerate the silica gel in the experiments carried out in Warwick, Queensland. The solar heater consists of seven solar collector modules connected in series. Each module has an effective collection area of 1.73 $m^2$ giving a total area of 12.1$m^2$. A detailed description of the solar collectors is given by Ahmad and Thorpe (1997). The axial fan is not operated during the daily reactivation cycle, during which the solenoid valve located in the pipe leaving the cooling unit is opened to allow warm air that has been humidified by the damp silica gel to be vented to atmosphere (air state 7 in figure 1) Figure 4 shows the grain cooling system connected to a 50 tonne capacity silo described by Kotzur and Thorpe (1996)

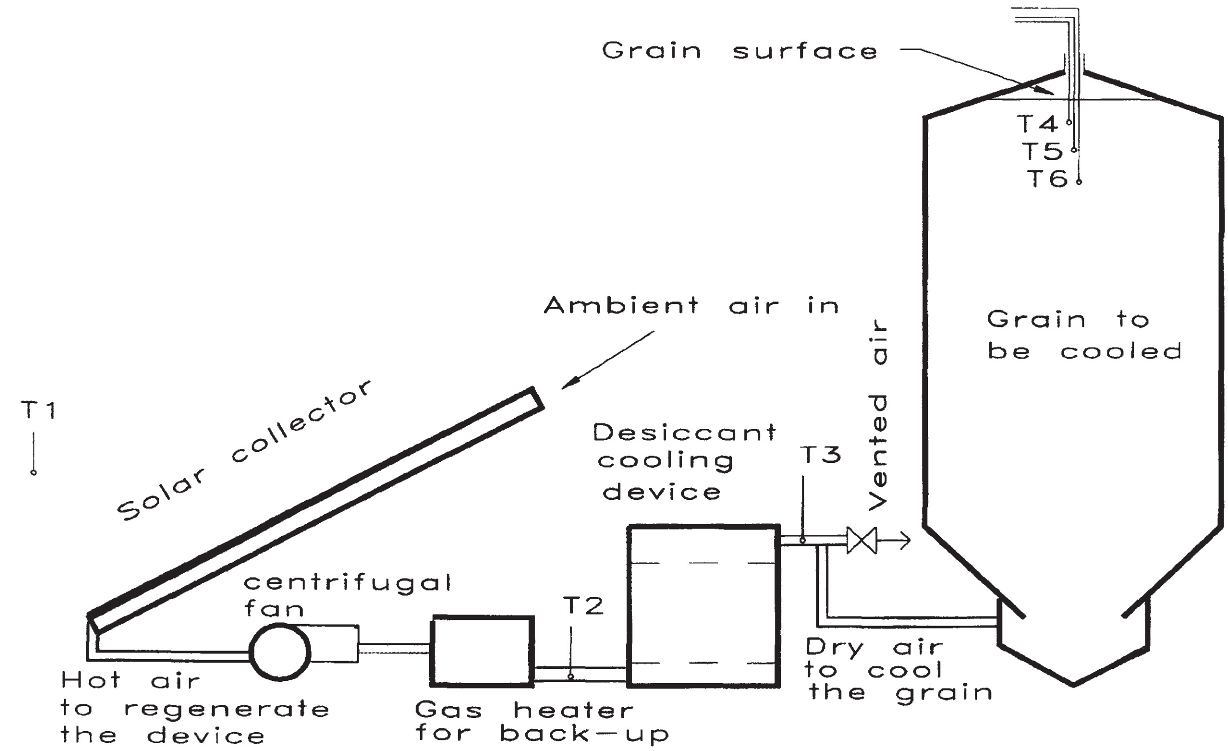


**Fig. 3.** A schematic diagram of the experimental set up showing the placement of thermocouples (all dimensions in m)

## Field Performance of the Desiccant Bed Grain Cooling System

The grain cooling system was originally tested under a range of climatic conditions simulated in the laboratory (Ahmad et al., 1996) and it was demonstrated that the wet-bulb temperature of ambient air could be reduced from 17℃ to 10℃ under conditions that are typical of subtropical grain growing climates The present paper reports the results of three field trials; the key performance parameters that were measured include:

- The reduction of wet-bulb temperature, enthalpy and absolute humidity of conditioned air after it passes through the grain cooling device under field conditions.
- The rate of adsorption and desorption of moisture during cooling and reactivation cycles, respectively.
- The coefficient of performance (COP) of the novel grain cooling system
- The reduction in wet-bulb temperature, dry-bulb temperature and moisture contents of bulks of stored grain after cooling with the desiccant cooling system

under different field and climatic conditions.

In the case of the experiments carried out at Warwick in Queensland the performance of the system incorporating the solar air heater was also investigated. To achieve these aims, the performance of the grain cooling system was evaluated at three locations during 1997 and 1998. Firstly, it was tested at Walla Walla located close to Albury in New South Wales which is situated at a latitude of 36 degree South at an altitude of 183m above sea level. Secondly, the desiccant cooling system was tested at Livingston Farm, Moree, New South Wales, which is situated at a latitude of 29.3 degree South at an altitude of 207 m above sea level and it was finally tested at Warwick 28.25 degree South at an altitude of 388 m above sea level.

## Materials and methodology

Figure 3 presents a schematic of the set-up used during the field performance evaluation of the grain cooling system at Warwick; the same system was used at Walla Walla and Moree except that the solar air heater was not fitted in the latter two cases. In each of the experiments, the system was connected to a recently developed grain silo (Kotzur and Thorpe, 1996) that features a built-in aeration duct that is self-cleaning and that gives rise to a more uniform air flow and a lower pressure drop than that across a conventionally aerated silo fitted with a single linear aeration duct. The silo was filled with about 104 tonnes of 10% (wet-basis) moisture content triticale during the Walla Walla trial, whereas it was filled with about 110 tonnes of 11.5% (wet-basis) moisture content sorghum during the Moree trial. In Queensland a smaller silo was filled with 50 tonnes of barley with a moisture content of 11.9% (wet-basis).

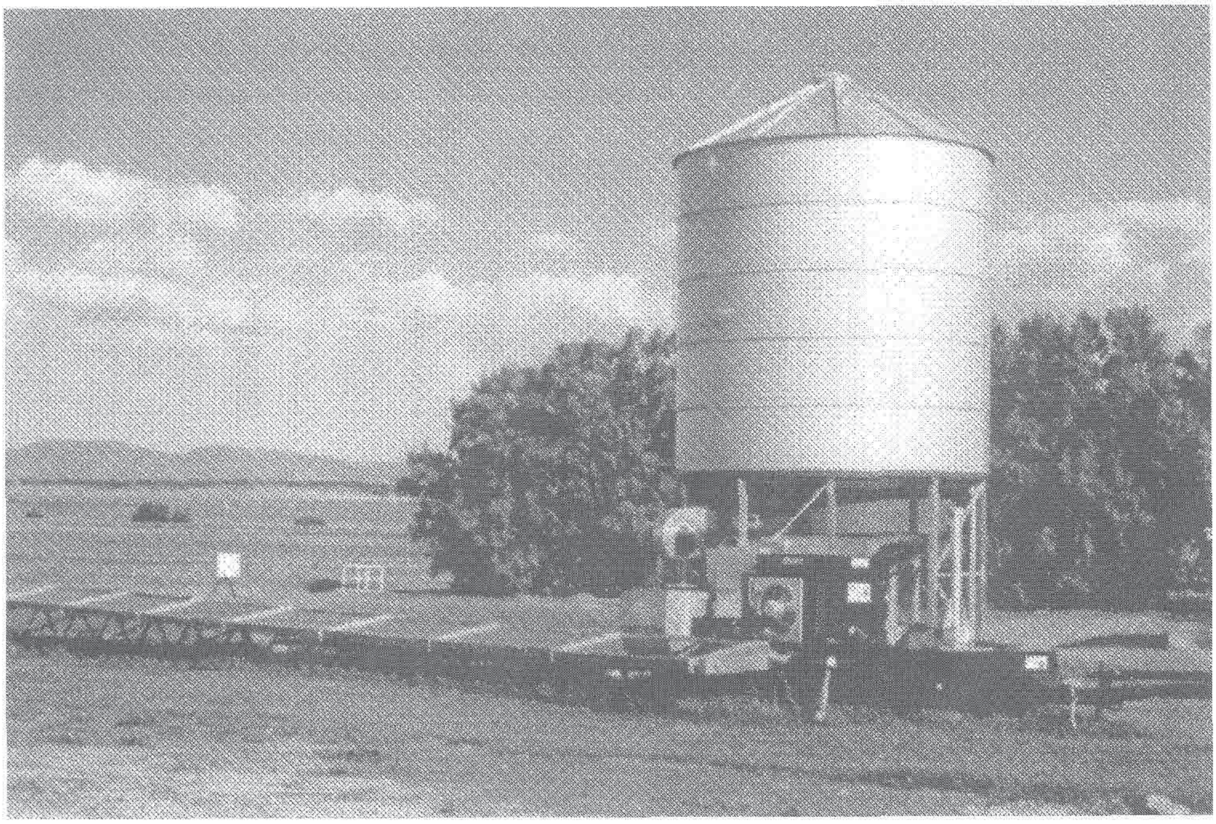

**Fig.4.** A general view of the grain cooling system installed at Walla Walla, New South Wales.

To measure the performance of the desiccant cooling system, seven experiments were carried out at Walla Walla, five experiments carried out at Livingston Farm, Moree and 12 were conducted at Warwick. Each experiment consisted of a cooling and a reactivation cycle. The dry-bulb temperature, relative humidity and dew-point temperature of the inlet and the conditioned air were measured immediately before and after the desiccant device. The air flow rate was measured down stream of the cooling system, and the corresponding pressure drop was measured across the desiccant beds. These measurements were made using a commercial hot-wire anemometer and manometer.

To monitor the performance of the desiccant cooling system and to measure the grain temperature, T-type thermocouples were placed at strategic locations around the cooling unit and in the grain bulk during the test period (Figure 3). The dry-bulb temperature measurements were made before and after the grain cooling system, before the air entered the silo, and at three locations within the silo, namely at depths of 1m, 2m and 3m below the upper surface of the grain. The dry-bulb temperature of the ambient air was also measured. The thermocouple probes were connected to the interface of a data logger (Datataker Model DT 500), and data were recorded at intervals of 15 minutes, and then down loaded onto a personal computer. The data were subsequently processed using proprietary software

## Results and Discussion

Desmarchelier (1988) correlated the population growth rates of eight species of stored product insects against seed wet-bulb temperature. He presented threshold seed wet-bulb temperatures, at or below which insect population growth rates are negative. Desmarchelier's empirical relationships constitute a powerful analytical tool that can be used when devising effective pest management strategies. Therefore, a key parameter that can be used to evaluate the grain cooling system under investigation is the reduction in wet-bulb temperature of the inlet air brought about by the grain cooling system. Table 1 shows the field performance data for the grain cooling system tested at Walla Walla, Table 2 shows the performance data of the experiments carried out at Moree and Table 3 presents the data obtained from the solar assisted grain cooling system The air flow rates during the cooling cycles at Walla Walla and Moree were 0.15 kg/s, whereas they were 0.16 kg/s during the reactivation cycles. At Warwick the flow rates were 0.13 kg/s.

**Table 1.** Field performance data for the desiccant cooling system tested at Walla Walla, New South Wales

| | | | Conditions at the inlet of the unit | | | | Conditions at the outlet of the unit | | | | Ambient conditions | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cycle | $H_2O$ Adsorbed/ Desorbed (kg) | Cycle time hours | Dry-bulb temp. ℃ | Wet-bulb temp ℃ | Humidity g/kg | Specific enthalpy kJ/kg | Dry bulb temp. ℃ | Wet-bulb temp. ℃ | Humidity g/kg | Specific enthalpy kJ/kg | Dry bulb temp ℃ | Humidity g/kg |
| Cooling | 18.7 | 5.5 | 15.1 | 11.1 | 6.7 | 32.2 | 14.7 | 4.2 | 0.8 | 17.0 | 12.7 | 6.8 |
| Reactivating | 18.0 | 5.0 | 75.0 | | 5.1 | | 45.4 | | 11.0 | | 30.2 | 5.1 |
| 9/01/97 | | | | | | | | | | | | |
| Cooling | 22.17 | 5.5 | 20.0 | 14.7 | 8.2 | 41.0 | 20.6 | 7.5 | 1.2 | 24.0 | 17.4 | 7.8 |
| Reactivating | 15.60 | 5.0 | 74.0 | | 8.1 | | 43.8 | | 13.2 | | 26.8 | 8.1 |
| 10/01/97 | | | | | | | | | | | | |
| Cooling | 17.52 | 5.5 | 14.8 | 11.2 | 6.9 | 32.5 | 14.6 | 4.4 | 1.0 | 17.5 | 12.4 | 6.5 |
| Reactivating | 21.08 | 6.0 | 77.6 | | 6.4 | | 46.5 | | 12.5 | | 29.1 | 6.4 |
| 17/01/97 | | | | | | | | | | | | |
| Cooling | 21.08 | 5.5 | 20.8 | 15.0 | 8.2 | 42.0 | 21.9 | 8.0 | 1.1 | 25.0 | 18.4 | 8.0 |
| Reactivating | 22.08 | 6.0 | 78.7 | | 6.82 | | 49.3 | | 13.2 | | 31.0 | 6.85 |
| 18/01/97 | | | | | | | | | | | | |
| Cooling | 23.42 | 5.5 | 21.8 | 15.8 | 8.75 | 44.5 | 23.1 | 8.7 | 1.2 | 26.4 | 19.5 | 8.4 |
| Reactivating | 22.32 | 6.0 | 79.3 | | 9.4 | | 49.0 | | 15.9 | | 33.0 | 9.4 |
| 19/01/97 | | | | | | | | | | | | |
| Cooling | 22.21 | 5.5 | 27.0 | 18.8 | 10.3 | 53.5 | 28.0 | 12.5 | 2.8 | 35.5 | 25.0 | 10.1 |
| Reactivating | 27.3 | 6.0 | 81.0 | | 8.78 | | 50.0 | | 16.7 | | 36.2 | 8.78 |
| 20/01/97 | | | | | | | | | | | | |
| Cooling | 20.8 | 5.5 | 26.5 | 17.0 | 8.2 | 46.5 | 27.7 | 11.9 | 1.2 | 34.0 | 25.0 | 8.3 |
| Reactivating | 18.0 | 6.0 | 79.8 | | 9.0 | | 48.3 | | 14.2 | | 35.6 | 9.0 |
| 20/02/97 | | | | | | | | | | | | |
| Av Cooling | 20.8 | 5.5 | 20.8 | 14.8 | 8.17 | 41.7 | 21.5 | 8.1 | 1.33 | 25.6 | 18.6 | 8.0 |
| Av.Reactivating | 20.6 | 5.7 | 77.9 | | 7.65 | | 47.5 | | 13.8 | | 31.7 | 7.7 |

**Table 2.** Field performance data for the desiccant cooling system tested at Moree, New South Wales

| Cycle | $H_2O$ Adsorbed/ Desorbed (kg) | Cycle time hours | Conditions at the inlet of the unit: Dry bulb temp ℃ | Wet-bulb temp ℃ | Humidity g/kg | Specific enthalpy kJ/kg | Conditions at the outlet of the unit: Dry bulb temp ℃ | Wet-bulb temp ℃ | Humidity g/kg | Specific enthalpy kJ/kg | Ambient conditions: Dry bulb temp ℃ | Humidity g/kg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cooling | 21.3 | 5.0 | 20.3 | 16.1 | 9.8 | 45.0 | 20.1 | 8.1 | 1.9 | 25.0 | 17.2 | 9.6 |
| Reactivating 9/01/97 | 18.7 | 8.0 | 71.0 | | 9.8 | | 41.4 | | 13.8 | | 28.5 | 9.8 |
| Cooling | 21.1 | 4.5 | 22.4 | 18.3 | 11.4 | 51.5 | 22.8 | 10.1 | 2.7 | 29.8 | 19.5 | 11.0 |
| Reactivating 10/01/97 | 20.6 | 7.0 | 74.0 | | 10.3 | | 45.3 | | 15.4 | | 29.2 | 10.3 |
| Cooling | 20.9 | 4.5 | 21.0 | 17.1 | 10.6 | 48.0 | 21.2 | 8.8 | 2.0 | 26.5 | 18.5 | 10.3 |
| Reactivating 17/01/97 | 18.5 | 7.0 | 75.3 | | 9.8 | | 46.0 | | 14.4 | | 29.6 | 9.8 |
| Cooling | 14.3 | 4.5 | 18.0 | 12.7 | 7.0 | 36.0 | 18.0 | 6.0 | 1.1 | 20.5 | 15.4 | 7.0 |
| Reactivating 18/01/97 | 20.6 | 6.0 | 77.2 | | 6.7 | | 47.7 | | 12.2 | | 30.3 | 6.7 |
| Cooling | 15.9 | 6.0 | 14.9 | 9.3 | 5.0 | 27.5 | 15.0 | 3.4 | 0.1 | 15.5 | 13.0 | 5.0 |
| Reactivating 19/01/97 | 14.6 | 6.5 | 71.7 | | 5.2 | | 46.5 | | 9.1 | | 28 7 | 5.2 |
| Av Cooling | 18.7 | 4.9 | 19.3 | 14.7 | 8.76 | 41.6 | 19.4 | 7.3 | 1.56 | 23.5 | 16.7 | 8.58 |
| Av.Reactivating | 18.6 | 6.9 | 73.8 | | 8.36 | | 45.4 | | 13.0 | | 29.3 | 8.36 |

**Table 3.** Performance data during the cooling cycles of the solar desiccant system tested at Warwick, Queensland

| Experiment number | $H_2O$ Adsorbed/ Desorbed (kg) | Cycle time hours | Conditions at the inlet of the unit: Dry bulb temp ℃ | Wet-bulb temp ℃ | Humidity g/kg | Specific enthalpy kJ/kg | Conditions at the outlet of the unit: Dry bulb temp ℃ | Wet-bulb temp. ℃ | Humidity g/kg | Specific enthalpy kJ/kg | Ambient conditions: Dry bulb temp ℃ | Humidity g/kg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.0 | 15.7 | 19.2 | 18.0 | 12.4 | 51.0 | 20.4 | 10.5 | 4.0 | 31.0 | 18.0 | 11.8 |
| 2 | 4.0 | 9.0 | 15.4 | 12.8 | 8.2 | 36.5 | 16.2 | 8.0 | 3.4 | 25.0 | 15.4 | 7.8 |
| 3 | 4.0 | 10.8 | 16.8 | 15.0 | 9.8 | 42.0 | 17.8 | 9.5 | 4.0 | 31.7 | 16.5 | 9.6 |
| 4 | 5.0 | 14.7 | 21.0 | 17.9 | 11.5 | 50.5 | 21.6 | 12.4 | 5.2 | 35.0 | 20.2 | 11.4 |
| 5 | 6.0 | 24.1 | 19.5 | 17.1 | 11.2 | 48.5 | 22.5 | 10.0 | 2.6 | 29.0 | 19.5 | 11.0 |
| 6 | 5.0 | 20.6 | 20.7 | 19.0 | 13.0 | 54.0 | 23.9 | 12.2 | 4.2 | 34.5 | 20.2 | 12.4 |
| 7 | 5.5 | 22.9 | 21.6 | 18.7 | 12.4 | 52.5 | 23.7 | 11.5 | 3.5 | 33.0 | 20.4 | 11.8 |
| 8 | 5.5 | 16.9 | 17.1 | 14.8 | 9.5 | 41.5 | 18 7 | 8.7 | 2.9 | 26.5 | 16.4 | 9.1 |
| 9 | 5.5 | 20.4 | 15.2 | 14.0 | 9.4 | 39.0 | 18.4 | 7.0 | 1.5 | 23.0 | 15 2 | 9.4 |
| 10 | 5.5 | 15.5 | 16.3 | 14.5 | 9.6 | 40.5 | 18.9 | 7.6 | 2.0 | 24.3 | 16.3 | 9 6 |
| 11 | 5.5 | 25.7 | 19.7 | 18.3 | 12.6 | 51.5 | 22.9 | 10.2 | 2.6 | 29.8 | 19.6 | 12.6 |
| 12 | 5.0 | 19.2 | 16.8 | 15.3 | 10.2 | 43.0 | 19.5 | 8.0 | 2.0 | 25.0 | 16.5 | 9.8 |
| Ave. | 5.0 | 18.0 | 18.3 | 16.3 | 10.8 | 45.9 | 20.4 | 9.6 | 3.2 | 29.0 | 17.9 | 10.5 |

## Performance during adsorption (grain cooling) cycles

Figure 5 shows the inlet and the conditioned air wet-bulb temperatures during the experiments carried out at Walla Walla. It is observed from Table 1 and Figure 5 that the average wet-bulb temperature of the inlet air was 14.8℃ during the cooling cycles of these experiments, whereas the average wet-bulb temperature of the conditioned air was 8.1℃, i. e. an average reduction in the wet-bulb temperatures of 6.7℃. We should note that during the cooling cycle of Experiment 7, the reduction in wet-bulb temperature was observed to be 5.1℃, which is somewhat lower than the average reduction of wet-bulb temperature of 6.7℃. This is because of the low relative humidity (38.4%) of the inlet air during the cooling cycle of Experiment 7, whereas the average relative humidity of the inlet air during these cooling cycles was 53.5%. This suggests that the higher the relative humidity of the inlet air, the higher the reduction in wet-bulb temperature of the conditioned air. This feature of the system is likely to make it well suited for operation in tropical climates, although this supposition must be tested by experiment. The average absolute humidities of the inlet and outlet air during these cooling cycles was 8.17 g/kg, and 1.33 g/kg, respectively. This average drop of 6.84 g/kg in the absolute humidity of inlet air during these cooling cycles is equivalent to an average rate of adsorption of 3.7 kg of water/hr. The average enthalpy of the inlet air during cooling cycles of various experiments conducted at Walla Walla was 41.7 kJ/kg, whilst the average enthalpy of the conditioned air was 25.6 kJ/kg which represents an average drop of 16.1 kJ/kg.

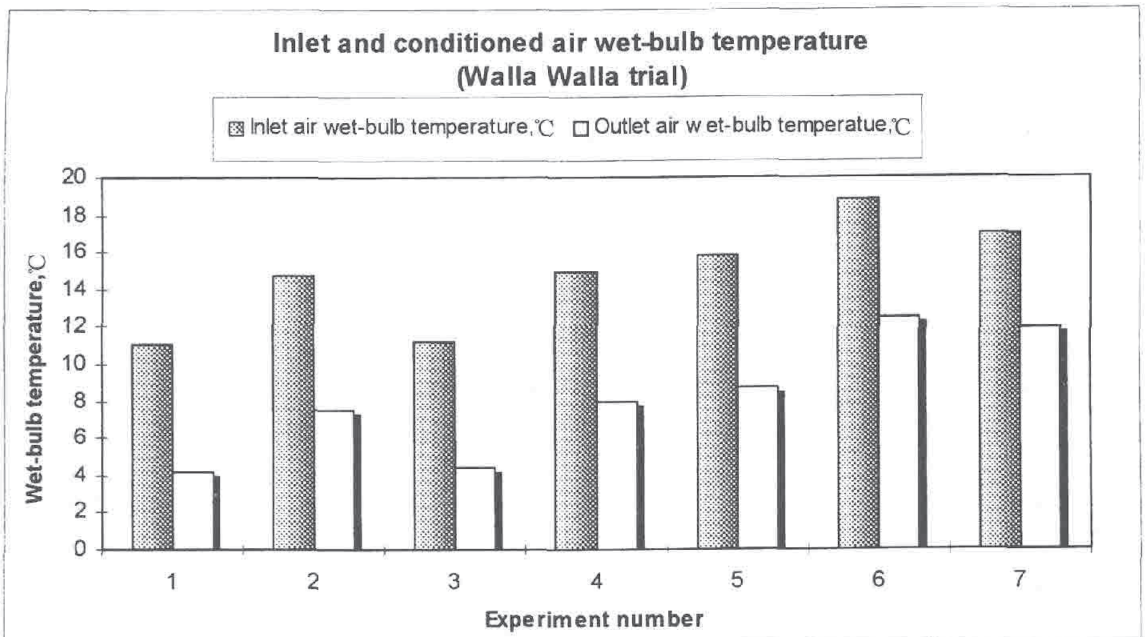


**Fig. 5.** The wet-bulb temperatures of the air entering and leaving the cooling unit at Walla Walla.

The enthalpy and wet-bulb temperature of moist air are closely related, and a reduction in the enthalpy of the air entering the silo is also conducive to good grain storage, and the reduction of enthalpy is also a measure of the thermodynamic effectiveness of the grain cooling device.

The wet-bulb temperature and enthalpy of the inlet and the conditioned air during a typical cooling cycle of Experiment 4 at Walla Walla are presented in Figure 6. It can be seen that the average enthalpy of the inlet air was 42 kJ/kg during this cycle, whereas the average enthalpy of the conditioned air was 25 kJ/kg, indicating a drop of 17 kJ/kg in the enthalpy of air after passing it through the desiccant cooling system. Figure 6 also indicates that the average wet-bulb temperature of the inlet air during a typical cooling cycle was 15℃ which was reduced to 8℃ after passing through the grain cooling system, a reduction of 7℃. The reduction in the wet-bulb temperature is likely to a have profound effect on the rate of population growth of insects that infest stored grains. For example, if ambient air (wet-bulb temperature of 15℃) were to be used to cool the grains, the population of the granary weevil, *Sitophilus granarius*, a cold tolerant insect, would increase about nine fold in one month. If the grains were to be aerated with conditioned air (8℃ wet-bulb temperature) leaving the novel desiccant cooling system the population would, at worst, remain constant as may be gleaned from data presented by Desmarchelier (1993) and Wilson and Desmarchelier (1994).

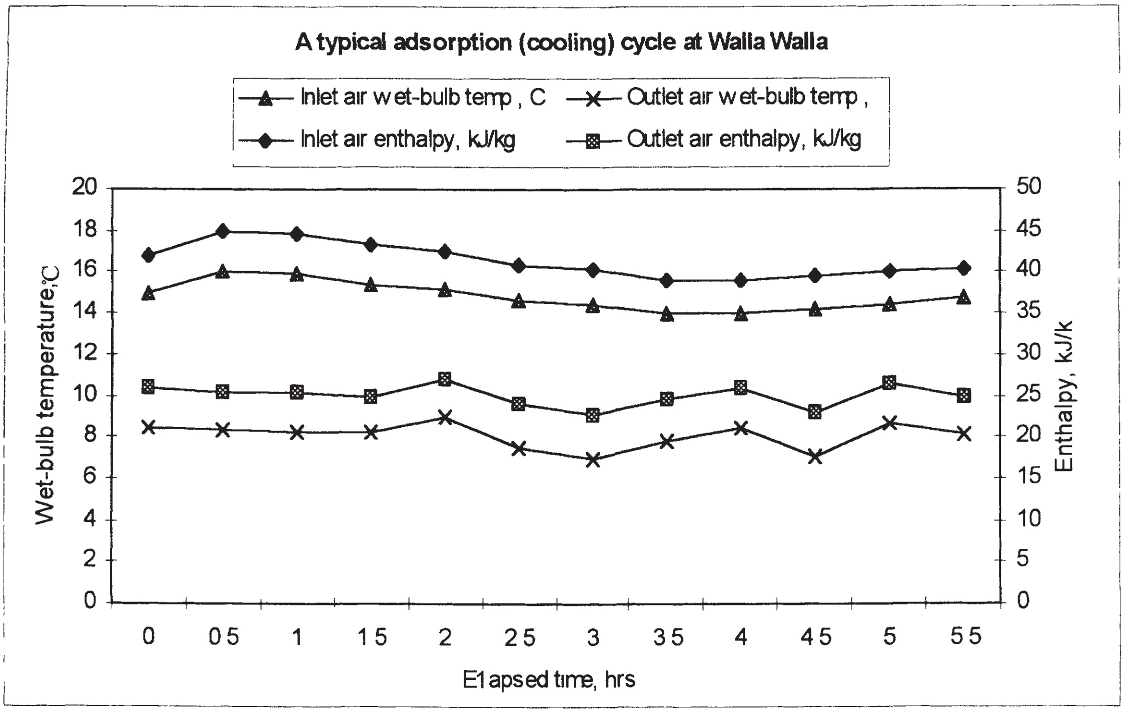


**Fig. 6.** The time trajectories of wet-bulb temperature and enthalpies of air passing through the grain cooling system.

Figure 7 shows the average wet-bulb temperature of the inlet and the conditioned air during typical experiments carried out at Moree. It can be seen from Table 2 and Figure 7 that the average wet-bulb temperature of the inlet air was 14.7℃ during the cooling cycles of these experiments, which was reduced to 7.3℃ after passing it through the desiccant cooling system, a reduction of 7.4℃ The average absolute humidity of the inlet and the conditioned air was 8.76 g/kg, and 1.56 g/kg, respectively. This means that on average the absolute humidity of the inlet air was reduced by about 7.2 g/kg during these cooling cycles, which is equivalent to the average rate of adsorption of 3.88 kg of water/hr. The average enthalpy of the inlet air during the cooling cycles of these experiments carried out at Moree was 41.6 kJ/kg, whereas the average enthalpy of the conditioned air was 23.5 kJ/kg, a reduction of 18.1 kJ/kg.

Figure 8 illustrates the variation of the wet-bulb temperature and enthalpy of the inlet air and the conditioned air with the elapsed time during Experiment 2, a typical cooling cycle, and the average enthalpy of the inlet air during the typical cooling cycle was 51.5 kJ/kg The average enthalpy of the conditioned air was 29.8 kJ/kg, a reduction of 21.7 kJ/kg. During this cooling cycle, the average wet-bulb temperature of the inlet air was 18.2℃ compared with the 10.1℃ wet-bulb temperature of the conditioned air, a drop of 8.1℃ It can be concluded that system is capable of reducing the wet-bulb temperature of the ambient air by about 8℃ By making use of the psychrometric chart we can determine that the aeration of grains with conditioned air at 10℃ wet-bulb temperature is sufficient to cool 12% moisture content wheat to a temperature of 14℃ ; if the same wheat were to be aerated with ambient air with a wet-bulb temperature of 18℃ , it would cool to only 23℃

During the first four experiments carried out at Warwick the desiccant was regenerated using solar energy alone. However, during the last eight experiments a gas heater was also used to regenerate the desiccant, after regenerating it with the heat available from the solar collector. The aim behind using the gas heater, in addition to solar collector for regenerating the desiccant was to desorb more water during the reactivation cycle. This yields larger wet-bulb temperature reductions during the cooling cycles and it also permits an increase in the duration of the cooling cycles. The average wet-bulb temperature of the inlet air during first four experiments was 15.9℃ , which was reduced to 10.1℃ after conditioning with the desiccant system. This shows a reduction of 5.8℃ in wet-bulb temperature of the inlet air after conditioning with the solar regenerated desiccant system. The average duration of the cooling cycle was 4.2 hours, and the average water adsorbed during a cooling cycle was 12.6 kg The average relative humidity and enthalpy of the inlet air was 79.2% and 45 0 kJ/kg during these first four experiments, which were reduced to 30.7% and 30.7 kJ/kg after conditioning with the solar desiccant system. This indicates a reduction of 48.5% in the relative humidity and 14.3 kJ/kg in the enthalpy of the inlet air. During the last eight experiments (Experiment 5 to 12), the desiccant was regenerated using a gas heater in addition to the solar collector. The average duration of these cooling cycles was 5.4 hours. It can be seen from Table 3 that the average relative humidity of the inlet air was 82.2% as compared to the relative humidity of 16.8% of the conditioned air. The average enthalpy of the inlet air during these cooling cycles was 46.3 kJ/kg, whilst the average enthalpy of the conditioned air was 28.1 kJ/kg, representing an average drop of 18.2 kJ/kg. The average absolute humidities of the inlet and the outlet (conditioned) air during these cooling cycles was 11.0 g/kg and 2.7 g/kg, respectively. This average drop of 8.3 g/kg in the absolute humidity of inlet air is equivalent to an average rate of adsorption of 3.88 kg of water/hr.

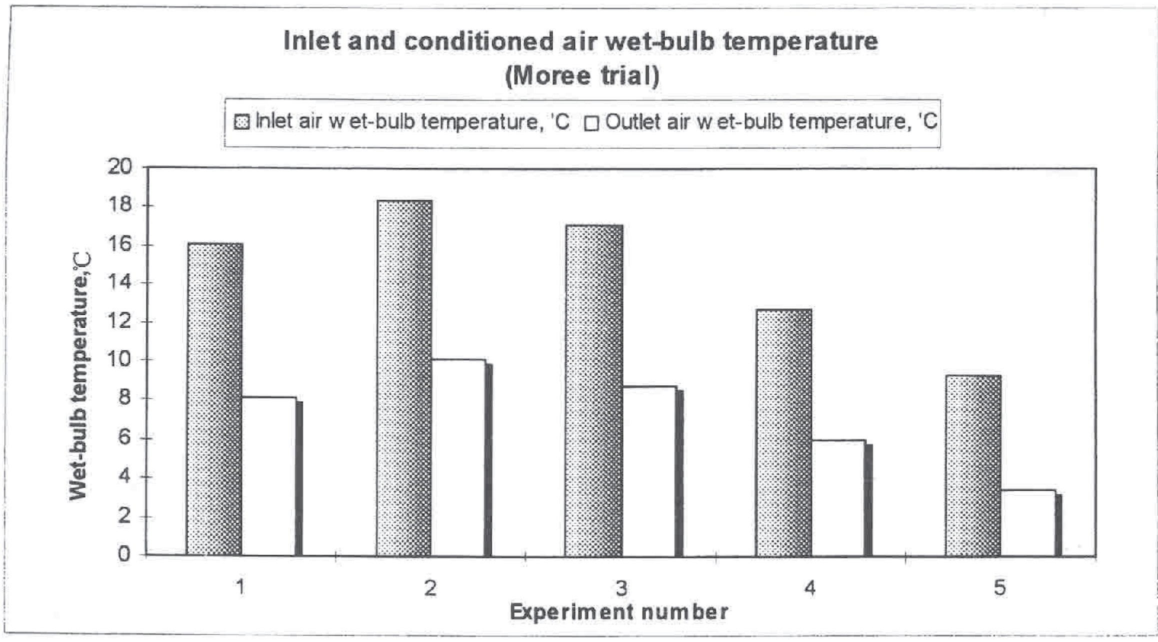


**Fig.7.** The depression of wet-bulb temperature and enthalpies of air passing through the grain cooling system at Moree.

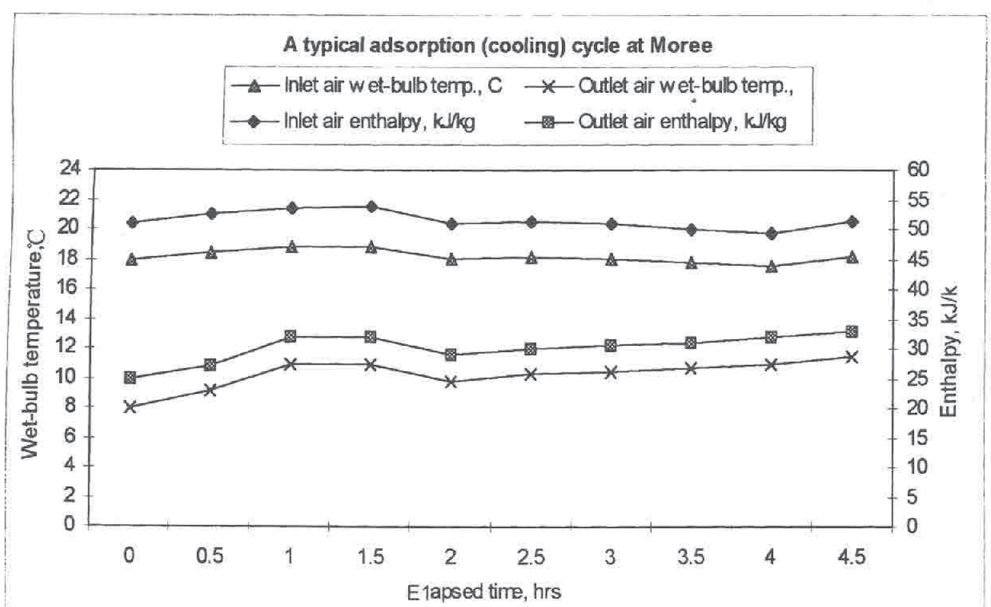


**Fig.8.** The time trajectories of wet-bulb temperatures and enthalpies of inlet and air conditioned by the grain cooling device at Moree, NSW.

It can also be seen from Table 3 that the average wet-bulb temperature of the inlet air was 16.5℃ during the cooling cycles of Experiment 5 to 12, whereas the average wet-bulb temperature of the conditioned air was 9.4℃, i. e. an average reduction in the wet-bulb temperatures of 7.1℃. The reduction in the wet-bulb temperature greatly affects the rate of population growth of insects that infest stored grains. For example, if ambient air (wet-bulb temperature of 16.5℃) were to be used to cool the grain, the population of the rice weevil, Sitophilus oryzae, a cold tolerant insect, would increase about five fold in one month. If the grains were to be aerated with conditioned air (9.4℃ wet-bulb temperature) leaving the desiccant system, the population would remain constant as may be gleaned from data presented by Desmarchelier (1993)

## Performance during desorption (reactivation) cycles

If the system is not adequately reactivated, the required reduction in wet-bulb temperature and enthalpy of ambient air cannot be achieved during the nightly cooling cycle. For this reason, it is important to have a good appreciation of the performance parameters that govern the reactivation cycle. This information is essential to ensure that a suitable heating system (gas or solar) can be specified.

The dry-bulb temperatures and absolute humidities of the inlet and the outlet (vented) air during the reactivation cycles of the experiments carried out at Walla Walla and Moree are also presented in Tables 1 and 2. Details of the reactivation conditions in the Warwick experiments are given in Table 4. The results of the Walla Walla experiments indicate that the average temperatures of the inlet and vented air during the reactivation cycles were 77.9℃ and 47.5℃, respectively. The absolute humidities of the inlet and the vented air were 7.65 g/kg and 13.8 g/kg, respectively This indicates an average rate of desorption of 3.55 kg of water / hr during the reactivation cycles. The results of the Moree experiments indicate that the average temperatures of the inlet and vented air during reactivation cycles were 73.8℃ and 45.4℃, respectively, and the average absolute humidities of inlet and vented air during these cycles were 8.36 g/kg and 13.0 g/kg, respectively. This results in an average rate of desorption of 2.67 kg of water/hr during these reactivation cycles. The rate of desorption was lower at Moree compared with Walla Walla, because of the higher absolute humidity of inlet air at Moree during the reactivation cycles

**Table 4.** Performance of the cooling unit located at Warwick during the regeneration cycle.

| Experiment number | Regeneration mode | Cycle time hours | $H_2O$ Desorbed kg | Condition of inlet air | | Condition of air vented to atmosphere | | | Mean solar radiation $W/m^2$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Dry bulb temp ℃ | Humidity g/kg | Dry bulb temp ℃ | Humidity g/kg | Dry bulb temp ℃ | |
| 1 | Solar | 8.0 | 8.9 | 56.7 | 13.9 | 40.5 | 16.2 | 31.6 | 808.1 |
| 2 | Solar | 7.5 | 16.4 | 61.6 | 8.5 | 40.7 | 13.0 | 34.1 | 820.0 |
| 3 | Solar | 7.5 | 9.5 | 56.1 | 10.3 | 36.9 | 12.9 | 29.5 | 826.2 |
| 4 | Solar | 7.5 | 10.2 | 51.0 | 12.1 | 36.4 | 14.9 | 30.3 | 754.4 |
| | Gas | 4 5 | 12.0 | 77.1 | 12.1 | 41.4 | 17.6 | 27.7 | |
| 5 | Solar | 7.5 | 11.3 | 56.0 | 11.7 | 39.0 | 14.8 | 33.4 | 760.9 |
| | Gas | 2.5 | 7.8 | 76.2 | 11.6 | 39.2 | 18.0 | 28.2 | |
| 6 | Solar | 1.5 | 0.4 | 44.0 | 13.2 | 38.5 | 13.7 | 27.7 | 429.8 |
| | Gas | 7.5 | 26.6 | 78.3 | 13.8 | 43.0 | 21.1 | 25.2 | |
| 7 | Solar | 1.0 | 2.2 | 54.0 | 12.8 | 36.7 | 17.3 | 29.8 | 758.4 |
| | Gas | 7.0 | 19.0 | 80.9 | 14.2 | 38.8 | 19.8 | 26.4 | |
| 8 | Solar | 6.0 | 5.5 | 50.0 | 9.5 | 35.3 | 11.4 | 25.8 | 774.0 |
| | Gas | 4.5 | 16.2 | 75.8 | 8.6 | 39.6 | 16.0 | 21.9 | |
| 9 | Solar | 6.0 | 9.0 | 55.0 | 8.8 | 38.6 | 11.9 | 27.3 | 855.3 |
| | Gas | 4.5 | 16.2 | 75.0 | 9.2 | 39.6 | 14.6 | 26.3 | |
| 10 | Solar | 7.5 | 17.8 | 60.3 | 8.3 | 39.2 | 13.4 | 31.5 | 854.5 |
| | Gas | 2.5 | 6.9 | 80.1 | 8.7 | 45.9 | 14.4 | 29.3 | |
| 11 | Solar | 8.0 | 17.1 | 58.7 | 10.2 | 39.9 | 14.6 | 33.2 | 794.8 |
| | Gas | 3.0 | 8.9 | 83.7 | 11.2 | 42.4 | 17.3 | 29.9 | |
| 12 | Solar | 7.0 | 12.6 | 57.0 | 8.8 | 40.1 | 12.5 | 26.0 | 863.1 |
| | Gas | 2.5 | 8.7 | 85.0 | 8.0 | 40.6 | 15.2 | 24.3 | |
| Mean | Solar | 6.2 | 10.0 | 55.0 | 10.7 | 38.5 | 13.9 | 30.0 | 775.0 |
| | Gas | 4.2 | 13.6 | 79.1 | 10.8 | 41.2 | 17.1 | 26.6 | |

Figure 9 depicts the rate of desorption and absolute humidities of the inlet and vented air during a typical reactivation cycle, Experiment 4, carried out at Walla Walla. It can be seen that in the beginning of the reactivation cycle the absolute humidity of the vented air was about 3.5 g/kg, which indicates that some desorption was taking place. It increased to 15.0 g/kg during the middle of the cycle, and dropped to 10.0 g/kg at the end of the cycle. This moisture loss trajectory occurred because the desiccant material was initially cold, hence the air initially in equilibrium with the silica gel had a low absolute humidity. It took about half an hour for a heating front to pass through the bed of desiccant, and as it did the absolute humidity of the air leaving the desiccant beds increased. The absolute humidity of the vented air rose to its maximum value during the middle of the reactivation cycle. At the end of the cycle, the desiccant became dry, and the absolute humidity of the vented air decreased. A similar trend was observed for the rate of desorption during this typical reactivation cycle as gleaned from Figure 9. The average rate of desorption during the 6 hours of the reactivation cycle was 3.18 kg/hr, i e about 22.5 kg moisture was removed during this reactivation cycle

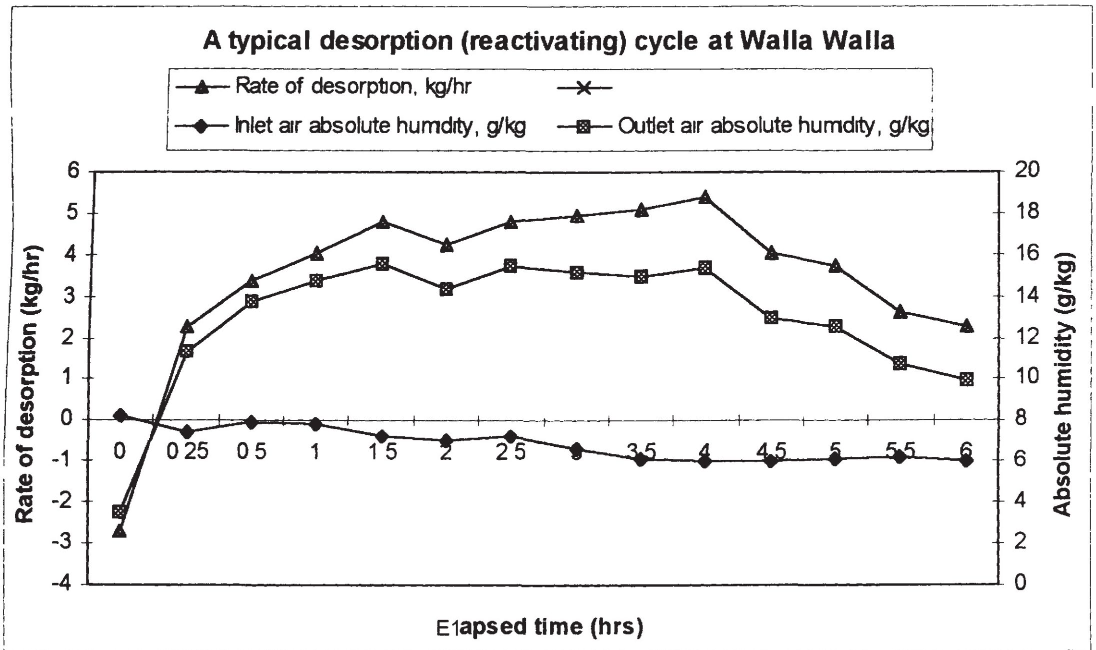


**Fig.9.** The rate of desorption of moisture from the silica gel during a regeneration cycle at Walla Walla, New South wales.

One method of specifying the energy efficiency of the grain cooling process is to use a coefficient of performance that is expressed as the ratio of the total energy reduction of ambient air to the total energy supplied to the system, as detailed by Ahmad et al. (1997) Using this definition, the coefficient of performance of the cooling unit is calculated to be 0.29. A second definition of the coefficient of performance is the ratio to the total energy reduction of the ambient air to the electrical energy supplied to the system. When this definition is used the coefficient of performance is greater than seven. This provides a strong incentive to develop solar energy as a heating medium. The dry-bulb temperatures and absolute humidities of the inlet and the outlet (vented) air and mean solar radiation during the regeneration cycles of various experiments are presented in Table 4. It is revealed that for the first three cycles, the regeneration mode was solar, whereas the rest of the cycles had combined (solar and gas) mode for regeneration of the desiccant. The average inlet temperature during the solar regenerated cycles of twelve experiments carried out at Warwick, Queensland was 55.0℃, and the mean solar radiation during these cycles was 775.0 W/m$^2$ During the solar regenerated cycles, the absolute humidities of the inlet and vented air were 10.7 g/kg and 13.8 g/kg, respectively This indicates an average rate of desorption of 1.55 kg of water per hour during the solar regenerated cycles. This shows a slow regeneration rate during the solar cycles, and this was because of the low regeneration temperature (55℃) of the inlet air. However, the low regeneration temperature was the result of low mean solar radiation incident on the collector surface during the regeneration cycles. Overcast weather conditions were experienced during the experiments and they gave rise to low solar radiation. During the gas regeneration cycles, the absolute humidities of the inlet and vented air were 10.8 g/kg and 17.1 g/kg, respectively. This indicates an average rate of desorption of 3.06 kg of water per hour during the gas regeneration cycles This high rate of desorption was the result of higher regeneration temperature (79℃).

Figure 10 presents the dry-bulb temperature of ambient and regeneration air and solar radiation during a typical regeneration cycle of Experiment 11. It can be seen that in the beginning of the cycle (9 30 am), the solar radiation intensity was 812 W/m$^2$, which rose to about 1000 W/m$^2$ at noon and then fell to about 200 W/m$^2$ at the end (5 30 pm) of the solar regeneration period The dry-bulb temperature at the desiccant device inlet was 48℃, at the beginning of the cycle, which rose to 67℃ at noon and then fell to 41℃ at the end of the solar regeneration period. However, the gas-heater was turned on at 5 30 pm after 8 hours of solar regeneration. The regeneration temperature rose to about 90℃. The gas regeneration cycle was continued for three hours. The regeneration air temperature fell to 80℃ at the end of 3 hours; this was because of the relatively low ambient temperature The average ambient temperature during the solar regeneration period was 33.2℃ compared to 29.9℃ during the gas regeneration period Figure 11 shows the absolute humidities of the inlet and vented air, and solar radiation intensity versus the elapsed time during the typical regeneration cycle. The absolute humidity of the inlet air was about 13.0 g/kg at the beginning (9 30 am) of the cycle It decreased to 10 g/kg at noon, and it further decreased to 9 g/kg at 5 00 pm. However, it again rose to 13.5 g/kg at 7 00 pm. Therefore, it may be concluded that the best time for the regeneration of the desiccant system in this particular subtropical climate is from 11 00 am to 5 00 pm, because of the low absolute humidity of the ambient air and low probability of thunder storms during this period. Thunder storms occurred in the evening hours during the experiments. It can also be seen from Figure 11 that in the beginning of the regeneration cycle the absolute humidity of the vented air was about 4.0 g/kg, which indicates that adsorption was taking place (Figure 12). The absolute humidity of the vented air increased to 17.0 g/kg during the noon hours, and dropped to 12 g/kg at the end (5:30 pm) of the solar regeneration cycle The average rate of desorption during the 8 hours of the regeneration cycle was 2.14 kg/hr, i. e. about 17.1 kg moisture was removed during this typical solar reactivation cycle. At 5:30 pm, the gas heater was turned on, it increased the inlet air temperature to about 90℃, consequently the absolute humidity of the vented air rose to 19.4 g/kg, which corresponds to a desorption rate of 5.0 kg of moisture/hr (Figure 12). After that the rate of desorption starts falling because of increase in absolute humidity of the ambient air, and the desiccant became dry. The average rate of desorption during the 3 hours of the gas regeneration cycle was 3.0 kg/hr, i. e. about 9.0 kg moisture was removed during this regeneration cycle. It should be noted that when the desiccant was wet and regeneration air temperature was high (90℃), the rate of desorption was about 5 kg of water/hour. This higher rate of desorption was because of higher regeneration air temperatures and relatively low absolute humidities of the inlet air Therefore, a solar collector that has about half the heating capacity (6 m$^2$ aperture area) of the present one could be used in series with gas-heater for regenerating the desiccant system.

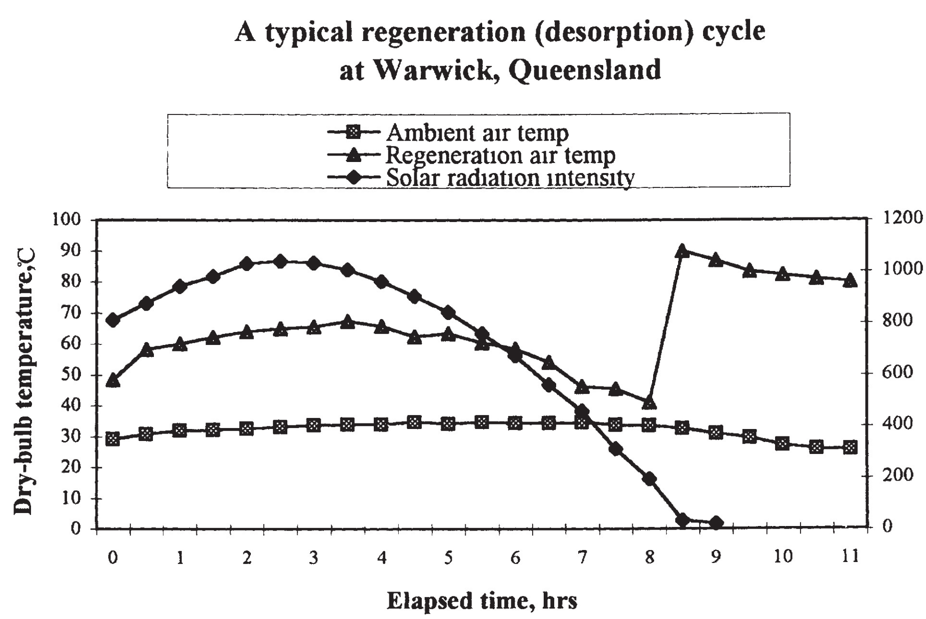


**Fig. 10.** Dry-bulb temperature of the ambient and regeneration air, and solar radiation versus the elapsed time.

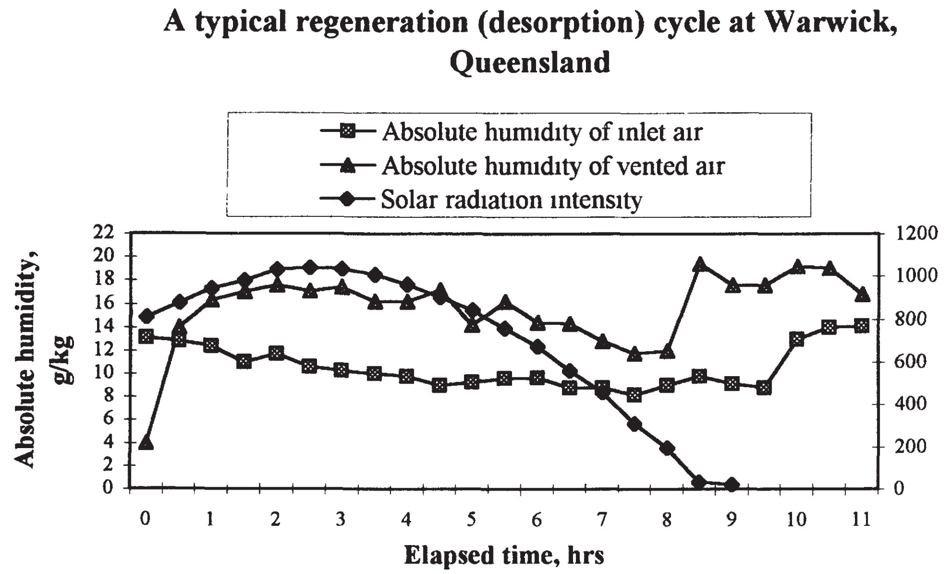


**Fig. 11.** Solar radiation intensity and the absolute humidities of inlet and vented air during the typical regeneration cycle

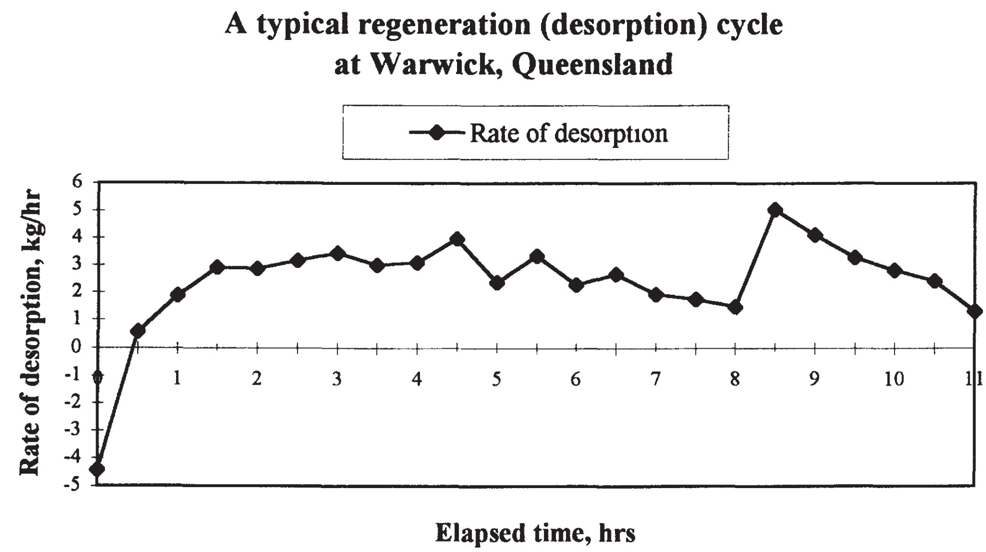


**Fig. 12.** Rate of desorption versus the elapsed time

## The Effects on Grain Temperature

### Walla Walla trial

The quantity of grain (Triticale) in the silo located at Walla Walla was 104 tonnes, and the average air flow rate was 1.02 l/s/tonne. The initial grain moisture was 10% (wet-basis) and the initial grain dry-bulb and wet-bulb temperatures were 22.5℃ and 13.2℃, respectively. The grain in the silo had been dried using heated air, and later this was cooled by forcing high volume flow rate of ambient air through them during a cold period that occurred prior to the commencement of the experiment. Therefore, the initial moisture content and temperature of grain were low.

The average dry-bulb and wet-bulb temperatures of grains at the end of the cooling period were 19.3℃ and 10.6℃, respectively, and the average grain moisture was 9.8 % (wet-basis) at the end of the trial (Table 5). With a wet-bulb temperature of 10.6℃ the rice weevil (*Sitophilus oryzae*), a cold tolerant insect species would scarcely breed as may be inferred from data presented by Desmarchelier (1993). If the grain had not been cooled using the desiccant cooling system, the grain temperature would have increased to about 25℃ during these hot summer days, which is a favourable temperature for multiplication of grain storage insect pests. It can be concluded that the novel desiccant cooling system performed well during the Walla Walla grain cooling trial, and dropped the grain wet-bulb temperature to 10.6℃, which is sufficient to restrict the rate of multiplication of most grain storage insect pests. The electrical energy consumed during the Walla Walla trial was 1.16 kWh/tonne, and the quantity of liquefied petroleum gas (LPG) consumed was 2.0 kg/tonne.

**Table 5.** Summary of results of Moree grain cooling trial using desiccant cooling system

| Trial name and location<br>Trial period | Walla Walla, Southern NSW<br>9 January – 4 March, 1997 |
|---|---|
| Average air flow rate (l/s per tonne of silo capacity) | 1.02 |
| Quantity of Triticale (t) | 104 |
| Initial grain moisture (% wet basis) | 10.0 |
| Final grain moisture (% wet basis) | 9.8 |
| Initial grain dry-bulb temperature (℃) | 22.5 |
| Initial grain wet-bulb temperature (℃) | 13.2 |
| Final grain dry-bulb temperature (℃) | 19.3 |
| Final grain wet-bulb temperature (℃) | 10.6 |
| Total cooling time (hours) | 280 |
| Electric energy used (kWh/tonne) | 1.16 |
| LPG used (kg/tonne) | 2.0 |

## Moree trial

The Moree grain cooling trial started on 13th March, 1997, and it was continued until 15th May, 1997. The system was turned off for two days (30/3/97 to 31/3/97) because of heavy rain, hence the system operated effectively for 62 days. The duration of the cooling cycle was 4.5 hours (3 00 am to 7 30 am) daily from 13th March to 15th April, however it was increased to 6 hours (2 00 am to 8·00 am) on 16 April, because of the onset of relatively cold weather in Moree. The average ambient air temperature during the cooling trial was 20.2℃. A summary of results from the Moree grain cooling trial is presented in Table 6. The quantity of grain in the silo was 110 tonnes and it had an initial moisture content of 11.5% (wet-basis), and its initial grain dry-bulb and wet-bulb temperatures were 28.4℃ and 20.3℃, respectively. These temperatures were measured at a depth of 2m from the upper surface of the grain in the silo. The average air flow rate was measured to be 0.97 l/s/tonne, and the total cooling time during this trial was 324 hours.

**Table 6.** Summary of results of Moree grain cooling trial using desiccant cooling system.

| Trial name and location<br>Trial period | Moree, Northern NSW 13 March – 15 May, 1997 |
|---|---|
| Average air flow rate (l/s per tonne of silo capacity) | 0.97 |
| Quantity of Sorghum (t) | 110 |
| Initial grain moisture (% wet basis) | 11.5 |
| Final grain moisture (% wet basis) | 11.25 |
| Initial grain dry-bulb temperature (℃) | 28.4 |
| Initial grain wet-bulb temperature (℃) | 20.3 |
| Final grain dry-bulb temperature (℃) | 14.6 |
| Final grain wet-bulb temperature (℃) | 9.6 |
| Total cooling time (hours) | 324 |
| Electric energy used (kWh / tonne) | 1.25 |
| LPG used (kg / tonne) | 2.75 |

Figure 13 shows the average dry-bulb temperatures of the ambient air, conditioned air and grains in the silo versus the number of days (cooling cycles) from the start of the cooling trial. It can be seen that during most of the cooling cycles the dry-bulb temperatures of the conditioned air was between 15 and 20℃. The average dry-bulb temperature of the conditioned air during the trial was 16.7℃, whereas the average dry-bulb temperature of the ambient air during these cooling cycles was 14.2℃ It is also seen from Figure 13 that at the beginning of the trial the grain temperatures at 3m, 2m, and 1m deep from the top surface of the grain were 26.5℃, 28℃ and 29℃, respectively. It can also be seen that grain temperatures at 3m, 2m and 1m depth started to fall after 21, 27 and 33 days, respectively from the start of the trial. At the end of the trial the grain temperatures at 3m, 2m and 1m depth from the top of the grain surface were 12.6℃, 14.2℃ and 17.4℃, respectively. The height of the grain silo is about 7.5 m, which suggests that the temperature of the most of the grain bulk was close to 12.6℃. The dry-bulb and wet-bulb temperatures of the grain at a depth of 2m depth were measured at the end of the trial with a grain psychrometer The dry-bulb and wet-bulb temperatures were 14.6℃ and 9.6℃, respectively. At this grain wet-bulb temperature, even cold tolerant insect species such as *Sitophilus oryzae* (rice weevil) and *Sitophilus granarius* (granary weevil) would scarcely breed. It can therefore be concluded that the desiccant system designed and developed at Victoria University of Technology, Melbourne is able to reduce the grain wet-bulb temperature close to or below the threshold seed wet-bulb temperature for various species of stored product (Desmarchelier, 1988, 1993, Wilson and

Desmarchelier, 1994). The electrical energy consumed during the Moree grain cooling trial was 1.25 kWh/tonne This compares with an energy consumption of 6 to 8 kWh/tonne using conventional air refrigeration systems (Maier, 1996). The LPG consumed was 2.75 kg/tonne. The LPG consumption can be eliminated by incorporating a solar collector with desiccant system to raise the temperature of the ambient air during the reactivation cycle.

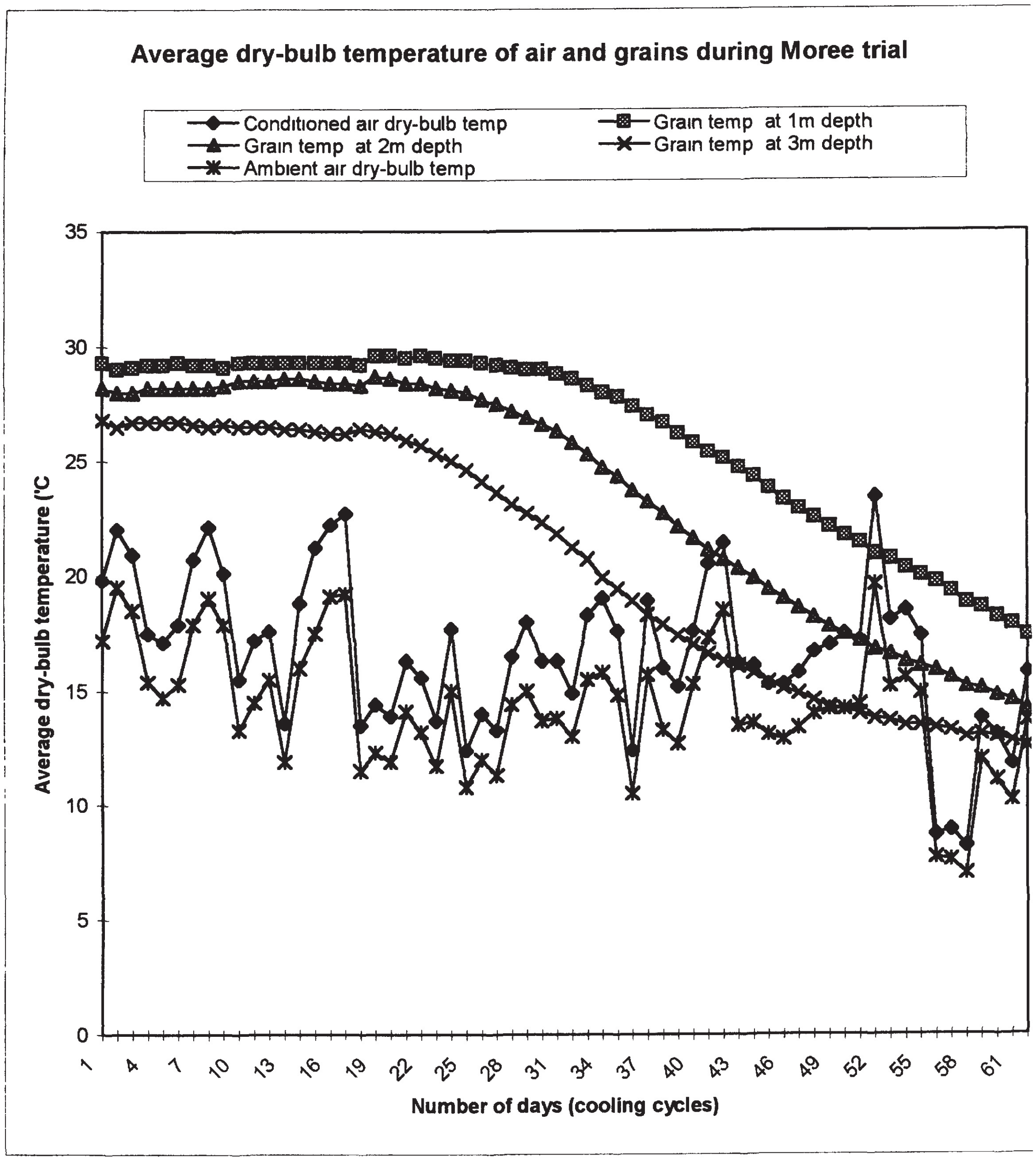


**Fig. 13.** Dry-bulb temperatures of air and the grains during the experiments carried out at Moree.

Table 7 presents a summary of results of the grain cooling experiment carried out at Warwick, Queensland. The quantity of barley in the silo was 50 tonnes and it had an initial moisture content of 11.9% (wet-basis), and its initial grain dry-bulb and wet-bulb temperatures were 32.1℃ and 23.5℃, respectively. These temperatures were measured with a grain psychrometer at a depth of 2m from the upper surface of the grain in the silo. The Warwick grain cooling trial started on 1st December, 1997 and it was continued until 2nd January, 1998. The system operated effectively for 32 days. The average duration of the cooling cycle was 5.0 hours during the trial period. This results total cooling time during this trial of 160 hours. The average air flow rate was measured to be 2.2 l/s tonne. The average ambient temperature during the cooling trial was 24 2℃. Figure 14 shows the average dry-bulb temperatures of the ambient air, conditioned air and grains in the silo versus the number of days (cooling cycles) from the start of the cooling trial. The average dry-bulb temperature of the ambient air during the cooling cycles of the trial was 18.3℃, whereas the average dry-bulb temperature of the conditioned air during the trial was 21.7℃. It can be observed from Figure 14 that in the beginning of the Warwick trial the grain temperatures measured with thermocouples at 2m and 1m from the top of the grain surface were about 32℃ The grain temperature at a 2m depth started to fall after the first cooling cycle, whereas the grain temperature at 1m depth started to fall after 5th cooling cycle At the end of the trial the grain temperature at 2m and 1m depth from the top of the grain surface were 16.5℃ and 18.3℃, respectively The grain temperature at 3 m depth at the start of the trial was 32.4℃, and it started to fall after the first cooling cycle but at a somewhat slower rate than the grain temperature at 2m depth from the top of grain surface. It reached to its minimum value of 18.8℃ after 25th cooling cycle and then started to rise slowly The most likely reason for the rise in grain temperature at a depth of 3 m is the increase in temperature of the ambient air at about the 20 th day of the experiments.

**Table 7.** Summary of results of the grain cooling trial carried out at Warwick, Queensland.

| Trial name and location | Warwick, Darling Downs, Queensland |
|---|---|
| Trial period | December 1, 1997 to January 2, 1998 |
| Quantity of barley (t) | 50 |
| Average air flow rate (l/s per tonne of grain) | 2.2 |
| Initial grain dry-bulb temperature (℃) | 32.1 |
| Initial grain wet-bulb temperature (℃) | 23.5 |
| Initial grain moisture (% wet-basis) | 11.9 |
| Final grain moisture (% wet-basis) | 11.7 |
| Final grain dry-bulb temperature (℃) | 17.3 |
| Final grain wet-bulb temperature (℃) | 12.5 |
| Total cooling time (hours) | 160 |
| Electric energy consumed (kWh/tonne) | 1.34 |
| Solar contribution to meet the system heat demand(%) | 50 |
| LPG consumed (kg/tonne) | 1.5 |

The dry-bulb and wet-bulb temperatures of the grain at a depth of 2m were measured at the end of the trial with a grain psychrometer. The dry-bulb and wet-bulb temperatures were 17.3℃, and 12.5℃, respectively This indicates a drop of 14.8℃ in dry-bulb temperature of grains, whereas the drop in wet-bulb temperature of the grains was 11℃. This reduction in wet-bulb temperature greatly affects the rate of population growth of insects that infest stored grains. If these grains had not been cooled and left untreated, the high grain wet-bulb temperature (23.5℃) would provide an environment conducive to the thriving of insects pests. It should be noted that a 23.5℃ grain wet-bulb temperature, insect species such as *Sitophilus oryzae* (rice weevil) would multiply 20 fold in one month, whereas at 12.5℃ grain wet-bulb temperature, its multiplication rate will be hardly two fold in one month. Other insect species such as *Rhyzopertha dominica* (lesser grain borer), *Sitophilus zeamais* (maize weevil), and *Tribolium castaneum* (rust-red flour beetle) would scarcely breed in 12.5℃ grain wet-bulb temperature as inferred from data presented by Desmarchelier (1993) and Wilson and Desmarchelier (1994). It can be concluded therefore that the solar desiccant system performed well during the Warwick grain cooling trial and reduced the grain wet-bulb temperature close to or below the reproductive threshold seed wet-bulb temperature for various species of stored products It was estimated that during the Warwick grain cooling trial that 50% of the heating demand of the desiccant system was met with solar energy, whereas gas consumption was measured to be 1.5 kg / tonne. This was about half the gas consumption of the Moree grain cooling trial (Ahmad and Thorpe, 1997). The electrical energy consumed during the Warwick grain cooling trial was predicted to be 1.34 kWh/tonne

# Conclusions

Field experiments have been carried out on a novel grain cooling system is very simple to build, has few moving parts and that has the potential to make use of renewable energy. The main outcomes of the work may be summarised thus:

- During experiments carried out at Walla Walla, New South Wales, it was observed that the average wet-bulb temperature of ambient air was reduced from 14.8℃ to 8.1℃ as it passed through the grain cooling system. The corresponding temperatures during the Moree trial are 14.7℃ and 7.3℃ Insect populations in both bulks of grain would scarcely be able to breed, and desirable grain properties would be maintained.
- The average rate of adsorption and desorption during the cooling and reactivation cycles at Walla Walla were 3.7 kg/hr and 3.55 kg/hr, respectively, whereas the average rate of adsorption and desorption during the cooling and reactivation cycles at Moree were 3.88 kg/hr and 2.67 kg/hr, respectively. This indicates that relatively more time is required to reactivate the desiccant system in Moree's climate compared with that of Walla Walla.

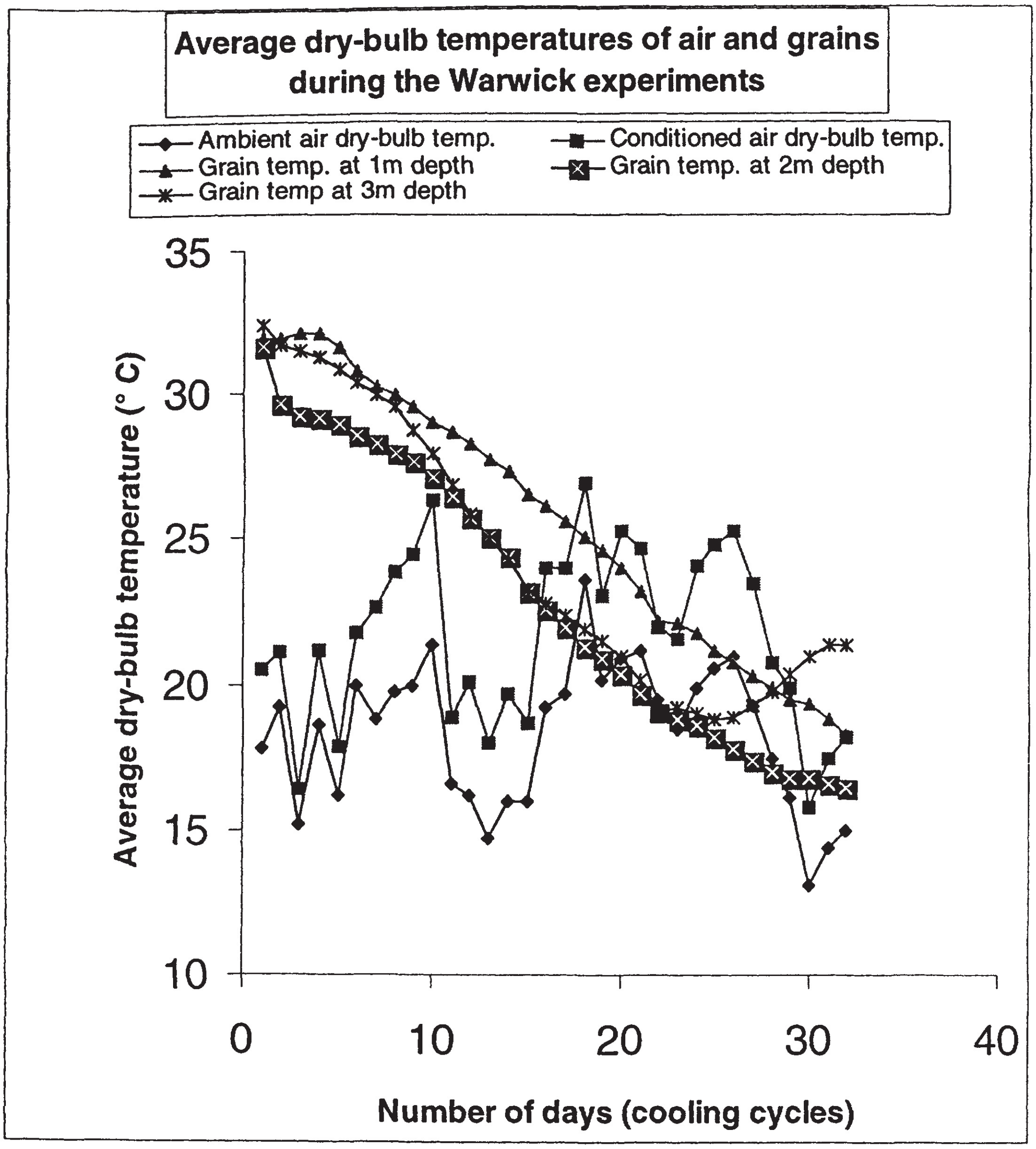


**Fig. 14.** Average dry-bulb temperatures of air and grain during the Warwick experiments.

- The coefficient of performance of the desiccant cooling system based on total energy input is predicted to be 0.29, whereas the coefficient of performance of the system based on the electrical power input (energy supplied to the fans) is over 7. There is an incentive to reduce the gas energy expended in heating the air during the reactivation cycle, and this may be achieved using solar energy.
- The initial grain moisture contents, dry-bulb temperature and wet-bulb temperature were 10%, 22.5℃ and 13.2℃, respectively during a grain cooling trial carried out at Walla Walla. The respective values reduced to 9.8%, 19.3℃ and 10.6℃ at the end of the cooling period.
- The grain moisture contents, dry-bulb and wet-bulb temperatures were 11.5%, 28.4℃ and 20.3℃, respectively at the beginning of a grain cooling trial carried out in Moree. These respective values reduced to 11.25%, 14.6℃ and 9.6℃ at the end of the cooling period.
- The results suggest that the grain cooling system may operate effectively in tropical climates, but this must be confirmed by experiment.
- During experiments carried out at Warwick in Queensland the gas heater was supplemented with a solar collector. It was observed that the effect of this was to halve the consumption of gas.

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