EXPERIMENTS ON AN OPEN-CYCLE SOLAR REGENERATED DESICCANT BED GRAIN COOLING SYSTEM

G R Thorpe and P W Fricke
Agricultural Engineering Section
C S I R O Division of Chemical and Wood Technology
PO Box 26, Highett, Victoria 3190

ABSTRACT

Grain can be protected from insect attack, and have its properties preserved by cooling it to temperatures around 15°C. In temperate climates, grain can be cooled effectively by aerating it with cool atmospheric air, but the degree of cooling is limited by the heat of absorption released as the grain absorbs moisture from the air. In tropical climates this problem is compounded by the generally high ambient dry-bulb temperatures. Lower grain temperatures may be achieved by reducing the enthalpy of the aeration air. Experiments on a single-stage and a two-stage open-cycle solar regenerated desiccant bed grain cooling system that reduces the enthalpy of the aeration air are described. The rate of energy loss from the device was about 20 times that of the electrical energy supplied to the system. This compares favourably with vapour compression systems.

INTRODUCTION

Cereal grains are harvested seasonally, yet they are consumed continually, and for this reason they have to be stored. During storage, severe losses may occur because of attack by insect pests, infestation by moulds and mites, and predation by birds and rodents. In addition, grains that are stored for prolonged periods may suffer a reduction in quality as indicated by a loss of seed germination, baking and milling characteristics, changes in colour and so on. Chemical insecticides applied to improperly stored grains are likely to lose their toxicity very rapidly. Cooling grain, either as an adjunct to chemical pesticide treatment, or alone improves the long-term storage of grain (Thorpe 1980).

The simplest method of cooling bulk stored grain is by blowing through it cool atmospheric air. The effectiveness of natural aeration is limited by the fact that the periphery of the grain store is not cooled sufficiently to control insect pests. Furthermore, the hygroscopic nature of cereal grains generally prevents the grain being cooled to ambient temperature, for reasons described below. Both of these drawbacks of natural aeration may be overcome by refrigerated aeration (Elder et al. 1983). this requires the grain store to be thermally insulated and the aeration air re-cycled through mechanical refrigeration units. This process involves more capital expenditure than natural aeration and it is energetically more demanding.

This paper describes an open-cycle, stage-wise solar regenerated desiccant bed grain cooling system, which embodies simple technology and has a very low energy consumption. The system enables grain temperatures lower than ambient to be attained.

THE COOLING MECHANISM

The passage of air through a packed bed of hygroscopic material such as cereal grains involves both heat and moisture transfer. This has profound consequences on the rate at which temperature waves move through the porous matrix and on the temperatures attained. In this paper we shall discuss only the bulk storage of grains, although the benefits conferred by cooling on the preservation of grain are independent of storage method.

Bulk grain may be cooled by blowing through it air of the appropriate conditions. Grain interacts with the moisture in the aeration (cooling) air and under normal storage conditions most of the grain will not cool to the air inlet temperature. The heat and moisture transfer phenomena governing grain cooling have been elucidated by Banks (1972) and Suntherland et al. (1971). One of the principal conclusions arising from their work is that the temperature to which most of the grain will cool is dependent on the initial grain moisture content and the wet-bulb temperature of the aeration air.

Using properties of the air-grain-water system presented by Sutherland et al. (1971), we find that aeration air at 15°C and 50% relative humidity (rh) will cool most of an initially 12% moisture content (mc) grain bulk at 30°C to about 15°C. If the grain were initially 9% mc it would cool to about 23°C. If the aeration air is 15°C but 90°C relative rh the corresponding temperatures to which most of the initially 12% and 9% stored grain would cool are about 19°C and 27°C respectively.

The speed at which cooling waves more through grain is about 2×10^{-3} times the superficial air velocity. A second cooling wave also travels through the grain during which the grain becomes in hygroscopic equilibrium with the aeration air. The speed of the second wave is about 5×10^{-5} that of the superficial air velocity.

A DESICCANT BED GRAIN COOLING SYSTEM

From the above it may be inferred that the effectiveness of grain cooling is enhanced by reducing the enthalpy of the aeration air. An effective method of doing this is to isothermally reduce ambient air humidity. This can be achieved by blowing ambient air at night through a narrow bed of desiccant material so the heat of sorption can be readily dissipated to atmosphere (Thorpe 1981). The desiccant becomes wet, but it can be dried out during the day by means of solar radiation falling on the desiccant bed. This method is effective, but the narrowness of the desiccant bed of porous medium results in a high pressure drop across the system.

A method of overcoming the pressure drop is to carry out the drying and cooling of the air in a stage-wise process. The principal elements of one such system is shown in Figure 1. During the air drying and cooling process night air from the aeration enters the first heat exchanger, HE1, and some of the heat of compression is lost to atmosphere by convection and radiation to the night sky. The cool, humid air then enters desiccant bed, DB1, where it is dried iso-enthalpically. As a consequence of this process the air increases in temperature and it is subsequently cooled in the second heat exchanger, HE2. The air is further dried in the second desiccant bed, DB2, before being finally cooled in the third heat exchanger, HE3.

The desiccant is regenerated by designing the heat exchangers HE1 and HE3 as effective solar collectors. Hence during the day ambient air leaving the fan is heated in the heat exchangers, thus reducing its relative humidity so that the desiccant beds are regenerated for the night cycle.

The underlying principles of operation of the stage-wise system can be understood from the psychrometric chart (Figure 2). Cool ambient air with a high relative humidity state 1 is compressed by the fan to state 2. It is this air that would normally be used for ventilating grain in natural aeration systems, but because of its high enthalpy it has limited cooling capacity. In the desiccant bed cooling system the air is cooled from state 2 to state 3 in the first heat exchanger, HE1. The air on entering the first desiccant bed, DB1, leaves at state 4, whence it is cooled by the atmosphere to state 5. Now this represents a reduction in enthalpy compared with natural aeration systems, but a further reduction is obtained by passing the air through the second desiccant bed, DB2, bringing it to state 6, before finally cooling it to state 7. It is this air that is used to cool the grain.

AN EXPERIMENTAL SINGLE-STAGE

In order to assess the likely performance of the above system, a single-stage consisting of a fan, heat exchanger (HE1) and desiccant bed (DB1) was constructed, and comprehensively instrumented. The layout of the single stage and its associated instrumentation is shown in figure 3.

The heat exchanger-cum-solar absorber is 1.14m wide and 1.18m long, and the desiccant bed rests on a 100m wide perforated metal sheet in a container integral with the heat exchanger. Those parts of the device not directly exposed to solar radiation are thermally insulated with fibre-glass wool. On leaving the desiccant bed which may be up to 200mm high the air flows through a return leg before being expelled through the base of the stage. This design was chosen so that stages could be conveniently placed side by side in series.

The unit is comprehensively instrumented to allow the air flow rate and thermodynamic states to be determined throughout the system. The inlet air state is measured by wet- and dry-bulb thermocouples, and the dry-bulb temperature of the air is measured after compression by the fan just before it enters the solar absorber. Radiation-shielded thermocouples measure the temperature of the air leaving the absorber at four points, and as it enters the return leg immediately after it has passed through the desiccant bed. Wet- and dry-bulb thermocouples measure the state of the air being expelled by the unit. Electrically insulated thermocouples in close contact with the upper and lower plates of the absorber measure surface temperatures, and six thermocouples placed in the desiccant bed measure the desiccant temperature. A sampling probe allows desiccant to be removed from any depth of the desiccant bed at the front, middle and back of the bed, so its moisture content can be determined.

The air flow rate is measured by an orifice plate manufactured according to British Standards and the level of radiation is measured by a solar pyranometer calibrated against a CSIRO Division of Energy Technology secondary standard.

The experiments were carried out in the CSIRO Division of Energy Technology solar simulator (Proctor and Peck 1979), which consists of an array of fourteen 1 kW compact source mercury iodide discharge lamps that accurately mimic the solar spectrum.

EXPERIMENTAL METHOD

When simulating daytime operation of the solar cooling stage the mercury iodide lamps were turned on together with the fan, and the air flow was adjusted to the required rate. At the beginning and end of each experimental run samples of silica gel were withdrawn from the bottom, middle and top of the desiccant bed, and the moisture contents of the gel were measured by an oven method. The thermocouples were scanned by a Hewlett-Packard 3421A thirty channel data logger, and the temperatures were stored on a mini 128 kbyte capacity cassette. Mean values of the intensity of solar radiation were determined by averaging the radiation measured at twenty five points on the absorber surface.

RESULTS AND DISCUSSION

A series of five pairs of cooling and bed regeneration experiments was carried out with an air flow of 0.014 kg/s. This would be sufficient to cool up to 20 tonnes of grain. The cooling runs were carried out in an enclosed building during the day, hence the relative humidity of the ambient air is somewhat lower than would occur at night, and there was no radiation heat loss to the night sky. Conditions during a typical cooling run were:

Ambient dry bulb	15°C
Air temperature leaving fan	17°C
Absolute humidity of ambient air	0.0075 kg/kg
Air temperature leaving desiccant bed	31°C
Air temperature leaving single stage	21°C
Absolute humidity of air leaving single stage	0.0040 kg/kg

These results imply that as the air passes from the entrance of the desiccant bed to the end of the heat exchanger it is reduced in enthalpy from 36.5 kj/kg to 31.5 kj/kg. This would result in the dwell temperature of 11% moisture content wheat being reduced from 20°C to 17.5°C. The fan was operated for 6 hours during the cooling cycle and the average moisture content of the gel increased from 6.5% to 17%.

A heating run performed the day immediately after the cooling run was carried out under the following conditions.

Solar radiation intensity	840 W/m^2
Ambient dry bulb	23°C
Air temperature leaving fan	26°C
Absolute humidity of ambient air	0.00085 kg/kg
Air temperature entering desiccant bed	52°C
Air temperature leaving desiccant bed	40°C

Absolute humidity of air leaving desiccant bed 0.0175 kg/kg

The mean moisture content of the desiccant bed decreased from 17.3% to a fairly uniform 4.4%. The efficiency of the solar collector was 32%, a figure that could clearly be improved by glazing.

Pressure measurements indicate that with an air flow rate of 0.014 kg/s the pressure drop across the solar collector/radiator is about 5 Pa, and that across the desiccant bed is around 55 Pa. Losses in the ducting and across the orifice plate were several hundred Pascals, but in commercial systems these would be readily engineered out.

EXPERIMENTS ON A TWO-STAGE SYSTEM

In order to assess the overall performance of a two-stage system, two of the single stages described above were connected in series. As the two stages were too large to be irradiated in the solar simulator, experiments were performed under naturally occurring ambient conditions. Daytime cycles were of the order of four hours and night cycles had a duration of three hours.

Results of a typical night run in which the air flow rate is 0.014 kg/s are shown in Table 1. The enthalpy of air leaving the fan is reduced by the system from 29.7 kj/kg to 13.4 kj/kg. This arises principally from a reduction of humidity from 0.0068 kg/kg to 0.0013 kg/kg. Another contributing factor is a reduction in the air dry-bulb temperature by 2.2°C from 12.3°C such that it leaves the unit with a dry-bulb temperature lower than that of ambient due to radiation to the night sky.

TABLE 1: Typical operating conditions during night cycle

	Ambient	After fan	Leaving 1st stage	Leaving 2nd stage
Dry-bulb temp °C	10.5	12.3	13.8	10.1
Humidity kg/kg	0.0068	0.0068	0.0031	0.0013
Enthalpy kj/kg	27.9	29.7	21.8	13.4

If ambient air were to be used for aeration, the dwell temperature of 11% moisture grain would be 16°C, whereas air leaving the solar cooler would be capable of cooling the grain to 6°C. The rate of heat reduction of the aeration air is 228 W, whilst the electrical power requirements is of the order 3.5 W. Assuming that the desiccant regeneration cycle has a duration twice that of the cooling cycle the coefficient of performance (COP) of the system based on the electrical power input is over 20. This is an order of magnitude greater than that of mechanical refrigeration sets. Based on total energy input, including solar energy, the COP is about 0.1.

The above results are most encouraging because they show that a substantial reduction in the enthalpy of ambient air can be obtained, with a small expenditure of electrical energy. However, further research is required in the following areas:

i. It is important to extend the range of experimental variables in order to assess performance under conditions of high ambient dry-bulb temperatures and humidities which cause considerable storage problems. The effects of air flow rate on performance should also be investigated, as this determines the quantity of grain that can be cooled.

ii. Systems studies, best carried out using computer simulations, are required to match grain cooling systems to the grain stores, and to determine the optimum operating schedule.

iii. The effects of glazing the collectors for daytime operation should be examined. If air of a higher temperature is used to regenerate the desiccant bed, then a given mass flow of air can dry out a larger mass of desiccant. Hence, for a given drying duty it would be necessary to expend less energy on pumping the air through the desiccant bed during the day, improving further the coefficient of performance of the system.

iv. The system would be improved if the dessicant bed were to work isothermally, as opposed to adiabatically, particularly during the cooling cycle. This could be achieved by placing heat transfer surfaces within the desiccant bed to facilitate the loss of heat of sorption to the atmosphere.

CONCLUSIONS

Experiments on a single stage and two stages of a stage-wise solar regenerated desiccant bed grain cooler have shown that the enthalpy of ambient air may be reduced, thus rendering it more suitable for the aeration of grain. Under the conditions of the experiment the energy removed from the air is about 20 times the electrical energy required to drive the system.

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FIGURE 1: **Components of a stage-wise solar re-generated dessicant bed grain cooling system**

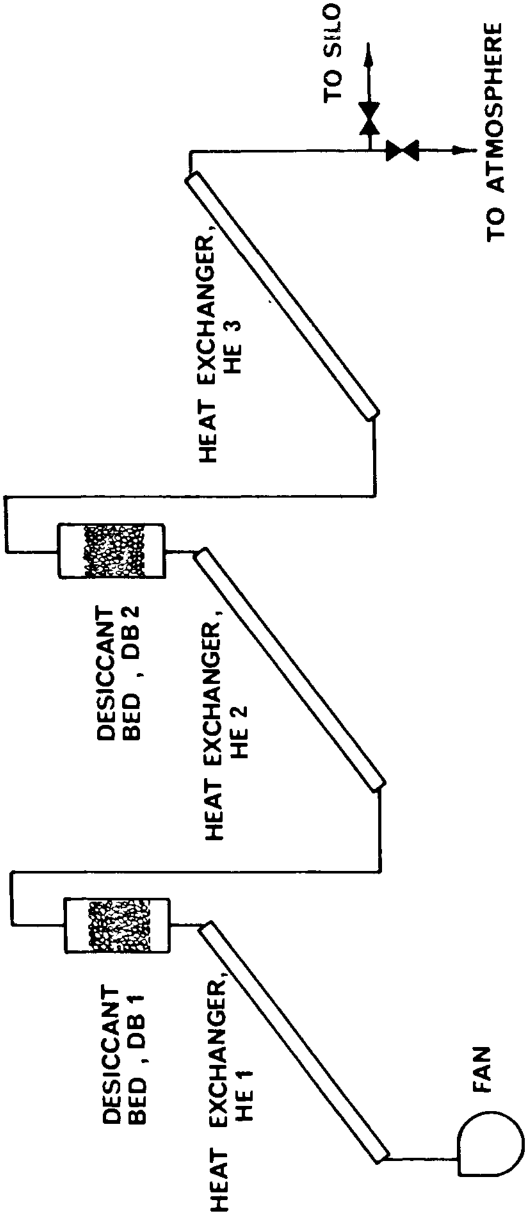

FIGURE 2: Air states represented on a psychrometric chart

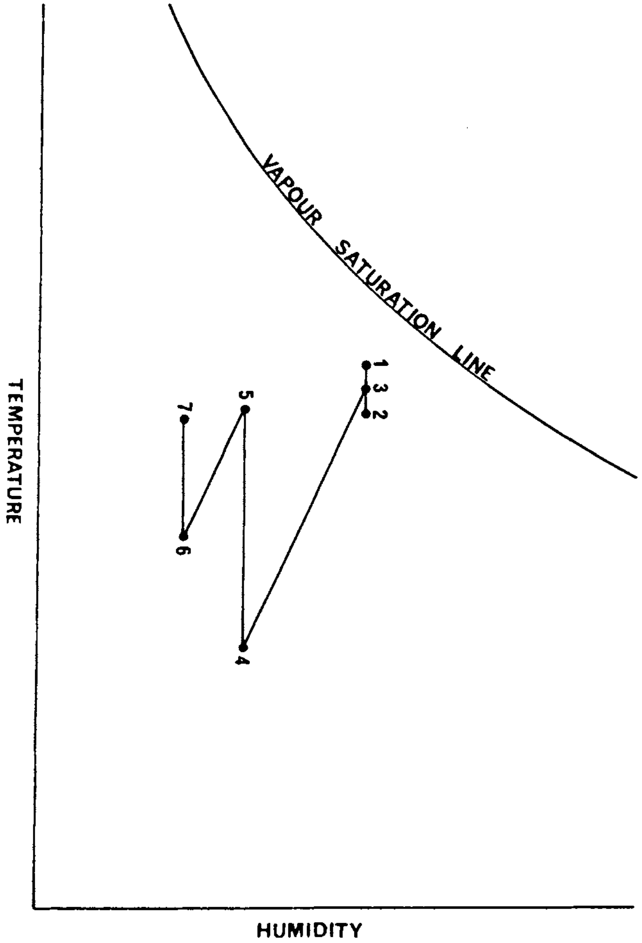

FIGURE 3: An instrumented single stage absorber