Chilled aeration and storage of U.S. crops — a review

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Abstract

The contamination of grain with insects, insect fragments, fungi and mycotoxins is one of the major concerns of the U.S. grain industry. In the past, pesticides have been used to achieve therapeutic control. However, insects are developing resistance, consumers are concerned about toxins and pesticide residues, many pesticides are being withdrawn from use because of high costs to register or develop new ones, and environmental considerations have made the production of certain pesticides illegal. Therefore, alternative, preferably non-chemical, methods of effective pest control are needed in the postharvest grain storage environment. One alternative, aeration cooling, can be used to lower the carrying capacity of the stored-grain ecosystem for insects. However, under certain climatic conditions and in various geographic locations, ambient aeration cannot completely inhibit insect activity and preserve grain quality. When grain temperatures cannot be sufficiently reduced, chilled aeration is a technically viable and economically feasible grain-conditioning alternative.

Grain chilling is a non-traditional, non-chemical treatment technology of bulk stored commodities to prevent spoilage and stored-product insects. Grain is cooled using a mobile refrigeration system that controls both the temperature and relative humidity of the aeration air. Grain chilling was first applied in the United States in the late 1950s, and subsequently investigated in the southwest and midwest for the storage of high-moisture grains. However, the technology was never commercialised. In 1988, researchers at Michigan State University began the first serious evaluation of chilled grain aeration in more than 20 years. The success of those tests led to the development and field testing of a new grain chiller developed by Purdue University in cooperation with AAG Manufacturing (Milwaukee, WI), which has resulted in the commercialisation and sale of the first U.S.-built grain chillers.

This paper reviews the trials that established the technical feasibility and biological desirability of chilled aeration and storage of grains in the U.S. It also presents the development and optimisation of the first generation U.S. grain chiller; field testing and computer simulation were used to optimise the system. The current status of utilisation of grain chilling and conditioning technology in the U.S. grain industry will be presented.

Introduction

A stored grain bulk is a man-made ecological system in which deterioration is an on-going process that results from interactions among physical, chemical and biological variables. Damage by insects, fungi, heating and sprouting causes millions of dollars in economic losses to U.S. grain farmers, handlers and processors every year. Although quality of harvested grain can never be improved with storage time, the rate of deterioration can be slowed with an integrated postharvest system management approach that combines engineering, biological, and economic principles. Sanitation of harvesting, handling, and processing equipment and storage structures is essential. Drying grain reduces its spoilage potential, and cleaning it before binning removes fines, filth, damaged kernels, and foreign material. Proper aeration practices maintain low grain temperatures, and the application of a residual pesticide may reduce insect damage.

Protecting grain with a pesticide is recommended for grains stored in the southern and south-eastern U.S. for any length of time, while it is recommended only for long-term (over one-season) storage in the midwest. As grain is marketed and moves through various facilities, the identity of a lot is lost and additional pesticide treatments occur. Thus, the number of pesticide applications can increase, and potentially toxic residues may accumulate in the final food and feed products. Recent reports from the mid-western United States indicate that the lesser grain borer, *Rhyzopertha dominica* (F.) may be developing resistance to chlorphyrifos-methyl (Reldan) (Beeman and Wright 1990; Zettler and Cuperus 1990). As a result, this pest has been removed from the label. The label for pirimiphos-methyl (Actellic) now specifies that it will only suppress, not control *R. dominica* (F.) if it is applied at the maximum recommended rate. As additional insects develop resistance to currently available pesticides, greater emphasis must be placed on alternative methods for protecting our food supply.

Alternative pest control techniques must focus on limiting insect reproduction and growth by controlling temperature and moisture content in the grain bulk, and by utilising multiple tools such as insect sampling with pheromone and pitfall traps, risk-benefit analysis of control strategies, plant resistance, and biological methods (Hagstrum and Flinn 1992). Maintaining low temperature- and moisture-levels in bulk-stored grain was identified in a major study on 'Enhancing the quality of U.S. grain for international trade' (U.S. Congress 1989) as the main way to preserve grain quality, and to prevent damage from moulds and insects. One technology that has been successfully utilised to preserve grain quality during storage is grain chilling. It permits the short- to long-term storage management of grain independent of the ambient conditions. The chilled aeration of grain has been applied commercially in over 50 countries during the past 30 years (H. Brunner, pers. comm., 1990), but only recently in the United States. It is estimated that annually over 20 million tonnes of grain are cooled with grain chilling systems. Grain chilling is accepted as a grain conditioning technology in much of Western Europe, while currently most units appear to be sold in Southeast Asia. In the 1960s grain chillers were primarily used as a means of preserving high moisture grain. Today, the primary application for grain

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chilling is in preserving the keeping quality of dry grain through chilled aeration and non-chemical pest management.

Commonly, grain is stored in bins, silos and flat storages that either do not allow cooling because of a lack of aeration systems, or allow cooling to within several degrees of the minimum ambient temperature using conventional aeration systems. In contrast, grain chilling is defined as the cooling of grain independent of the minimum ambient temperature by using a refrigerated air system. In a grain chilling system, ambient air is ducted over a bank of refrigeration coils in order to decrease the air temperature (Fig. 1). Because dry grain will absorb moisture from wet air, the air is reheated a few degrees to reduce the relative humidity to 60-75%. The amount of reheating and the final air temperature are adjustable by the operator to achieve the desired aeration conditions. Once the grain has been initially cooled, only occasional rechilling for short time periods is required to maintain chilled storage conditions due to the insulating properties of the grain itself. The ability to control both the bin inlet temperature and relative humidity is desirable for conditioning stored grain and maximising its end-use processing value.

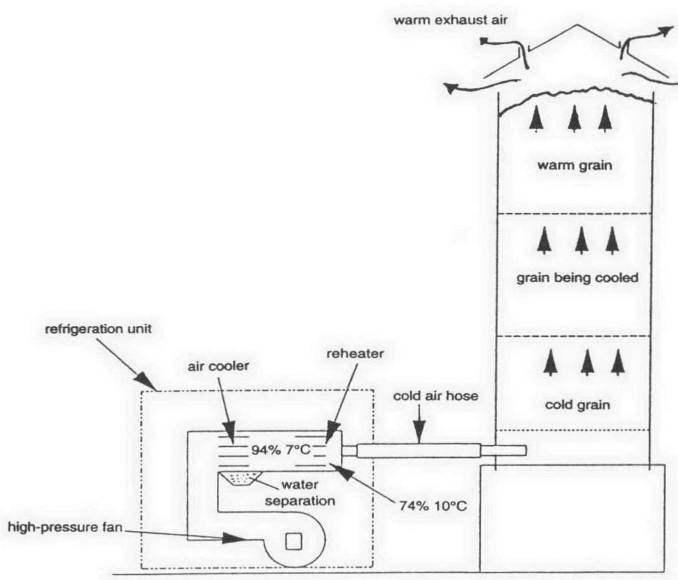

Fig. 1. Schematic of the grain chilling process. The binned grain is cooled independent of the minimum ambient temperature by using air conditioned to operator-selected temperature and relative humidity levels.

Historical Development of Grain Chilling

The change-over from traditional harvesting methods to high-volume combining of grain crops after World War II caused a rapid expansion in the use of heated-air drying to preserve grains (Hall 1980). However, in many installations the limited capacity of grain dryers soon created bottlenecks (Saul and Lind 1958). In Europe the search for an alternative preservation method led to the application of refrigerated aeration with saturated air (Burrell 1974). Lowering the temperature of wet grain to less than 10°C within 24 hours of harvest allowed for the 2–3 week risk-free storage of small grains up to 20% moisture, and of maize up to 35% moisture (Heidt 1963).

According to Reimann (1927) the idea of cooling grain artificially was first proposed by a German engineer in 1917. The concept seemed impractical and expensive at the time. According to Burrell (1974), the use of a refrigeration system to dry grain from 20% moisture to 16% was proposed in France by Leroy in 1950. As early as 1958 a cold-air drying system was sold in Germany (Escher-Wyss 1960). These closed-cycle batch systems consisted of a heat pump to dehumidify and cool the exhaust air from the top of the grain pile. The cold, dry air was forced back into the bottom of the bulk. In 1961 the Escher–Wyss company of Lindau, Germany began with the production of commercial grain chillers (Heidt 1963), which consisted of a cold-air fan, evaporator coil, compressor, condenser and cooling fan. The chillers had cooling capacities of 50 t of grain/day.

Munday (1965) described commercial grain chillers manufactured in England primarily designed for on-farm use. By 1970 grain chillers incorporated automatic cold air regulation and a reheater after the evaporator to control the relative humidity of the chilling air automatically (Sulzer-Escher Wyss 1970). Reheating is generally accomplished with waste heat from the condenser. In the newly developed American chiller, however, a separate glycol loop returns heat to the chilled air after the evaporator (Maier et al. 1993a). This approach reduces the cooling load on the evaporator and minimises the use of refrigerant. Most chiller manufacturers use motorised dampers to control the airflow across the evaporator, and thus provide a constant cold-air temperature into the grain bin. Only recently has a chiller been introduced with a variable-frequency blower drive to optimise airflow performance (IKZ 1993).

There are at least seven major commercial manufacturers of grain chillers worldwide: 1) Series 'Goldsaat' by Fritz Döring Co. (Prüm, Germany); 2) Series 'Grain Cooler' by PM-Luft Co. (Kvänum, Sweden); 3) Series 'Granifrigor' by Sulzer-Escher Wyss Co. (Lindau, Germany) (Fig. 2); 4) Series 'DUK' by Uniblock Zanotti Co. (Suzzara, Italy); 5) Series

Table 1. Summary of the main design parameters of the largest commercial grain chillers of each of four manufacturers (Fritz Döring, Prüm, Germany; Sulzer-Escher Wyss, Lindau, Germany; PM-Luft, Kvänum, Sweden; Uniblock Zanotti, Suzzara, Italy; AAG Manufacturing, Milwaukee, Wisconsin, USA.).

	Goldsaat GK 480 NDI	Granifrigor KK400	Grain Cooler 8000	DUK 100	Chill'd Aire GTC 3000
Chilling capacity [t/day]	400	335	350	350	350
Airflow at 2000 Pa [m^3/hour]	16750	16300	16250	17000	16900
Evaporator capacity [kW]	128	107	107	110	115
Connected load [kW]	N/A	54	55	55	55

'RM Grain Cooling Units' by MacBea Co. (Parkdale, Australia); 6) Series 'LK Grain Coolers' by IKZ (Zwickau, Germany); and 7) Series 'Chill'd Aire' by AAG Manufacturing (Milwaukee, WI). The largest chilling units of the leading manufacturers are similar in performance and capacity (Table 1). The compressor capacities range from 107 to 130 kW. The fans provide airflow rates of about 16500 m^3/hour at 2000 Pa of static counter pressure. The average grain chilling capacity is about 350 t/day.

Fig. 2. Commercial grain chiller Granifrigor KK400 manufactured by Sulzer-Escher Wyss, Lindau, Germany.

In his comprehensive state-of-the-art review, Burrell (1982) summarised one of the main uses of grain chilling as the protection of grain from insect infestation by storing cooler grain. He concluded that 'refrigeration has so far had little worldwide impact.' Although grain chilling may so far have had little impact on the grain industry, Maier (1992) has summarised the wealth of application experiences that has been reported from around the world, i.e., Germany (Heidt 1963; Heidt and Bolling 1965; Brunner 1985), Great Britain (Burrell 1964; Sullivan and Sebestyen 1973; McLean and Barlett 1991), Australia (Sutherland et al. 1970; Hunter and Taylor 1980; Sutherland 1986), Israel (Navarro et al. 1973; Donahaye 1974; Ben-Efrain et al. 1985), Italy (Baldo and Brunner 1983; Finassi 1987; Bissaro and Bertoni 1989 et al.), France (Lasseran and Fleurat-Lessart 1988; Berhaut et al. 1988), Spain (Clapers 1970; Torres 1983, 1985; Rius 1987), Latin America (Malaga 1973; Cunille 1988; Moreira et al. 1993), and Southeast Asia (Tuckett 1982; Brunner 1985; Chek 1989; Maier et al. 1993c). The application experiences in the United States are the main focus of this review.

Chilling of High-Moisture U.S. Grains

Sorghum chilling in Texas in 1959–68

In the United States conditioned-air storage to maintain grain quality found its first application in 1959 at a commercial elevator in Texas (McCune 1962). The objectives of using conditioned-air were (1) to reduce moisture losses due to ambient aeration in Texas, (2) to control insect infestation by lowering grain temperatures, and (3) to store grain at higher moisture contents for feeding purposes. The initial field test employed a 26.4 kW evaporator coil. The results showed that conditioned-air grain storage had good potential, and that the grain temperatures could be maintained below 10°C. The field work was followed by detailed laboratory tests to determine the design factors, such as equipment size, operating parameters, appropriate moisture contents, and allowable storage times (McCune et al. 1963). In later work, Person et al. (1966) and Sorensen et al. (1967) described the thermodynamic considerations necessary to design chilled grain storage systems. Haile and Sorenson (1968) determined the effect of respiration heat of sorghum on the cooling load requirements for conditioned-air storage systems in Texas.

Maize chilling in Illinois 1965–66

Shove (1966) proposed a process called 'dehydrofrigidation' to dry grain at low temperatures in an insulated dome structure using a refrigeration system. The first phase consisted of cooling the shelled maize from its harvest temperature to –1 to 10°C within 24 hours. Thirty-five kW of refrigeration were considered sufficient to cool a daily load of 102–122 t in the corn belt of the United States. The experimental test encountered several problems, including moulding of the wet grain in the top layers, and inadequate controls to properly condition the air. However, refinement of the process was not pursued further.

Maize chilling in Indiana 1966–70

Ambient and refrigerated aeration in the United States was further investigated by Tuite et al. (1970). Maize at moisture contents of 18–22% was evaluated with respect to changes in moisture content, temperature, mould population and fat acidity. Tests were conducted between 1965 and 1969 with field-harvested shelled maize in 6.5 t insulated bins. The treatments included continuous aeration, intermittent aeration, and refrigerated aeration with and without recirculation at airflow rates of 0.5–1.0 m^3/minute. Continuous ambient aeration was sufficient if the maximum initial maize moisture content was not higher than 21% and was reduced below 16% by April. The refrigerated aeration system had several design shortcomings, including the lack of automatic de-icing of the evaporator coil. However, the system did cool the maize faster in the fall, maintained the temperatures closer to the desired level, and maintained lower temperatures for 4–6 weeks longer in the spring than the ambient aeration system.

Maize chilling in Nebraska 1967–69

Thompson et al. (1969) compared the performance of temperature control systems for the storage of high-moisture maize at 23.3–24.8%. The main objective of cooling was to maintain quality until drying, feeding, or processing. One bin was equipped with a standard ambient aeration system, and the second bin with a 5.3 kW refrigeration system. Both systems delivered airflow rates of 0.4 m^3/minute. Since the tests were conducted between November and April, no significant performance differences between the systems were observed. It was concluded that under midwestern conditions a system with continuous ambient aeration performs better than a more complicated mechanical refrigeration system when storing high-moisture maize. However, the refrigerated aeration system controlled the grain temperature and moisture content in the bulk better than the conventional system.

The temporary storage of high-moisture grain in the United States continued to be of interest to researchers over the next 20 years (Thompson 1972; Stewart 1975; Felkel 1978; Friday et al. 1989; Strohshine and Yang 1990), but, no additional work on chilling high-moisture grains has been reported.

Chilling of Low-Moisture U.S. Grains

Maize and wheat chilling in Michigan in 1988–91

Maier (1992) utilised field tests and simulation techniques for an in-depth analysis of the chilled aeration and storage of low-moisture maize and wheat in the midwestern U.S. The simulation model of the chilled aeration and storage system consists of three parts: (1) the chilled aeration model, (2) the grain chiller model, and (3) the chilled grain storage model. The single-stage refrigeration cycle of the commercial grain chiller used in the study is modelled with steady-state external energy balances across the condenser, reheater and evaporator. The model developed accurately predicts performance in terms of the flow rate, temperature and relative humidity of the air into and out of the chiller, the evaporating and condensing refrigerant temperatures and capacities of the chiller refrigeration cycle, and the electrical power consumption under transient conditions. The chiller model was successfully integrated into a time-dependent grain aeration and storage model for upright, steel silos that simulates the heat and mass transfer with two coupled differential equations in the grain bulk during the aerated period, and the heat transfer with a two-dimensional conduction equation during the non-aerated period (Maier and Bakker-Arkema, 1994). The effect of the aeration and storage conditions on the deterioration of stored grain due to respiration was evaluated using the concept of dry matter loss. Experimental data collected at a commercial elevator for a three-year period were used to validate the systems model (Bakker-Arkema et al. 1989; Maier et al. 1989).

Fall cool-down of maize

The simulated cool-down of a 597-t bin of maize is compared in Figure 3 for the 1988 through 1990 seasons. The temperature profiles and the lengths of the cool-down cycles are obviously influenced by the year-to-year variation of the ambient conditions. In October of 1988 it required 195 hours to chill the maize from 17°C to below 7°C, compared with 180 hours in 1990, and 162 hours in 1989. Associated with longer cooling times are higher energy costs. In addition, managing the cool-down is critical since the bins are filled in rapid sequence during the fall harvest, and sufficient cooling capacity has to be available to keep up with the harvest rate. The predicted power consumption is 2296 kWh in 1988, 1842 kWh in 1989, and 2157 kWh in 1990, resulting in efficiencies of 0.38 kWh/t/°C, 0.31 kWh/t/°C, and 0.36 kWh/t/°C, respectively, during the three seasons.

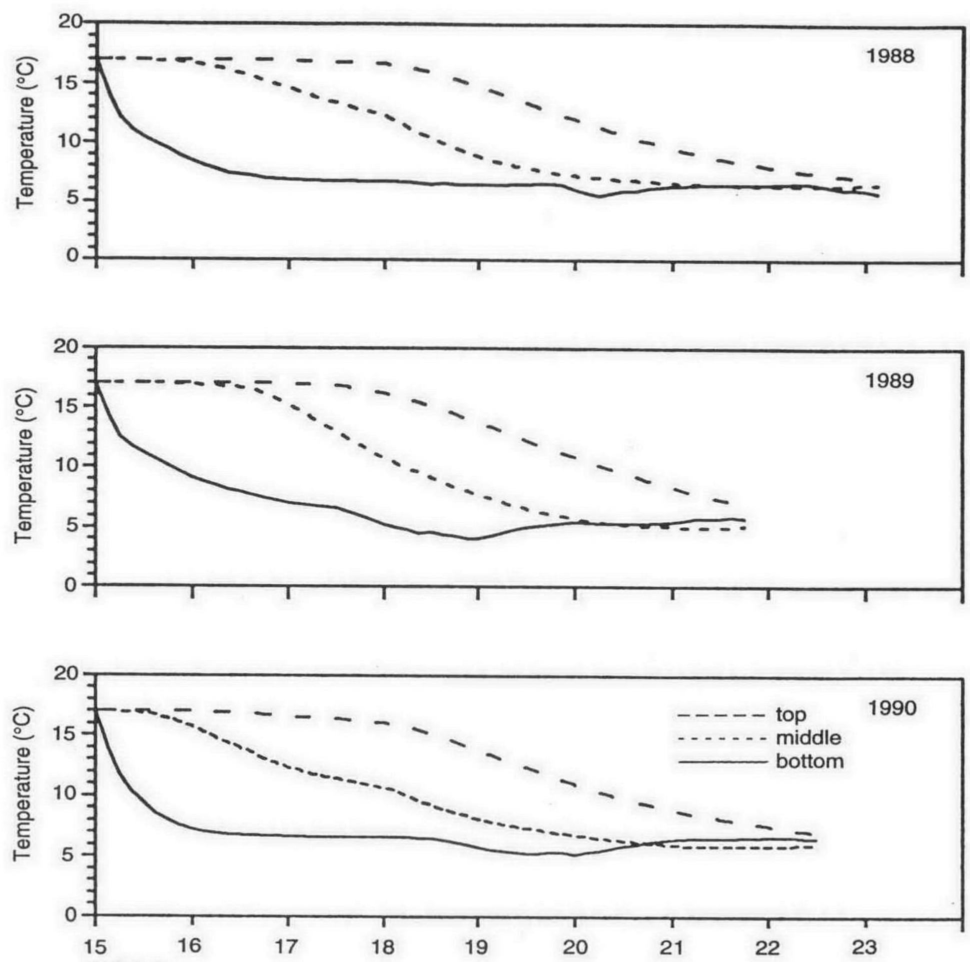

Fig. 3. Simulated chilled aeration of a 597-t bin of maize in mid-October for the 1988, 1989 and 1990 seasons in Michigan. Initial maize temperature 17°C and moisture content 16.5%. Top: – – –; Middle - - -; Bottom ——.

Summer cool-down of wheat

The simulated cool-down of a 579-t bin of wheat is compared in Figure 4 for the 1988 through 1991 seasons. Given the same grain conditions, bin dimensions and chiller settings, the cooling times vary by as much as 3 days. The fastest and slowest cool-downs are predicted in back-to-back years. In July of 1988 it requires 207 hours to chill the wheat from 30°C to below 15°C, compared with 270 hours in 1989, 225 hours in 1990, and 258 hours in 1991. The predicted power consumption is 2632 kWh in 1988, 3517 kWh in 1989, 2854 kWh in 1990, and 3335 kWh in 1991. This results in cooling efficiencies of 0.30 kWh/t/°C, 0.40 kWh/t/°C, 0.33 kWh/t/°C, and 0.38 kWh/t/°C during the four seasons, respectively.

The simulated performance of the grain chiller is shown in Figure 5 for the 1989 cool-down. Given the cyclical behaviour of the ambient temperature and relative humidity, the chiller opens and closes the air throttle to maintain the bin inlet air conditions at a constant 14°C (13°C at the chiller plus 1°C heat gain in the duct) and 67% r.h. The variable airflow is a unique characteristic of a chilled aeration system; ambient aeration maintains a constant airflow but has variable air inlet conditions.

Chilled versus ambient versus no aeration

In the northern United States ambient temperatures drop low enough in the late fall (and winter) to reduce temperatures in stored grain to safe levels. Even in the southern United States ambient temperatures usually decrease sufficiently in the late fall or early winter to achieve stored grain temperatures below 10–15°C with conventional ambient aeration systems. In other parts of the country, such as the Great Plains, grain storage is frequently practiced in bins without aeration systems entirely. There the crop is stored after the harvest and left to cool as a function of the weather conditions. Thus, for chilled aeration to be adopted as an alternative technology, it must be biologically desirable, and have additional economic and environmental benefits. The following summary of results

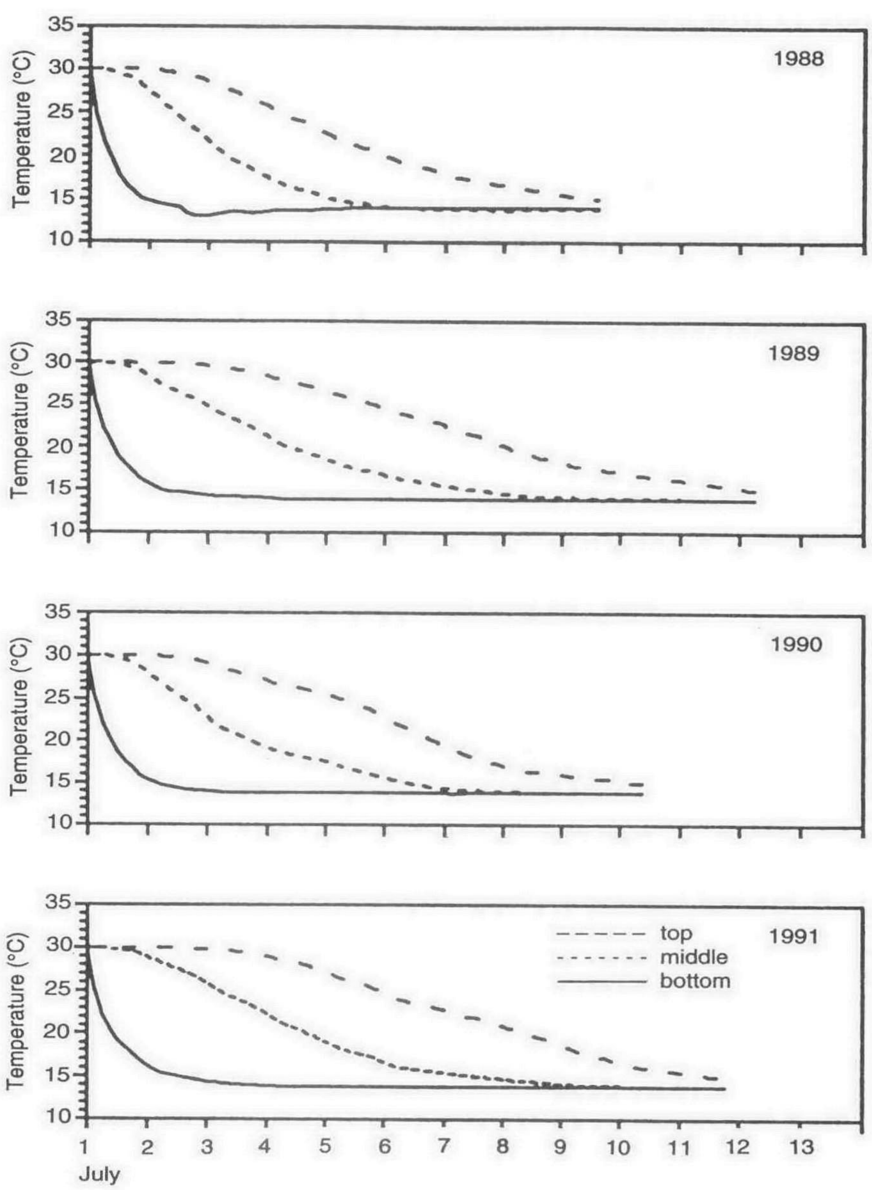

Fig. 4. Simulated chilled aeration of a 579-t bin of wheat in early July for the 1988, 1989, 1990 and 1991 seasons in Michigan. Initial wheat temperature 30°C and moisture content 14%. Top: – – –; Middle - - -; Bottom ——

demonstrates its benefits under Michigan conditions, and makes the technology at least as desirable in the warmer climates of the southern United States.

Maize

Table 2 summarises the comparison of chilled, continuous ambient and no aeration in a bin containing 597 t of maize stored between 15 October 1989 and 14 October 1990 in mid-Michigan. The initial grain temperature is 17°C, and the initial moisture content is 16.5%. The minimum bulk temperature in the non-aerated maize reaches 7.5°C after about 5 months of storage; after 11 months the bulk temperature reaches 17°C again. The ambient aeration of the maize to 7°C at an airflow rate of 0.1 m^3/minute/t takes 4 times longer than cooling the bulk to 10°C. The reason for this significant difference is a period of warmer weather during which the fan rewarmed the grain before it could reach 7°C. Chilling the grain to 7°C and 10°C is accomplished within about 1 week in both cases.

The average dry matter loss of the maize after 12-month storage is 37% less for chilled aeration to 7°C than for ambient cooling, and 68% better than for no aeration. Chilled and ambient aeration to 10°C are equally successful in minimising dry matter loss. The critical dry matter loss limit of 0.5%, which indicates a loss in grade, is reached after 10 months of non-aerated storage. Without close manual supervision, or an automatic aeration controller to selectively cool the bin, the temperature and moisture content may cycle significantly during the cool-down with ambient air. The effect of cycling appears to be more damaging to the long-term grain quality than simply storing at a 3°C higher grain temperature.

Obviously, the costs of chilled versus ambient aeration have to be taken into account to make an economic recommendation of the preferred system. The operating costs for one-time chilling of a 597-t maize bin under mid-Michigan conditions immediately after harvest to 10°C are about double per tonne compared with aerating with ambient air using a comparable 5.5 kW fan. Chilled and ambient aeration to 7°C require the same amount of energy. The comparison also indicates that one-time chilling to a low of 7°C in the fall may be sufficient with respect to the quality preservation of maize during the 12-month storage under Michigan conditions.

Wheat

Table 3 compares the chilled, continuous ambient and no aeration in a bin containing 579 t of wheat stored between 1 July 1989 and 30 June 1990 in mid-Michigan. The initial grain temperature is 30°C, and the initial moisture content is 14%. The lowest bulk temperature in the non-aerated wheat is 13°C after about 10 months of storage. Continuous ambient aeration to 10°C at 0.1 m^3/minute/t takes 1.5 times longer than cooling the bulk to 15°C. Chilling the wheat to either 10 or 15°C is accomplished within about 1 week in each case. The average dry matter loss of the wheat after 12-month storage is 63–67% lower for chilled aeration than for ambient cooling, and 68–71% better than for no aeration. The operating costs for one-time chilling after summer harvest to 10°C are about 31% higher compared with chilling to 15°C. Aerating continuously with ambient air can be 5–7 times more expensive than chilling once.

Rice chilling in Louisiana and Michigan in 1991

In a field test utilising a German-built chiller, 86 t of rice were chilled from 30°C to less than 22°C while ambient temperatures and relative humidities were as high as 38°C and 90%, respectively. The chilled rice was successfully shipped to a midwestern processing plant by rail in the middle of the summer without any fumigation application. Normally, each rail car is fumigated before sealing and remains under fumigation during shipment. The rice was rechilled and stored without quality deterioration for several months before end-use processing. The trial was conducted by Michigan State University, and the detailed results remain confidential.

Table 2. Comparison of chilled, ambient and no aeration of a 597-t maize bin between 15 October 1989 and 14 October 1990. Initial grain temperature 17°C and moisture 16.5%.

	Cool-down time for bulk to reach		DM loss (%) after cooling and 12 months storage[a]		Moisture content (%) after cooling and 12 months storage[a]		Specific energy (kWh/t) for cooling to	
	7°C	10°C	7°C	10°C	7°C	10°C	7°C	10°C
No aeration	5 months[b]	2.5 months	0.641	0.64	16.51	16.5	–	--
Ambient	4 wks	1 wk	0.52	0.41	16.1	16.2	3.1	1.3
Chilled	1 wk	1 wk	0.38	0.41	16.1	16.2	3.1	2.6

[a] Assuming no moisture changes during storage
[b] Lowest bulk temperature reached was 7.5°C

Table 3. Comparison of chilled, ambient and no aeration of a 579-t wheat bin between 1 July 1989 and 30 June 1990. Initial grain temperature 30°C and moisture 14%.

	Cool-down time for bulk to reach		DM loss (%) after cooling and 12 months storage[a]		Moisture content (%) after cooling and 12 months storage[a]		Specific energy (kWh/t) for cooling to	
	10°C	15°C	10°C	15°C	10°C	15°C	10°C	15°C
No aeration	10 months[b]	8 months	1.1[b]	1.1	14.01	14.0	–	–
Ambient	4.5 months	3 months	0.96	0.95	11.0	11.3	65	40
Chilled	1 wk	1 wk	0.32	0.35	13.2	13.3	8.9	6.1

[a] Assuming no moisture changes during storage
[b] Lowest bulk temperature reached was 13°C

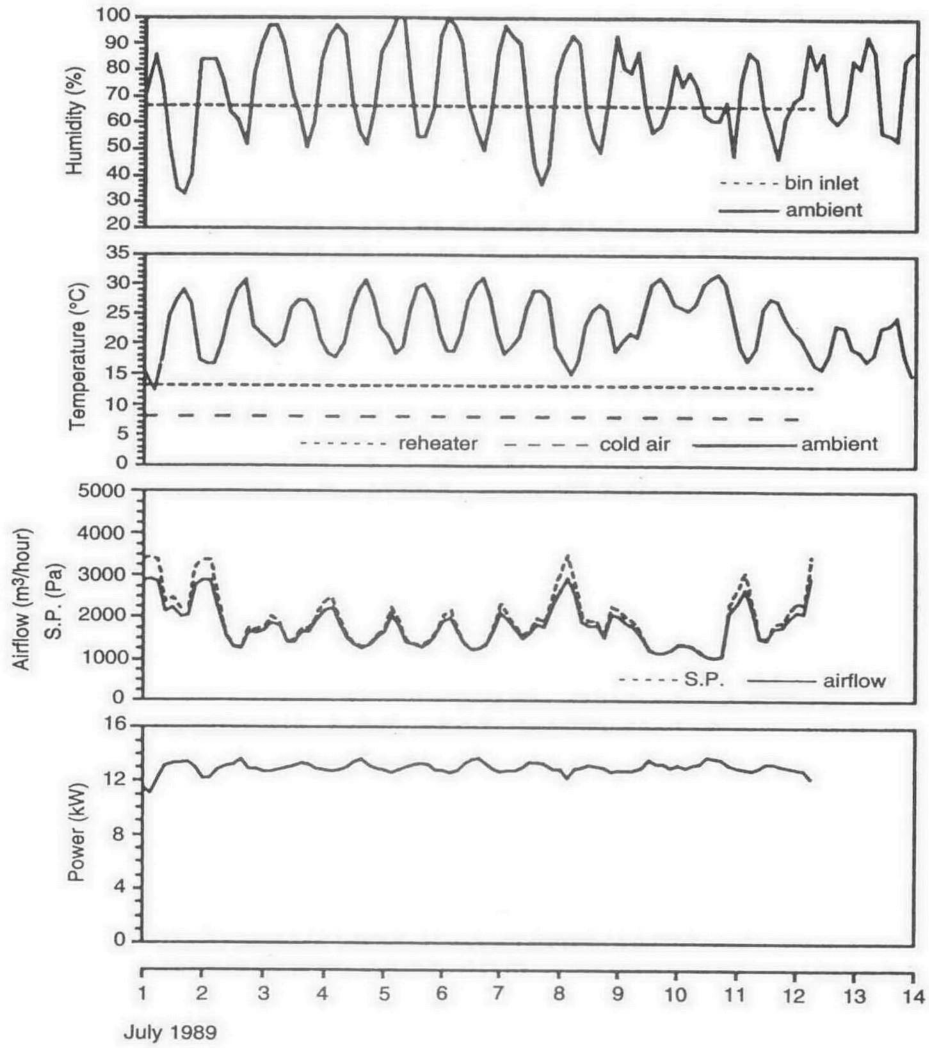

Fig. 5. Simulated performance of a German-built grain chiller cooling the 579-t bin of wheat in July 1989. Bin inlet air temperature 14°C and 67% r.h.

Rice and maize chilling in Texas

Conventional and chilled aeration of rough rice and food maize were investigated for summer conditions (August-October) along the humid gulf coast of Texas (Maier et al. 1992). Of four ambient aeration strategies — continuous; fan on from 10 a.m.. to 4 p.m.; fan on from 10 p.m. to 4 a.m.; fan on whenever the relative humidity is below 75% — continuous aeration performed best because it resulted in the smallest moisture losses and gradients in the commercially-sized silos. Chilled aeration was able to minimise moisture losses and maintained average grain temperatures below 15°C while bulk temperatures in conventionally aerated rice and maize remained between 21° and 38°C. Significant cycling of the grain temperatures and moisture contents was observed in the aerated bins where several warming and cooling cycles moved through the grain before final storage temperatures were reached in the fall. One-time chilled aeration of maize immediately after harvest to 15°C was completed within 120–160 hours of cooling, while maintaining the moisture content uniformly at 13%.

Wheat chilling in Kansas in 1991

Hellemar (1993) reported the successful chilling of a 2500 t concrete silo of wheat at a commercial elevator in Kansas during the summer of 1991. Initial grain temperatures were 32–35°C and 14.5% moisture. Chilling to 15–17°C was completed within 144 hours. After 4 months of storage the wheat was shipped by rail. The moistures and temperatures remained unchanged, and no insects were detected. In comparison, an additional 2500 t silo of wheat was stored at the same initial temperatures but at only 12–13% moisture. During the 4-month storage period the wheat was turned once and fumigated twice in the silo. Because of insect activity the rail car had to be fumigated at the time of shipment. The wheat temperature was 29°C and the moisture 10–11% at the time of shipping. Treatment costs were estimated at $0.20/t for chilling, and $0.80/t for turning and fumigating. In addition, approximately 56 t of wheat were lost in the non-chilled silo.

Maize chilling in Indiana in 1992

During the summer of 1992, 80 t of maize were chilled and maintained at temperatures below 13°C. Repeated chilling cycles were administered while optimising the performance of a prototype U.S. grain chiller developed by Purdue University researchers in cooperation with AAG Manufacturing, Milwaukee, WI (Maier et al. 1993a) (Fig. 6). At the end of the trial, the maize was sold as No. 1 grade to a local wet milling plant. The performance characteristics of the prototype chiller are summarised in Table 4. They are compared to the Granifrigor KK140 (Sulzer-Escher Wyss, Lindau, Germany), which was previously used by Michigan State University researchers. Five test runs were conducted (Table 5). In runs 1 and 2 the chiller operated with the initial factory settings. Runs 3 and 4 were conducted after raising the compressor pressure limit to increase refrigeration capacity. Before run 5 the air throttle controller and a faulty glycol valve were replaced. The optimisation of the outlet chiller air conditions during the five tests is illustrated using data from runs 1 and 5. The ambient inlet and chilled air temperatures and relative humidities during run 1 are shown in Figure 7. [A power failure of 3 hours occurred 36 hours into the test.] The average chilled air outlet temperature and relative humidity were 0.6°C and 6.5 percentage points above the set points, respectively (Table 6). The airflow rate

Fig. 6. Prototype grain chiller developed jointly by Purdue University and AAG Manufacturing (Milwaukee, Wisconsin, USA) operating during the optimisation test runs in 1992.

from the chiller into the bin ranged from a low of 1783 m^3/hour to a high of about 2377 m^3/hour. The average airflow was 2094 m^3/hour with a standard deviation of 319 m^3/hour. The air throttle reacted to increasing and decreasing ambient refrigeration loads of the evaporator coil. However, the reaction of the controller was somewhat abrupt. Some hunting of the feedback controller occurred during high temperature periods, which contributed to increased chilled air conditions after the reheater coil. Closer examination of the subsequent test runs revealed that the off-the-shelf feedback air throttle controller did not have sufficient capability to interact with the variable load on the reheat cycle. Additionally, a faulty glycol flow control valve was detected.

The ambient and chilled temperatures and relative humidities during run 5 are shown in Figure 8. Although the outlet air temperature was about 1.8°C above the set point, the relative humidity was within 3 percentage points of the expected LARH (Table 6). The effect of the corrected glycol valve was significant. The heat gain of the air across the reheater coil was the highest for any of the test runs, and accounted for the improved control over the relative humidity of the chilled air. A significant pre-cooling effect reduced the cooling load on the evaporator, which was highest in terms of temperature reduction compared to previous runs. The sought-after control over the chilled air conditions by regulating both the airflow given a fixed refrigeration capacity, and the load on the evaporator coil through pre-cooling the air is one of the distinguishing features of the Purdue-AAG chiller compared with other commercial units

The results of the experimental test runs clearly indicated that the Purdue-AAG prototype grain chiller operated exceptionally well. The refrigeration capacity of the unit was maximised, and control over the chilled air temperature and relative humidity was improved. Variability of the relative humidity was reduced from 6.5–8.8 percentage points to

Table 4. Specifications of the Purdue prototype grain chiller versus a similar-sized commercial unit.

	Purdue prototype[a]	Granfrigor KK140[b]
Evaporator capacity (kW)	26.4	32.7
Airflow at 2000 Pa (m^3/hour)	2300	4400
Chilling capacity (t/day)	53[c]	100
Connected load (kW)	9.3	13.0

[a]Manufactured by AAG Manufacturing, Milwaukee, WI
[b] Manufactured by Sulzer-Escher Wyss, Lindau, Germany
[c] Estimated based on airflow-chilling capacity

Table 5. Experimental test runs conducted with the Purdue prototype grain chiller, leaving air temperature (LAT) settings at the evaporator and reheater coils, and estimated leaving air relative humidity (LARH) at the chiller outlet.

Run ID	Duration	Evaporator LAT	Reheater LAT	Expected LARH[a]
1[b]	5/19 - 5/23/92	7.2°C	12.8°C	70%
2[b]	5/27 - 6/05/92	4.4°C	7.2°C	80%
3[c]	6/19 - 6/26/92	7.2°C	12.8°C	70%
4[c]	6/08 - 6/12/92	4.4°C	7.2°C	80%
5[d]	6/29 - 7/06/92	7.2°C	12.8°C	70%

[a] Calculated assuming saturation at the evaporator coil
[b] Factory settings
[c] After raising compressor pressure limit
[d] After replacing the air throttle controller and faulty glycol valve

2.1–3.0 points during the tests. Outlet temperatures were achieved within 2°C of the set point. Successful testing of this prototype has resulted in the commercialisation of the first U.S.-built grain chillers.

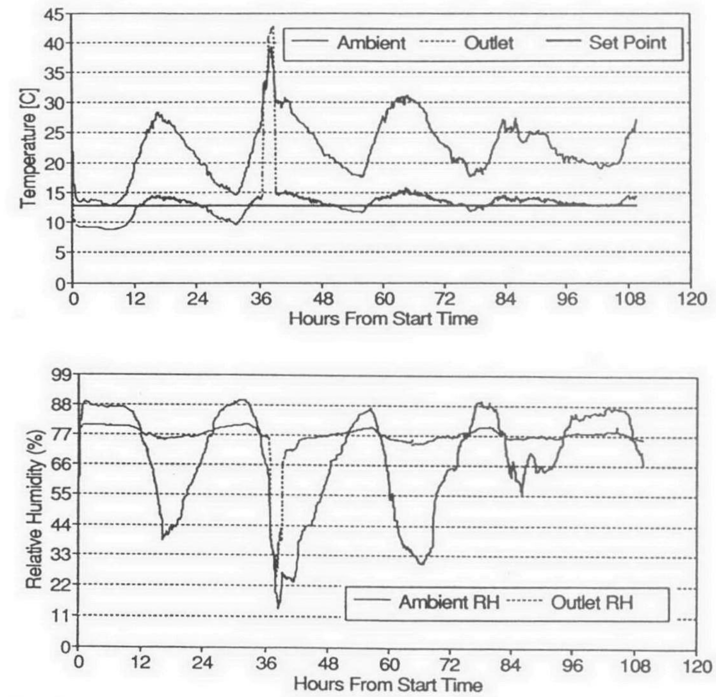

Fig. 7. Inlet and outlet temperatures and relative humidities during the first test run of the Purdue-AAG prototype grain chiller in the summer of 1992. Top: ambient/outlet temperature vs. time. Bottom: ambient/outlet r.h. vs. time. Runs started 5/19 11: 50 am and ended 5/23 at 12:10 pm.

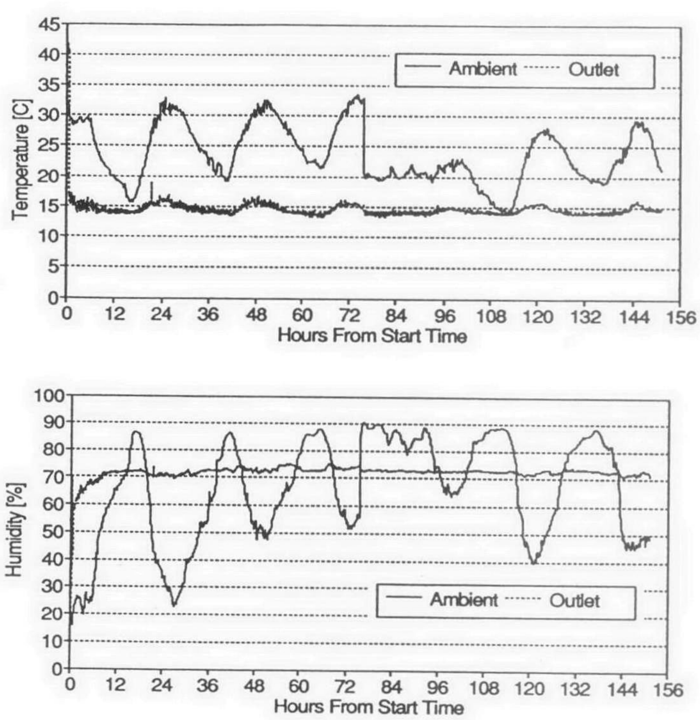

Fig. 8. Inlet and outlet temperatures and relative humidities during the final test run of the Purdue-AAG prototype grain chiller in the summer of 1992. Top: ambient/outlet temperature vs. time. Bottom: ambient/outlet r.h. vs. time. Runs started 6/29 1: 03 pm and ended 7/6 at 10:50 am.

Wheat chilling in Carrolton, Texas in 1992

Approximately 2250 t of 12% moisture wheat were chilled in a concrete silo from an initial temperature of 23–24°C to 15–16°C in the middle of June at a commercial elevator in Texas (Hellemar 1993). The wheat was stored through the end of December, and quality was maintained without any additional pest management treatments. The trial was conducted utilising a Swedish-made grain chiller.

Maize chilling in Indiana since 1992

Four 6-t bins were filled in July 1992 with No. 2 yellow maize and intentionally infested with adult *Sitophilus oryzae* (L.) (rice weevils) (Adams et al. 1993). Four different pest management techniques have been employed: fumigation, continuous/controlled ambient aeration, no aeration, and intermittent chilling. Temperatures, moisture contents, mould development and insect development have been measured intermittently. The study is on-going at Purdue University, and its preliminary results are reported elsewhere in these proceedings.

Rice chilling in California since 1993

Of primary concern to the rice miller is the head yield, or the amount of unbroken kernels. Broken kernels are worth only approximately 50% that of whole rice kernels. It is estimated that an average-sized U. S. rice miller can increase returns by $262500 with a 1% decrease in broken kernels (Spadaro et al. 1980). Milled rice is extremely sensitive to changes in air temperature and relative humidity. When rice is exposed to high or low humidities, it is likely to fissure, which destroys its processing value. Once the rice is milled it must be slowly cooled to a suitable storage temperature (Lan and Kunze 1992). If ambient weather conditions are not favourable for ambient aeration, controllers must be used to operate the fans only when air conditions permit. The aeration process must be accomplished gradually and within a relatively narrow band of relative humidity in order to prevent (or minimise) fissuring of the rice kernels due to excessive adsorption (or desorption) of moisture. This approach can result in prolonged storage times and delayed shipment of rice. Humidity controllers were used by one commercial rice processor to operate aeration fans whenever ambient conditions allowed. However, daily and seasonal changes in the ambient weather conditions limited the usefulness of this system, and made operation unpredictable. This approach also revealed that ambient aeration did not always prevent fissuring. The only viable solution appeared to be to utilise a conditioning system that controls both the temperature and the relative humidity of the aeration air independent of climatic conditions.

The Chill'd Aire Aeration and Conditioning System developed jointly by Purdue University and AAG Manufacturing (Milwaukee, Wisconsin) was used to conduct a field test to verify the benefits of this chilling system for the conditioning of milled rice (Maier et al. 1993b). At a commercial rice processing facility in California, 175 t of milled rice were chilled in a concrete silo from an initial temperature of 26–29°C to 11–12°C within 48 hours (Fig. 9). [The unit automatically shut down for a brief period due to cool ambient conditions.] The movement of the cooling front through the rice is obvious from the temperature readings of the thermocouples located at 3.6, 5.4, and 7.2 m. The cooling front reached the top of the pile after about 27 hours (i.e., 21 hours of operating time). Airflow during the trial averaged 1872 m^3/h. Control over the temperature and relative humidity of the air entering the storage silo within 0.5°C and 0.2% of set

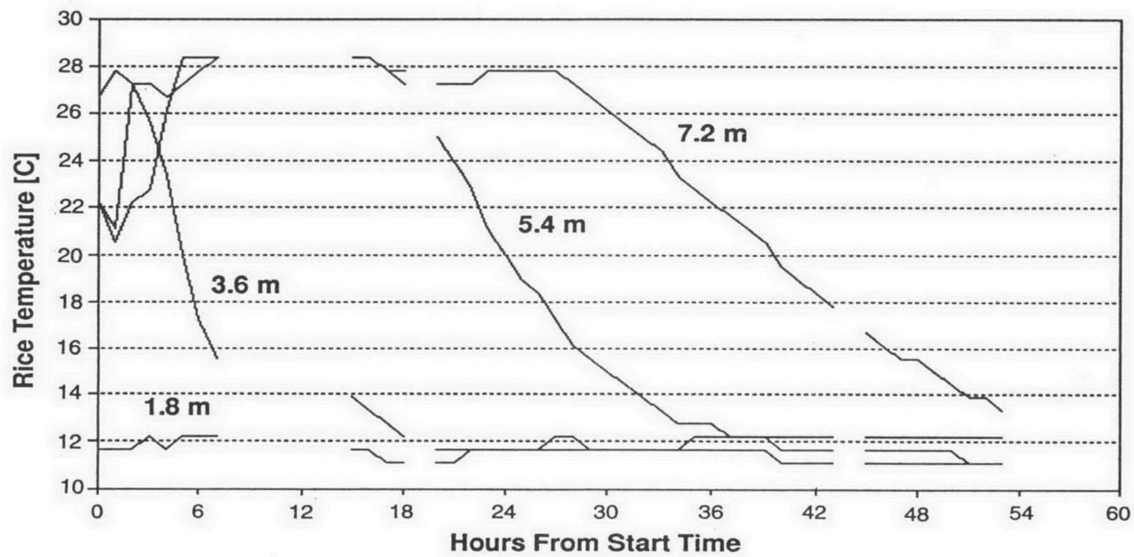

Fig. 9. Temperatures of milled rice conditioned with the Chill'd Aire Aeration and Conditioning System (AAG Manufacturing, Milwaukee, Wisconsin, USA) operating at a commercial rice processing facility in California in 1993.

point, respectively, was critical to minimise damage to the rice. The rice was used for further processing and was of superior quality to milled rice aerated with ambient air. The results were confirmed in a second test. Because the air used to chill the rice is temperature and humidity controlled, conditioning can be accomplished in a predictable time period, cost-effective manner, and independent of weather conditions. This application has been scaled-up and is the first commercial implementation of the grain chilling technology in the United States.

Future plans

Currently, field tests for research and demonstration purposes are continuing and additional ones are planned in the southern, south-eastern and mid-western United States. The primary focus will be on specialty and food-grade crops such as popcorn, white and yellow food maize, rice and wheat. Additionally, the potential benefits of chilled aeration and storage as a non-chemical pest management technology will be further quantified.

Summary

The effectiveness of chilled aeration for the optimisation of end-use processing quality by conditioning bulk grain, and its potential as a non-chemical pest control technology, have been investigated and demonstrated for the past 6 years for a variety of crops and geographic locations in the United States. Commercialisation of a U.S.-built grain chiller and the first sale of any grain chiller in the U.S. represent the beginning of what is expected to lead to a more broad-scale adoption and utilisation of chilled aeration in the next few years. The need for the adoption of this particular postharvest technology has only recently been highlighted in the report 'Alternatives to methyl bromide: assessment of research needs and priorities', published by the U.S. Department of Agriculture, which identified chilled aeration of unprocessed grains as one of only four immediately available alternative technologies.

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Table 6. Summary of the average ambient (in) and chilled (out) air conditions with standard deviations during the five test runs of the Purdue prototype grain chiller.

Run ID	T_{in} (°C)	r.h.$_{in}$ (%)	T_{out} (°C)	r.h.$_{out}$ (%)
1	22.2 ± 5.1	68.4 ± 19.1	13.4 ± 3.9	76.5 ± 6.5
2	17.6 ± 5.3	60.7 ± 25.2	9.0 ± 1.2	75.9 ± 8.8
3	16.9 ± 6.0	64.9 ± 19.8	11.1 ± 1.7	72.8 ± 6.9
4	21.2 ± 4.8	45.1 ± 17.3	10.5 ± 1.5	77.1 ± 2.1
5	23.2 ± 4.9	66.7 ± 19.0	14.6 ± 1.8	72.2 ± 3.0

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