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Evaluation and Optimization of a New Commercial Grain Chiller

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EVALUATION AND OPTIMIZATION OF A NEW COMMERCIAL GRAIN CHILLER

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ABSTRACT. *A prototype grain chiller was designed and built to evaluate its potential for commercialization. Testing resulted in optimization of the final design. Refrigeration was maximized and control over the chilled air conditions improved. Variability of the relative humidity of the outlet air was reduced from a range of 6.5 to 8.8 percentage points to 2.1 to 3.0 points. Outlet temperatures were achieved within 2° of the set point temperature. The success of these tests has resulted in the commercialization of the first U.S.-built grain chiller.*

Keywords. *Grain chilling, Grain quality, Optimization, Crop storage, Refrigeration, Aeration.*

Grain chilling is a technology that has been utilized successfully to preserve grain quality during storage. 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 (Brunner, 1990), but only recently in the United States. Grain is usually cooled using conventional aeration systems, which are able to lower grain temperatures to within a few degrees of the average ambient temperature. In contrast, grain chilling is defined as the cooling of grain independent of the minimum ambient temperature using a mechanical refrigeration system.

Over a three-year period in the late 1980s, Michigan State University researchers confirmed the effectiveness of a German-made grain chiller. Corn was stored for periods exceeding six months under Michigan conditions (Maier, 1992). The success of these corn chilling tests led to the development and field testing of a new grain chiller designed by Purdue University and constructed by AAG Manufacturing (Milwaukee, Wis.). The evaluation and optimization of this prototype chiller was the focus of this research.

LITERATURE REVIEW

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 idea of a refrigeration system to dry grain from 20% to 16% moisture was proposed in France by Leroy in 1950. As early as 1958 a cold-air drying system was sold in Germany (Escher-Wyss, 1960). In 1961 the Escher-Wyss company of Lindau, Germany, started production of commercial grain chillers (Heidt, 1963). The Escher-Wyss chillers, consisting of a cold-air fan, evaporator coil, compressor, condenser and cooling fan, had cooling capacities of 50 t of grain per day.

Munday (1965) described grain chillers manufactured in England designed primarily for on-farm use. By 1970, commercial 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 a refrigerant by-pass between the evaporator and the condenser. In the Purdue-AAG chiller, however, an independent glycol loop returns heat to the chilled air after the evaporator. This approach simplifies the control of the refrigeration cycle by eliminating a more complicated refrigerant flow control and by-pass mechanism. With the exception of one company (IKZ, 1993), chiller manufacturers use motorized dampers to control the airflow across the evaporator, and thus provide a constant cold-air temperature into the grain bin. In its final design, the Purdue-AAG chiller incorporates a variable-frequency blower drive to optimize airflow and cold-air temperature.

There are at least seven major commercial manufacturers of grain chillers worldwide: (1) "Goldsaat" by Agrartechnik Co. (Prüm, Germany); (2) "Grain Cooler" by PM-Luft Co. (Kvänum, Sweden); (3) "Granifrigor" by Sulzer-Escher Wyss Co. (Lindau, Germany); (4) "DUK" by Uniblock Zanotti Co. (Suzzara, Italy); (5) "RM Grain Cooling Units" by MacBea Co. (Parkdale, Australia); (6) "LK Grain Coolers" by IKZ (Zwickau, Germany); and (7) "Chill'd Aire" by AAG Manufacturing (Milwaukee, Wis.). The largest chilling units of the leading European manufacturers are similar in performance and capacity (table 1). Compressor capacities range from 107 to 130 kW. Fans provide airflow rates of about 16,500 m^3/h at 2000 Pa of static counter pressure. The average grain chilling capacity is about 350 t per day.

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Table 1. Summary of the main design parameters of the largest commercial grain chiller of each of four European manufacturers as published in their respective sales brochures (Agrar technik, Prüm, Germany; Sulzer-Escher Wyss, Lindau, Germany; PM-Luft, Kvänum, Sweden; Uniblock Zanotti, Suzzara, Italy)

	Goldsaat GK 480 NDI	Granifrigor KK400	Grain Cooler 8000	DUK 100
Rated chilling capacity (t/day)	400	335	350	350
Airflow at 2000 Pa (m^3/h)	16,750	16,300	16,250	17,000
Evaporator capacity (kW)	127 8	107 0	107 0	110 0
Connected load (kW)	N/A	54 0	55 0	55 0

In the 1960s grain chillers were primarily used as a means of preserving high moisture grain. Today, the primary application for grain chilling is in preserving the quality of dry stored grain using non-chemical pest management through chilled aeration. Only recently have attempts been made to evaluate the benefit of storing dry grain in the U.S. with the help of a chilled aeration system (Bakker-Arkema et al., 1989; Maier et al., 1989; Maier et al., 1991; Maier and Bakker-Arkema, 1992). Commercial application of grain chilling is starting to take place in a limited number of facilities in the United States (Hellemar, 1993; Maier et al., 1993; Maier, 1994; Rulon et al., 1995).

METHODS

EQUIPMENT

The Purdue prototype grain chiller was tested in the summer of 1992 at the Purdue Agronomy Research Center. The 178 t storage bin was equipped with a fully perforated floor and was filled to a depth of 2.1 m with about 82 t of 15% moisture corn with an initial grain temperature of 18°C. The prototype grain chiller was connected to the bin via a specially designed base plate and air duct. The non-insulated duct was 0.30 m in diameter. The first 3.7 m length of duct consisted of two 1.8 m sections of steel tubing that were connected by an orifice plate with a 0.15 m diameter opening. Pressure drop across the orifice plate was used to calculate air flow. The second 3.7 m length of duct consisted of flexible nylon that connected the steel duct to the base-plate of the bin aeration system.

The chiller tested in this project was a prototype unit built by AAG Manufacturing (Milwaukee, Wis.) based on Purdue design specifications. Performance characteristics of the prototype chiller, summarized in table 2, are compared to the Granifrigor KK140 (Sulzer-Escher Wyss, Lindau, Germany), which was previously used by Michigan State University researchers. Five cooling tests were conducted between 19 May and 6 July 1992.

INSTRUMENTATION

The chiller (fig. 1) was instrumented with a 21X (Campbell Scientific, Logan, Utah) data logger to monitor the temperatures and relative humidities of the inlet and outlet air using Campbell Model 201 probes, which use Fenwal UUT-51J1 thermistors and PhysChem PCRC-11 humidity sensors. Data values were recorded on tape every five minutes. In addition, the position of the throttle governing the airflow from the fan and the pressure drop across the orifice plate were recorded. These data were subsequently converted to actual airflow from the chiller into the bin. The cumulative operating time of the unit was monitored by recording start-up and shut-down times. Electrical power consumption of the unit was measured with a three-phase 480 V kWh meter.

Table 2. Specifications of the Purdue-AAG prototype grain chiller versus a similar size commercial unit

	Purdue-AAG*	KK140†
Evaporator capacity (kW)	26.4	32.7
Airflow at 2000 Pa (m^3/h)	2326	4400
Chilling capacity (t/day)	48‡	100
Connected load (kW)	9 3	13 0

* Manufactured by AAG Manufacturing, Milwaukee, Wis
† Manufactured by Sulzer-Escher Wyss, Lindau, Germany
‡ Estimated based on airflow-chilling capacity

The temperature performance of the grain chiller was monitored by placing 21 T-type thermocouples at various locations in its refrigeration and glycol cycles. Thermocouples were connected to a CR5 (Campbell Scientific, Logan, Utah) data logger that recorded the values to tape every five minutes. The glycol loop was monitored by clamping the thermocouples to the copper tubing at the inlet and outlet of both the pre-cool and the reheat coils. The refrigeration cycle performance was monitored by clamping the thermocouples to the copper tubing at the inlet and outlet of the evaporator and the condenser, and at the suction and pressure sides of the compressor. Additionally, air temperatures were monitored before the fan, the pre-cool coil, the evaporator, before and after the reheat coil, and at the outlet of each condenser fan.

The temperature changes in the corn during chilling and later during storage were monitored with two temperature probes. One was placed in the center, and the second near the south side of the grain bin about one foot from the wall. Each probe was equipped with four thermistors. Temperatures of the corn were read intermittently. Corn samples were taken during loading, intermittently by probing the grain bulk, and during load-out. The corn was

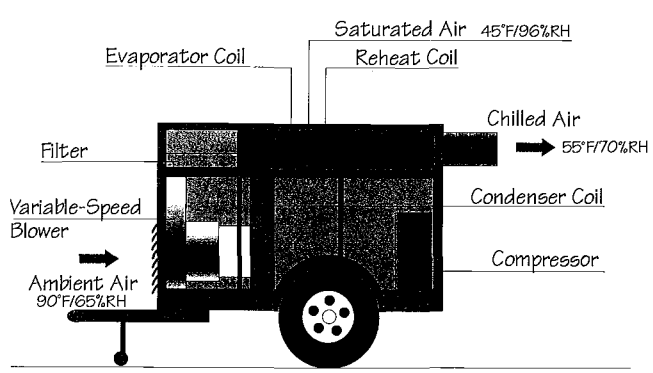

Figure 1–Schematic of the prototype Purdue-AAG grain chiller used in the optimization test runs during the summer of 1992.

Table 3. Experimental test runs conducted with the Purdue-AAG prototype grain chiller and temperature setpoints at the evaporator and reheater coils

Run ID	Duration	Evaporator LAT (°C)	Reheater LAT (°C)	Expected LARH§ (%)
1*	5/19-5/23/92	7.2	12 8	70
2*	5/27-6/05/92	4.4	7.2	80
3†	6/19-6/26/92	7 2	12 8	70
4†	6/08-6/12/92	4 4	7 2	80
5‡	6/29-7/06/92	7 2	12 8	70

* Factory settings
† After raising compressor pressure limit
‡ After replacing the air throttle controller and faulty glycol valve
§ Calculated assuming saturation at the evaporator coil

subsequently sold with a moisture content of about 14.5% w.b. as no. 1 grade to a local wet miller.

Results and Discussion

The primary results of this research are summarized in tables 3-6 and figures 2-6. Runs 1 and 2 were conducted with the chiller operating with the initial factory settings (table 3). Runs 3 and 4 were conducted after raising the compressor pressure limit to increase refrigeration capacity. Run 5 was conducted after replacing the air throttle controller and a faulty glycol valve. Leaving air temperatures (LAT) after the evaporator and reheater were set at 7.2°C and 12.8°C, respectively, in runs 1, 3, and 5, and at 4.4°C and 7.2°C, respectively, in runs 2 and 4. The leaving air relative humidity (LARH) after the reheater was calculated assuming saturated air after the evaporator coil. The expected LARHs were 70% and 80% for the 7.2°C, 12.8°C, and 4.4°C/7.2°C settings, respectively. Results of a sixth run collected during the summer of 1994 at a commercial grain facility are presented when the prototype chiller was operated using a variable-speed blower drive to control airflow and cold-air temperature (figs. 7-8).

Optimizing Airflow and Reheating

To illustrate the optimization of the outlet chiller air conditions during the five tests, runs 1 and 5 are discussed in detail. During Run 1 the ambient inlet temperature to the chiller ranged from 13 to 33°C with an average of 22.2°C and a standard deviation of ± 5.1°C during the 108-h test run (table 4 and fig. 2). [A power outage of 3 h occurred 36 h into the test.] The chiller outlet air temperature into the bin varied between 9°C and 15°C with an average of 13.4°C and a standard deviation of ± 3.9°C. The ambient relative humidity varied between 12% and 89% with an average of 68.4% and a standard deviation of ± 19.1%. The relative humidity of the outlet air varied between 70% and 80% with an average of 76.5% and a standard deviation of ± 6.5% (table 4 and fig. 3). Thus, the average chilled air outlet temperature and relative humidity were 0.6°C and 6.5% above the set points, respectively.

Table 4. Summary of the average ambient (in) and chilled (out) air conditions with standard deviations during five test runs

Run ID	T_{in} (°C)	RH_{in} (%)	T_{out}(°C)	RH_{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

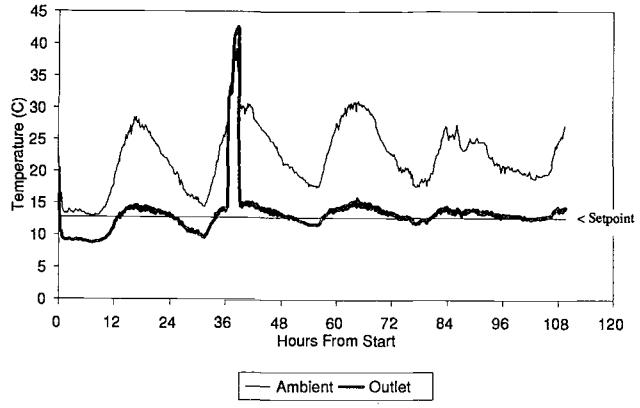

Figure 2–Inlet, outlet, and set point temperatures during the first test run of the prototype grain chiller in the summer of 1992. (Run started on 5/19 at 11:50 A.M. and ended on 5/23 at 12:10 P.M.)

The variability of the outlet air temperature and relative humidity during the first 48 h was larger than desirable. During the remaining 70 h the LAT and LARH into the bin appeared more steady. However, closer examination of the air temperature after the evaporator revealed that it remained about 3°C above the set point temperature (not shown). This indicated that either the refrigeration capacity was insufficient to chill the ambient air to the desired set point of 7.2°C, or the airflow across the evaporator coil was not throttled sufficiently (or a combination of both) In addition, the amount of reheat from the glycol loop appeared insufficient to rewarm the saturated air after the evaporator coil to achieve the desired relative humidity. Run 2 revealed a similar problem with lower temperature settings at the evaporator and reheater coils. Subsequently, the compressor pressure limit was raised to maximize the refrigeration capacity across the evaporator coil of the prototype chiller. Although this resulted in lower evaporator LATs during runs 3,4, and 5 (not shown), it did not optimize the airflow and reheating of the chilled air (table 4).

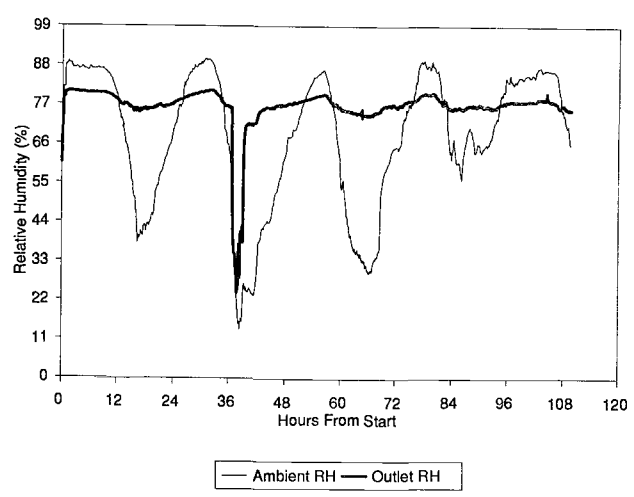

Figure 3–Inlet and outlet relative humidities during the first test run of the prototype grain chiller in the summer of 1992. (Run started on 5/19 at 11:50 A.M. and ended on 5/23 at 12:10 P.M.)

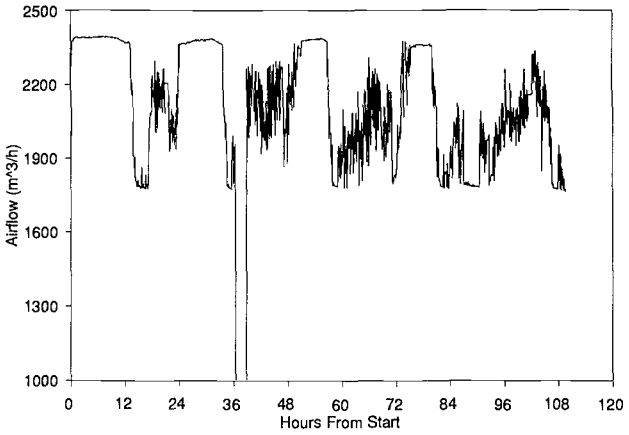

Figure 4–Air flow rate from the prototype grain chiller during the first test run in the summer of 199 (Run started on 5/19 at 11:50 A.M. and ended on 5/23 at 12:10 P.M.)

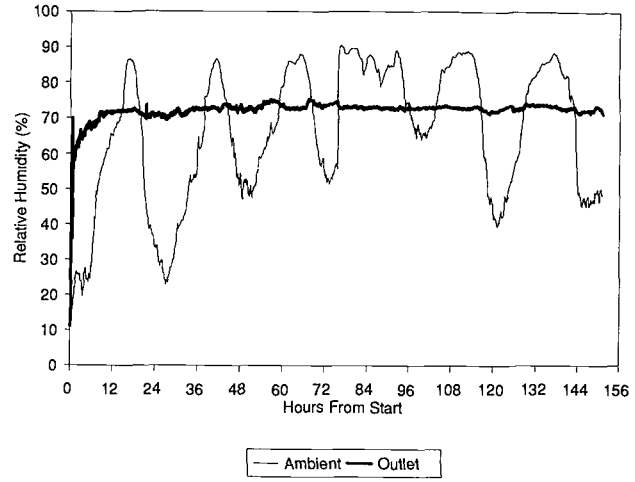

Figure 6–Inlet and outlet relative humidities during the last test run of the prototype grain chiller in the summer of 1992. (Run started on 6/29 at 1:03 P.M. and ended on 7/6 at 10:50 A.M.)

The airflow rate from the chiller into the bin ranged from a low of 1783 m^3/h to a high of about 2377 m^3/h. The average airflow was 2094 m^3/h with a standard deviation of ± 319 m^3/h (fig. 4). 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 searching of the feedback controller occurred during the high temperature periods, which contributed to higher chilled air LATs after the reheater coil. Close 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 during Run 4. Thus, both the faulty valve and the air throttle controller were replaced for Run 5.

During Run 5 ambient temperatures ranged from 14°C to 33°C with an average of 23.2°C and a standard deviation of ± 4.9°C (table 4 and fig. 5). The outlet temperature ranged from 14 to 16°C with an average of 14.6°C and a standard deviation of ± 1.8°C. The relative humidity of the inlet air ranged from 25 to 90%, while the outlet air was fairly constant at about 72.2% with a standard deviation of only ± 3% (table 4 and fig. 6). Although the outlet air temperature was about 1.8°C above the set point, the relative humidity was within 3% of the expected LARH.

The effect of the corrected glycol valve is revealed by examining tables 5 and 6. The heat gain of the air across the reheater coil, 4.6°C, was the highest of the test runs (table 5). This temperature rise accounted for the improved control over the relative humidity of the chilled air. The glycol temperature increased in the pre-cool coil by an average of 8.8°C, while the glycol temperature was reduced by only 1.1°C in the reheat coil (table 6) The significant pre-cooling effect reduced the cooling load on the evaporator, which experienced the largest temperature reduction compared to previous runs. Additionally, the inlet and outlet glycol temperatures of the reheat and pre-cool coils had the smallest standard deviations of any test run.

The obvious improvement over the chilled air conditions could not be attributed to better control over the air throttle. The throttle essentially remained in a fixed position during most of the run. Thus, final chilled air

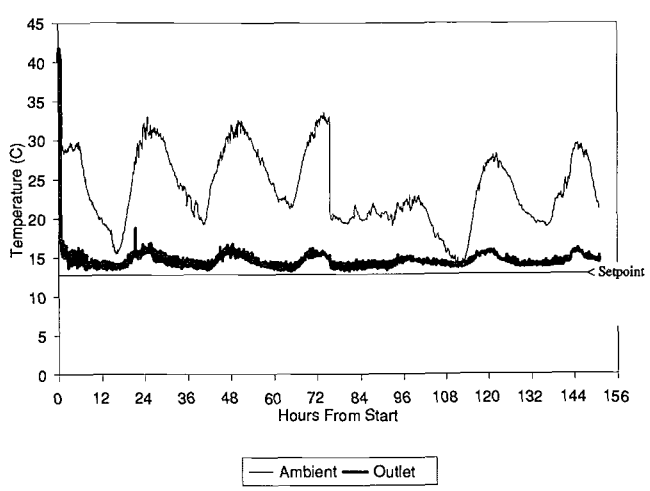

Figure 5–Inlet, outlet, and set point temperatures during the last test run of the prototype grain chiller in the summer of 1992. (Run started on 6/29 at 1:03 P.M. and ended on 7/6 at 10:50 A.M.)

Table 5. Air heat gain across the fan (°C), amount of air pre-cooling (°C), air temperature drop across the evaporator(°C), air heat gain across the reheater (°C), air heat gain across the condenser (°C)

Run ID*	Fan	Pre-cool	Evaporator	Reheater	Condenser
2	+3 8	−0 96	−14 4	+3 0	+17 8
3	+4.6	−2 1	−11 2	+3 0	+18 3
4	+4 6	−0 1	−18 0	+2 6	+15 0
5	+8 6	−2 2	−19 5	+4 6	+13 3

* Data for Run 1 was lost due to disk error before final analysis

Table 6. Average glycol temperatures (°C) in and out of the pre-cool and reheat coils with standard deviations, and glycol temperature change (△) across heat exchangers

	Pre-cool			Reheat		
Run ID*	In	Out	△	In	Out	△
2	17 3 ± 6 3	19 5 ± 6 2	+2 2	11 9 ± 2 1	10 6 ± 1 4	−1 3
3	15 4 ± 3 4	17 1 ± 4 9	+1 7	15.8 ± 2 6	13 9 ± 2 1	−1 9
4	25 3 ± 4 6	25 3 ± 4 8	+0 0	10 5 ± 1 4	10 1 ± 1 2	−0 4
5	21 6 ± 2 8	30 4 ± 4 3	+8 8	16 3 ± 0 8	15 2 ± 0 7	−1 1

* Data for Run 1 was lost due to disk error before final analysis

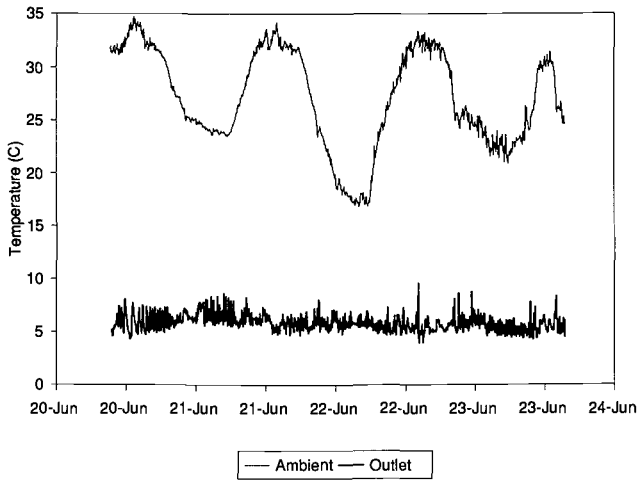

Figure 7–Inlet and outlet temperature during a test run of the prototype grain chiller in the summer of 1994 utilizing a variable-speed blower drive.

conditions were solely controlled by the glycol loop. The total airflow into the bin averaged 1051 m^3/h with a standard deviation of ± 47.5 m^3/h. [Note: The range of the throttle position was changed by mistake when the new controller was installed. Thus, a lower airflow was observed in Run 5 compared to the previous four runs.] Although the variability of the outlet temperature and relative humidity from the chiller into the bin was minimized, the airflow was not maximized for the given conditions. However, 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 were demonstrated for this prototype chiller.

In a subsequent modification of the design, a variable-frequency blower drive was added to replace the air throttle. Figure 7 shows ambient temperatures ranging from 16.8 to 34.7°C with an average of 27.1°C over the three-day run. The chiller outlet air temperatures ranged from 4.0 to 9.6°C with an average of 5.8°C. The successful control over the outlet air conditions is reflected in the airflow rate from the chiller to the bin (fig. 8). The airflow rates ranged

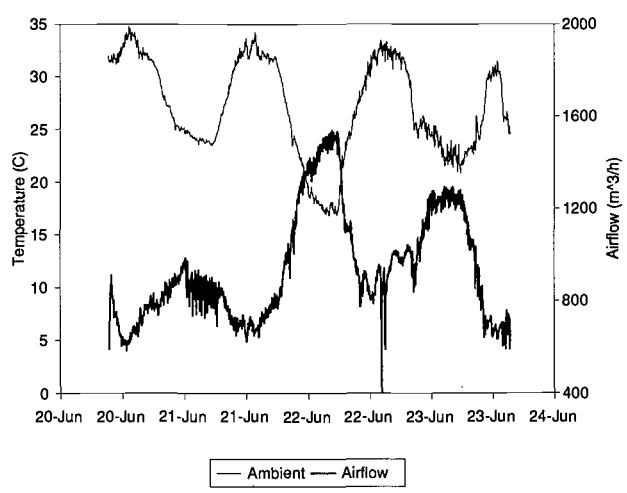

Figure 8–Inlet temperature and airflow rate during a test run of the prototype grain chiller in the summer of 1994 using a variable-speed blower drive.

Table 7. Average refrigerant temperatures (°C) in and out of the evaporator, compressor, condenser, and expansion valve

	Evaporator		Compressor	
Run ID*	In	Out	In	Out
2	7.6 ± 0.8	5.6 ± 3.0	13.1 ± 3.0	92.2 ± 3.8
3	10.3 ± 2.0	7.1 ± 2.0	13.0 ± 3.3	89.7 ± 3.4
4	10.6 ± 1.3	7.3 ± 3.3	14.6 ± 1.6	91.3 ± 1.9
5	11.8 ± 0.9	8.4 ± 2.2	15.2 ± 2.0	90.2 ± 3.2
	Condenser		**Expansion Valve**	
Run ID*	In	Out	By-pass†	In
2	82.7 ± 2.9	38.5 ± 1.6	51.3 ± 6.9	36.9 ± 2.2
3	79.7 ± 4.0	37.8 ± 1.6	56.6 ± 3.6	35.5 ± 3.1
4	80.8 ± 2.3	38.8 ± 1.4	58.8 ± 4.4	37.8 ± 2.0
5	78.7 ± 3.3	39.4 ± 1.4	64.7 ± 2.3	38.6 ± 1.3

* Data for run 1 was lost due to disk error before final analysis

† 'By-pass' is hot gas from the compressor, while 'in' is the refrigerant temperature before the mixing chamber The outlet from the expansion valve is the same as the evaporator 'in'.

from 353 to 1540 m^3/h with an average of 943 m^3/h. The variable-speed drive adjusted the airflow as a function of the refrigeration load to maintain near constant outlet air temperatures. The variable-speed blower drive is one of the distinguishing features of the Purdue-AAG chiller compared to other commercial units, which utilize more complicated control systems that also throttle the refrigerant.

Performance of the Refrigeration Cycle

Table 7 shows the average refrigerant temperatures in and out of the evaporator, compressor, condenser and expansion valve, and their standard deviations. The inlet and outlet conditions across each component showed that the refrigeration cycle performed within its design limits. The change in refrigerant temperatures across each component of the refrigeration cycle ranged from 2 to 3.3°C in the evaporator and from 75 to 79.1°C across the compressor. The temperature changes were fairly consistent for all runs.

Only in Run 3 was the evaporator refrigerant temperature lower than the desired evaporator LAT set-point of 7.2°C. The refrigeration capacity in runs 2 and 4 was not sufficient to reach the set-point LAT of 4.4°C despite maximizing capacity. In Run 5 air temperature reduction across the pre-cool and evaporator coils was the highest of any run (i.e., 21.7°C) (table 5). However, due to the increased throttling effect, a temperature rise of 8.6°C across the fan apparently overloaded the refrigeration capacity. Thus, the average refrigerant temperature out of the evaporator remained 1.2°C above the set-point LAT (table 7).

Summary

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 and control over the chilled air temperature and relative humidity were maximized. Variability of the relative humidity was reduced from 6.5 to 8.8% to 2.1 to 3.0% during the tests. In the final test, outlet temperatures were achieved within 2° of the set point. Although a new air throttle controller was installed, its performance was not optimized during the initial tests. However, during

subsequent testing of the chiller at a rice processing facility it was decided that airflow in the final commercial design would be optimized by means of a variable-frequency blower drive. The utilization of this variable-speed drive has helped to maximize airflow and reduce heat gain by the ambient air before the pre-cool coil. Successful testing and evaluation of this prototype has resulted in the first sale of a U.S.-built grain chiller.

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REFERENCES

Bakker-Arkema, F. W., D. E. Maier, W. Mühlbauer and H. Brunner. 1989 Initial cool-down in chilled maize storage. In *Agricultural Engineering*, Vol. 4, eds. V. A. Dodd and P. A Grace, 2261-2266. Rotterdam, The Netherlands: Balkema Inc.

Brunner, H. 1990 Personal Communication. Sulzer-Escher Wyss, Lindau, Germany.

Burrell, N. J. 1974. Chilling. In *Storage of Cereal Grains and Their Products*, ed. C. M. Christensen. St. Paul, Minn : AACC.

Escher Wyss. 1960. User note for grain drying with the Escher Wyss cooling unit (in German). Lindau, Germany: Escher Wyss.

Heidt, H. 1963. Grain chilling, a valuable aid in combine harvesting (in German). *Die Mühle* 100(39):417-418.

Hellemar, J. 1993. The big chill: A grain handling alternative. In *Proceed GEAPS Exchange '93*. Minneapolis, Minn.: GEAPS.

IKZ 1993. Sales brochure "Getreidekühler" Zwickau, Germany: Industriekühlung GmbH.

Maier, D. E. 1992. The chilled aeration and storage of cereal grains. Ph.D. thesis. E. Lansing, Mich.: Michigan State University.

Maier, D. E., R. E. Kelley, F. W. Bakker-Arkema and H. Brunner. 1989. Long-term chilled grain storage. ASAE Paper No. 89-6541. St. Joseph, Mich.: ASAE.

Maier, D. E., K. D. Weidmayer, F. W. Bakker-Arkema and R G. Moreira. 1991. Regular and chilled aeration of grains in Texas. ASAE Paper No. 91-6062. St. Joseph, Mich.: ASAE.

Maier, D. E. and F. W. Bakker-Arkema. 1992. Analysis of chilled corn storage in the Midwest. ASAE Paper No. 92-6045. St Joseph, Mich : ASAE.

Maier, D E., W. H. Adams, P. Hudson and A. A. Guiffre. 1993 Chilled conditioning of milled rice. ASAE Paper No. 93-6515. St. Joseph, Mich.: ASAE.

Maier, D. E. 1994. Chilled aeration and storage of U.S. crops — A review. In *Stored Product Protection*, ed. E. Highley, E. J. Wright, H. J. Banks and B. R. Champ. In *Proc. of the 6th International Working Conference on Stored-product Protection*, Canberra, Australia, 17-23 April 1994 Oxon, U.K.: CAB International.

Munday, G. D. 1965. Refrigerated grain storage. *J. and Proceed. of the Instit. of Agric. Engineers* 21(2): 65-74.

Reimann, E 1927. The influence of temperature on grain storage (in German). *Die Mühle* 12:367-368.

Rulon, R. A., D. E. Maier and L. J. Mason. 1995. Chilled conditioning and pest management of stored popcorn. ASAE Paper No. 95-6133. St Joseph, Mich.: ASAE.

Sulzer-Escher Wyss. 1970. Kernel cooling unit Granifrigor (in German). Sales brochure Lindau, Germany: Sulzer-Escher Wyss