Energy Use in Vacuum Coolers for Fresh Market Vegetables

J. F. Thompson, Y. L. Chen, T. R. Rumsey
MEMBER ASAE | ASSOC. MEMBER ASAE | MEMBER ASAE

This article is reprinted from APPLIED ENGINEERING IN AGRICULTURE (Vol. 3, No. 2, pp. 196-199, 1987)
Published by the American Society of Agricultural Engineers, St. Joseph, Michigan

ABSTRACT

ENERGY use characteristics of two commercial vacuum coolers were evaluated. Total energy use per unit cooled and energy use by various components are reported. Energy use can be reduced by (a) reducing vacuum pump capacity after commodity begins cooling, (b) operating cooler with maximum amount of commodity, (c) shutting off equipment between cooling cycles.

INTRODUCTION

Vacuum cooling has proven to be a fast way of removing field heat from certain vegetables. For example, a present-day unit can cool a load of up to 800 lettuce cartons (24 heads per carton) from 27 °C to 1 °C in 30 min. Cooling by this method is a specific application of evaporative cooling (Greiner and Kleis, 1962). The absolute pressure of the atmosphere surrounding the product is reduced, which results in lowering the boiling temperature of water in the product. If the pressure is lowered enough, water will boil at the temperature of the vegetable. Sensible heat is given up by the product to change liquid water into vapor, and the product cools.

Vacuum cooling was first introduced on a commercial scale in Salinas, CA, in 1948. The plant was used to cool iceberg lettuce (Friedman and Radspinner, 1956). The process has been tried on a number of fruits and vegetables with varing degrees of success (Friedman and Radspinner, 1956; Greiner and Kleis, 1962; Barger, 1963). Vacuum cooling is now used commercially with iceberg lettuce, other leafy green vegetables and cauliflower.

Very little research has been done on energy use and conservation in vacuum coolers. An engineering consulting firm (Anon. 1981) conducted a brief study and suggested that there were a few methods that could reduce energy use by a small amount. On the basis of discussions with vacuum cooler operators and several tests where compressor and vacuum pump current were measured, the study recommended that energy could be saved by (a) turning off motors when not needed, (b) reducing vacuum pump capacity during the cooling cycle, (c) exchanging vacuum between a cooler that is just about to finish and one that is just beginning a cycle, and d) loading coolers to maximum capacity. The authors did not attempt to measure energy use and did not report energy savings for any of their recommendations.

The objectives of this study are to:

1. Quantify the typical energy use by commercial vacuum coolers.
2. Measure the amount of energy use per cycle and electrical power demand as a function of time of the major components (refrigeration compressor and vacuum pumps) of two coolers.
3. Measure energy use when operating a full versus partially loaded cooler.
4. Measure the effects of reducing vacuum pump capacity during the cooling cycle on energy use.

PROCEDURE

1. Survey cooler owners to determine their plants seasonal average energy use per carton based on total number of cartons cooled and utility bills.
2. Measure energy use characteristics of refrigeration compressor(s) and vacuum pumps of two vacuum coolers. (A typical cooler design is described in Fig. 1 and specifications of coolers tested are listed in Table 1).
   (a) measure temperature of lettuce entering and exiting each load.
   (b) measure incoming weight of each load of lettuce.
   (c) measure electrical power demand (kW) of compressor and vacuum pump motors using Esterline Angus Power III multimeters. Data were recorded manually once per minute.

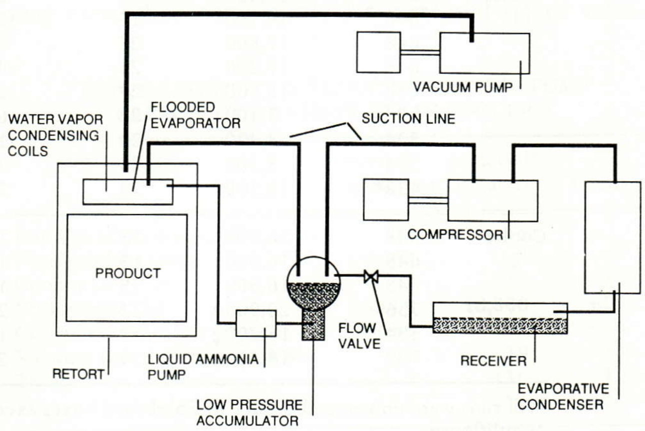

Fig. 1—Schematic of a typical vacuum cooler.

Article was submitted for publication in February, 1987; reviewed and approved for publication by the Food and Process Engineering Institute of ASAE in July, 1987. Presented as ASAE Paper No. 86-6010.

The authors are: J. F. THOMPSON, Extension Agricultural Engineer, Y. L. CHEN, Visiting Professor, and T. R. RUMSEY, Associate Professor, Agricultural Engineering Dept., University of California, Davis.

Acknowledgments: This project is financially supported by the California Iceberg Lettuce Research Advisory Board and the Committee on the Relationship of Energy to Agriculture. We would like to especially thank Jack Helm at Pacific Gas and Electric Company for providing metering equipment and personnel for the energy use tests.

TABLE 1. LIST OF COMPONENTS IN VACUUM COOLERS TESTED

	Cooler 1	Cooler 2
Retort inside dim.	2.7 m x 3.4 m x 13.4 m	2.7 m x 3.4 m x 13.4 m
Vacuum pumps	2-112 kW rotary vane	4-22 kW rotary vane
Compressor (s)	370 kW screw	150 kW recip. 90 kW recip.
Condensor	evaporative	evaporative
Refrigerant	ammonia	ammonia
Control system	manual	manual

TABLE 2. ENERGY USE OF TWO VACUUM COOLERS. DATA ARE FOR COOLERS FULLY LOADED WITH UNWRAPPED LETTUCE

	Cooler 1	Cooler 2
kWh/carton	0.21	0.18
EC	2.8	2.1

3. Test the effect of partially loading a cooler on energy use. Three tests were conducted with the retort fully loaded (648 iceberg lettuce cartons) and three tests were conducted with 324 cartons. Tests were conducted with cooler 1.

4. Test the effect of shutting off half of the vacuum pump capacity on energy use. Three tests were conducted with all four vacuum pumps on for the entire cooling cycle, and two tests were conducted with two pumps turned off after the lettuce began to drop in temperature. Tests were conducted with cooler 2.

RESULTS

We collected energy use and quantity of lettuce cooled for eight operations. Average seasonal energy use was 0.22 kWh/carton (a packed lettuce carton weighs 23 to 27 kg). The lowest seasonal energy use was 0.16 kWh/carton and the highest was 0.26 kWh/carton.

Average energy use for the two coolers we tested fell well within this range as seen in Table 2. A summary of the field data we collected is in Table 3. Reporting energy use as kW/carton does not truly reflect a cooler's efficiency. Carton weights vary from load to load and incoming and outgoing lettuce temperature can change dramatically during the day. To account for these factors, we defined an energy coefficient (EC) which takes into account these variables:

$$EC = \frac{W}{E}$$

W is the sensible heat removed from the product and E is the total electrical energy consumed in operating the cooler (The sensible heat calculation assumed a specific heat of 4.18 kJ/kg-C. EC is similar to the coefficient of performance (COP) for vapor recompression refrigeration systems but describes the efficiency of the entire cooling process rather than just efficiency of the refrigeration system.

Cooler 2 has a lower energy use per carton than cooler 1 and would seem to be more energy efficient, but the EC of cooler 2 is significantly lower than the EC of cooler 1. This reflects that fact that the lettuce entering cooler 2 was significantly cooler than the lettuce entering cooler 1. Actually, cooler 2 requires 33% more energy per unit of cooling work done than cooler 1 requires.

Distribution of energy use among the major components of the coolers is listed in Fig. 2. Compressor energy use is by far the largest, accounting for about two-thirds of the total. Vacuum pumps account for about 20% of energy use and miscellaneous motors; such as evaporative condenser fans, cooling water pumps and conveyors, cause the remainder of the energy use.

Fig. 3 shows a typical load profile for the screen compressor in cooler 1. During the first eight minutes of operation, there is virtually no demand for refrigeration because the retort pressure is not low enough to cause rapid moisture release, but there was a 100 kW demand

TABLE 3. COOLING TEST* DATA

	Number of cartons cooled	Quantity cooled, kg	Initial product temp, °C	Final product temp, °C	Energy Use: Compressor, kWh	Energy Use: Vacuum pump(s), kWh	Energy Use: total kWh	Cooling time, min
Cooler 1	648	17,400	19	1	87	29	128	23
	648	14,700	16	2	76	26	114	21
	648	17,800	23	2	96	30	139	25
	648	17,200	25	4	99	30	143	26
	648	15,800	27	2	123	32	169	27
	324	8,100	23	6	50	23	83	18
	324	8,400	24	1	68	30	109	22
	324	8,300	25	2	74	32	109	25
	1,432*	18,300†	18	2	209	95	358	107
Cooler 2	648	16,000	13	1	57	22	95	28
	648	16,000	13	1	74	32	125	36
	648	16,300	13	1	64	27	107	32
	756	20,900‡	13	2	74	19	121	30
	594	16,700‡	15	1	74	19	110	33
	702	18,100‡	19	2	82	19	117	37

*All runs were unwrapped lettuce in fiberboard boxes except for one run with cauliflower.
†Cauliflower.
‡Vacuum pump capacity reduced by 50% after flash.

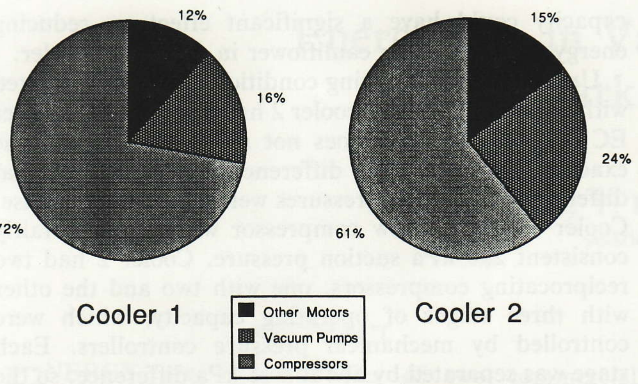

Fig. 2—Average distribution of energy use for two vacuum coolers operated in normal fashion.

by the 375 kW motor driving the idling compressor. The energy use during idling is about 25% of the total energy used by the compressor motor during the entire cooling cycle.

Vacuum pump power demand starts high, at about 140 kW, and tapers off to 50kW after several minutes. Power demand for the miscellaneous motors is constant at 30kW. The power demand pattern for cooler 2 (Fig. 4) is similar to cooler 1, except that the smaller compressor capacity of cooler 2 causes the compressors to operate at full capacity longer than in cooler 1.

Loading cooler 1 with half its normal capacity of cartons significantly ($P \leq 0.05$) reduced its energy coefficient by 28% as seen in Table 4. This corresponds to a 38% increase in energy use to cool a carton of lettuce

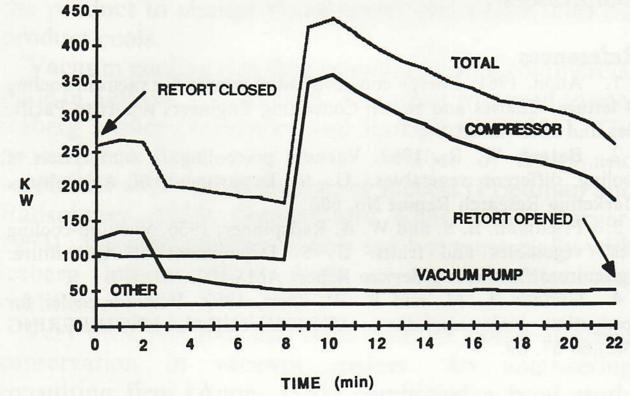

Fig. 3—Typical electrical power demand vs. time relationships for Cooler 1.

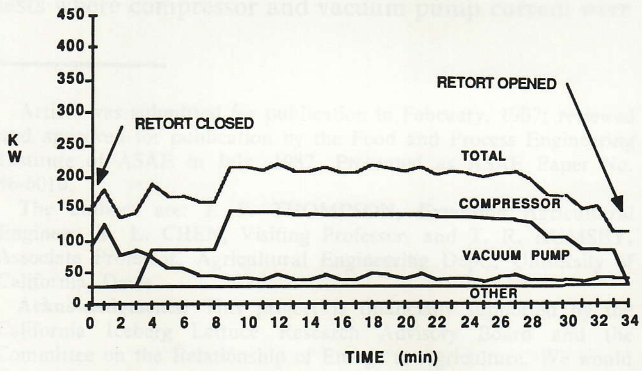

Fig. 4—Typical electrical power demand vs. time relationships for Cooler 2.

TABLE 4. EFFECT OF LOADING COOLER 1 WITH HALF VS. FULL NUMBER OF CARTONS

	Full load*	Half load†	% Change
Initial product temperature, °C	26	26	-
Final product temperature, °C	3	3	-
Cooling time, min	26	22	-15
Load weight, kg	16,900	8,300	-15
Compressor energy use, kWh	106	64	-40
Vacuum pump energy use, kWh	26	23	-11
Total energy use, kWh	150	104	-31
EC	2.8	2.0	-28

*Average of 5 runs.
†Average of 3 runs.

compared with a fully loaded retort. Compressor energy use dropped almost in proportion to the lower mass of lettuce in the cooler. This is expected because there is half as much water vapor to condense. Vacuum pump energy dropped slightly, probably because of the shorter cooling time for the half loads.

Reducing vacuum pump capacity, after the product began to loose temperature, significantly ($P \leq 0.05$) reduced vacuum pump energy use by 30% as seen in Table 5. This resulted in a 13% improvement in energy coefficient. This corresponds to a 13% decrease in energy to cool a carton of lettuce compared with operating all vacuum pumps for the entire cooling period. Cooling time was not significantly ($P > 0.05$) affected by the change in operation of the vacuum pumps.

DISCUSSION

Energy use of only 0.2 kWh per carton is a small part of the total cost of vacuum cooling. A typical price for contract cooling is $0.65 per carton and at an electricity cost of $0.10 kWh, energy is only 3% of the total price. However, monthly utility bills are large enough that operators are interested in reducing them.

The electrical power demand profiles show that there are significant periods during the first eight to nine minutes of a cycle, and between cycles where a refrigeration compressor is not required but may be left idling. For a screw compressor, the demand for idling may be 25% of maximum demand.

Idling energy use could be reduced in a number of ways. Compressors can be shut off during these two or three periods per hour. More frequent cycling would reduce the motor life somewhat, however, energy savings may more than compensate for increased repair costs.

TABLE 5. EFFECT OF REDUCING VACUUM PUMP CAPACITY ON ENERGY USE IN COOLER 2

	Normal* operation	Reduced* capacity	% Change
Initial product temp., °C	13	16	-
Final product temp., °C	1	2	-
Cooling time, min	32	33	+3
Load weight, kg	16,000	18,800	+17
Compressor energy use, kWh	65	74	+14
Vacuum pump energy use, kWh	27	19	--30
Total energy use, kWh	109	116	--3
EC	2.1	2.6	+24

*Average of 3 runs.

Some cooling installations consist of two or more retorts operating from a common refrigeration system. This design would probably result in a more uniform refrigeration demand and less inefficiency caused by idling compressors. If motors must be left on (large motors turning on and off can cause significant voltage fluctuations in a local utility network), idling time could be reduced by shortening time between cycles by installing faster conveyors. Installing larger vacuum pumps to decrease the time betwen start of a cycle and start of temperature drop would also reduce compressor idling time.

The test on cooler 1 showed a 28% decrease in energy coefficient caused by cooling a half load of lettuce. Most of the decrease in efficiency is caused by the vacuum pump energy use being spread over fewer cartons. Vacuum pump energy use per cooling cycle is primarily a function of the interior volume of the retort and total cooling time and is hardly affected by the amount of lettuce in the retort. (If lettuce is assumed to be 100% water, which it is nearly, the solid/liquid mass of the lettuce occupies only 15% of the interior volume of a vacuum cooler.) Some of the decrease in efficiency may have been caused by the compressor operating at low capacities where it is less efficient.

Usually a vacuum cooler is operated with a full load although half loads are common near the end of a day's cooling when lettuce arrives at the cooler sporadically. Some new retorts are built to handle loads that are eight cartons high but often field harvest constraints result in loads that are only six cartons high. The unused volume in the retort contributes to higher than necessary vacuum pump energy use. Old retorts typically have a circular cross section which is not well filled by rectangular loads. This design should be inherently less coefficient than a rectangular design.

The vacuum pump test showed that vacuum pump capacity can be reduced during the cycle. Capacity could possibly be reduced even further than the 50% reduction we tried. Minimum capacity could be determined by reducing it until cooling time was increased compared with standard capacity. Timing of the reduction should also be investigated.

Cauliflower is sometimes cooled in vacuum coolers. A typical cycle requires 90 to 150 min and most of this time after cooling has begun. Reducing vacuum pump capacity could have a significant effect on reducing energy cost of cooling cauliflower in a vacuum cooler.

Under normal operating conditions, cooler 1 operated with an EC of 2.8 while cooler 2 had a significantly lower EC of 2.1. Our data does not allow us to determine exactly what caused the difference, but we believe that differences in suction pressures were a significant cause. Cooler 1 had a screw compressor which kept a fairly consistent 230 kPa suction pressure. Cooler 2 had two reciprocating compressors, one with two and the other with three stages of operating capacity, which were controlled by mechanical pressure controllers. Each stage was separated by about a 15 kPa difference, so the first stage started at about 110 kPa and the last at 230 to 260 kPa. This resulted in an average suction pressure during a cycle of only 170 kPa. Theoretically, increasing the suction pressure from 170 to 230 kPa should reduce compressor energy use by 15% to 20%.

CONCLUSIONS

Typical energy use for vacuum coolers is 0.22 kWh/carton. Our tests showed that this level of energy use can be reduced by 13% by shutting off half of the vacuum pump capacity after lettuce begins to cool. Increasing the quantity of lettuce loaded into a cooler will significantly reduce per carton energy use. Level of savings for a particular cooler is a function of the increase in average load weight. If load weight can be increased by 50%, energy use per carton will drop by 28%. Our data also show that there can be long periods during a cooling cycle where refrigeration compressors are not needed. Energy can be saved by reducing idling time or by shutting off some or all of the refrigeration compressors.

References

1. Anon, 1981. Energy conservation measures for vacuum cooling of lettuce. Charles and Braun Consulting Engineers report to Pacific Gas and Electric Co.

2. Barger, W. R., 1963. Vacuum precooling: a comparison of cooling different vegetables. U. S. Department of Agriculture. Marketing Research Report No. 600.

3. Friedman, B. S. and W. A. Radspinner, 1956. Vacuum-cooling fresh vegetables and fruits. U. S. Department of Agriculture. Agricultural Marketing Service Report AMS-107.

4. Greiner. L. M. and R. W. Kleis, 1962. Vacuum cooler for production scale operation. AGRICULTURAL ENGINEERING 43(2):86-87, 89.