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Energy Use in Hydrocooling Stone Fruit

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ABSTRACT

Energy use per unit of product cooled is reported for two commercial hydrocoolers. Energy use by major components is listed. Heat input measurements and operational data are used to evaluate possible energy conservation methods such as minimizing external heat gain, operating coolers at maximum capacity, minimizing water flow, and reducing water reservoir capacity.

INTRODUCTION

Hydrocooling is a common method of rapidly bringing fruits and vegetables to recommended storage temperatures. Stone fruit (peaches, plums, nectarines, and cherries), asparagus, sweet corn, celery, radishes, and carrots are often hydrocooled.

Hydrocooling uses chilled water to cool perishable commodities. Water is distributed over the top surface of fruit or vegetables which are packed in boxes or pallet bins. Mitchell et al. (1972) indicate that there is little difference in cooling times when water flow rates of 7 L/m^2-s (0.17 gal/ft^2-s) or 10 L/m^2-s (0.25 gal/ft^2-s) are used on a single bin of peaches. Water flow rates are listed in terms of water volume per time divided by the area of the water distribution pan. Zahradnik and Reinhart (1972) show that there is only a 20% increase in the effective heat transfer coefficient when water flow rates are increased from 5.3 L/m^2-s (0.13 gal/ft^2-s) to 20.7 L/m^2-s (0.51 gal/ft^2-s) for apples. They conclude that heat flow resistance within the fruit limits cooling at water flow rates above 5.3 L/m^2-s (0.13 gal/ft^2-s).

Some of the earliest work on hydrocooling includes some data on energy use characteristics of hydrocoolers. Guillou (1958) indicates that 55% of the refrigeration capacity (ice is used for refrigeration in this research) is used for cooling product when the cooler operates in a continuous fashion. Intermittent operation causes only 23% of the ice to be used for cooling fruit. He mentions poor insulation, open handling of ice and inability to use the cooling capacity of ice left in the cooler at day's end as reasons for poor efficiency. Perry and Perkins (1968) recommend reducing the volume of water contained in a hydrocooler to reduce energy consumption. This reduces energy used to cool water before the start of each day's cooling. They also indicate that uninsulated hydrocooler surfaces result in unnecessary heat gain during operation.

We compare the energy efficiency of four types of coolers, Thompson and Chen (1988). Efficiency of hydro, vacuum, water spray vacuum, and forced air coolers are listed in terms of an energy coefficient, which is defined as the total product cooling done divided by the electricity purchased to operate the cooler. The vacuum coolers, for which we have data, have an average energy coefficient of 1.8, with a range of 2.4 to 1.4. An average hydrocooler is slightly less efficient, having an energy coefficient of 1.4. However, the energy coefficient data for hydrocoolers have a range of 2.2 to 0.7 indicating that a well designed and operated hydrocooler can be more efficient than the average vacuum cooler. This range also indicates that there is significant opportunity to improve the efficiency of some of the coolers in use. However, none of the previous work provides a detailed energy analysis of hydrocoolers with a breakdown of the heat inputs to the coolers.

The goals of our study are to 1) verify the hydrocooler energy use and the energy efficiency data presented by others, 2) determine the source and magnitude of heat input to typical hydrocoolers, and 3) suggest possible energy conservation measures.

PROCEDURE

We accomplish these goals by testing two hydrocoolers that each have a refrigeration source that is independent of any other refrigeration loads. Figures 1 and 2 are diagrams of the hydrocoolers and Table 1 is a listing of the design features for each. The product cooled is either peaches or plums in pallet bins or a combination of bins of each fruit.

Energy use and energy efficiency are determined by measuring total electricity consumption and heat removed during product cooling. The energy flows used in calculations are shown in Fig. 3. Energy use is expressed in kJ of electricity consumed per kg of product cooled. The energy efficiency is expressed as an energy coefficient (EC), and defined as

$$EC = \frac{W}{E} \qquad [1]$$

W is the sensible heat removed from the product and wooden bins, assuming a overall specific heat for the fruit and bins of 3.8 kJ/kg-°C (0.908 BTU/lb °F. (Mass of bins is about 5% of total mass cooled.) E is the total electrical energy (expressed in kJ) consumed in operating

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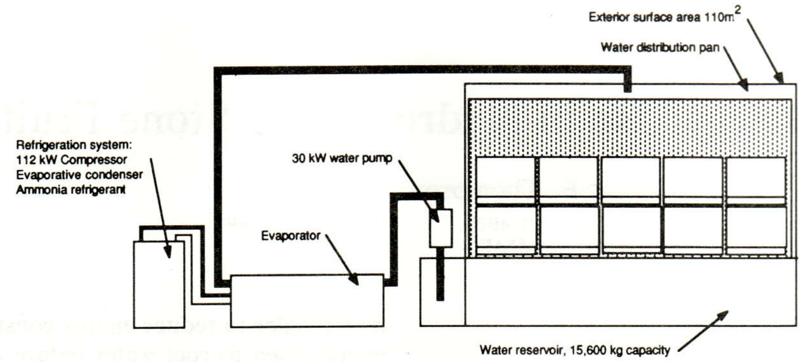

Fig. 1—Side view schematic of hydrocooler A, a batch type cooler for pallet bins.

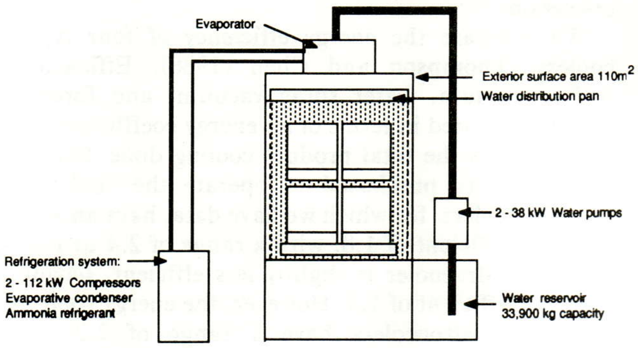

Fig. 2—End view schematic of hydrocooler B, a continuous flow cooler for pallet bins.

the cooler. EC is similar to the coefficient of performance in vapor recompression refrigeration systems but it is a measure of the overall efficiency of the cooling system not just the efficiency of the refrigerant fluid.

Portable kilowatt meters are used to measure electricity demand of compressor(s), water pump(s), and total demand of the system which includes evaporative condenser pump and fans, conveyor motors, and other miscellaneous motors. Data for compressor and total demand are recorded manually at 5-min intervals. Demand for water pumps is constant and is measured only at the beginning of a series of tests.

Product cooling is determined by sampling product mass flow and temperature drop of the fruit during cooling. Temperature of one or two fruit from the top of every other bin is measured with a hand held electronic thermometer. We find little difference in temperature between top and bottom fruit in a bin. Two to four bins are weighed before cooling for each 20 to 64 bin run.

The heat input to the cooler is based on the heat flows

TABLE 1. Design features of tested hydrocoolers

	Hydrocooler A	Hydrocooler B
Type	batch	continuous
Maximum capacity*	30 bins/batch	80 bins/hr
Compressor(s)	1-112 kW recip.	2-112 kW recip.
Water pump(s)	1-30 kW	2-38 kW
Exterior surface area	110 m^2	110 m^2
Reservoir capacity	15,700 kg water	33,900 kg water
Refrigerant	ammonia	ammonia
Condenser type	evaporative	evaporative

* A bin of peaches or plums weighs approximately 450 kg.
NOTE: To convert m^2 to ft^2 multiply by 10.8
To convert kg to lbs multiply by 2.20

into and out of the coolers as diagrammed in Fig. 4. Exterior heat gain, caused by air infiltration and heat conducted through exterior surfaces, is determined by cooling the water reservoir to operating temperature, turning off the refrigeration system and operating the cooler without any fruit in it. Heat gained from the outside and from the water pump causes an increase in the reservoir water temperature. Under these conditions, the heat balance of the cooler is

$$Q_{ext.} - Q_{pump} = (m_c\, c_{pc} + m_w\, c_{pw})\frac{\Delta T}{\Delta t} \quad \ldots\ldots\ldots [2]$$

where

Q_{ext} = rate of heat added to cooler from air infiltration and conduction through walls, kJ/min,

Q_{pump} = rate of heat added to water from the pump, kJ/min,

m_c = mass of empty cooler, kg,

m_w = mass of water in cooler, kg,

c_{pc} = specific heat of the empty cooler, kJ/kg-°C,

c_{pw} = specific heat of water, kJ/kg-°C,

$\frac{\Delta T}{\Delta t}$ = rate of water reservoir temperature rise, °C/min.

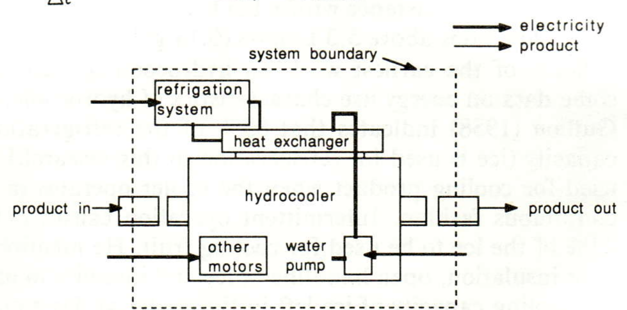

Fig. 3—Electricity input and product heat flow used in the energy efficiency and energy use calculations.

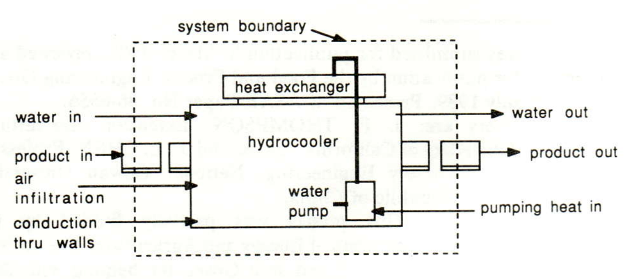

Fig. 4—Heat flows used in the heat input calculations.

TABLE 2. Hydrocooler energy use

a	b	c	d	e	f	g	h	i	j	k	l
Run ID	Product	Mass Cooled (kg)	Initial Fruit Temp. (°C)	Final Fruit Temp. (°C)	Temp. Drop (°C)	Run Time (min)	Pump (kWh)	Comp. (kWh)	Total (kWh)	Energy/ Mass Cooled (kJ/kg)	Energy Coefficient
Hydrocooler A											
1	Peach	10,600	16.6	5.6	11.0	91	44	136	212	72*	0.55*
2	Peach	10,600	21.7	6.6	15.1	63	30	91	142	48	1.17
3	Peach	10,600	25.3	6.1	19.2	81	39	117	182	62	1.12
4	Peach	11,600	29.2	6.4	22.8	89	43	128	200	62	1.26
Average					17.0					61	1.00
Hydrocooler B											
Cool down	—	—	—	—	—	65	64	159	255	—	—
1	Peach/Plum	20,400	22.2	8.1	14.1	83	59	107	195	79*	0.73*
2	Plum	25,600	25.4	8.1	17.3	87	86	268	396	56	1.08
3	Plum	25,600	26.0	7.8	18.2	71	70	179	284	40	1.63
4	Peach/Plum	16,600	24.7	9.2	15.5	51	50	152	227	49	1.10
Cool down	—	—	—	—	—	10	6	42	53	—	—
5	Peach/Plum	35,800	26.0	9.7	16.3	78	78	269	385	44*	1.61*
Average					16.2					54	1.14

* Includes cool down of water to operating temperature
NOTE: To convert kg to lbs multiply by 2.20
To convert °C to °F: F = C + 1.8 + 32
To convert kJ/kg to BTU/lb multiply by 0.431

Manufacturer's data is used to determine the cooler's mass and mass of the water is based on the measured capacity of the water reservoir. (These data show that water is 90% of the heat capacity of the coolers). Heat input from the pump is constant and is estimated from its electricity consumption, assuming a 90% motor efficiency and that all of the shaft energy input to the pump is converted to heat in the water. Exterior heat gain is then directly related to the rate of water temperature rise. Water temperature rise is measured over a 20-min period.

Energy use by the pumps is a function of the lift and the flow rate. Lift is very minimal in the coolers under test and we see no way to influence it. However, reducing water flow may save energy and we determine it by placing a vertical-walled bucket in the cooler and measuring the time needed for the bucket to fill. Results are expressed in water flow rate unit area of shower pan.

Heat input associated with water loss is determined by measuring the mass of the bins into and out of the coolers. The weight added to the bins during cooling is assumed to be water lost from the cooler. This cooled water is replaced with well water at 24° C (75° F) which must be cooled to operating temperature.

RESULTS

Even though the coolers are of somewhat different design, they have similar levels of energy use per unit of fruit cooled, as noted in Table 2, column k. Cooler A has an average energy use per mass of product cooled of 61 kJ/kg (26 BTU/lb) and cooler B uses an average of 54 kJ/kg (23 BTU/lb), a 12% lower energy use. Because the average product temperature drop is nearly the same (17° C vs. 16.2° C (63° F vs. 61° F), Table 2, column f) for the two coolers, the EC data show they have similar energy efficiencies. Cooler A had an average EC of 1.00 vs. an EC of 1.14 for cooler B, Table 2, column 1.

TABLE 3. Distribution of energy use by various motors for two hydrocoolers

Motor location	Cooler A	Cooler B	Average
	% of total		
Compressor	64	67	65
Water Pump(s)	21	23	22
Other Motors	15	11	13

The electricity use data shown in Table 2, columns h-j, allow us to determine the relative consumption of the various motors in the coolers. Table 3 indicates that the two coolers have a similar distribution of energy use. The compressor motor is responsible for two-thirds of the total electricity use. The water pump motor(s) account for an average of 22% of the total and other motors, such as those that operate evaporative condenser fans and water pumps, contribute the remaining 13% of the energy use.

The results of the heat input measurements are shown in Table 4. Fruit cooling contributes 49% of the heat input to cooler A and 56% of the heat input to cooler B. This is the largest source of heat input to the coolers. The

TABLE 4. Distribution of heat input to hydrocoolers under test*

	Cooler A		Cooler B	
	10^6kJ	%	10^6kJ	%
Fruit cooling (bins incl.)	2.66	49	7.36	56
Exterior heat gain	1.52	28	3.47	26
Water pumps	0.51	9	1.43	11
Cooler startup	0.67	12	0.72	5
Water lost	0.09	2	0.23	2

* Sum over all tests including water cool down periods
NOTE: To convert kJ to BTU multiply by 0.948

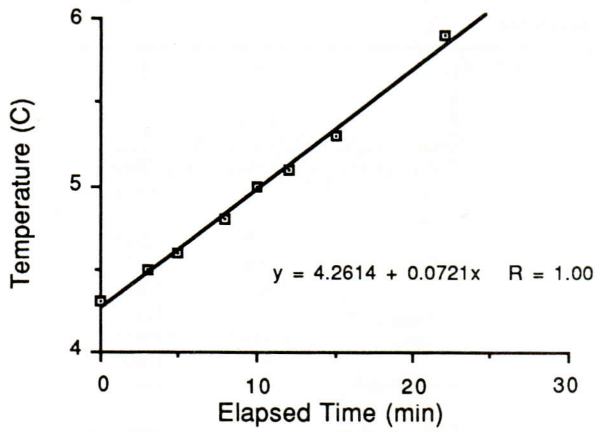

Fig. 5—Results of exterior heat gain test for hydrocooler A. (°F = °C*1.8 + 32)

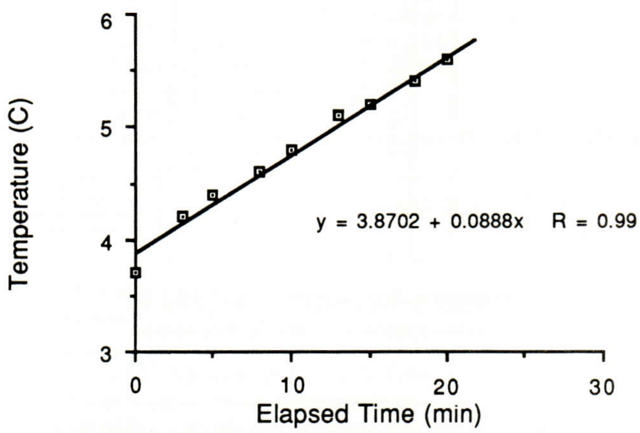

Fig. 6—Results of exterior heat gain test for hydrocooler B. (°F = °C*1.8 + 32)

remaining heat inputs are not associated with useful work and represent a significant potential for energy savings.

The rate of exterior heat gain is calculated using equation [2] and the slope of the regression lines in Figs. 5 and 6. Exterior heat gain is 28% of the total heat gain for cooler A and 26% for cooler B, as shown in Table 5. Cooler A has a 40% lower exterior heat gain/hour than cooler B. But cooler A has a smaller product cooling capacity than cooler B. If they are compared on the basis of an equal cooling capacity (maximum number of bins/hour) cooler B has the lower rate of external heat gain. Table 5 shows that cooler A has an exterior heat gain of 10 000 kJ/bin (9480 BTU/bin) while cooler B has 6 200 kJ/bin (5878 BTU/bin) , a 38% lower rate of heat gain/unit of cooling capacity. (Notice that the heat input data in Table 4 do not show this great a difference between the two coolers because ambient temperature conditions are different during the two tests.) Cooler B is insulated with 1.5 cm of foam rubber and painted white but was exposed to direct solar radiation. Cooler A is not insulated but installed under a cover to reduce solar heat gain. Also, cooler B is more efficient because it has half the exterior surface area per unit capacity compared with cooler A. Both coolers have plastic curtains to reduce air infiltration through product inlet and outlet openings.

TABLE 5. Exterior heat gain test of two hydrocoolers

	Cooler A	Cooler B
Heat gain (kJ/hr)	299 000	499 000
Max. cooling capacity (bin/hr)	30	80
Heat gain per cooling capacity (kJ/bin)	10 000	6 200
Reservoir-air temperature difference during test (°C)	25	27

NOTE: To convert kJ to BTU multiply by 0.948
°F = °C * 1.8 + 32

The next largest source of heat gain is the water pumps. Pump heat input is 9% of the total for cooler A and 11% of the total for cooler B. Both coolers are designed to operate against a minimum head by using a perforated pan to distribute water instead of a nozzle system. But both coolers operate with a water flow rate of 50 L/m^2-s(1.2 gal/ft^2-s), which is much higher than recommended.

Heat load associated with cooling water before start-up each morning ranges from 12% in cooler A to 5% in cooler B. Water in the reservoirs warms to about 10° C (50° F) between shut down on one day and start-up the next and is cooled to 1° C to 2° C (33.8° F to 36° F) before cooling begins. Every second or third day the coolers are thoroughly cleaned and the water is changed. On these days the water is cooled from 24° C (75° F) to operating temperature.

Heat gain associated with water leaving the coolers on fruit and bin surfaces is only 2% of the total heat input.

DISCUSSION

The coolers have ECs of 1.00 for A and 1.14 for B, which are well within the 0.7 to 2.2 range, although slightly below the 1.4 average EC reported in our previous work on hydrocoolers (Thompson and Chen, 1988).

On the basis of the heat input results for the two coolers tested, energy use in hydrocoolers can be reduced significantly by reducing exterior heat gain. As an example of the potential savings, if cooler A were insulated to reduce its exterior gain by 38%, to the same rate of exterior heat gain/bin as cooler B, its exterior gain based on the data in Table 4 would be only 0.95 x 10^6 kJ (935 x 10^3 BTU) , reducing total heat input by 11%. We assume that reducing the total heat input by 11% would reduce the total energy use of the cooler 7% because refrigeration is 65% of total energy use.

The low exterior heat gain of cooler B is partially due to its low external surface area per unit of cooling capacity. Cooler A cannot be easily modified to reduce external area but it certainly could be insulated with more than the 1.5 cm (0.6 in.) of insulation in cooler B. Exterior heat gain associated with air infiltration may also contribute to the difference in heat gain between the two coolers, but we have not measured air infiltration apart from the rest of the other sources of exterior heat gain, so we can not estimate the potential effect of this. Reducing solar heat input by shading an uncovered cooler or at least painting it a light color should also reduce exterior heat input, but again we do not have data on the magnitude of the potential savings.

A key concern with the insulation is that it must be able to maintain its insulating ability in a wet environment. Durable, closed cell foam insulation materials appear to be best choice for hydrocoolers. Most other types of insulation absorb water easily and lose insulation ability when wet. Some operators have placed their hydrocoolers inside a refrigerated room to eliminate heat conducted through exterior surfaces and avoid the problem of protecting insulation from becoming wet.

Both coolers lose efficiency because they do not operate continuously. For example, each run for cooler B lasted only 50 to 80 min., and because it is a continuous flow type, it is only partially full of bins during the first 20 minutes and the last 20 minutes of a run. In our tests, this causes cooler B to operate with an effective capacity of 45 bins/hr, which is 44% less than its maximum capacity of 80 bins/hour. Heat inputs, which are primarily a function of total operation time such as exterior heat gain and pump operation, are spread over fewer bins when a continuous flow hydrocooler operates intermittently. Continuous operation of cooler B would cause a 44% reduction in pump energy use and exterior heat gain per bin. Based on Table 4, this would reduce heat input and therefore energy use of cooler B by 2.15 x 10^6 kJ (2.0 x 10^6 BTU) . This is equal to 16% of the total heat input. Continuous operation reduces pump energy use by a similar amount and causes a net 14% decrease in total energy use.

Cooler A has nearly the same potential energy saving if it is operated at full capacity. It can hold 30 bins of fruit, but it usually filled with only 20. Because it appears to have more than adequate water flow to cool 30 bins as quickly as 20 bins, filling it to capacity would spread exterior heat gain and water pumping energy use over 50% more bins. This would reduce exterior heat gain and pump heat input per bin by 33%. This is equal to 0.67 x 10^6 kJ (0.64 x 10^6 BTU) and to 12% of the total heat input.

The water pumps for cooler B provide 50 L/m^2-s (1.2 gal/ft^3-s). Previous research shows that 7 L/m^2-s (0.17 gal/ft^2-s) is an adequate flow for a single bin of peaches. Cooler B operates with bins stacked two high, so perhaps as much as 14 L/m^2-s (0.35 gal/ft^2-s) may be required. If water flow is reduced by 72%, from 50 L/m^2-s to 14 L/m^2-s (1.2 to 0.35 gal/ft^2-s) , pump energy use would be reduced by 72%, equal to a 17% reduction in total energy use, based on the data in Table 3. Heat input to the cooler would also be reduced by 1.0 x 10^6 kJ (0.95 x 10^6 BTU), equal to 8% of the total. We assume that a reduction in heat input would translate into 65% reduction in total energy use, the total effect of reducing the pump capacity is a 22% reduction in total energy use.

Some commercial cooler manufacturers indicate that they design coolers with extra water flow capacity to account for uneven distribution of water within the bins. Often water flow capacities for commercial stone fruit hydrocoolers are at least 17 Lm^2-s (0.42 gal/ft^2-s). The need for this extra capacity should be further studied. There is also a possibility that the water flow can be reduced at the product exit end of a continuous flow cooler because heat flow through the product is probably limiting cooling not heat flow from the product's surface.

Energy use for start-up can be reduced by decreasing the volume of the water reservoir. In both coolers, reservoirs are about 1 m (3.3 ft) deep, but pump draw down is only 20 cm (8 in.), so most of the depth is not needed for pumps. A small volume with a depth of at least 0.5 m (1.6 ft) deep is required for the trash removal screens, but this volume does not need to extend over the entire length of the cooler. Some coolers are designed with a shallow, gently sloping pan that directs water back to a small sump for the pump. If reservoir capacities could be reduced by 70%, the data for cooler B in Table 2 indicate that initial cool down energy could be reduced from 255 kWh to 77 kWh, which equals a 13.5% reduction in heat input and a 9% reduction in total energy use.

TABLE 6. Summary of potential energy saving methods for hydrocoolers in tests

Energy Saving Method	Potential Saving
Reduce water flow	22%
Operate continuously	14%
Insulate cooler	7%
Reduce reservoir volume	9%

We did not test the efficiency of the refrigeration system, but obviously this can influence energy use of a cooler. Proper design should incorporate energy conservation factors such as optimum sizing of heat exchangers, flash gas recompression, minimizing head pressures, and reducing pressure drops in piping and equipment. Proper maintenance of equipment is also important in minimizing energy use.

SUMMARY

The energy use data for the two test coolers agrees with the data we presented earlier, Thompson and Chen (1988). The performance data indicate that there are several methods that should be considered in attempting to reduce the energy use of a hydrocooler. Table 6 presents estimates of potential energy saving techniques for the coolers in our tests. These estimates may not apply to other hydrocoolers because of differences in design and operation. For example, if a cooler already has a proper water flow rate, then there is no potential for energy saving by modifying the flow. But energy savings greater than our estimates may be possible in other coolers. Our testing compares a cooler with 1.5 cm of foam insulation vs. a cooler with no insulation. Certainly a cooler can have greater levels of insulation applied and would of course have even greater savings than our estimates indicate. Table 6 is a useful guide for planning an energy conservation strategy for a hydrocooler.

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