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COMPARATIVE ENERGY USE OF VACUUM, HYDRO, AND FORCED AIR COOLERS FOR FRUITS AND VEGETABLES

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ABSTRACT

Energy use efficiency of cooling systems varys with the type of cooler used. Vacuum coolers are the most efficient, followed by hydrocoolers, water spray vacuum coolers, and forced-air coolers. Levels of non-product heat input and operational practices have been identified as reasons for the differences. Energy use efficiency varys significantly within coolers of the same type. Level of product throughput, commodity type, and operational procedures have been identified as major reasons for this.

INTRODUCTION

Cooling perishable commodities as quickly as possible after harvest has become a widely used method of maximizing post harvest life. Four methods of cooling are commonly used.

Vacuum cooling is used for certain vegetable crops. It is basically an evaporative cooling process where water is supplied by the commodity being cooled (Greiner and Kleis 1962). Absolute pressure surrounding the commodity is reduced, which results in lowering the boiling temperature of water. 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 water vapor, and the product cools. Mushrooms and leafy vegetables, such as lettuce, release water vapor rapidly enough to be practically used with vacuum cooling (Friedman and Radspinner 1956). Cooling time varies from 0.5 hours for head lettuce to two hours for cauliflower.

Water spray vacuum cooling is a variation of vacuum cooling. Water is sprayed on the commodity just before actual temperature drop begins and sometimes just before the cooling cycle ends. The added water supplies much of the water which evaporates, resulting in less water being removed from the product itself. Celery, leaf lettuces, and green onions may be cooled with this method. Cooling times are 0.5 to 0.6 hours.

Hydrocooling uses chilled water to cool perishable commodities (Mitchell, Guillou and Parsons 1972). Water is distributed over the top surface of fruit or vegetables which may be packed in boxes or pallet bins. After passing through the commodity, water is collected, recooled, and used again for cooling. Peaches, plums, nectarines, cherries, sweet corn, celery, radishes, and carrots are commonly hydrocooled. Cooling time is similar to that of vacuum cooling.

Forced air cooling utilizes air as a cooling medium (Mitchell, Guillou and Parsons 1972). Refrigerated air is forced through stacks of vented containers by creating a pressure difference across the containers. The system is set up in a refrigerated room with enough refrigerating capacity to handle the large heat load associated with the rapidly cooling product. Cauliflower, strawberries, melons, vine-ripe red tomatoes, grapes, and peppers are commonly forced-air cooled. Forced-air cooling times range from two hours for packed strawberries to 24 hours for boxes of paper wrapped pears.

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A limited amount of research has been done on energy use in coolers. An engineering consulting firm (Anon 1981) reported that one lettuce vacuum cooler operation had an energy use of 0.25 kWh per carton. (A carton of head lettuce weighs 50-60 lb (23-27kg) and is typically cooled from field temperatures of 60-70 F (15C-25C) to a final temperature of 36-39 F (1C-4C). Some of the earliest work on an ice cooled hydrocooler (Redit, Smith and Benfield 1955) indicated an average energy use of 0.0147 lb of melted ice per lb-F (0.0265kg/kg-C) of product cooling. Energy use ranged from 0.0114 lb/lbF to 0.0194 lb/lb-F (0.021 kg/kg-C to 0.035 kg/kg-C) with resulting energy use efficiencies of 0.32 to 0.53 (sensible heat removed from product divided by total cooling effect used). They suggested that efficiency was low because of cold water spillage and lack of insulation. Other work (Perry and Perkins 1968) indicated that energy efficiency could be improved by reducing the volume of water contained in a hydrocooler. This reduces energy used to cool water before the start of each day's cooling. Perry and Perkins also indicated that uninsulated hydrocooler surfaces result in excess heat gain during operation. We have not found any reported energy use data for forced-air cooling operations.

This paper summarizes research we have done on energy use of commercial scale cooling systems. We determined the energy use for the four main types of coolers and identified possible reasons for differences in energy use between the systems.

MATERIALS AND METHODS

1. We collected monthly utility bills and monthly product throughput data for eight vacuum coolers which cooled head lettuce and cauliflower; four water spray vacuum coolers which cooled celery and leaf lettuces; three forced-air cooling operations which cooled kiwi fruit, pears, or strawberries; and seven hydrocoolers which cooled peaches or pears. These data and product temperature data from cooler managers were used to calculate energy use efficiencies.

2. Detailed energy use monitoring was conducted on two hydrocoolers and two vacuum coolers. All electricity inputs were monitored with kilowatt meters. Product weights and incoming and outgoing temperatures were measured. Details of vacuum and hydrocooler monitoring are contained in Thompson, Chen and Rumsey (1986) and Thompson and Chen (1986). These data were used to evaluate the level of heat inputs to coolers and verify overall energy use efficiency data calculated from company records.

3. Heat inputs to the three forced-air coolers were calculated based on standard ASHRAE procedures (ASHRAE 1977), using construction details and operational procedures provided by cooler managers. We did not have enough operational data on water spray vacuum coolers to calculate heat inputs.

RESULTS AND DISCUSSION

Energy efficiency data are expressed as an energy coefficient (EC). Where:

$$EC = \frac{W}{E} \qquad (1)$$

W is the sensible heat removed from the product, assuming a specific heat of 0.90 Btu/lb-F (3.8 kJ/kg-C) for fruits and 0.95 Btu/lb-F (4.0 kJ/kg-C) for vegetables and E is the electrical energy (expressed in Btu) consumed in operating the cooler.

Figure 1 is a plot of the EC data for the four types of coolers. The data clearly show that there are differences in energy efficiency between cooler types. Average energy coefficient was 1.8 for vacuum cooling, 1.4 for hydrocooling, 1.1 for water spray vacuum cooling, and 0.4 for forced-air cooling. There are also large differences between coolers of the same type for vacuum coolers and hydrocoolers. Vacuum coolers and hydrocoolers had a range of 0.8 and 1.3 respectively. The three forced-air coolers and four water spray vacuum coolers had less variability within each type. On the basis of the other two types of coolers, we expect additional data would reveal more variable energy efficiency use data for forced-air and water spray coolers.

Variation between cooler types is partially explainable by the levels and types of heat input to them. Water spray vacuum coolers, hydrocoolers, and forced-air coolers have a number of heat inputs other than the product, while vacuum coolers remove heat only from the product. There are no lights, lift trucks, or people in a vacuum cooler. A vacuum cooler is obviously sealed tightly during operation, so infiltration does not contribute heat to the system. Very low atmospheric pressure in the chamber limits conduction heat exchange. Radiant heat exchange is small because of the small temperature difference between the chamber and the product. Table 1 shows heat inputs to the three types of coolers. The forced-air cooler data is an average of the data calculated from the three operations we studied. The hydrocooling data is an average calculated from data presented by Thompson and Chen 1986. Water spray vacuum coolers have most of the same low extraneous heat input advantages as vacuum coolers do. However, the water reservoir inside the cooler must be cooled to operating temperature each day and about 150 gallons (570 liters) of cold water leave the cooler with the wetted boxes and product on each 400 carton load. Also the cold water spray cools the side walls of the retort allowing heat to be conducted into the cooler. These factors are at least partially responsible for the low efficiency of water spray vacuum coolers compared with vacuum coolers.

The heat input data indicate that fan operation is part of the reason for the low efficiency of forced-air coolers. Improper design and operation of air moving systems is part of the reason for this high level of heat input. For example, in the kiwi fruit cooler, the air moving system consisted of a common air plenum for five cooling positions (see figure 2). All five lower fans must be operated to cool just one position because of the common plenum. A set of louvers on each position would allow fans in unused positions to turn off if the entire cooler is not needed. We also found that there was no pressure drop across the top five fans during cooling. This suggests that these fans are not needed and could be removed and replaced with several large openings. For this particular cooler the changes we have suggested could reduce fan energy use by as much as 50%.

But, high levels of heat input from sources other than the cooled commodity do not explain all of the poor efficiency of forced-air coolers. All of the forced-air coolers we studied also stored fruit for varying lengths of time. The strawberry cooler stored fruit after cooling for a few hours to a day. The pear cooler stored fruit for as long as one month, and the kiwi fruit cooler held fruit for up to six months. The data we presented were only for the time when cooling was actually being done, but the storage or temporary holding rooms were operating during this time and contributed to the overall energy use. Also, forced-air coolers are usually not turned off if there is no product to be cooled because of the need to keep the facility cool and ready for the next load. Vacuum coolers, water spray vacuum coolers, and hydrocoolers are usually shut down between loads.

Differences in energy coefficient among vacuum coolers are partially a result of not operating a cooler at full capacity and of the type of product cooled. For example, at one of the vacuum coolers we monitored, the EC for a fully loaded cooler averaged 3.0 (see Table 2). However, three out of the ten runs of the day had only a half load of product and operated with an average EC of 2.0. One run was a load of cauliflower which had an EC of only 1.0 because of the 1.8 hours required to cool cauliflower versus an average of 0.4 hours for lettuce. The net effect of these inefficiencies was an average EC of 2.1 for the entire day's cooling.

Thompson, Chen and Rumsey (1986), provide data to show that continuous operation of vacuum cooler refrigeration compressors, even when there is no demand for refrigerant, which is very common with equipment using screw compressors, can result in excess energy use. Some vacuum coolers are operated with reciprocating compressors and they are usually controlled so that as refrigeration demand decreases, equipment is turned off. Their data should show that coolers with this type of design would use at least 10% less energy than coolers with continuously operating compressors. A cooler managed to minimize energy use may achieve a monthly average energy coefficient close to the 2.5 maximum, but poor use of cooler capacity and poor operational techniques can lead to the 1.8 average for the vacuum cooling data seen in Figure 1.

Hydrocooling data indicated similar reasons for variation in EC results. Table 3 shows that for the two coolers tested, the first cooling run for the day had an average EC of about 0.6 because of the energy required to cool the large water reservoir before product cooling could begin. EC data for individual runs after initial water cooldown was much higher, ranging from 1.1 to 1.6. Hydrocoolers that cool only a few loads of product per day will have lower efficiencies than coolers that have many loads per day. However, the EC of the continuous flow cooler could have been increased even further if it had been operated at greater product throughputs. Each of the runs listed in the table lasted for only about one hour. During this hour, it was not completely full of fruit for the first 20 minutes as it was being filled and not completely filled for the last 20 minutes as it was being emptied. This caused an average product throughput of 45 bins of fruit per hour, when the cooler is capable of 80 bins per hour when operated in a fully loaded fashion. Therefore, heat inputs for water pumps, conduction, infiltration, condensation, and water leakage, that are a function of operation time, are spread over nearly half as many bins as they would have been if the cooler had been operating at full capacity. Variation in levels of product throughput could easily account for the range of hydrocooler EC data seen in Figure 1.

Inadequate insulation and excess water pumping capacity have also been identified as reasons for excess energy use in hydrocoolers. But nearly all the data in Figure 1 were from coolers built by one company and had similar levels of insulation and water pumping capacity.

Other causes for variation in EC data for coolers may be design and maintenance of refrigeration systems. We did not evaluate these for the operations we studied, but others (Hampson 1981) have discussed these in detail.

CONCLUSIONS

Operator records and field testing indicate that there is a wide range in energy efficiencies (as measured by an energy coefficient equal to cooling work done divided by energy purchased to operate cooler) between commercially operated fruit and vegetable coolers. Vacuum coolers have the highest levels of energy efficiency, followed in decreasing order by hydrocoolers, water spray vacuum coolers, and forced-air coolers. There is also significant variation among coolers of the same type. In fact, an inefficient vacuum cooler can have lower energy efficiencies than an efficient hydrocooler. Levels of non-product heat input was demonstrated to be a major reason for the difference between cooler types. Operational procedures such as using a forced-air cooler for product storage and not shutting down a cooler between cycles can also contribute to differences between cooler types.

Variability among coolers of the same type can be caused by 1) not using a cooler at maximum capacity, 2) type of commodity cooled in a vacuum cooler, (caulifower cools less efficiently than head lettuce) and 3) operational procedures (such as not turning off equipment between cooling cycles).

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TABLE 1

Distribution of Heat Input to Fruit and Vegetable Coolers

	Percent of Total Heat Input		
	Vacuum	Hydro	Forced Air
Product	100	54	47
Fans or Pumps	0	9	37
Infiltration, Startup, Conduction	0	37	7
Lift Trucks	0	0	8
Lights, People, etc	0	0	1

TABLE 2

Effect of Operating Conditions on Energy Coefficient of a Vacuum Cooler

	EC for Individual Runs	AVG.EC
Fully loaded retort (lettuce)	3.1, 2.2, 3.4, 3.1, 3.0	3.0
Half full retort (lettuce)	2.2, 2.2, 2.0	2.0
Fully loaded Retort (Cauliflower)	1.0	1.0
Daily average		2.1

TABLE 3

Energy Coefficient Data for Two Hydrocoolers

	Energy Coefficient					
	Run Number					Daily[1] Average
Cooler	1	2	3	4	5	
A (bath type)	0.55	1.2	1.1	1.3	---	1.0
B (continuous flow)	0.73	1.1	1.6	1.1	1.6	1.1

1/ Individual runs are weighted according to amount of cooling work done per run to determine daily average.

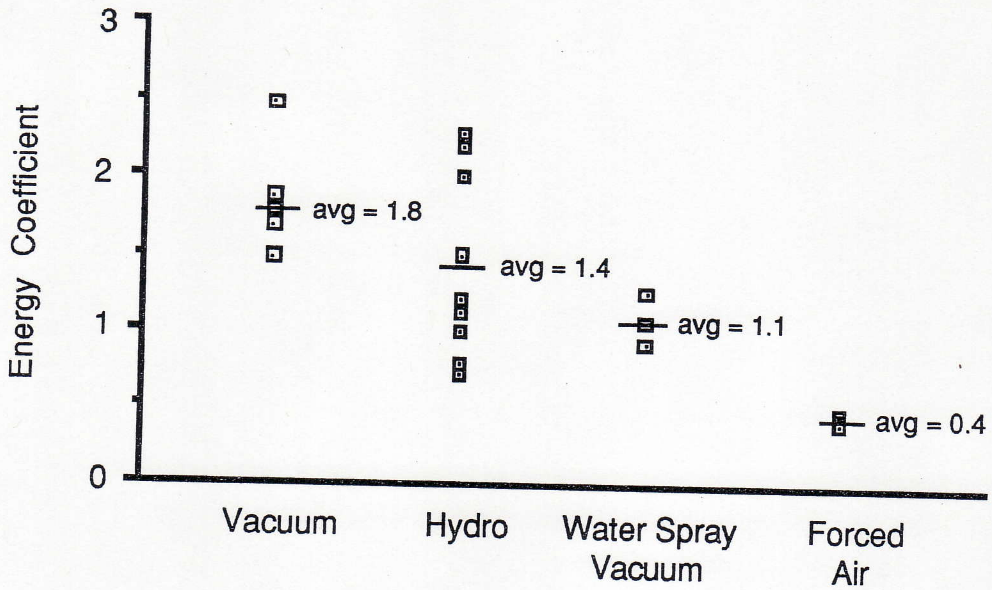

Figure 1 Energy coefficient data for four types of cooling systems

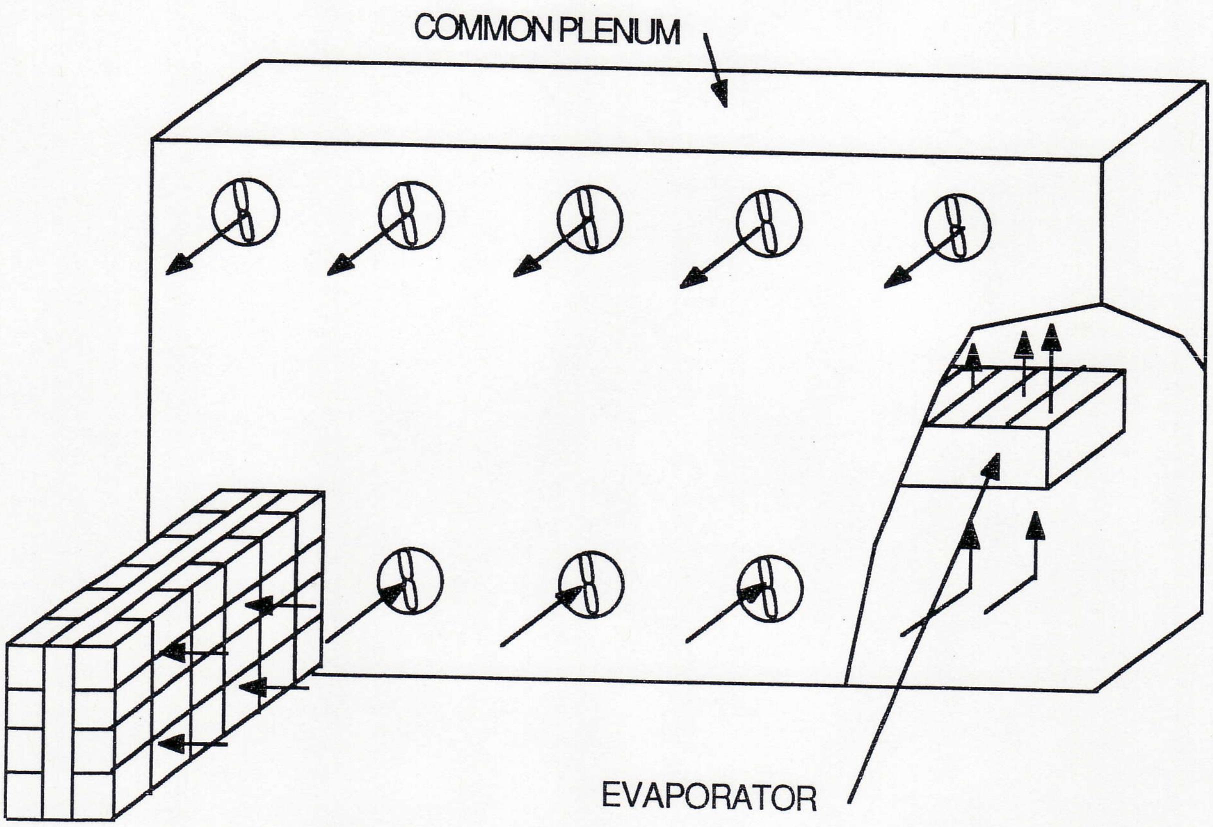

Figure 2 Schematic of forced-air cooler for kiwi fruit

Discussion

W.C. FAIRBANK, University of California, Riverside: For better vacuum cooling, why not shower the commodity with cold water before packaging to provide more moisture for evaporation?

J.F. THOMPSON: Water spray vacuum cooling uses this idea by wetting the commodity in the vacuum cooler just prior to cooling. It reduces product moisture loss and wilting but does require the use of a carton that will withstand being wetted.

E.G. PLETT, Carleton University, Ottawa, Ontario: Does the removal of moisture from fruit or vegetables in the vacuum cooling process degrade their quality, and to what extent is this tolerable?

THOMPSON: Vacuum cooling removes about 1 percent of product moisture for each ~~5.6°F~~ 5-6°C of temperature drop. This can cause unacceptable quality loss in some commodities, and these commodities are either cooled in a water spray vacum cooler or some other type of cooler. Iceberg lettuce is the largest volume of product cooled in vacuum coolers, and its quality is not significantly affected by vacuum cooling.