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TUNNEL FORCED - AIR COOLERS

Hugh W. Fraser P. Eng,

Introduction

This leaflet describes how to design, build, and manage a commercial-size tunnel forced-air cooler for 2 to 6 pallets of fresh fruits and vegetables at one time. A tunnel is formed by pallets of produce placed in pairs against a duct with a tarp pulled over the tunnel. See Figure 1. Some crops need to be cooled more quickly after harvest than others, so the design is important to ensure that the airflow per unit weight of product is suited to the crop needs used to help design smaller or larger systems as required.

Why Cool as Soon as Possible After Harvest?

All fresh horticultural crops are living organisms, even after harvest, and they must remain alive and healthy until they are either processed or consumed (Fraser, 1991). The energy needed to carry on living comes from the food reserves in the product itself. The process by which these reserves are converted into energy is called *respiration*. Heat energy is released during respiration, but the rate I varies depending on the type and variety of product, the level of maturity, the amount of injuries, and the product *temperature.*

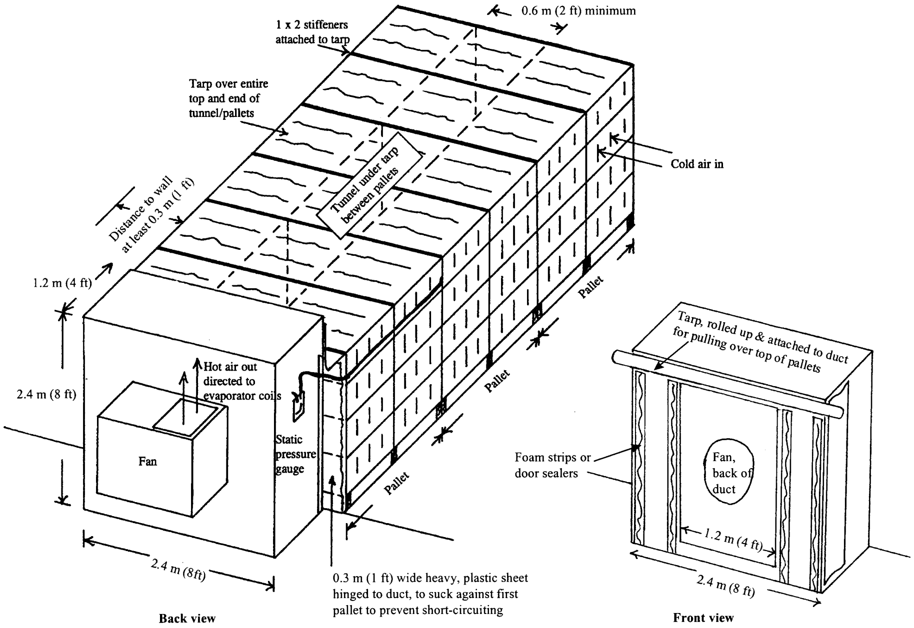


Figure 1. Schematic of back and front of a tunnel forced-air cooler for fresh fruits and vegetables in containers or pallets.

COMPLETE INSTRUCTIONS

The Canada Plan Service, a Canadian federal/provincial organization, promotes the transfer of technology through factsheets, design aids and construction drawings that show how to plan and build modern farm structures and equipment for Canadian agriculture.

For more information, contact your local provincial agricultural engineer or extension advisor.

Produce temperature has the greatest influence on respiratory activity. Rapid, uniform cooling as soon as possible after harvest to remove the *field heat*, is critical in lowering the respiration rate. This reduces the rate of deterioration, and helps provide a longer shelf-life. A rule of thumb is that a *one-hour delay in cooling reduces a product's shelf-life by one day*. This is not true for all crops, but especially for very highly perishable crops during hot weather.

Lowering the temperature also reduces the rate of ethylene production, moisture loss, spread of microorganisms, and deterioration from injuries.

How is Forced-Air Cooling Accomplished?

Forced-air cooling is just one method of quickly removing field heat from freshly picked produce. Most fresh fruits and vegetables can be forced-air cooled. High capacity fans are used to pull refrigerated air through the produce. Rapid and uniform cooling results, from the forced-convective contact of the high-speed, refrigerated air with the warm produce. This is different from room cooling, where produce is simply placed in a cold storage room and cools slowly and non-uniformly, mainly through conduction and the natural convective contact with refrigerated air.

Pulling air, rather than *blowing* it through is preferable since it is easier to minimize air short-circuiting and it results in more uniform cooling. Short-circuiting occurs if refrigerated air flows directly to the fan instead of going through the produce mass. Air will not flow as uniformly if it is pushed, as it will if it is pulled through the produce. With proper container design and orientation, produce can be rapidly and uniformly cooled in baskets, boxes, bins, or bags. Forced-air cooling simply does a better job with the refrigerated air in the cold storage.

Although more costly, it is better to provide a dedicated forced-air cooling room, then move the produce to a longer term storage. Most cold storages used for forced-air cooling will rise in temperature after each fresh batch of warmer produce is added. If this temperature rise is great because of an undersized refrigeration system, cold produce already in the room would sweat and increase in temperature. Both situations are unacceptable. A good compromise is to form a forced-air cooling area by partitioning part of the storage using tarp suspended from the ceiling. This helps reduce temperature fluctuations, but should be considered as a temporary measure.

7/8 Cooling Times

All fruits and vegetables cool quickly at first, then more slowly over time. Factors that affect the rate of forced-air cooling include:

- density of produce in the container (the less dense the produce pile, the faster is cooling);
- container type, orientation, and ventingcharacteristics (if air passes uniformly and evenly by the produce, cooling is faster);
- volume to surface area of produce; the lower the ratio, the faster is cooling (cherries cool quicker than melons);
- travel distance of the cooling air (the shorter the distance, the faster is the cooling of the overall pile);
- airflow capacity (the higher the airflow, the faster is cooling).

The relative humidity of the cooling air has little affect on moisture loss, if it is above 85% and the cooling period is under 1 to 2 hours.

Regardless of the temperature of the cooling air or the starting temperature of the produce, the shape of the cooling curve remains the same, providing all the other factors listed above are kept constant. Only the rate of cooling changes.

The *7/8 cooling time* is a standard industry term that describes the time to remove seven-eighths (87.5%) of the temperature difference between the starting produce temperature and the temperature of the cooling medium (refrigerated air, in the case of forced-air cooling). It is a convenient method of indicating when produce has come as close as practical to the temperature of the cooling medium. Forced-air cooling should start as soon as practical after harvest, preferably within 1 hour. Don't let produce accumulate before putting it on the forced-air cooler, otherwise it will lose quality and shelf-life. The *7/8 cooling time* is measured from the time the produce is first placed on the forced-air cooler. See Figure 2.

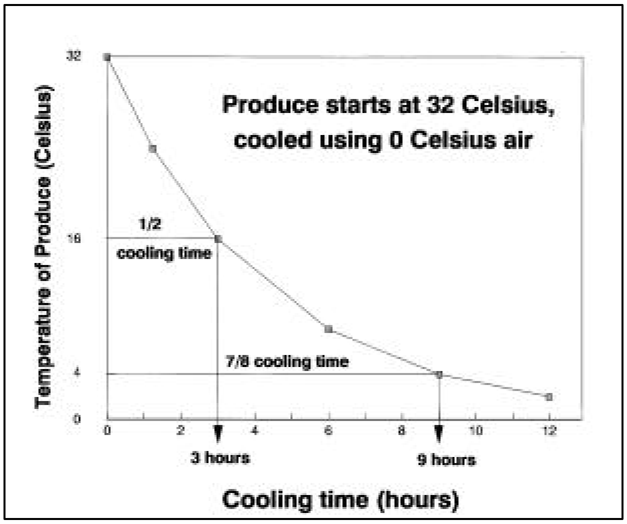


Figure 2: Typical time-temperature relationship for produce

For example, if a 32^{o}C peach cooled using 0^{o}C air reaches 4^{o}C in 9 hours, the *7/8 cooling time* is 9 hours. That is, a 28^{o}C temperature drop out of 32^{o}C difference between the produce and air. The *7/8 cooling time* is theoretically three times as long as the *1/2 cooling time*. So, the same peach that took 9 hours to cool to 4°C above, would take only 3 hours to reach 16°C, the temperature at the *1/2 cooling time*, if everything else remained the same. In practice, the *7/8 cooling time* is usually different than three times the *1/2 cooling time* because conditions rarely remain exactly the same over the forced-air cooling period.

Sometimes one can estimate when a product will be *7/8 cool* by knowing other cooling times. Table 1 lists some other relationships.

Table 1: Relationships to 7/8 cooling times

If you know this cooling time…	**…then multiply by the following to estimate the *7/8 cooling time***
1/4 cool time	7.25
3/8 cool time	4.4
1/2 cool time	3
3/4 cool time	1.5

For some crops, it might not be necessary to operate the forced-air cooler at temperatures as low as the optimum holding temperature for the produce. For instance, some produce might be forced-air cooled 5°C, then slowly room-cooled in an adjacent holding room. This compromise could eliminate the need to have a refrigeration defrosting system in the forced-air cooling room.

What Products Can Be Forced-Air Cooled?

Most produce can be forced-air cooled, but the *7/8 cooling time* should be shorter for some produce that have special needs:

- have high respiration rates at harvest;
- lose moisture easily (berries/leaf vegetables);
- are quite mature such as tree ripened peaches;
- are shipped to distant markets.

Table 2 lists produce requiring quick cooling and suggested *7/8 cooling times* and airflows.

Crops with very high perishability

These crops all have very high respiration rates at harvest temperatures, and lose moisture rapidly after harvest. They *must* be rapidly cooled as soon as practical after harvest, or they will have little or no shelf-life. Some of these crops are more traditionally hydrocooled, iced, or vacuum cooled. However, all of them can be forced-air cooled, providing cooling is done quickly with high airflow rates and high relative humidity air to reduce the danger of drying them out. It is recommended that airflow rates of at least 2 to 6 L/s/kg of produce (*2 to 6 CFM/lb*) be used, attempting to have *7/8 cooling times* of no more than 45-90 minutes. These products must be monitored for signs of drying out. Sprinkling water on them before forced-air cooling (except mushrooms) might be helpful. Do not run the forced-air cooler any longer than necessary.

Crops with high perishability

These crops have high respiration rates at harvest temperatures, and/or lose moisture rapidly, but it is not as critical to cool these products as rapidly as the ones listed previously. Experience has shown growers that these products *should* be forced-air cooled as quickly as practical after harvest. Watch for signs of the products drying out. Airflow rates of at least 1 to 3 L/s/kg of product *(1 to 3 CFM/lb)* should be used, with *7/8 cooling times* of no more than 1 to 3 hours.

Table 2: Relative perishability of fresh fruits and vegetables and recommended 7/8 cooling times and airflows

Relative Perishability of Crops	**Crop**	**7/8 Cool Time (hr)**	**[b]Airflow L/s/kg *(CFM/lb)***
Very High	[a]Asparagus, [a]broccoli, [a]leaf lettuce, [a]spinach, [a]sweet corn, mushrooms	0.75-1.5	6 - 2 (6 - *2*)
High	Blueberries, raspberries, strawberries, sweet cherries, cauliflower, snap beans, head lettuce	1-2.5	4 - 1.25 (*4 - 1.25*)
Moderate	Apples (early), cabbage (early), cantaloupes, [a]celery, peaches, plums, peppers, summer squash	2-6	1.5-0.5 (*1.5-0.5*)

[a] Sprinkling water on the produce, or misting the cooling air before it enters the produce containers could be of benefit.

[b] Higher airflows are shown first to correspond with faster 7/8 cool times.

Snap beans should only be cooled to about 4°C to 7°C *(40°F to 45°F)*, depending on the cultivar. Otherwise, they are susceptible to chilling injury. Avoid forced-air cooling them with refrigerated air below 4°C. Try to cool snap beans in less than 3 hours if possible. Snap beans are often washed after harvest, so a side-benefit of forced-air cooling is the drying effect of the airflow.

Crops with moderate perishability

Although these crops are less perishable than those already listed, it is still *recommended* that these crops be rapidly cooled as soon as practical after harvest. The shelf-life will be improved. Airflow rates of at least 0.5 to 1.5 L/s/kg of produce *(0.5 to 1.5 CFM/lb)* and *7/8 cooling times* of no more than 3 to 6 hours are suggested.

Cantaloupes and summer squash are sensitive to chilling injury, so avoid forced-air cooling them with very cold refrigerated air. Cantaloupes should be cooled to about 2^{o}C to 5^{o}C *(34^{o}F to 41^{o}F)*, while summer squash should be cooled to about 7^{o}C to 10^{o}C *(45^{o}F to 50^{o}F).*

What Are Forced-Air Cooler Components?

There are four components to a forced-air cooler:

- Fan and duct system;
- Foam/tarp/plastic to prevent short-circuiting ;
- Refrigeration system;
- Monitoring equipment.

Fan and duct system

The fan powers the forced-air cooling system. Its airflow is measured in litres of air per second, L/s, *(cubic feet of air per minute or CFM)* based on its type (axial or centrifugal); its design (blade type and orientation); the difficulty in pulling the air through the produce (static pressure); the motor size (horsepower or Watts); and the revolutions per minute (RPM) of the fan blades.

Fans should be selected based on the airflow they produce at a given *static pressure* between the inlet and outlet of the fan. For most forced-air cooling systems, static pressures range from about 15 to 25 mm *(0.6-1.0 inches)* of water gauge. Both centrifugal (squirrel-cage or furnace-type) and axial-flow (propeller) fans can be used for forced-air cooling. Many forced-air coolers in Canada use centrifugal fans because of the availability of used equipment, and because they are quieter to work around. See Figure 3.

Figure 3: Centrifugal, squirrel-cage, or furnace-type fan often used for forced-air cooling

Many growers find used centrifugal fans for their forced-air coolers, but it is difficult to establish the airflow rates for them. However, for *planning purposes only,* use Table 3 to help *estimate* the capacity of these fans.

Table 3: Approximate airflow ranges in L/s *(CFM)* of centrifugal fans (standard RPM drive range; one-way entry)

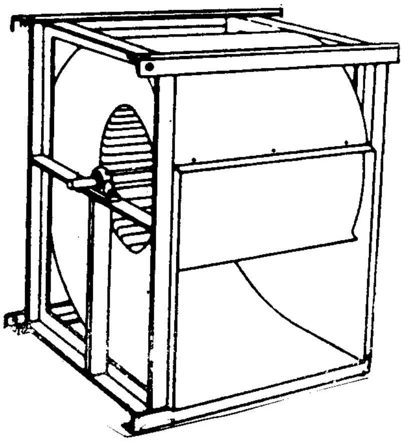
Motor size kW *(hp)*	**Approximate airflow, L/s (CFM) at the indicated static pressure**	
	12 mm *(0.5 in)*	25 mm *(1 in)*
0.37 *(.5)*	1125-1225 *(2400-2600)*	-
0.75 *(1)*	1700-2450 (3600-5200)	1275-1500 *(2700-3200)*
1.1 *(1.5)*	2025-3075 *(4300-6525*	1650-2275 *(3500-4800)*
1.5 *(2)*	2175-3550 *(4600-7525)*	1925-2825 *(4100-6000)*
2.25 *(3)*	2500-4250 *(5300-9000)*	2300-3575 *(4900-7600)*
3.75 *(5)*	3250-5200 *(6900-11000)*	3075-4750 *(6500-10000)*

Predicting the static pressure a forced-air cooling fan must operate against is difficult. It is affected by the airflow, amount of air entry area on container sides, vent alignment, distance the air must travel through the produce, density of the produce in the containers, and any ducting restrictions for the air. For most systems, fans should be selected based on a maximum static pressure of 25 mm *(1 in)* water gauge.

There are many fan types and models. Smaller centrifugal fans need larger motors running at higher RPM, to obtain the same airflow as larger centrifugal fans. In general, larger fans with smaller motors are more efficient. Choose them to keep operating costs, noise, wear, and heat loads on the refrigeration system to a minimum. This allows flexibility to install a larger motor in future to provide higher airflow rates if needed.

Any air supply areas (outside of pallets) or air return (tunnel) areas should be designed to keep airspeeds under about 5 m/s *(1000 ft/min)*. This means providing at least 1 m^2 of cross-section for every 5000 L/s of airflow *(1 ft^2/1000 CFM).* Smaller openings will restrict airflows, make the fan work harder, cause air to short-circuit near the fan, and cause uneven cooling.

To determine the minimum air supply area sizes and cross-sectional dimensions of the tunnel, suppose a forced-air cooling system is designed to cool 2250 kg *(4950 lbs)* of produce on 6 pallets, with an airflow of 4500 L/s, or 2 L/s per kg *(9530 CFM or 1.9 CFM/lb).* See Figure 1. The pallets are 1.2 m *(4 ft)* wide and 1.5 m high *(5 ft).* The equation for airflow is:



$$Q = A \times V \qquad \text{or,} \qquad A = Q \div V$$

where, Q, is the airflow rate, L/s *(CFM)*
A, is the cross-sectional area perpendicular to the airflow, m^2 *(ft^2)*
V, is air velocity, m/s *(ft/min)*

The airflow is 4500 L/s (or 4.5 m^3/s), so all cross-sectional areas should be a minimum of:

$$A = 4.5\ m^3/s \div 5\ m/s = 0.9\ m^2$$
$$(A = 9530\ CFM \div 1000\ ft/min = 9.5\ ft^2)$$

So, if the pallets are 1.5 m high *(5 ft),* the tunnel should be at least:

$$W = 0.9\ m^2 \div 1.5\ m = 0.6\ m\ \text{wide}$$
$$(W = 9.5\ ft^2 \div 5\ ft = 1.9\ ft\ \text{wide})$$

For practical reasons, the tunnel should not be less than 0.6 m *(2 ft)* in width.

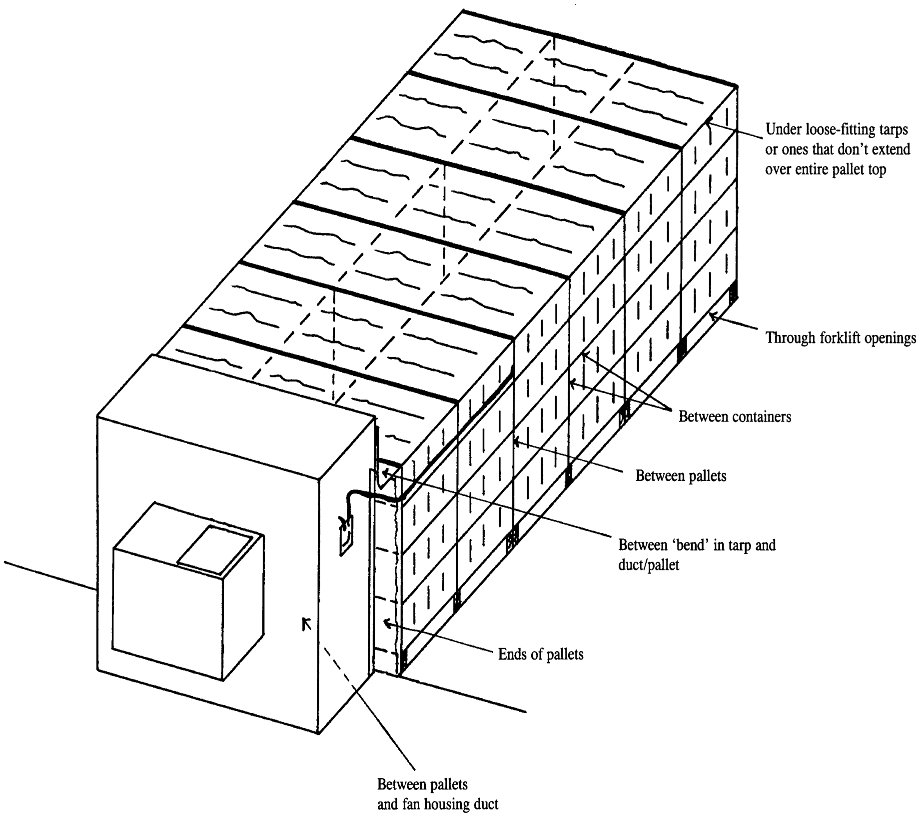
The cold air supply gap between the outside of the pallets and a wall or pallets on another adjacent forced-air cooler, must also be wide enough to allow cold air to enter easily. For practical reasons, this gap should be at *least* 0.3 m *(1 ft),* or more so that someone can walk down the gap to check things out. Unless airflows are extremely high, this width is plenty wide enough to allow air to flow freely into the pallet sides.

For most applications minimum dimensions should be:

- tunnels; 0.6 - 1.2 m wide *(2 - 4 ft;)*
- gaps to walls; 0.3 - 0.6 m wide *(1 - 2 ft);*
- gaps to adjacent units; 0.6 - 1 m *(2 - 3 ft)*

The dimensions of the plywood fan housing duct should be 2.4 m *(8 ft)* wide and 2.4 m *(8 ft)* high to accommodate various pallet sizes and heights. It should also be 1.2 m *(4 ft)* deep from front to back, to help create more uniform airflow, and to help stabilize the duct, considering the weight of the fan on the back side of the duct. The opening into the front side of the duct for the return air to the fan should be centred, be 1.2 m *(4 ft)* wide, and be as high as possible on the fan housing duct. See Figure 1.

Most forced-air coolers used in Canada operate with airflows in the range of 0.5 to 6 L/s/kg of product being cooled *(0.5 to 6 CFM/lbs).* Higher airflow rates may reduce the cooling time, but doubling the airflow rate does <u>not</u> cut the time in half. It is very important to understand that *higher airflows do not necessarily mean the product will always cool quicker, since adequate refrigeration and prevention of short-circuiting are usually more critical.* Also, it may be impractical to operate with very high airflows, since the fans might need to be extremely large. There are reports of situations where very high airflows have caused such high static pressures that tarps have been pulled into the tunnnel. Regardless of how small the airflows, any amount of



refrigerated air properly pulled through the produce will dramatically reduce cooling times compared to simple room cooling.

Foam/tarp/plastic to prevent short-circuiting

One of the most important, but most often overlooked requirements of a good forced-air cooler is the method used to prevent short-circuiting of the cooling air. Air always takes the path of least resistance, so even small cracks must be plugged. It doesn't take much of a hole to reduce airflows through the mass of produce. A well designed, tight system may have at least 10% of its air short-circuiting (Thompson, 1996). Poorly designed and operated systems could have most of their air short-circuiting.

There are many locations for air to short-circuit (see Figure 4):

- forklift openings;
- shipping containers that do not fit tightly on the sides or top, or to the pallet dimensions;
- where pallets fit against the forced-air cooler;
- between the top containers on a pallet and a loose-fitting tarp.

To demonstrate the problem of short-circuiting, consider the previous example in Figure 4. Cooling air can enter the tunnel only via the outside face of the containers, an area of:

1.5 m x 1.2 m x 3 pallets/side x 2 sides = 10.8 m^2
(5 ft x 4 ft x 3 x 2 = 120 ft^2)

The tunnel area required was previously calculated to be about 1.0 m^2 *(10.5 ft^2).* Thus, a short-circuit leakage area of only 10% would supply all the necessary return air area. Little air would pass through the produce, which already has a higher resistance to air flow. The 6 pallet forklift openings alone have a combined opening of about 0.12 m^2 *(1.5 ft^2)* This is why it is important to seal off any and all leakage paths.

Heavy plastic or canvas tarps must be pulled over the produce containers to help force the cooling air to travel uniformly in one direction through the produce. Heavy foam strips or door sealers are often installed on the front of the fan-housing duct to press the first pair of pallets against, creating an effective air seal. See Figure 1. *The importance of checking for air leaks after construction cannot be stressed enough.*

For pallet systems, the ideal shipping containers to forced-air cool are ones that stack tightly on all sides and fill out the entire footprint of the pallet. Figure 5 compares a straight-walled container that fits on all six sides, top and bottom like *LEGO*™ blocks with those that have tapered-walls and don't fit tightly on the tops and bottom. For tapered-walled containers, air short-circuits through the tapered areas rather than through the produce, even if the taper angle is very slight (Vigneault & Goyette, 1995). For straight-walled containers that fit tightly on the sides and top, air must travel through the produce, resulting in quicker, more uniform cooling. More specifically, the ideal containers to forced-air cool have vents that are:

- 25% of the area perpendicular to the airflow direction (Vigneault & Goyette, 1995)
- evenly distributed;
- lined up along the cooling path;
- long slots rather than round holes to prevent plugging with produce;
- unrestricted by liners, trays, pack materials.

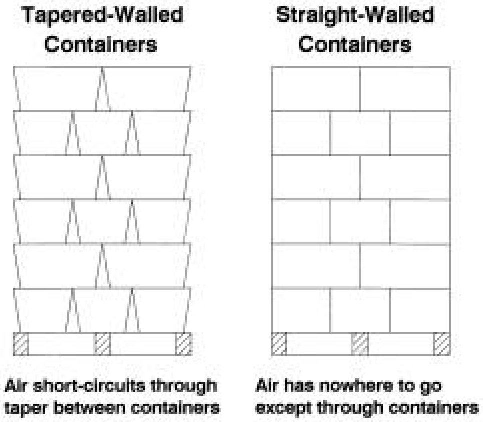


Figure 5: Containers should fit tightly on all sides, be vented to provide uniform airflow, and fit the pallet footprint, usually 1.2 m x 1.0 m *(48 x 40 in)*

A $50 static pressure gauge, or manometer (Figure 6) assists in determining how much short-circuiting is occurring. The low pressure tube should be installed inside the tunnel between the pallets as far as possible from the fan (Boyette, 1994). See Figure 1. The high pressure tube should be installed in the normal airflow of the cold storage room. For most applications, the difference should measure about 12 mm *(0.5 in)* static pressure of water column. This measures the load that the fan must work against to pull the air through. By plugging short-circuiting holes, the static pressure will rise, indicating that the fan is working harder to pull the air through the produce and ensuring that cooling air is travelling through the containers and not around them.

Common methods of preventing short-circuiting are; foam or door seals between the pallets and the forced-air cooling unit; corrugated cardboard or plastic strips between pallets and on the ends of them or on forklift

Figure 4: Plugging up locations where air can short circuit is critical with a forced-air cooler

openings that are sucked into place by the air pressure; or cushioned floor bumpers that pallets butt up against to prevent short-circuiting through the forklift openings.

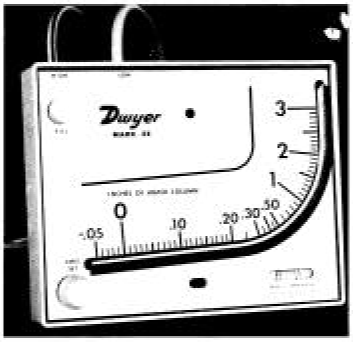


Figure 6: A manometer can help find air short-circuiting locations

Refrigeration System

There is an old saying that *you can never have too much refrigeration* in a cold storage. This certainly applies for forced-air cooling systems. Because cooling commences immediately after produce is placed on the unit, and the slope of the cooling curve is so steep initially (Figure 2), the amount of refrigeration required right at the beginning of cooling is enormous. It is often much more than most growers can afford, or need. The formula for the *refrigeration* in kilowatts, kW, *(Btu/h)* needed at any time is adapted from the formula for the *momentary* cooling rate (Mitchell et al, 1972):

kilowatts needed *(Btu/hr)* = 2.1 x (A-B) x C x D ÷E

A = Temperature of produce, °C *(°F)*
B = Temperature of cooling air, °C *(°F)*
C = Weight of produce being cooled, kg *(lbs)*
D = Specific heat of produce, usually about
3.77 kJ/kg/ °C *(0.9 Btu/lb/°F)*
E = 7/8 cooling time (h)

In the previous example, what cooling capacity is required to cool 2275 kg *(5,000 lbs)* of strawberries from 28°C *(82°F)* to 3.5°C *(38°F)* in 2 hours, using 0°C *(32°F)* cooling air (*7/8 cooling time* of 2 hours)?

Using the formula above, the *momentary* refrigeration at the beginning of cooling (worst case scenario) would be:

2.1 x (28°C-0°C) x 2275 kg x 3.77 kJ/kg/°C ÷ 2 h = 252,150 kJ/h, or 70 kJ/s or 70 kW
2.1x (82°F-32°F)x 5000 lbs x 0.9 Btu/lb/°F ¸ 2 h = 236,250 Btu/h

This is almost 20 tons of refrigeration! There are 3.5 kW *(12,000 Btu/hr)* in a ton of refrigeration, a term used by industry. Most growers cannot afford to design for the worst case. However, if they learn to accept that the temperature of the room will rise slightly initially when produce is placed on the forced-air cooler, but that it will gradually recover, they can design with lower refrigeration levels. With good management, the suggested rule of thumb is to design for about 2/3 of the *momentary* maximum refrigeration rate at the beginning of cooling;

70 kW x 2/3 = 47 kW

(236,250 Btu/h x 2/3 = 157,500 Btu/h)

This is about 13 tons of refrigeration *over and above* the amount required for heat loads produced elsewhere in the storage such as through doors, walls and ceiling. The produce heat load would likely represent at least 80% of the total heat load in the storage.

Unless the system is designed for it, do not duct the warmed air from the forced-air cooling fan directly to the evaporator coils, or the cold air from the evaporator coils directly to the pallets being forced-air cooled. In most cases, the evaporator coils and fans were not designed for this application. When using a forced-air cooling system in a room used for holding produce that is already cooled, direct the exhaust air from the forced-air cooling fan away from any produce, and towards the evaporator coils.

The relative humidity of the cooling air in the forced-air cooling room should be greater than 85% to help prevent wilting of the produce. This means large evaporator coil cooling surfaces, and small temperature drops across the cooling coils. If a cold storage room is kept at 0°C *(32°F),* and the evaporator cooling coils are sized too small, the air coming off the coils will be several degrees below freezing. This dries out the air and keeps the relative humidity in the room too low for fresh fruits and vegetables. The produce could be damaged through chilling if this air is not allowed to warm up slightly in the room first, before being drawn through the produce by the forced-air cooler.

It is important to keep the cooling air as close as possible to the set point temperature, especially near the end of the forced-air cooling period. If the air rises a few degrees, the product could stop cooling and even rise in temperature. This points out the need to have separate forced-air cooling rooms, with plenty of refrigeration capacity.

Some refrigeration systems such as the *Filacell System*, are specifically designed with forced-air cooling in mind. It has high capacity fans that can handle high static pressures, while providing very high humidity. Consult a refrigeration contractor on the options available.

Monitoring equipment

Monitoring equipment can help manage the forced-air cooler. Some of the important pieces of management information are the:

- starting temperature of the produce;
- desired ending temperature of the produce;
- maximum time that produce can be forced-air cooled

All of these issues are more critical for first-time users of a forced-air cooler.

The internal temperature should be taken on a few pieces of produce on the pallet before placement on the forced-air cooler. This means probing the centre of the produce with good temperature measuring equipment that give an instantaneous digital readout. The produce temperature may not be the same as the surrounding air temperature. Large produce such as cantaloupe or cabbage will take longer to warm up (or cool down) than smaller produce such as plums, even if the surrounding air temperature is rising (or falling) rapidly. For example, the outside air temperature at mid-morning may be higher than the temperature of the peaches still on the tree because they may still be cool from the night before, or because of leaf shading. Conversely, strawberries may be hotter than the air temperature if the sun is beating down on their dark colouring. Also, produce on the top of a bin, basket, or box may be warmer than produce buried underneath because of direct sunlight, or heat conducting from a hot, dark container.

Most operators know at what temperature they want their produce stored. Unfortunately, when things get busy at harvest, produce sometimes cannot stay on the forced-air cooler as long as necessary. However, by knowing the starting temperature of the produce, operators can make better judgements about what temperature the produce will be after a period of time on the forced-air cooler.
It is difficult and time-consuming to monitor the temperature of the produce as it is cooling. However, one way of estimating the actual temperature of the produce at any time is to monitor the temperature of the exhaust air from the forced-air cooling fan, then compare it to the temperature of the cooling air in the room as it enters the pallet. The exhaust air, will be about midway between the cooling air entering the pallet and the produce temperature at that time.

If the cooling air in the room entering the pallet is at 2^{o}C, and the exhaust air from the forced-air cooling fan is at 10^{o}C, the produce would be at about 18^{o}C, since 10^{o}C is midway between 2^{o}C and 18^{o}C. Produce that feels the cold air first will cool more quickly than produce that is downstream, because downstream produce feels warmer air. If there is a lot of short-circuiting of air, this method of monitoring is <u>not</u> reliable, since more cold air would make its way to the fan, lowering the exhaust air temperature, and giving the operator a false sense of the cooling progress.

A thermostat can be placed in the exhaust air from the forced-air cooling fan to either shut it off when the airflow reaches a certain temperature, or slow it down if it is a variable speed fan. This can help prevent running the equipment longer than needed, saves on electrical power, and prevents needless adding of heat from motors in the cold storage. A timer to turn off the fan after a period of time could be installed, if appropriate.

10 Steps to Designing a Forced-Air Cooler

1. Determine average day's production, kg *(lbs)*
2. Determine heavy day's production, kg *(lbs)*
3. Determine available cooling time (hours/day)
4. Establish number of batches (batches/day)
5. Calculate size of batch, kg/batch *(lbs/batch)*
6. Pick an airflow rate, L/s/kg *(CFM/lbs)*
7. Calculate fan airflow rate, L/s *(CFM)*
8. Calculate peak refrigeration, kW *(Btu/hr)*
9. Use *2/3 refrigeration rule*, kW *(Btu/hr)*
10. Determine tunnel width & gap to wall, m *(ft)*

Case study

A grower has 4 ha *(10 ac)* of strawberries, and picks 3000 masters/ha *(1200 masters/ac)* at 6 kg/master *(13.2 lbs/master)* over a 25 day harvest season. Pallets hold 64 masters, are 1.5 m high *(5 ft),* and weigh 384 kg *(845 lbs)*. Picking is from 6:00 a.m.-12:00 noon, with berries at an average of 25^{o}C *(77^{o}F)*. The cold storage is at 0^{o}C *(32^{o}F)*. Determine the size of fan, extra refrigeration needed and the width of the tunnel and gaps.

1. Determine average day's production, kg (lbs)

4 ha x 3000 masters/ha x 6 kg/master ÷ 25 d =
2880 kg/d

10 ac x 1200 masters/ac x 13.2 lbs/mast ÷ 25 d =
6340 lbs/d

2. Determine heavy day's production, kg (lbs)

The daily harvest could probably range all the way up to 10000 kg picked (22000 lbs). It is unrealistic to design for the busiest day of the season, but one rule of thumb is to design for a *typical heavy* day, which is often *twice the average day.* So;

2880 kg/ave.day x 2 = 5760 kg/typical heavy day
(6340 lbs/ave.day x 2 = 12680 lbs/typical heavy day)

3. Determine available cooling time (hours/day)

Picking is from 6:00-12:00 noon, or 6 hours. The earliest berries to go on the forced-air cooler would be at about 7 a.m., with berries arriving at the cold storage continually after that until 12:00 noon. Forced-air cooling can proceed as long as necessary after 12:00 noon, so estimate the available cooling time as *6 hours*, from 7:00 a.m. to 1:00 p.m. The last berries picked are generally the hottest berries picked, so they can stay on the forced-air cooler longer, if necessary.

4. Establish number of batches (batches/day)

From Table 2, it is reasonable to want a *7/8 cooling time* of 1.5 hours for strawberries, so:

6 hrs available/day ÷ 1.5 hr/batch = 4 batches/day

5. Calculate size of batch, kg/batch (lbs/batch)

5760 kg/day ÷ 4 batches/day = 1440 kg/batch
(12680 lbs/day ÷ 4 batches/day = 3170 lbs/batch)

This would be 240 masters/batch, or 4 pallets.

6. Pick an airflow rate, L/s/kg (CFM/lbs)

From Table 2, a *7/8 cooling time* of 1.5 hours corresponds approximately to an airflow rate of 2.0 L/s/kg of produce *(2 CFM/lbs).* The higher the airflow, the quicker the cooling time, and the lower the airflow, the slower the cooling time. Predicting the *7/8 cooling time* is difficult, since it depends on so many variables.

7. Calculate fan airflow rate, L/s (CFM)

2.0 L/s/kg x 1440 kg/batch = 2880 L/s (2.88 m^3/s)
(2.0 CFM/lbs x 3170 lbs/batch = 6340 CFM)

Table 3 suggests a centrifugal fan with a 2.25 kW motor *(3 h.p.)* would suffice. Otherwise, ask a fan supplier for a fan that will deliver at least 2880 L/s at a static pressure of 25 mm *(6340 CFM at 1 inch static pressure)*

8. Calculate peak refrigeration, kW (Btu/hr)

2.1 x (25°C-0°C) x 1440 kg x 3.77 kJ/kg/°C÷1.5 h
= 190000 kJ/hr or 53 kJ/s or 53 kW or 15 tons

2.1x(77°F-32°F)x3170 lbs x0.9 Btu/lb/°F ÷1.5 hr
= 179750 Btu/hr or 15 tons refrigeration

This is for cooling the berries, not the room itself!

9. Use 2/3 refrigeration rule, Watts (Btu/hr)

15 tons of refrigeration is a lot for a forced-air cooler with 4 pallets of berries at one time. So:

53 kW (theory) x 2/3 = 35 kW (practical); 10 tons
179750 Btu/hr x 2/3 = 119,800 Btu/hr; 10 tons

10. ***Determine tunnel width & gap to wall, m (ft)***

2.88 m^3/s ÷ 5 m/s max airspeed=0.58 m^2 min area

6340 CFM ÷ 1000 ft/min max = 6.34 ft^2 *min area*

With pallets 1.5 m high *(5 ft)*, the tunnel width must be a minimum of 0.58 m^2 ÷ 1.5 m = 0.4 m, however a practical minimum is 0.6 m *(2 ft).* The gap to wall would also be the minimum 0.3 m *(1 ft)* to allow an operator to squeeze down the gap.

Other Considerations

- The tarp over the tunnel should extend to the top outer edge of the pallets as possible, and all the way to the floor at the end of the pallet row to prevent short-circuiting of air
- Stiffeners in the tarp are needed to prevent it from being sucked into the tunnel
- Check for air leakage using cellophane that will suck into uncovered holes
- The fan should be centred in the duct so as to draw as evenly as possible from the tunnel.
- Large batches harvested early in the day represent a similar heat load to small batches harvested later the same day
- Empty containers and harvested product should be covered with tents or awnings in the field to minimize heat gain
- As the day heats up, reduce the time that product sits in the field before being cooled.

This leaflet was reviewed by:

- Bert Van Dalfsen, P.Eng., British Columbia Ministry of Agriculture, Fisheries and Food
- Dennis Darby, P.Eng., Alberta Agriculture

Don Allen, P.Eng., D.A. Allen Engineering Services, Nova Scotia

- Florent Mercier, P.Ing. Université Laval, Québec

Clément Vigneault, Ph.D., P.Eng, Agriculture and Agrifood Canada

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