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1 Transportation of fresh horticultural produce

Clément Vigneault[1], James Thompson[2], Stefanie Wu[1]
K.P. Catherine Hui[3] and Denyse I. LeBlanc[4]
[1]Agriculture and Agri-Food Canada, Horticultural Research and Development Centre, 430 Gouin, Saint-Jean-sur-Richelieu, Québec, Canada J3B 3E6
[2] Biological and Agricultural Engineering Department, University of California Davis, Davis, California, 95616 USA; [3]University of Saskatchewan Department of Agricultural and Bioresource Engineering, 57 Campus Drive Saskatoon, Saskatchewan, Canada S7N 5A9; [4]Agriculture and Agri-Food Canada, Atlantic Food and Horticulture Research Centre, Université de Moncton, Moncton, New Brunswick, Canada, E1A 3E9

Abstract

Most fresh produce is transported from the packing facility to the local grocery store in refrigerated vehicles. Highway trailers are the primary means of transportation for perishables produced in North America while air freight or marine containers are used for off-shore produce. With all three modes of transport, produce is susceptible to a loss of quality.

Correspondence/Reprint request: Dr. Clément Vigneault, Agriculture and Agri-Food Canada, Horticultural Research and Development Centre, 430 Gouin, Saint-Jean-sur-Richelieu, Québec, J3B 3E6, Canada.
E-mail: vigneaultc@agr.gc.ca

Factors affecting produce quality and systems for preserving this quality during transport are presented. Physical and structural characteristics needed for produce transport vehicles and management of produce transport systems are also discussed.

1. Introduction

In 1992, world trade in fruits was estimated at 25 million tons, approximately 12% of total annual production [1]. The domestic and international trade in fresh produce exceeded 70×10^9 US$ annually [2]. Consumers are expecting improved produce quality from their retailers as well as a wider variety of fresh fruits and vegetables. The globalization of fresh produce trade is creating a need for better long distance transportation systems and handling methods to preserve produce quality.

During transport, produce is rarely held under optimum environmental conditions; approximately 40% of the vegetables never make it to the supermarket shelves due to damage during transit [3]. This produce loss can only be reduced by improved refrigerated transport. According to the same authors, packing and shipping of produce in temperature-controlled containers could reduce the spoilage to about 5% [3]

Temperature is the main environmental condition influencing produce quality. Excessively low temperature causes chilling or freezing injury [4]; and high temperature accelerates produce respiration and water loss, and causes a decrease in internal flesh quality, shriveling and premature softening. Other factors affecting produce quality are: initial quality, environmental humidity and water loss, atmospheric gas concentration, mixed loads, physical injury and stress and transport conditions (surface road conditions, time of the day…).

2. Factors affecting produce quality during transport

2.1. Initial quality

Produce leaving the packing facility must be suited to the handling it will receive as it is transported to market. Locally produced fruits can be fairly mature and ripe because the time to market is short. Produce shipped from great distances is often a little less mature than locally produced produce and must be free of mechanical damage and other conditions predisposing it to noticeable quality loss in a long postharvest handling period.

2.2. Temperature

Produce temperature is the most important factor affecting the quality of horticultural produce. Fresh fruits and vegetables remain alive by respiration, a process where carbohydrate in the produce and oxygen are used and carbon dioxide, water and heat are produced. High respiration rates rapidly deplete stored carbohydrates, shortening produce life. Temperature is the primary factor controlling respiration rate. For fruits and vegetables, respiration increases by a factor of two to five for each 10ºC increase in temperature above its recommended holding temperatures. For example, berries like strawberries, raspberries and blackberries, have a shelf life of 7 days at 0ºC but only 1 day at 20ºC. Longer-lived produce such as green beans, mushrooms, green onions, and pod peas last only 2 to 3 days at 20ºC. Above 30ºC, increases in respiration rate slow down, and at higher temperatures the produce will die or lose quality very quickly. Many handbooks contain lists of optimal environmental conditions for long-term storage and transport conditions for fruits and vegetables [5-9].

At any point in the cold chain, produce should always be held at its lowest recommended storage temperature even if future conditions are not known. A cardinal rule in handling perishable horticulture produce is to keep it as cool as possible for as long as possible, even if it is warmed later in handling.

Temperatures below recommended levels cause freeze damage or chilling injury to produce with recommended storage temperatures above 0ºC [10]. Chilling injury usually occurs in fruits and vegetables native to tropical or sub-tropical regions. Signs of chilling injury are: tissue darkening or drying, surface pitting, failure to ripen normally, off flavours, or increased susceptibility to decay [5]. Repeated low temperature exposures have a cumulative effect on chilling injury.

Maintaining proper temperature can be difficult in some handling systems [11]. For example in air transport, the cargo area is not refrigerated and there can be considerable waiting time outside in ambient conditions varying from hot to freezing, with direct sunlight or precipitation. Once arrived at the destination, internationally shipped produce may be held at ambient for many hours before being cleared by local authorities. Policies and processes must be designed to minimize the time in unprotected environments.

2.3. Humidity and water loss

A 90 to 95% relative humidity (RH) environment is needed for maximal shelf life of most fruits and vegetables. A few produce such as bulb onions, garlic, winter squashes, and ginger should be kept below 70% RH [6]. Low RH around produce causes wilting or shriveling. This is aesthetically displeasing and generally reduces marketability. Loss of produce weight caused by water loss is a direct marketing loss. Water loss also weakens the plant cells, making them more susceptible to decay. In addition, fungal growth causes increased ethylene production, causing chlorophyll loss and yellowing [5].

Refrigerated highway trailers do not have RH control capability. Produce susceptible to wilting should be waxed or packaged in liners, bags or plastic boxes to slow moisture loss. Special packaging capable of slowing moisture loss is particularly important in air freight. Airplanes usually have very low RH, often around 10% [8].

Some marine containers are equipped with spray humidification systems. These increase RH but air temperatures have to be slightly above 0ºC to prevent ice from clogging the spray nozzle. Packaging material for produce requiring high relative humidity must be selected carefully. Fiberboard and wooden boxes absorb moisture from the produce and can cause more than 1% weight loss from the produce. The absorbed moisture also weakens the box. For example, fiberboard held in a moisture equilibrium of 90% RH retains only 40% of its original stacking strength after a relatively short exposure period. Under high humidity conditions, waxed fiberboard, plastic and wooden boxes would perform better, as they can better withstand high humidity conditions.

Marine containers are much more airtight than highway trailers and they are equipped with an adjustable fresh air exchange vent to control the amount of air entering the container. Excessive air exchange in humid areas results in unnecessary use of refrigeration capacity to condense excess moisture from the air.

2.4. Atmospheric composition

As fruits and vegetables respire, CO_2 and ethylene levels may increase, and oxygen levels decrease around the produce. CO_2 levels should be kept below 0.3 percent in a tightly sealed container. This is much lower than the damage threshold for many commodities. Highway trailers usually have enough air leakage to prevent damage from accidental build up of CO_2.

ThermoKing [12] markets systems (AFAM and AFAM+) to enhance ventilation management of marine containers. Both systems have an electric controller to set the ventilation rate and to restrict ventilation during initial cooling to reduce the heat load. The AFAM+ system has a gas sensor to adjust the ventilation rate based on CO_2 concentration. Independent testing of these systems has still not been reported in scientific literature.

Marine containers are sometimes equipped with controlled atmosphere devices. These measure CO_2 and O_2 concentrations and control them within a specific range depending on the commodity [13]. Controlled atmosphere systems typically increase the storage life of produce by 30%. They add significantly to the cost of using the container and find only limited use in commerce.

2.5. Mixed loads

Fresh fruits and vegetables have varying requirements for temperature and humidity, and have varying sensitivity to absorbing odours or ethylene induced damage from other produce [5-9, 14]. Many trucks leaving the production areas of US West Coast, a primary production area for North America, have several types of produce in a single trailer. If some produce is mixed with a commodity with differing storage requirements, the quality of the load can be compromised in the three to four day trip to Eastern markets. The problem is even more severe in marine containers travelling several weeks to their destination.

If logistically possible, produce should be loaded as mixed loads only if their temperature and humidity requirements and ethylene sensitivity and odor absorption capability are compatible. Incompatibility between ethylene producing produce and ethylene sensitive produce can be dealt with in several ways. Some fruits and vegetables can be protected from ethylene damage by using a 1-MCP product called Smartfresh [8]. Damage in refrigerated containers or semi-trailer load may also be reduced by using a fresh air exchange rate of 0.2 L s^{-1} [8] or by using ethylene scrubbers [13]. Controlled atmospheres (CA) can allow ethylene producers and ethylene sensitive commodities to be stowed together, but the acceptable produce combinations have not been well researched. Holding produce at its lowest possible temperature reduces ethylene production and ethylene sensitivity.

There are fewer options for dealing with temperature incompatibility. The general rule is plan the load with produce that have the lowest possible range of recommended temperatures, remembering that long transport times accentuate damage caused by incompatibility. Shipments from local distribution centers to markets or food service institutions are always mixed loads and often have produce with widely varying storage requirements and even have other refrigerated food such as milk, juice and meat. However transit times are often less than 8 hours.

LeBlanc and Hui [14] discussed several transport methods developed for transporting mixed loads: multi-compartment vehicles, mini-containers and insulating covers. Multi-compartment trucks or semi-trailers have removable partition panels to divide the vehicle into smaller compartments. Mini-containers are usually the size of a standard pallet load. Some are insulated compartments and others are also refrigerated. The mini-containers are highly flexible, easy to handle and can be used in different sizes of vehicles.

Insulated-only models, can only maintain temperatures for a limited time. Refrigerated models require additional equipment and consume fuel. Their key disadvantages are high cost and non-standardized sizes that do not necessarily match produce container sizes or transport vehicle dimensions therefore resulting in poor space utilization efficiency [14]. Insulating covers cause a stagnant air layer around the produce or within the cover reducing air infiltration and conductive heat transfer. Their main disadvantages are cost and the fact that they have a life of only 6-12 months [14].

Some produce have a short postharvest life and are not suited for container shipment. This is particularly true if they are held at non-optimal temperatures. Modified atmosphere (MA) packaging or CA can sometimes increase shelf life and allows produce to be shipped to destinations that require several weeks of transportation time. If a MA environment is used to hold different produce all together within a single space, it should, as a minimum requirement, not reduce the postharvest life of any of the mixed commodities.

Dried vegetables should not be mixed with other produce when transit times are of a week or more. These vegetables should be held in a 50% to 70% RH environment to prevent decay. Most vegetables in the lowest temperature range (0ºC to 2ºC) are sensitive to moisture loss and should be held at higher than 90% RH or packaged to minimize water loss. The other vegetables and fruits should be held at 85 to 95% RH.

2.6. Physical injury

Vibration, compression, and impact cause physical damage to produce. The damage can be minimized by using proper packaging, good package management, and correct placement in the refrigerated vehicle.

Compression damage occurs when the weight of the load is supported by the produce, rather than the produce container. Compression occurs generally when the boxes are overfilled, are not properly palletized, are not strong enough or lose strength through moisture absorption or mechanical damage.

Compression damage can be avoided by not over-filling boxes, properly aligning all boxes and ensuring that the edge of pallet load aligns with the pallet edge [14]. The corners of corrugated fibreboard boxes provide most of their strength and they should not extend over the edge of the pallet. A 25 mm over-hang reduces strength by 14% to 34% [15]. Corrugated fibreboard loses strength over time when it is supporting a load. For example, after supporting weight for 10 days, a fibreboard box has only 65% of its original laboratory determined strength [15]. Fibreboard also absorbs moisture and weakens when it is exposed to high RH, generated by the produce within the box.

Reusable and recyclable plastic containers are structurally stronger than corrugated fibreboard boxes, and provide more protection against compression damage [14]. If fibreboard boxes are used, they should be designed to be strong enough to withstand the length of the journey under high RH conditions.

Pallet loads should be unitized and secured so that they do not shift during handling or transportation. Stacking tabs or palletizing glue assist in preventing boxes from sliding past each other. The pallet and load can also be unitized, tied together with net wrapping or corner braces and/or banding. Boxes should extend to the edge of the pallet. Free space at the periphery will allow the load to shift in transport. Most reusable plastic containers are designed with an interlocking system and when they are properly stacked they do not shift in transport [16].

Vibration damage is due to the constant vibrating motion of a vehicle [14] when it is transported over the road. Vibration damage is greatest in locations over steel-spring-suspended axles. Air ride suspension dramatically reduces vibration damage. The frame of a semi-trailer is supported by the tractor and most long haul tractors in North America have air-ride suspension. Most refrigerated semi-trailers manufactured within the last 5 years are equipped with air-ride suspensions. Before loading a trailer check the suspension system of the rear axles. If it has steel springs (leaf springs), do not load vibration-sensitive produce, like berries and Bartlett pears at least in the last two pallet positions.

3. Systems for preserving quality during transport

Produce should be kept at optimum conditions during transport. Adequate temperature control systems and air circulation systems are the most important means to ensure quality preservation of perishables.

3.1. Cooling requirements

The refrigeration system used in a transport vehicle must have adequate cooling capacity. With properly cooled produce, most of the heat input is from air infiltration and heat conducted across the walls of the vehicle. Therefore, it is important to consider extreme high or low temperature conditions when calculating the cooling capacity. During the cooler months of the year, the temperature control system may need to add heat to the vehicle to prevent chilling or freezing damage.

The three main sources of heat are internal heat, external heat and residual heat loads. As a basic rule, the total cooling capacity of the refrigeration system is the sum of these three heat loads multiplied by a safety factor. Precise cooling capacity calculations tend to be more complicated as they account for additional effects such as solar heat gain and air speed past the vehicle.

3.1.1. Internal heat loads

The internal heat loads include residual field heat and heat of respiration generated by the produce during transit. Produce should be properly precooled before loading and maintained at the recommended temperature during transit to minimize this type of heat load.

3.1.2. External heat loads

External heat loads depend on the external environmental conditions and enter the transport vehicle by conduction, convection, infiltration and radiation. External heat loads are the main source of heat gain or loss in refrigerated transport.

Conduction is the movement of heat through solid objects. It occurs through the roof, floor, sidewalls and doors of refrigerated vehicles. Insulating material is used to reduce the heat gained through conduction.

Infiltration is the largest external heat load in refrigerated trailers. Ambient air circulates through small holes, cracks and broken door seals. Opening trailer doors unnecessarily also contributes to the infiltration load. Infiltration through open doors can be five times more than the conduction heat gain [9]. Infiltration can be minimized by repairing damage to trailer walls, doors and door seals, and opening doors only when necessary.

Radiation is heat transferred through a vacuum or a gaseous medium, like the sun heating the earth. Light colored objects tend to absorb radiant heat at a lower rate than dark colored objects. The cooling requirement of stationary vehicles increase by 20 % when exposed to direct sunlight for several hours [9]. Ashby [17] suggests using clean reflective surfaces like polished steel and aluminum, or reflective paints to reflect radiant heat from the sun or the hot road. Frequent cleaning is also required to maintain the reflective properties of exterior surfaces. At night, a vehicle can lose heat to the cold sky however, this heat loss is small.

3.1.3. Residual heat loads

Residual heat loads include heat initially contained in the transport vehicle and any heat load not included as internal or external loads. The usual sources of residual heat are the uncooled mass of the transport vehicle [17] and any heat in boxes, pallets and devices used to secure the load. Depending on the mode of transport, it may also include heat generated by the loading equipment.

The refrigeration systems installed in transport trailers have the capacity to remove some residual heat, but they do not have the capacity to remove the large amount of heat in uncooled produce. Therefore, produce must be cooled to the optimum transport temperature prior to loading.

A well-cooled trailer may gain heat during the loading or unloading operation. When trailer doors are open at an unrefrigerated loading dock, the refrigeration system should be turned off and the produce should be loaded rapidly. When loading is completed, the doors should be closed immediately and the refrigeration system restarted. This will minimize the amount of ambient air entering the trailer and the amount of moisture condensing on the evaporator coil. At a refrigerated dock, the refrigeration unit is usually shut off to reduce fuel use.

3.2. Refrigeration systems

There are several systems used to control the temperature of perishables during transportation. The most commonly used cooling systems are mechanical refrigeration, ice and cryogenic cooling. During cold winter months, heating systems are used for produce protection against freezing or chilling injury.

3.2.1. Mechanical refrigeration

Mechanical refrigeration is the most commonly used temperature control method in refrigerated transport vehicles. It is based on a vapour compression cycle common to most refrigeration equipment and has been used for transport vehicles since 1957. New designs and materials have resulted in lighter, more flexible systems. Chlorofluorocarbon refrigerants were commonly used due to their excellent physical characteristics, however they were found to contribute to the depletion of the earth's protective ozone layer. They have been outlawed and new families of refrigerant fluids that have no ozone depleting potential are now commonly used.

The refrigeration system on highway vehicles is usually powered by a diesel engine. All components of the system are built into a self-contained unit mounted on the front wall of the trailer. The engine and condenser are installed outside while the evaporator and blower are located inside the trailer.

Two control modes are available in mechanical refrigeration systems, continuous and automatic. The compressor and fan operate without stopping in continuous mode while only the fan operates continuously in automatic mode. Continuous mode is recommended for highly perishable produce due to its ability to maintain the temperature close to the setpoint. The downside to continuous mode is the fact that it requires more fuel to operate than automatic mode [18].

3.2.2. Ice cooling

Ice is one of the simplest and oldest methods of maintaining a low temperature of produce. It is most commonly used with produce shipped in a non-refrigerated transit system. Ice has a cooling capacity of $335 kJ \cdot kg^{-1}$ and one unit weight of ice will drop the temperature of three times its weight of produce by about 28ºC [19]. Ice also maintains a high humidity around the produce and minimizes produce moisture loss.

Finely crushed ice, flaked-ice or liquid ice (a mixture of crushed ice and water) can be blown onto the top of produce boxes; this is called top-icing. Crushed ice or liquid ice can also be applied on the top of pallet loads or injected into individual boxes (package icing) before loading [19]. Package-icing can also be used to cool produce. The ice remaining after cooling protects the produce from warming and dehydration during transport.

Flaked or crushed ice is usually manufactured on site and stored in an ice bunker. The storage allows the ice manufacturing equipment to be operated with inexpensive off-peak electricity when available. If the cooling season is short and only a few tons of ice are used per day, it is often cheaper to buy block ice and transport it to an on-site crusher. Liquid ice equipment can be made portable, and some companies lease the equipment and move it to cooling sites as needed.

The use of ice for produce cooling and transport is declining because of a number of disadvantages. It is very energy inefficient [20]. A typical liquid ice machine used for a 9 kg broccoli box requires 14.5 kg of ice although the produce temperature reduction requires the equivalent of only 3 kg of ice. Water-resistant containers have to be used with ice. In a mixed load, the melting ice can damage neighboring containers that are not water resistant. In package icing, a layer of air forms between the ice particles and the produce when the ice melts. This air gap will slow down the rate of heat removal since it acts as an insulator. Liquid icing is used with only a few produce items such as broccoli, sweet corn and leafy vegetables. Also, the weight of ice reduces the quantity of produce that can be loaded on trucks and trailers, since there are limits on the weights of vehicles circulating on highways. When ice is used in semi-trailers, these should be equipped with holes on the trailer floor to drain melt water and to prevent damage to the produce or equipment. Floor and drain holes must be cleaned before loading an iced produce.

In airplanes, melt water must be contained within the packaging to prevent it from causing damage to the airplane or neighbouring containers. If crushed ice is used, it must be contained in its own sealed packaging and usually the box containing that package must also be sealed. Many airlines prohibit or discourage the use of ice. There are a number of commercially available gel ice formulations that prevent liquid leakage even if the package is broken. Gel ice usually has a lower melting temperature than water ice and may have to be separated from the produce to prevent freeze injury to sensitive produce.

3.2.3. Cryogenic cooling

Cryogenic cooling with liquid N_2, liquid CO_2 or solid CO_2 (dry ice) is occasionally used to maintain temperature of fresh fruits and vegetables. It was developed before mechanical refrigeration was widely used in transport. An advantage of dry ice is that it does not produce a liquid, but sublimates to a gas. As with all cryogenic materials, the gaseous N_2 or CO_2 must be vented from the cargo area to prevent an unintended modified atmosphere around the produce. Due to the difficulty in controlling atmospheric conditions and the development of efficient mechanical refrigeration, cryogenic cooling is limited mostly to frozen products, local deliveries, and air transport [21].

Dry ice is solidified carbon dioxide and has 92% more refrigeration capacity per mass (645 kJ/kg) than water ice (335 kJ/kg). In air transport, this may make freight costs lower for dry ice than ice if there is a weight restriction. Dry ice has a temperature of -78ºC which is too cold to be packed with horticultural produce. In air flight, dry ice must be kept away from the produce in order to prevent freezing or chilling damage that would result in direct contact [22]. Often dry ice is put on a sheet of foam insulation placed above the produce so that the cold CO_2 gas and air mix together before they finally contact the produce. One kg of dry ice produces about 1100 m^3 of CO_2 gas under standard atmospheric conditions. Dry ice is used as a refrigerant in special enclosed unit load devices equipped with a temperature control system.

A package that contains dry ice in air transport must be labelled with the amount of dry ice it contains when packed and must be identified with the "UN 1845" code. The total amount of dry ice in an aircraft's cargo compartment is limited to an amount determined by each airline in order to prevent any harm to passengers, crew or live plants or animals on the aircraft. The shipping company must be notified of the use of dry ice so they can take proper steps to prevent the excess accumulation of CO_2 in the aircraft.

The amount of coolant needed depends on many factors such as surface area of the package, its interior volume, its insulating properties, and the anticipated outside temperature conditions. The most dependable way to determine the amount of dry ice needed is to conduct a test. Pack several boxes with produce and different amounts of coolant. Then place them in an environment that simulates trip conditions and record the produce temperature for the expected duration of the trip. In this way, a shipper can determine how much coolant is needed to maintain constant produce temperature. In the case of dry ice, its loss can be measured by weighing the package before and after the simulation. Dry ice tests must be conducted in a well ventilated environment due to hazardous CO_2 concentrations that can accumulate.

3.2.4. Heating under low temperature condition

During cold weather conditions, transport vehicles must be heated to avoid chilling or freezing of fresh produce. Mechanically refrigerated trucks, trailers, railcars and containers are usually heated by electric heating or by running the refrigeration unit in reverse-cycle. However, the heating capacity of the mechanical refrigeration system operating in reverse cycle is only about a third of the effective refrigeration capacity of the unit when set at 0°C in a 30°C ambient temperature [1]. Thus, supplemental electric heating may be required when transporting produce in very cold conditions.

3.3. Air circulation systems

Air circulation plays a vital role in maintaining optimal temperatures during transport [23]. Regardless of the capacity or sophistication of the refrigeration system, without an air circulation system the produce will not be protected from temperature extremes. Good air circulation is needed to transfer heat inside the temperature controlled volume to the refrigeration system [23]. The insulation of trailers or containers can only slow down the external heat from penetrating, however it cannot economically stop the heat flow.

Air circulation systems must be designed to allow rapid heat removal and uniform air distribution. Rapid heat removal also helps to reduce temperature gradients across the evaporator and prevents frequent defrosting of the refrigeration unit. If air is unevenly distributed throughout the load, parts of the load may over-heat and other parts may be over-cooled [24], which accelerates produce spoilage.

3.3.1. Top-air delivery

The top-air delivery system (Fig. 1) is used for air circulation in refrigerated semi-trailers and railcars. The refrigeration unit blows cold, high velocity air along the ceiling above the load from the front to the rear of the trailer. As the air flows toward the rear of the vehicle, some of it moves downward

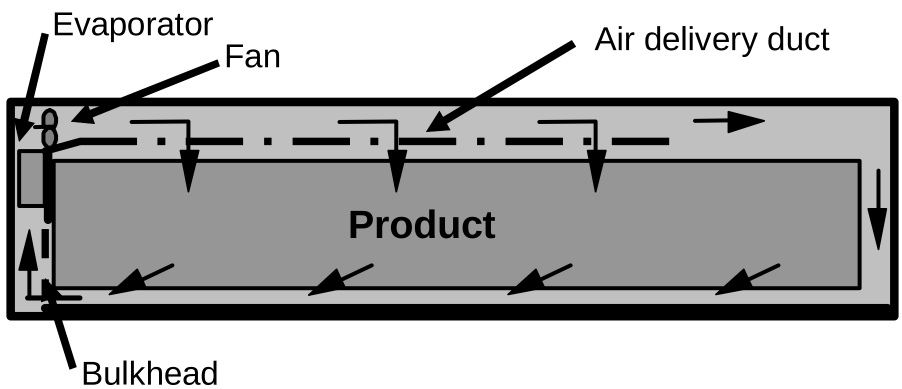

Figure 1. General aspect of a refrigerated container equipped with a top-air delivery system.

along the sidewalls. When air reaches the rear of the trailer, it then flows down along the rear door and then flows underneath the load along floor, returning to the front of the trailer. It then flows up to the evaporator for re-cooling. Common top-air delivery systems include an air delivery duct along the ceiling, floor channels and a return-air bulkhead.

3.3.2. Bottom-air delivery system

The bottom-air delivery system (Fig. 2) is commonly used in intermodal and marine containers. In sea containers, it generally consists of a T-beam floor [25], vertically ribbed rear doors, vertically ribbed sidewalls and a solid bulkhead in the front. It requires these extra features to support the pressurized vertical airflow [17] that is used for this delivery system. Like the top-air delivery system, the refrigeration system is in the front and circulates the air from the front to the rear. However, in the bottom-air delivery system, air is blown to the bottom along the T-beam floors and through pallets, rather than along the ceiling. As the air flows from the front to the rear, it is forced upwards through the cargo. When air reaches the rear of the container, it flows up between the load and the rear doors to the ceiling and then returns to the refrigeration unit, at the front of the container, through bulkhead openings.

The packaging system shipped in marine containers should be designed to work with the container's airflow pattern. Pallets, boxes and inner packaging should have enough venting and airspaces to allow vertical airflow through the pallet load. If air cannot flow through the packages, it will flow around the pallet loads, causing greater temperature variation in produce throughout the container load. A minimum of 3% venting area is recommended on the top and bottom surfaces of the boxes however, Vigneault and Goyette [26] and Castro et al. [27] recommend a much larger venting ratio. Most boxes also have vents on their side walls to allow initial cooling. These vents allow air to flow horizontally to find open vertical venting if top or bottom vents are blocked by pallet deck boards or packaging material. Vents on horizontal box edges are less likely to be blocked by produce or packaging material than vents that are more towards the middle of the box height. Vents for vertical and horizontal airflow should align when boxes are column-stacked or cross-stacked. Interior packaging and pallet deck boards should not block airflow through vents.

Since bottom-air delivery requires refrigerated air to be supplied to the produce through a floor plenum, produce can be slowly cooled only when the floor is completely covered, forcing refrigerated air through the packed boxes.

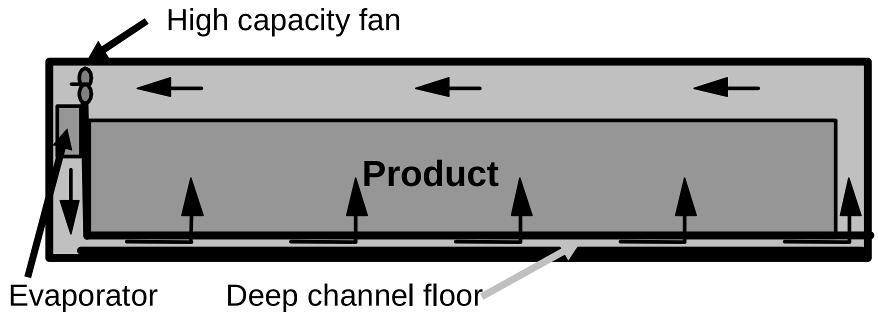

Figure 2. General aspect of a refrigerated container equipped with a bottom-air delivery system.

4. Physical and structural considerations during the selection of a transport system

4.1. Floor

4.1.1. Top-air delivery

In a top-air delivery system (Fig. 3), the space between the load and the floor of the trailer acts as a plenum for returning air to the evaporator. If there is insufficient space for return-air between the floor and the load, airflow will be inhibited preventing conditioned air from reaching the load. To achieve maximum fan capacity around 0.15 to 0.19 m^2 of return air space is required [23,24].

The most common types of floors found in refrigerated semi-trailers are flat floors (without any channels), duct board floors, duct-T floors, and T-beam floors [25]. Each design offers a different cross-sectional area for return air passage, whereas flat floor provides no return air space. T-beam floors provide more return air passage than other designs, but it has several disadvantages. It

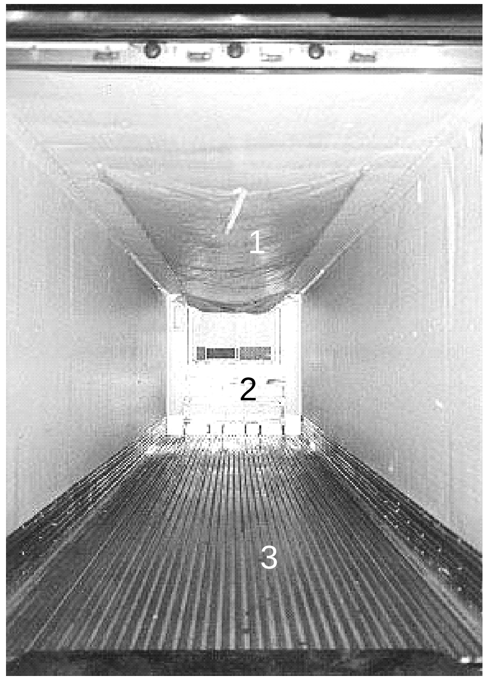

Figure 3. Inside view of a refrigerated semi-trailer equipped with (1) an air-delivery duct, (2) a return-air bulkhead, and (3) a deep-channel floor.

is more susceptible to forklift damage during loading and unloading operations compared to other floor designs. Debris can easily accumulate in the deep channels, making the floor very difficult to clean and reducing the effectiveness of the floor design. Furthermore, forklifts are more susceptible to slippage during handling operation on this type of floor due to the reduced contact area between the floor and tires. Placing produce on pallets significantly increases the area available for air circulation and should be used in trailers with duct board floors and is a necessity in flat floor trailers [25].

4.1.2. Bottom-air delivery

An uniform temperature can be maintained in the load only if the floor of the trailer or container is completely covered with produce on pallets or in boxes, or with other solid material from the bulk-head to the end of the floor rails. When the floor is covered, refrigerated air is forced up through and around the packages. If the produce is palletized, the pallet opening for forklift tines (sometimes called pallet pockets) should also be covered to prevent air from traveling horizontally through these openings and escaping into an open vertical channel between pallet loads. Under hot ambient conditions, produce surrounded by poor airflow will tend to warm up during the transit period, especially if it had not been thoroughly cooled prior to transport or if it has a high respiration rate. An open space in the front of the container allows refrigerated air to flow through these open areas, causing produce in the rear of the container to be warm due to very little refrigerated air reaching it. The floor area between pallets can be covered with sections of fiberboard. Covering the floor and any pallet openings with fiberboard held down with boxes of produce is an effective way to cover the space at the rear of the trailer and avoid short-circuiting in airflow. Under cold ambient conditions, produce in areas with low airflow is more susceptible to freezing or chilling injury.

4.2. Ceiling

The air-delivery duct helps to distribute air from the outlet of the refrigeration unit to the rear and both sides of the load. The duct is usually made of canvas or vinyl [25] and is connected to the blower discharge through an adapter. Quick release fasteners can be used as connectors to the refrigeration unit or bulkhead adapter to ensure accessibility of the evaporator coils for cleaning, inspection and maintenance. The air-delivery duct should be mounted in the middle of the ceiling.

The National Perishable Logistics Association/Refrigerated Transportation Foundation (NPLA/RTF) recommends a minimum cross-sectional area of 0.155 m^2 for the air duct [17, 22]. The air delivery duct should also extend from the front of the vehicle to 3 to 5 m from the rear [17]. Openings on both sides of the air duct should be provided to allow air "spill" down the side walls. The International Institute of Refrigeration [1] recommends a different configuration for the air delivery duct. Rather than having air spill down the side walls along the full length of the air delivery duct, it recommends discharging the air at three different positions along the ceiling: 20% should be discharged near the front of the vehicle, 50% at approximately 1/3 of its length from the front to the rear, and 30% at 3/4 of its length. This configuration ensures air will spill down the side walls along the full length of the vehicle.

Another way to distribute the air along the truck load is using progressive air spills placed along the length of the duct to divert the airflow and allow some air to flow sideways [23]. Spacers of 6.4 to 7.9 mm are used with fasteners to create the side air spills [28]. For the first 3 m from the refrigeration system, no air spills are present and the edges of the duct are fastened tightly to the ceiling [28]. If the connection is not tight, air can short-circuit to the bulkhead affecting the thermostat reading and causing poor temperature regulation. The size of the air duct is normally matched to the type of refrigeration unit used and the ceiling area of the trailer.

One disadvantage of the air duct is that it can obstruct the movement of the forklift during loading or unloading. To prevent damage, the duct must be hung less than 150 mm below the ceiling and the middle of the rear opening must be secured to prevent getting caught up in the pallets or forklift [28]. Securing the rear opening also pressurizes air inside the duct and improves sideways spilling of air. To prevent the air duct from collapsing against the ceiling and blocking air movement, produce must remain below the level of the air duct. Blockage of the air duct can be avoided by painting a line on the sidewalls to indicate the maximum allowable load height [23].

4.3. Ventilation of marine containers

Ventilation should be specified based on volume of airflow per unit of time ($m^3 h^{-1}$ or $L s^{-1}$). Ventilation settings described as "percent vent opening" are not meaningful because performance characteristics and the wide-open vent capacity can vary considerably for different container designs. For example a 20 % vent opening corresponds to about 80 $m^3 h^{-1}$ in one particular container and less than 60 $m^3 h^{-1}$ in another. Airflow for a particular vent settings is also influenced by factors that influence evaporator fan output. For example, a 60 Hz electrical supply usually increases airflow by 20% compared with a 50 Hz electrical supply because of higher airflow from the container fan system. Also, dirty fan blades reduce fan airflow and ventilation.

Ventilation rates above the recommended levels should not be used. Excess ventilation increases energy consumption. In hot, humid environments, it may also increase evaporator coil icing, decrease the cooling capacity and reduce the consistency of temperature control.

4.4. Doors and walls

Door seals should be kept in good condition to prevent air leakage. Doors should be kept closed whenever the refrigeration system is operating. Opened doors are very detrimental to temperature uniformity maintenance.

Vertical channels on the rear doors and side walls have been found to improve air movement and reduce heat conduction through the rear doors and side walls [25]. However ribbed or fluted walls are more likely to be damaged by forklifts during loading and unloading. Most semi-trailers are equipped with smooth doors and flat side walls.

4.5. Insulation

Insulation materials are used to reduce the amount of heat load entering the trailer. The amount of heat transferred by conduction through a wall depends on the wall surface area, the type and thickness of insulation, and the temperature difference between the inside and outside of the vehicle. Insulating materials should be of moderate cost, easy to apply, light in weight, and should have low thermal conductivity, low moisture permeability and very low water retention capacity [9]. The insulation should also be resistant to fire, to breakdown at extreme temperatures, to cracking, to crumbling, to shifting, and any type of mechanical abrasion [9]. Insulation used for the vehicle floor should have enough strength to support loading equipment and the load.

Insulation effectiveness decreases as the insulation material ages and gains water in normal use. Trailers can gain much more than 50 kg due to water-soaked insulation. Water gain is difficult to prevent. Older trailers with less insulation capacity have temperature control inefficiency and greater fuel consumption.

4.6. Return air bulkhead

A return-air bulkhead (Figure 1) is a false wall that provides a clear pathway for air to return to the evaporator and isolates the load from the front wall. It also forces air to go around and under the load without short-circuiting [25]. The bulkhead can cover the full width and half the height of the front wall. Frame and solid bulkheads are commonly used. A frame bulkhead is a lattice made of aluminum or wooden beams.

A solid or pressure bulkhead generates a pressure difference across the outlet and inlet of the fan [25]. This causes air to circulate through, around and underneath the load before returning to the refrigeration unit rather than short circuit from the ceiling directly to the evaporator. Various designs of solid bulkheads are available in the market. They can be classified as standard solid bulkheads or molded bulkheads. The standard pressure bulkhead is usually made of fiberglass-reinforced plywood and aluminum. They can be a single solid wall or a composite of solid and frame walls. The one-piece molded bulkhead is a newer design generally made of polyethylene. This design takes into account the air intake area, the air movement, and the impact strength [29].

The bulkhead should have a space of at least 75 mm between it and the front wall and a minimum open space of 150 mm between its bottom edge and the trailer floor [23]. Bumpers or pallet stops may be installed at the bottom opening to prevent blockage due to load shifting or improper loading. The air return at the bottom of solid/pressure bulkheads is usually covered with screens to prevent debris from entering the return area. The top of the bulkhead must have an open area of 0.02 to 0.03 m^2 to allow mixing of top and bottom-air and allow some airflow to the thermostat in case of blockage at the bottom of the bulkhead [23].

5. Management of produce transport systems

5.1. Selection of transport equipment

A semi-trailer for produce transportation should be in good physical condition, equipped with a duct floor, an air delivery duct and a solid bulkhead. It is also important to ask for a trailer equipped with an air ride suspension system, which will absorb the shock and reduce vibration damage to the produce.

5.2. Preparation of the load

Produce should have enough postharvest life for the trip and subsequent marketing after it reaches its destination, otherwise it should not be included in the load. Produce stored before shipping will have a shorter shelf life for transportation and at destination.

Most transport refrigeration systems do not have the refrigeration or airflow capacity to rapidly cool produce which should be cooled to its optimum storage temperature before stowing. One exception to this rule is cut flowers that can be cooled in about 24 hours, in refrigerated highway trailers, because of their low mass. Precooling is a process in which heat is rapidly removed from the produce immediately after harvest [5]. The four most common precooling methods are forced-air cooling, hydrocooling, vacuum cooling and liquid icing [30]. If applicable, CA treatment should be applied before loading. Standard trailers and semi-trailers are not airtight enough to be used for CA systems, so CA systems for these vehicles must operate independent of the vehicle.

5.3. Preparation of the trailer

5.3.1. Cleaning

Cleanliness of all refrigeration system components ensures proper air circulation around the load. It also reduces plant pathogen levels, and chemical and odor contamination. Refrigerated trailers can be used for transporting a wide variety of commodities including non-food or even toxic material; thus previous loads may be a source of contamination if the cleaning process is not adequate [31]. Some transportation companies have policies that restrict toxic material from being shipped in trailers that are designated for shipping food or feed. However, most trailer operations have few restrictions for shipping dry cargoes in refrigerated trailers. The transportation company should monitor and record the types of cargo previously moved in a trailer. This practice will be more frequent, and even mandatory with the new traceability systems [31, 31].

Floors should be washed or swept thoroughly before loading. Floor ducts should be free of debris to provide clear pathways for air circulation. To ensure proper drainage and prevent disease development, floor drain holes should be free from obstructions.

Semi-trailers, containers, or railcars used for transporting fruits and vegetables may also be used to deliver seafood or frozen produce. In such cases, thorough cleaning and airing of the vehicle may be necessary to eliminate odors. This is particularly important when shipping odor absorbing produce such as apples, banana and berries. Freshly opened cans of ground coffee may be helpful in absorbing odors if they are left for 8 h or more in a closed vehicle [17]. Ground coffee can also be spread directly on the floor and swept away before loading.

5.3.2. Trailer condition

The trailer should have no serious damage. Doors should seal tightly when closed, the air chute should be intact, and the interior wall surfaces should be in good repair. Refrigerated trailers should have a solid front bulkhead. The air delivery duct should be inspected for damage and cleanliness prior to each trip. Torn ducts create uneven air distribution inside trailers [28]. Dirt accumulation inside the air duct will be blown by the air and cause contamination of the load. The air duct should be removed and cleaned at regular intervals using cleaning agents approved by government agencies [28].

5.3.3. Precooling or pre-warming of transport vehicle

Transport vehicles should be precooled or pre-warmed before loading. This reduces the initial cooling or heating load on the vehicle's refrigeration or heating system. During summer, precooling the vehicle reduces the chance of the produce warming after loading and causing a larger demand on the refrigeration system. During winter, pre-warming of the vehicle reduces the chance of chilling or freezing injuries for produce.

Ashby [17] recommends setting the thermostat at the desired transport temperature, closing the vehicle doors, and running the cooling or heating system until the vehicle body reaches the set-point temperature. The set-point temperature should clearly be specified in both Celsius and Fahrenheit scales to reduce confusion between the two systems where applicable. Modern mechanically refrigerated vehicles are equipped with microprocessors that automatically run the precooling cycle. In all cases, sufficient time has to be scheduled ahead of loading, as the precooling process may be long. Production areas for tropical fruits often do not have cold storage facilities and produce is loaded without initial cooling from an open dock. Under these circumstances a marine container should not be cooled below the dew point temperature of the ambient air. Cold interior walls may have large amounts of condensation that will damage corrugated boxes and result in a great amount of frost on the evaporator coil.

For all types of vehicles, it is important to turn off the mechanical refrigeration system once the doors are opened for loading. When the refrigeration system is on, open doors allow the fan to draw in outside air. Outside air usually has a higher dew point temperature than the air in the vehicle, and excess moisture condenses on the refrigeration system coils. The ice formed on the evaporator coils will limit or block the air circulation during transport [17]. Similar conditions occur when the vehicle’s doors are left open longer than required, even when the refrigeration system is turned off. Thus, reducing the open door period to its minimum is highly recommended.

5.4. Loading

During the loading of transport vehicles, the following handling practices should be followed to prevent an excessive loss of quality during the transportation step:

- Avoid bumping pallets during handling;
- Avoid puncturing MA plastic bags;
- Load together produce that is compatible;
- Load produce in centerline loading pattern;
- Apply bracing between the pallets and both side walls;
- Apply bracing to secure the rear pallets;
- Do not load produce sensitive to vibration damage directly above steel-spring, suspended axles.

5.4.1. Additional considerations

Some produce, such as green onions and broccoli, are sometimes shipped with crushed ice in waxed corrugated cartons or plastic container units. They should never be stowed on top of other produce not packaged in ice. Water from the melting ice damages packages that are not water resistant. If ice-packed produce must be shipped with produce packed in conventional corrugated boxes, use moisture proof divider sheets to protect corrugated boxes. However, dividers should not extend to the floor where they can block the air flow through pallet openings. Never distribute crushed ice on top of a load of fresh produce except if the produce has been packed in containers specifically designed for this purpose [16]. Furthermore, an excess height of ice could block airflow passages.

Protective wrapping should cover the top, sides and bottom of the pallets or the load. Reflective wrap is more effective than opaque plastics or paper for reducing heat gain when the load is exposed to the sun. Do not use clear plastic film as a pallet cover. Solar heat passes through it and it is then trapped under it as in a greenhouse, resulting in a very rapid temperature increase. Insulated covers add some protection from heat gain, but the benefit is relatively small compared to the use of a simple reflective cover. Covers that incorporate gel ice are also available.

5.4.2. Loading patterns

The loading pattern used for arranging produce in a vehicle depends on the type of transport vehicle (semi-trailer, container, railcar, ship or airplane), the type of load (palletized or unitized), and the type of air delivery system (top or bottom). Special attention has to be given to mixed loads [24]. Horticultural produce can either be handled as palletized or unitized loads. The palletized load is the most commonly used loading arrangement because of its ease of handling and its reduced labor requirement. In North America, a larger quantity of produce could be transported if unitized loads were used in transport vehicles rather than palletized loads. However, this method is rarely used with the long semi-trailers in use today. These new semi-trailers usually reach their maximum weight limit before filling the available volume. This situation is specific to each country since it is based on road regulations as well as labor and fuel costs. Nevertheless, unitized loads also allow better air circulation through the cargo when boxes are stacked evenly and air passages are left between rows of boxes.

Numerous loading patterns are available for both types of loads [17, 22]. No matter what type of loading pattern is used, the basic guideline is to load produce such that conduction heat transfer from the outside is minimized and air circulation is maximized. Refrigerated produce should be loaded away from sidewalls when transported on long trips through extreme hot or cold outside temperatures to prevent heat conduction. Also, loading produce away from the walls of the trailer increases air circulation in the space between the produce and the wall. This air circulation allows any heat transferred through the wall of the trailer to be eliminated before it reaches the produce. In bottom air delivery vehicles the entire floor should be covered with cargo or fillers to maintain uniform air flow through the produce. For mechanically refrigerated semi-trailers or railcars using a top-air delivery systems, the centerline loading pattern is recommended for palletized cargo.

5.5. Handling at destination and during retailing

When the produce arrives at destination, pallet covers and wraps should be removed and temperature and quality of the produce should be inspected. Produce still within 2°C of its optimum temperature range should be immediately transferred to a refrigerated room. Produce more than 2ºC above its recommended temperature range needs to be rapidly cooled again [33].

At retail, produce should be refrigerated upon arrival. Since display cabinets or counters do not have the refrigeration capacity to cool produce, fruits and vegetables should be at their optimum temperature before being stacked for display. To prevent an increase in temperature during display, produce should not be stacked above the load line of the display cabinet or counter.

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