

COMMERCIAL-SCALE FORCED-AIR COOLING OF PACKAGED STRAWBERRIES

B. A. Anderson, A. Sarkar, J. F. Thompson, R. P. Singh

ABSTRACT. *Strawberries are an extremely valuable crop, but they are also very sensitive to decay if not cooled and maintained at proper temperatures. Strawberries are typically packaged in the field and quickly transported to a cooling facility, where they are precooled by forcing cold air through the vents of the packaging. Over the last several years, there has been a shift in the packaging used for strawberries. Many of the open-top pint baskets have been replaced by clamshell designs with hinged lids and less vent area. In addition, there has been an increased retail demand for a larger tray that fits five trays to a pallet layer rather than six trays per layer. In this work, strawberries packaged in clamshell containers and a variety of tray designs were precooled in commercial cooling systems. To determine the speed of cooling for each treatment, both the 7/8th cooling time and the cooling coefficient were calculated. It was found that the control package combination (with a design that fits six trays per pallet layer) cooled significantly faster than the other treatments, which fit five trays per pallet layer. It is thought that the cross-orientation of trays that occurs in the five trays per layer configuration may slow cooling if the vents are not designed properly. No major differences were found for cooling using corrugated trays versus returnable plastic containers. It was found that the clamshell container and tray should be designed together and chosen properly to allow maximum air-to-product contact during cooling. Variations in air temperature during commercial cooling tests may cause errors in determining 7/8th cooling times.*

Keywords. *5-down trays, 7/8th cooling time, Cooling coefficient, Forced-air cooling, Precooling, Strawberries.*

Strawberries are an extremely valuable crop in the U.S., and are second only to apples in fresh market value among fruits. California produces over 635 million kg (1,400 million pounds) of strawberries per year with a value of over \$800 million, accounting for over 80% of the total U.S. production. Approximately 75% of the strawberry production is harvested for the fresh market (California Strawberry Commission, 2002). Strawberries are also one of the most perishable fruits. They are very susceptible to mechanical damage, microbial decay, and water loss. One of the most important factors in maintaining quality of strawberries is rapid cooling and distribution under refrigerated conditions. Freshly picked strawberries are typically field packed and rushed to a cooling facility, where they are forced-air cooled to approximately 0°C for refrigerated distribution and storage. This process is termed “precooling” of strawberries.

Good temperature management is the most important factor in maximizing the postharvest life of strawberries, and delays in cooling over 1 h reduce the percentage of marketable fruit (Mitcham and Mitchell, 2002). Nunes et al. (1995) found that delaying cooling of strawberries for as little as 6 h at 30°C resulted in fruit that had a significant decrease in firmness and size, as well as a less attractive appearance. In addition, strawberries have a relatively high respiration rate of 12 to 18 mg CO₂/kg h at 0°C (Hardenburg et al., 1986). Respiration is the process by which the fruit converts sugars and starches into carbon dioxide, water, and energy. Some of the energy produced is used by the fruit for life processes, but excess energy is given off in the form of heat. The respiration rate increases by a factor of 2 to 4 for every 10°C increase in temperature, which leads to even more rapid deterioration. Therefore, it is important to cool strawberries as quickly as possible after harvesting. The USDA recommends precooling strawberries to near 0°C within 1 h of harvesting and to maintain that temperature throughout distribution and sale (Hardenburg et al., 1986). Increasing the cooling rate will not only potentially increase the postharvest life of the fruit being cooled, it will also allow more throughput at a cooling facility, so that less fruit is left waiting for the cooling tunnels to become available.

The most common method used for precooling of strawberries is the use of forced air. Alternative methods, such as hydrocooling or vacuum cooling, run the risk of damaging the fruit by physical means and/or by increasing moisture on the surface of the fruit, which promotes increased microbial growth. In a common setup for forced-air precooling, two rows of palletized strawberry containers are lined up against an open cooler wall, through which a suction fan stands equidistant from either row. The top of the

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center aisle and the end opposite to the fan are sealed with a tarp, and the fan is turned on. This creates a negative pressure in the aisle between the pallets. Air is pulled from the refrigerated room, through the vents in the containers, and then through the suction fan. The air removes heat from the strawberries as it is pulled through the vents and cools the fruit (Thompson et al., 1998).

Strawberries sent to the consumer market are typically packaged in individual containers. Depending on the size of the package, 4 to 18 of the individual containers are placed in a tray. The trays are made of either corrugated fiberboard or plastic. The plastic trays are called RPCs (returnable plastic containers), which are cleaned and returned to the strawberry growers for reuse. The design of the vents on both the individual container and on the tray is critical for optimizing the rate of precooling. Ideally, the vents on the individual container and tray should be designed to allow the maximum air-to-product contact when the containers are palletized and forced-air cooled.

There has been a shift in the consumer packaging of strawberries over the last several years in the U.S. In the past, the pint basket has been the most popular container for consumer strawberry sales, and was thus subjected to cooling tests by Arifin and Chau (1988), Talbot and Chau (1991), Émond et al. (1996), and others. However, recently the 0.454 kg (1 lb) consumer pack has become most popular. According to the California Strawberry Commission (2002), in 1999 the 0.454 kg (1 lb) consumer pack accounted for 61% of the packages sold in the spring and 84% of those sold in the summer. Unlike the pint basket, which typically has an open top and a mesh body for a greater vent area, the 0.454 kg consumer pack typically is a thermoformed plastic with a clamshell-type design, a hinged lid, and less venting. This design leads to less bruising and cutting of strawberries than the pint basket (Singh, 1992). However, limited testing has been published on cooling using this clamshell package. In addition, there has been an increased retail demand for the 0.406×0.610 m (16×24 in.) tray with 5-down configuration, as opposed to the 0.406×0.508 m (16×20 in.) tray with 6-down configuration (fig. 1), for standardization. However, it is not known if the cross-orientation of trays with the 5-down configuration affects the cooling rate of strawberries.

For this work, strawberries were pre-cooled in full-scale commercial systems. Few experimental studies have been published where cooling rates were measured on commercial systems. Strawberries were packaged in plastic clamshell containers placed in either corrugated or returnable plastic trays. These clamshell containers and trays had varied vent-hole designs. To determine the speed of cooling for

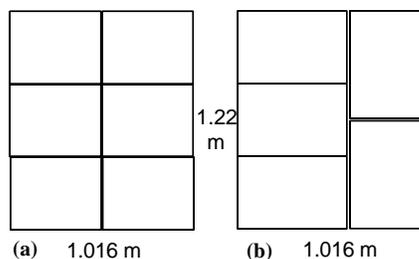


Figure 1. Top view of pallet arrangements for (a) 0.406×0.508 m (16×20 in.) trays in 6-down configuration, and (b) 0.406×0.610 m (16×24 in.) trays in 5-down configuration.

each strawberry treatment, both the 7/8th cooling time and the cooling coefficient method were calculated.

The objectives of this work were to measure cooling rates of strawberries in 0.454 kg plastic clamshell containers, which are now more commonly used in the U.S. The 5-down and 6-down pallet configurations were compared, and the use of corrugated trays versus returnable plastic containers (RPCs) was compared. In addition, the 5-down corrugated trays were cooled in different orientations, and one RPC design was cooled with different clamshell designs.

COOLING CALCULATIONS

For evaluating the cooling of strawberries, transient heat transfer principles must be analyzed. In particular, the Biot number and Fourier number are critical and are defined below for a sphere:

$$Bi = \frac{hR}{k} \quad (1)$$

$$Fo = \frac{\alpha t}{R^2} = \frac{kt}{\rho c_p R^2} \quad (2)$$

The Biot number is a ratio of the external resistance to heat transfer to the internal resistance. For low Biot numbers (<0.1), the external resistance to heat transfer is much greater than the internal resistance; therefore, there is negligible temperature gradient within the product (i.e., a lumped capacitance system). In this case, if constant thermal properties, initial temperature, and air temperature are assumed, then the transient heat transfer equation can be solved as shown in equation 3 (Incropera and DeWitt, 1996):

$$\text{Temperature ratio} = \frac{T_i - T_a}{T_i - T_a} = \exp\left(-\frac{hA}{mc_p} t\right) \quad (3)$$

Therefore, plotting the natural log of the temperature ratio versus time will give a straight line.

On the other hand, if the Biot number is greater than 0.1 and less than 10, the external and internal resistances are on the same order and there will be temperature gradients within the product, which makes the solution more complicated. For precooling of most horticultural crops, including strawberries, the Biot number falls within this range.

However, for Fourier numbers greater than 0.2, the solution for the temperature in the sphere can be accurately estimated as shown in equation 4 (Incropera and DeWitt, 1996):

$$\frac{T_i - T_a}{T_i - T_a} = C_1 \exp(-\zeta_1^2 Fo) = C_1 \exp\left(-\zeta_1^2 \frac{kt}{\rho c_p R^2}\right) \quad (4)$$

For strawberries, assuming a thermal diffusivity of 1.26×10^{-7} m²/s (Güemes et al., 1989), the Fourier number will be greater than 0.2 after approximately 3 min of cooling. Again in this case, if the natural log of the temperature ratio is plotted against time, a straight line will result after a short lag period.

Equations 3 and 4 require knowledge of thermal properties, heat transfer coefficients, and product dimensions; therefore, as a simplification, the speed of cooling can be

evaluated using what is called the cooling coefficient. The cooling coefficient is defined as the slope of the line resulting from a plot of the natural log of the temperature ratio versus time (Guillou, 1958). The cooling coefficient has units of inverse time, and a steeper slope indicates a faster rate of cooling. If the total cooling time is relatively long, and the initial lag period is relatively short, as is the case for the experiments described in this article, then the lag period has a negligible effect on the resulting cooling coefficient. The cooling coefficient was used as one means of comparison for the experiments described in this article.

Another measure of the speed of cooling that is typically used for forced-air cooling is the 7/8th cooling time. The 7/8th cooling time is a means to normalize the cooling data since it accounts for different initial fruit and cooling air temperatures. The 7/8th cooling time is defined as the time required for the product to drop in temperature by 7/8th the difference between the initial fruit temperature and the air temperature. In other words, it is the time required for the temperature ratio to reach the value of 1/8. The 7/8th cooling time is useful for strawberries because it is sometimes recommended that 7/8th of the field heat be removed by forced-air cooling, while the final 1/8th can be removed during cold storage. The 7/8th cooling time was also used as means of comparison for the experimental data in this article.

For experiments, if the fruit cools very slowly, it may be preferable to determine the 1/2 cooling time, and then extrapolate to find what the 7/8th cooling time would be. This is acceptable if a constant air temperature and constant thermal properties can be assumed, as discussed earlier. In this case, the 7/8th cooling time is equal to three times the 1/2 cooling time.

A graphical representation of an ideal cooling curve with constant air temperature and log-linear cooling profile is shown in figure 2. In this example, the initial product temperature (T_i) is 23°C, and the air temperature (T_a) is constant at -1°C. The temperature for 1/2 cooling time is 11°C, and the temperature for 7/8th cooling time is 2°C. The time required for the product to reach 11°C is called the 1/2 cooling time (30 min in this case), and the time required for the product to reach 2°C is called the 7/8th cooling time (90 min in this case). In figure 2, the cooling coefficient for the example is -0.023 min^{-1} .

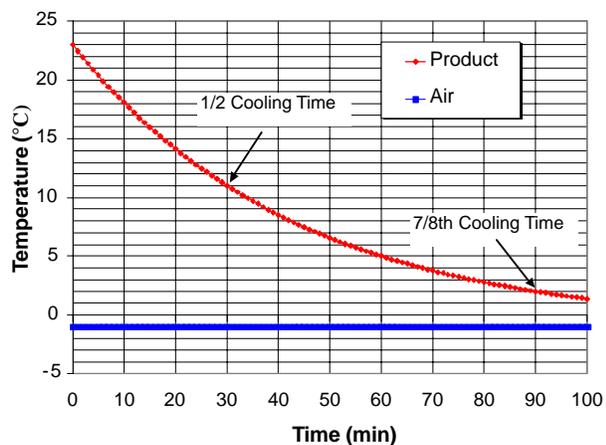


Figure 2. Example cooling curve with logarithmic cooling and constant air temperature.

FLOW THROUGH POROUS PACKAGES

Flow through bulk-packed beds has been described using porous media assumptions by various authors. For certain products, such as flow in grains, the flow is often described using Darcy's law (eq. 5) and the continuity equation (eq. 6):

$$-\nabla p = \frac{\mu}{\kappa} \vec{u} \quad (5)$$

$$\nabla \cdot \vec{u} = 0 \quad (6)$$

For larger products (e.g., oranges and potatoes) stored in bulk bins, corrections have to be added to the original Darcy's equation to accommodate acceleration effects known as the Forchheimer term. For produce stored and cooled in boxes, other considerations are added for viscous wall effects, known as the Brinkman correction. A complete form of the momentum equation, known as the Darcy-Forchheimer-Brinkman (DFB) equation (eq. 7), has been used by Vafai and Tien (1980). A detailed description of the development and limitations of these equations from basic principles can be found in Whitaker (1999).

$$-\nabla p = \frac{\mu}{\kappa} \vec{u} + \beta \rho u \vec{u} + \mu_{eff} \nabla^2 \vec{u} \quad (7)$$

Recently, some researchers have proposed models that can accommodate such effects and apply the porous media assumptions to flow through packaged agricultural commodities (Alvarez and Flick, 1999; van der Sman, 2002). This type of porous media modeling requires an assumption of continuous media. However, in the case of strawberry cooling, as described in this article, there is a two-tiered package involved, with a clamshell package enclosed in a secondary tray. Thus, the media is essentially discontinuous, and the continuum assumptions may have limitations.

For heat transfer inside porous media, either the lumped control volume approach (Bakker-Arkema and Bickert, 1966) or the transient conduction approach (Xu and Burfoot, 1999) can be used. The lumped approach requires control volumes that may be relatively large compared to the size of the clamshell, while the transient approach is computationally intensive. Therefore, comparing cooling rates for different packages in commercial systems using cooling coefficients and 7/8th cooling times was the focus of this work, rather than attempting to model the actual airflow and heat transfer through strawberry packages.

MATERIALS AND METHODS

Strawberry cooling experiments were performed on full-scale commercial systems in conjunction with the California Strawberry Commission. Strawberries were packaged in 0.454 kg minimum net weight, plastic clamshell containers placed in either corrugated fiberboard trays or RPCs. A total of eight different clamshell and tray combinations were tested (table 1 and fig. 3). Most of the cooling tests took place at a commercial forced-air cooling facility in Watsonville, California. Additional experiments were completed at a commercial forced-air cooling facility in Oxnard, California.

Table 1. Summary of package combinations used in the cooling tests.

Package Combination	Plastic Clamshell Container	Containers per Tray	Tray Design	Side Vent Area (%)	End Vent Area (%)
1	Pactiv 9762	8	Standard: 16 × 20 in. corrugated	N/A	20
2	Pactiv Euro	8	Corrugated tray 2: 16 × 24 in.	15	11
3	Ivex 9805	8	Corrugated tray 3: 16 × 24 in.	12	16
4	Pactiv 9762	18	RPC tray design 1	13	16
5	Pactiv 9762	9	RPC tray design 2	4	13
6	Ivex 9805	16	RPC tray design 3	22	26
7	Ivex 9805	8	RPC tray design 4	13	22
8	Pactiv 9762	9	RPC tray design 4	13	22

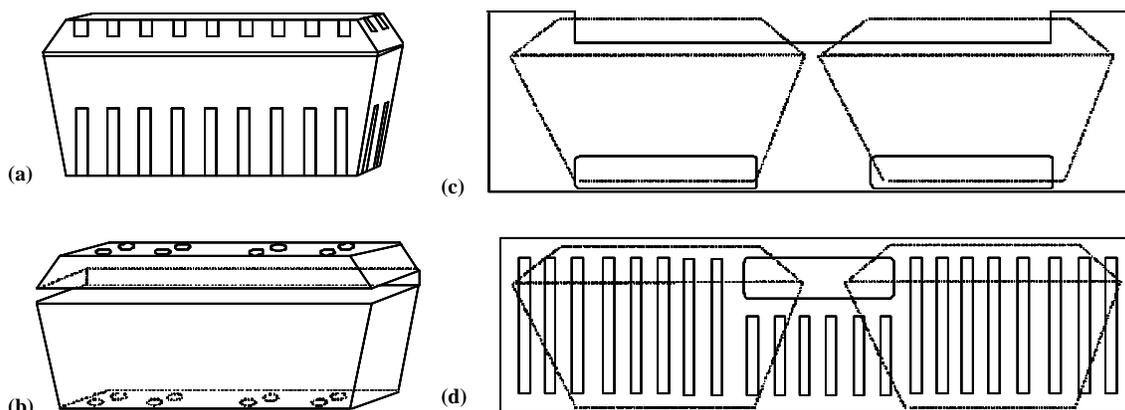


Figure 3. Typical strawberry packaging: (a) 0.454 kg plastic clamshell with slot vents on top and bottom of sides, (b) plastic clamshell with side vent at hinge and round vents on top and bottom, (c) end view of corrugated fiber tray, and (d) end view of returnable plastic container (RPC) tray.

The cooling tests in Watsonville were conducted with Diamonte variety of strawberries that were commercially harvested on the morning of the test. Seven separate package combinations were used, consisting of different plastic clamshell containers and either corrugated or plastic trays (RPCs). Each package combination contained different air vent designs. The package combinations used are the first seven listed in table 1. The cooling test setup for package combination 1 is shown in figure 4. As the control, package combination 1, which is currently used commercially, contained six trays on each layer. All the other package combinations contained five trays on each layer. Each treatment consisted of five layers per pallet. The three middle layers of each treatment were monitored for temperature, while the upper and lower layers were used as buffers. Strawberry core temperatures and air temperatures were measured using type-T, 24-gauge thermocouple wire. Linear calibration of the thermocouples was done in ice water and boiling water, and accuracy is $\pm 0.5^{\circ}\text{C}$.

Each pallet typically contained two package combinations, one stacked on top of the other; therefore, all pallets contained at least ten layers. The test pallets were located in rows with other pallets against the wall of a forced-air cooler, as shown in figure 5. Test pallets were located at a distance away from the plenum, where the pressure drop across the pallets was between 155 and 175 Pa at both the top and bottom of the pallets. Pressure drop across each of the test pallets was measured using a handheld digital manometer (Series 475, Dwyer Instruments, Inc., Michigan City, Ind.). All package combinations were cooled in an orientation such that air flowed parallel to the 1.016 m (40 in.) dimension of the pallet. Additionally, package combinations 2 and 3 were cooled and oriented such that air flowed parallel to the

1.220 m (48 in.) dimension of the pallet. Each plastic clamshell container had a gross weight of 0.50 to 0.59 kg and contained 15 to 20 berries.

Additional cooling tests took place at a commercial cooling facility in Oxnard, California. Camorosa strawberries were harvested on the morning of the test at a field nearby. Tests were conducted using two different designs of plastic clamshell containers (Pactiv 9762 and Ivex 9805) placed in the RPC tray design 4 (Package combinations 7 and 8 in table 1). These package combinations were cooled parallel to both the 1.016 m (40 in.) pallet dimension and the 1.220 m (48 in.) dimension. As with the Watsonville tests, five layers were used for each treatment, and the three middle layers were monitored for temperature. For pallets cooled parallel to the 1.016 m dimension, pressure drop across the pallet was measured to be 210 to 230 Pa, while those cooled parallel to the 1.220 m direction had a pressure drop of 150 to 190 Pa on the top and bottom.

Averaging thermocouples were used for temperature measurements. A single thermocouple was placed in a berry that was located at approximately the center of a tray. This was done for berries in five different trays on each layer. Two or three of the thermocouples were placed into a berry on the top layer in a basket, and the remaining two or three thermocouples were placed into a berry on the bottom layer in a basket. These five thermocouples per layer were connected in parallel, and a single temperature was recorded every minute using a 21X data logger (Campbell Scientific, Inc., Logan, Utah). Air temperatures entering each of the pallets were also collected using individual thermocouples.

The 7/8th cooling time determination and cooling coefficient calculations were done for each treatment since they are the industry standards. However, both methods require a



Figure 4. Setup for package combination 1 (additional layers were added on top prior to cooling).

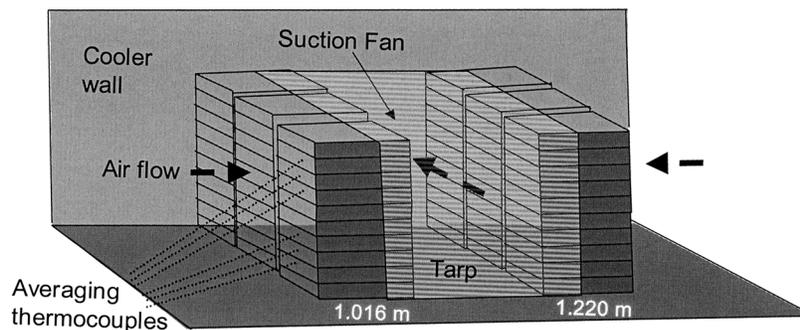


Figure 5. Forced-air cooling setup for cooling experiments (1.016 and 1.220 m treatments were cooled at different times).

constant air temperature throughout cooling. Since the actual air temperature varied with time, the air temperature after approximately 30 min was averaged, and this was used as the constant air temperature.

RESULTS AND DISCUSSION

The 7/8th cooling times and cooling coefficients were calculated for each set of thermocouples and averaged for each treatment. Each set of thermocouples measured an average cooling time for a layer, since the thermocouples were connected in parallel. Sample cooling curves from the experiments are shown in figure 6. For the Watsonville experiments, cooling coefficients and 7/8th cooling times are given in table 2. Cooling times are similar to those found by other researchers using pint baskets. The 7/8th cooling time for the control (package combination 1) was 58 min. The other package combinations had significantly longer 7/8th cooling times than package combination 1 based on Duncan's multiple range test. Their average 7/8th cooling times ranged from 73.7 to 84.3 min. Package combination 1, which had the fastest 7/8th cooling time, did not have the greatest percentage of vent area. This suggests that simply increasing

vent area does not necessarily increase cooling rates. The vents should be matched up well between trays and should channel air through the clamshells to maximize product-to-air contact.

For pallets with five trays on a layer (5-down) that were cooled with air flowing parallel to the 1.016 m (40 in.) dimension, there was an added issue of cross-orientation. In this arrangement, the end of one tray matched up with the side of another. This can reduce the effective vent area by over 50% if the trays are not properly designed for the vents to line up. The control package combination, which was a 6-down orientation, had a significantly faster cooling speed than did any of the 5-down configurations, suggesting that cross-orientation of trays slowed cooling in the 5-down configuration.

For the 5-down configurations, cooling times can be compared between the package combinations with corrugated trays versus those with RPC trays. The only significant difference found was that package combination 2 (corrugated) cooled significantly faster than package combination 5 (RPC). The RPC used for package combination 5 actually had the lowest vent area of any tray tested, which may have led to the slower cooling. With the exception of package combination 5, there were no other significant differences in cooling for corrugated versus RPC trays.

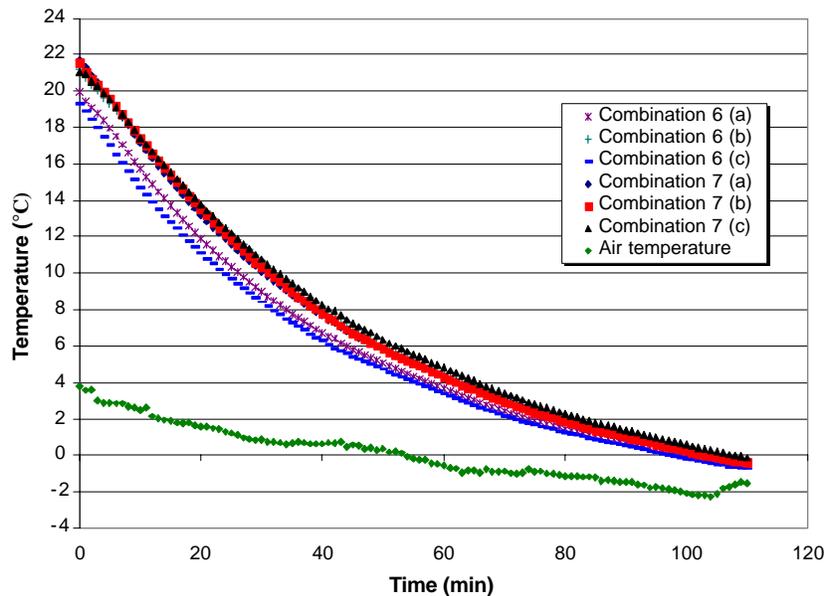


Figure 6. Sample cooling curves for cooling experiments (average berry temperatures for three different layers of package combinations 6 and 7).

Table 2. 7/8th cooling times and cooling coefficients for cooling tests in Watsonville.

Package Combination	Airflow Parallel to Pallet Dimension	7/8th Cooling Time (min) ^[a]	Cooling Coefficient (min ⁻¹)
1	1.016 m	58.0 a	-0.0357
2	1.016 m	73.7 b	-0.0295
2	1.220 m	75.7 b,c	-0.0283
3	1.016 m	76.0 b,c	-0.0285
3	1.220 m	81.5 b,c	-0.0255
4	1.016 m	79.0 b,c	-0.0257
5	1.016 m	84.3 c	-0.0239
6	1.016 m	79.0 b,c	-0.0266
7	1.016 m	82.7 b,c	-0.0252

^[a] Times following by the same letter are not significantly different based on Duncan's multiple range test.

For the cooling of 5-down corrugated trays (package combinations 2 and 3), the effect of cooling using different pallet orientations can be observed. These package combinations were cooled with air flowing parallel to the 1.016 m dimension and the 1.220 m dimension, and no significant differences were found. When air flows parallel to the 1.016 m dimension, the trays are cross-oriented, which could slow cooling if the vents are not designed properly. However, when they are cooled in the 1.220 m dimension, the air must travel farther and should warm up to a greater extent.

The cooling tests from Oxnard give a comparison of the effect that different clamshell packages have on cooling when placed inside the same RPC trays. Package combinations included eight Ivex 9805 clamshells (package combination 7) or nine Pactiv 9762 clamshells (package combination 8) in each RPC tray. Regardless of whether cooled with air flowing parallel to the 1.016 m pallet dimension or parallel to the 1.220 m dimension, the strawberries packaged in the Ivex clamshell cooled significantly faster than those packaged in the Pactiv clamshell based on the Student's t-test at the 95% confidence level (table 3). This suggests that the Ivex clamshell design is better suited to be cooled in RPC tray design 4. The Pactiv clamshell design allows more containers

Table 3. 7/8th cooling times and cooling coefficient for cooling tests in Oxnard.

Package Combination	Airflow Parallel to Pallet Dimension	Pressure Drop (Pa)	7/8th Cooling Time (min)	Cooling Coefficient (min ⁻¹)
7	1.016 m	210-230	38	-0.0577
8	1.016 m	210-230	45	-0.0430
7	1.220 m	150-190	51	-0.0436
8	1.220 m	150-190	66	-0.0320

(and 12.5% more fruit) to be fit into the same RPC tray; however, this increases the heat load that must be removed during cooling and increases cooling times by 18% to 30%.

One issue that was discovered during the commercial cooling tests was that air temperature was very difficult to keep constant during cooling. Inlet air temperatures were found to vary by as much as 6°C during the course of the cooling (fig. 7). Under actual commercial cooling conditions, it is extremely difficult to maintain a completely constant air temperature. Warm fruit is constantly being brought into the cooler during operation, and forklifts must pass in and out of the cooler. When the air temperatures continue to vary during cooling, it is rather arbitrary which air temperature to use, or what period of time to average, for calculating the 7/8th cooling time. Choosing an air temperature that is different by as little as 1°C changes temperature for the 7/8th cooling time by 0.875°C, and in the case of these experiments, the 7/8th cooling time by as much as 14 min.

Cooling coefficients and 7/8th cooling times were used to evaluate cooling rates for these experiments because they are the industry standard and they are easy to calculate. However, one should be aware that both these methods assume constant air temperature throughout cooling. The cooling rates calculated in these studies were rerun using various air temperatures within the range of measured values. These resulted in different calculated cooling times but did not affect the trends previously reported. No other simple comparative method could be found that accounts for variable air temperatures without making other compromises to the analysis.

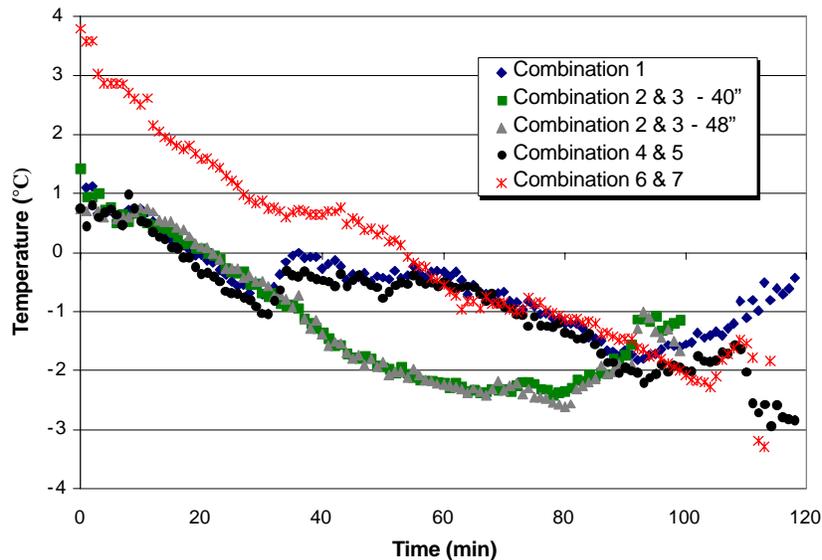


Figure 7. Inlet air temperatures during cooling tests in Watsonville.

It was found that other factors also make commercial cooling tests difficult. External conditions, such as static pressure drop, are more difficult to control in full-scale commercial tests. Ideally, all six pallets placed in rows against the cooler wall during precooling would be of the same design for each treatment; however, because of the cost involved, other commercial pallets were used along with the test pallet to increase the cooling load for each cooling experiment. Because of all these factors, it is recommended that future cooling tests take place on a laboratory scale, where external factors may be better controlled and product and packaging cost is much less. Once the package design has been optimized, verification studies may be done on a full commercial scale.

CONCLUSIONS

Forced-air precooling of commercially packaged strawberries was conducted on full commercial-scale systems. The cooling times for the clamshell packages tested were comparable to those found by Arifin and Chau (1988), Talbot and Chau (1991), and Émond et al. (1996) for pint containers and by Singh (1992) for the clamshell container.

The control package (6-down configuration) cooled significantly faster than did the test packages (5-down configuration), suggesting that the cross-orientation of trays in the 5-down configuration may slow cooling. It is important to ensure that the cross-orientation does not reduce the effective vent area when designing the trays.

For the 5-down configuration, no major differences in cooling times were found when using corrugated trays versus RPCs. In addition, no significant differences were found when cooling of 5-down, corrugated trays in different pallet orientations.

The clamshell design had a significant effect on cooling rate when used in the same tray design. It can be concluded that the vent-hole design plays a significant role on the forced-air cooling time. The percentage of vents on the trays did not necessarily correspond with the fastest cooling package. Therefore, the clamshell container and tray should

be designed together to maximize air-to-product contact during cooling.

Variations in inlet air temperatures during cooling can have a significant effect on the calculated 7/8th cooling times for strawberries. It is very difficult to ensure a constant air temperature in an industrial operation with all the external factors. Conducting experiments on a laboratory scale, where external factors can be better controlled, is preferred for future studies.

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NOMENCLATURE

- A = area (m^2)
- Bi = Biot number
- c_p = specific heat ($J/kg\ K$)
- Fo = Fourier number
- h = convective heat transfer coefficient ($W/m^2\ K$)
- k = thermal conductivity ($W/m\ K$)
- m = mass (kg)
- p = pressure (Pa)
- R = sphere radius (m)
- t = time (s)
- T_a = constant or average air temperature ($^{\circ}C$)
- T_{at} = air temperature at time t ($^{\circ}C$)
- T_i = initial fruit temperature ($^{\circ}C$)
- T_t = fruit temperature at time t ($^{\circ}C$)
- \vec{u} = velocity vector (m/s)
- α = thermal diffusivity (m^2/s)
- β = Ergun constant
- κ = Ergun constant
- μ = viscosity ($Pa\ s$)
- μ_{eff} = effective dynamic viscosity at the boundary layer ($Pa\ s$)
- ρ = density (kg/m^3)
- ζ_1 = first positive root of the transcendental equation ($1 - \zeta_n \cot \zeta_n = Bi$)