COOLING RATES OF FRUITS AND VEGETABLES

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Abstract: *Rapid cooling after harvest is essential for quality maintenance of fresh fruits and vegetables. This study evaluates the cooling rates of selected fruits and vegetables in an experimental device designed and built to investigate temperature effects on fresh fruits and vegetables. 'Rocha' pear (*Pyrus communis*), 'Camarosa' strawberry (*Fragaria × ananassa*), 'Farbaly' apricot (*Prunus armeniaca*), 'Maris Peer' white potato tuber (*Solanum tuberosum*) and white mushroom (*Agaricus bisporum*) were used in the experiments in samples of three mass ranges: (1) 81.8 to 90.1 g; (2) 190.9 to 249.7 g; and (3) 403.3 to 506.3 g. Produce were cooled from initial temperatures ranging of 22.8 °C to 26.3 °C to a final steady state temperature with a cooling fluid at 0.3 °C and cooling parameters were determined from the experimental measurements. At the same mass range between 81.8 to 90.1 g the produce were ordered by decreasing cooling rate as follows: mushroom > strawberry > potato > apricot > pear. However, at mass range from 403.1 to 453.9 g the cooling rate differences among commodities were not as large as with lower masses and their order was: mushroom > potato > strawberry = apricot > pear. In general, all produce, masses and sizes tested, cooled to 0.6 °C in 24 h. Furthermore, a deviation of 0.3 °C between samples of potato, strawberry, apricot and pear, and glycol solution temperature was observed. In the case of mushroom, a higher temperature deviation of 0.5 °C was measured. The results suggest that in the experimental cooling system used, product specific heat and respiratory heat production are not the only determinants of the cooling rate. Product size and density play major roles.*

Keywords: cooling, fresh horticultural produce, heat transfer, precooling, quality, refrigeration.

1. INTRODUCTION

Cooling and subsequent temperature maintenance at the recommended levels during transportation or storage have long been known to be the most effective means of extending postharvest life of fresh fruits and vegetables [1]. Refrigeration is effective as a postharvest technology because low temperature simultaneously affects in a positive way most causes of losses: it lowers the metabolic rate; slows compositional changes; diminishes water loss and decay development [2].

Cooling, i.e. the removal of “sensible” heat, also known in the postharvest context as “field heat”, requires a much greater refrigeration capacity than holding produce at a constant temperature [3, 4]. In the postharvest lingo heat removal is often referred to as *precooling* to emphasize that produce should be cooled prior to transportation or storage [5]. Since *precooling* is the actual cooling and not an operation prior to cooling, the phrase *rapid cooling* is used instead in this work. Specific methods and equipments for rapid cooling of fruits and vegetables have been developed [2, 4, 5]. These cooling methods fall into four main types, in addition to the standard room cooling: forced air-cooling, hydrocooling, ice cooling, and vacuum cooling.

In addition to the compatibility between the cooling system and the commodity, the design and operation of cooling systems for fruits and vegetables requires the accurate calculation of heat loads and cooling rates. The heat to be removed per unit mass of product (Q) to cool it from the initial temperature T_i to a final T_f depends on the specific heat (C_p), as described in equation 1.

$$Q = C_p (T_i - T_f) \tag{1}$$

The cooling rate is a key determinant not only of the product heat load, but of the duration of operations and the quality and postharvest life of produce. Cooling rates can be effectively described by the calculation of the cooling coefficient (C) and the half-cooling time (Z) [5].

The cooling ratio (sin. temperature ratio, Y) is the unaccomplished temperature change as a percentage of the total cooling possible in the system. This ratio is calculated by equation 2, where, T is the flesh temperature (ºC) at the time t (h), T_0 is temperature in the cooling fluid (ºC), and T_i is the initial temperature of the flesh (ºC).

$$Y = \frac{T - T_0}{T_i - T_0} \tag{2}$$

Cooling time also may be predicted using the cooling coefficient. The cooling coefficient indicates the change in the fractional unaccomplished temperature difference between the product and its environment per unit change in cooling time [5]. Under the non-Newtonian heat transfer conditions that often occur in postharvest situations, C is calculated using equation 3, where the subscripts for Y and t indicate sampling times.

$$C = \frac{\ln Y_1 - \ln Y_2}{t_1 - t_2} \tag{3}$$

The half-cooling time ($t_{1/2}$) is time required to reduce the temperature difference between the product and the refrigeration fluid by one-half, and is calculated from the cooling coefficient (Equation 4).

$$t_{1\!/\!2} = \frac{\ln\left(1\!/\!2\right)}{C} \tag{4}$$

The instantaneous cooling rate (R, expressed in ºC h^{-1}) is calculated with Equation 5.

$$R = C \cdot (T - T_0) \tag{5}$$

The time required to remove one-half of the difference between the initial flesh temperature and the temperature of cooling medium is known as the half cooling time. This value remains constant for the particular set of cooling conditions from which it was determined [4, 6].

For best quality and storage life, harvested produce should be rapidly cooled to seven-eighths of the difference between the initial flesh temperature and that of the cooling fluid. Additional cooling to the final storage or transportation temperature is achieved in the cold rooms or transport containers [4, 6, 7].

This study describes the cooling rates of fruits and vegetables in an experimental cooling system, as affected by commodity type, sample mass and size.

2. MATERIAL AND METHODS

2.1. Plant materials

'Rocha' pear (*Pyrus communis*), 'Camarosa' strawberry (*Fragaria* × *ananassa*), 'Farbaly' apricot (*Prunus armeniaca*) fruit, and 'Maris Peer' white potato tuber (*Solanum tuberosum*) and white mushroom (*Agaricus bisporum*) were used in the experiments. Cooling of each product was performed at three sample mass ranges named (1) 80 to 89 g, (2) 190 to 250 g and (3) 403 to 506. Mass and size (grade) of produce samples are indicated in the Table 1.

Table 1. Mass and size of product samples used in the experiments.

Plant material	**Sample mass per range (g)**			**Diameter (mm)**
	(1)	**(2)**	**(3)**	
Apricot	85.6	222.4	453.9	40 – 45
White mushroom	85.6	203.5	403.1	30 – 40
Potato	88.7	206.6	506.3	28 – 32
Pear	81.8	249.7	415.6	55 – 60
Strawberry	80.5	190.9	403.3	28 – 32

2.2. Experimental cooling conditions and temperature measurements

Produce were cooled in a custom-made experimental device in operation at the Freshness Lab, Instituto Superior de Agronomia, University of Lisbon [8]. Produce samples with different mass (Table 1) were placed inside of 2.15 L glass jars immersed in a 10% glycol solution previously cooled to 0 ºC. Six replicated glass jars were used for pear, strawberry and potato, and three replicates used for apricot and mushroom.

Temperature was measured at 30 min intervals with a digital thermistor thermometer (model Checktemp 1, Hanna Instruments, Woonsocket, RI, USA), while maintaining the produce samples inside the immersed glass jars. The thermometer probe was inserted into a fruit, tuber or mushroom with the tip near the center of the organ. Four temperature measurements were made in each replicate at each sampling time. Different individual produce pieces were punctured in each sampling measurement. The temperature of the glycol solution was measured at regular intervals in the 12 sampling points at a depth of 15 cm.

2.3. Cooling calculations

Cooling parameters were calculated from the direct temperature measurements. The cooling ratio (Y) was calculated using the equation 2, the cooling coefficient (C) was calculated using the equation 3, the half-time of cooling ($t_{1/2}$) was calculated from the cooling coefficient (equation 4) and the instantaneous cooling rate (R) was calculated with the equation 5.

3. RESULTS

3.1. Apricot

Apricot samples with initial temperature of 25.4 ºC cooled with a coefficient of 2.2, 1.7, and 1.2 h for mass ranges 1, 2 and 3, respectively. Apricots had higher flesh temperature than the other produce, even when subjected to the same initial room temperature (Table 3). In this fruit, the stone can act as a thermo-accumulator keeping the fruit flesh at higher temperature than the surface. The time to 7/8 cooling of apricots was similar for sample mass range 1 (85.6 g) and sample mass range 2 (222.4 g) but longer in the sample mass range 3 with 454 g (Table 2).

3.2. Mushroom

White mushroom cooled faster in the first hours of refrigeration, including samples with mass range 3 (Table 2 and Figure 1B). The time to 7/8 cooling was 0.75 h and 1.5 h for mass range 1 and mass 3, respectively. Further cooling of mushroom samples was slow when the temperature reached about 1.0 °C with a lowest temperature of 0.6 °C achieved independently on the mass (Figure 1 B). Mushrooms has the highest cooling coefficients among the produce examined at any given mass (Table 3).

3.3. Potato tuber

Cooling rates of the small ‘Maris Peer’ potato tuber are given in Tables 2 and 3, and Figure 1 C. Potato tuber with sample mass range 1 and 2 cooled to 0.9 °C with a 7/8 cooling time of 1.00 h (Table 2). Additional 2 h were required to cool sample mass range 3 to the same temperature of 0.9 °C (Figure 1C).

3.4. Pear

Initial flesh temperature ranged from 22.4 °C to 24.5 °C depending on the day of measurements (Table 1). Results are presented in Tables 2 and 3, and Figure 1 D. Sample mass range 3 (415.6 g) and fruit flesh temperature of 22.4 °C cooled to 0.6 °C after 24 h. There were no difference in time of 7/8 cooling rate measurements among samples with different mass (Table 2). In all experiments, pear needed at least 24 h to cool fruit flesh temperature to 0.6 °C (Figure 1 D). Pear was the product with the lowest cooling coefficient (Table 3).

3.5. Strawberry

Strawberry was cooled to 0.5 °C after 24 h. Among the products tested, strawberry was the one that reached the lowest temperature (a 0.5 ºC difference between product and fluid temperatures, Figure 1 E). Strawberry samples required 0.75 h, 1.00 h, and 1.75 h to 7/8 cooling in sample mass 1, 2 and 3, respectively (Table 2). This cooling time was the second fastest, after mushroom, among the produce used in the experiments (Table 2).

Table 2. Initial temperature of samples, glycol, and time to 7/8 cooling.

Commodity	**Initial temperature of samples (°C)**	**Glycol temperature (°C)**	**Time to 7/8 cooling (h)**		
			(1)[x]	**(2)**	**(3)**
Apricot	25.4	0.3	1.00	1.25	1.90
White mushroom	24.3	0.3	0.75	1.00	1.50
Potato tuber	24.4	0.3	1.00	1.00	2.25
Pear	23.7	0.3	2.00	2.00	2.00
Strawberry	24.7	0.3	0.75	1.00	1.75

[x]Sample mass range (1) 80.5 to 88.7 g, (2) 190.9 to 249.7 g, and (3) 403.1 to 453.9 g.

Table 3. Cooling coefficient (*C*), instantaneous cooling rate (*R*) and half time cooling ($t_{1/2}$) of samples.

Commodity	***C*** **(h^{-1})**			***R*** **(°C h^{-1})**			**$t_{1/2}$ (h)**		
	(1)[x]	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**
Apricot	2.2	1.7	1.2	55.5	45.0	30.0	0.3	0.4	0.6
White mushroom	4.0	2.5	1.6	95.8	59.0	38.6	0.2	0.3	0.4
Potato tuber	2.4	2.4	1.5	57.6	57.2	36.6	0.3	0.3	0.5
Pear	1.1	0.8	1.1	23.8	17.7	24.4	0.7	0.9	0.6
Strawberry	3.2	2.0	1.2	79.4	50.0	28.8	0.2	0.3	0.6

[x]Sample mass range (1) 80.5 to 88.7 g; (2) 190.9 to 249.7 g, and (3) 403.1 to 453.9 g.

4. DISCUSSION

Differences in the cooling rates were observed among produce. At a mass range from 80.5 to 88.7 g the produce were ordered by decreasing cooling rates as: mushroom > strawberry > potato > apricot > pear (Table 3). At the mass range from 403.1 to 453.9 g the cooling rate differences were not as large produce order was: mushroom > potato > strawberry = apricot > pear (Table 3).

In the cooling system adopted, cooling rates and respective cooling times were a function of the i) specific heat of produce; ii) size of individual pieces; iii) respiration rate; and iv) contact between produce pieces and the exchange surface, and the proportion of heat transfer by conduction and convection within each jar.

Specific heat depends on produce composition and is largely determined by their water content (Table 4). Interestingly, the two fastest cooling commodities, mushroom and strawberry, were the ones with higher specific heat, suggesting that other factors have a stronger effect on the cooling rate.

Table 4. Composition and specific heat [5], respiratory heat production [3] and density of fresh fruits and vegetables [9, 10, 11, 12, 13].

Commodity	**Moisture (%)**	**Specific heat (kJ kg^{-1} °C^{-1})**	**Respiration heat at 0 °C (kJ kg^{-1} d^{-1})**	**Density (kg m^{-3})**
Apricot	86.3	3.9	1.4	1012-1322 [9]
Mushroom	91.8	4.0	9.4	460-650 [10,11]
Potato tuber	78.9	3.7	1.6[*]	1050-1250 [12]
Pear	83.8	3.8	1.3	991-1144 [12]
Strawberry	91.6	4.0	3.9	1043 [13]

[*]Respiration heat at 5 °C.

Strawberry and mushroom have higher specific heat and higher respiratory heat production than pear, potato, and apricot (Table 4). Strawberry and mushroom had higher cooling coefficients at the lower mass range (1) but differences among produce were attenuated at the mass rage (3) (Table 3, Figure 1). Therefore, produce size and contact with the exchange surface or fluid seems to have a significant effect on the cooling rates that overcome differences in specific heat or respiration rate at the largest mass ranges. Smaller size of individual strawberry and mushroom and the higher surface contact partially justify the differences in cooling rate. Potato used in this experiments had small individual size (Table 1) and lower water content than the other produce (Table 4).

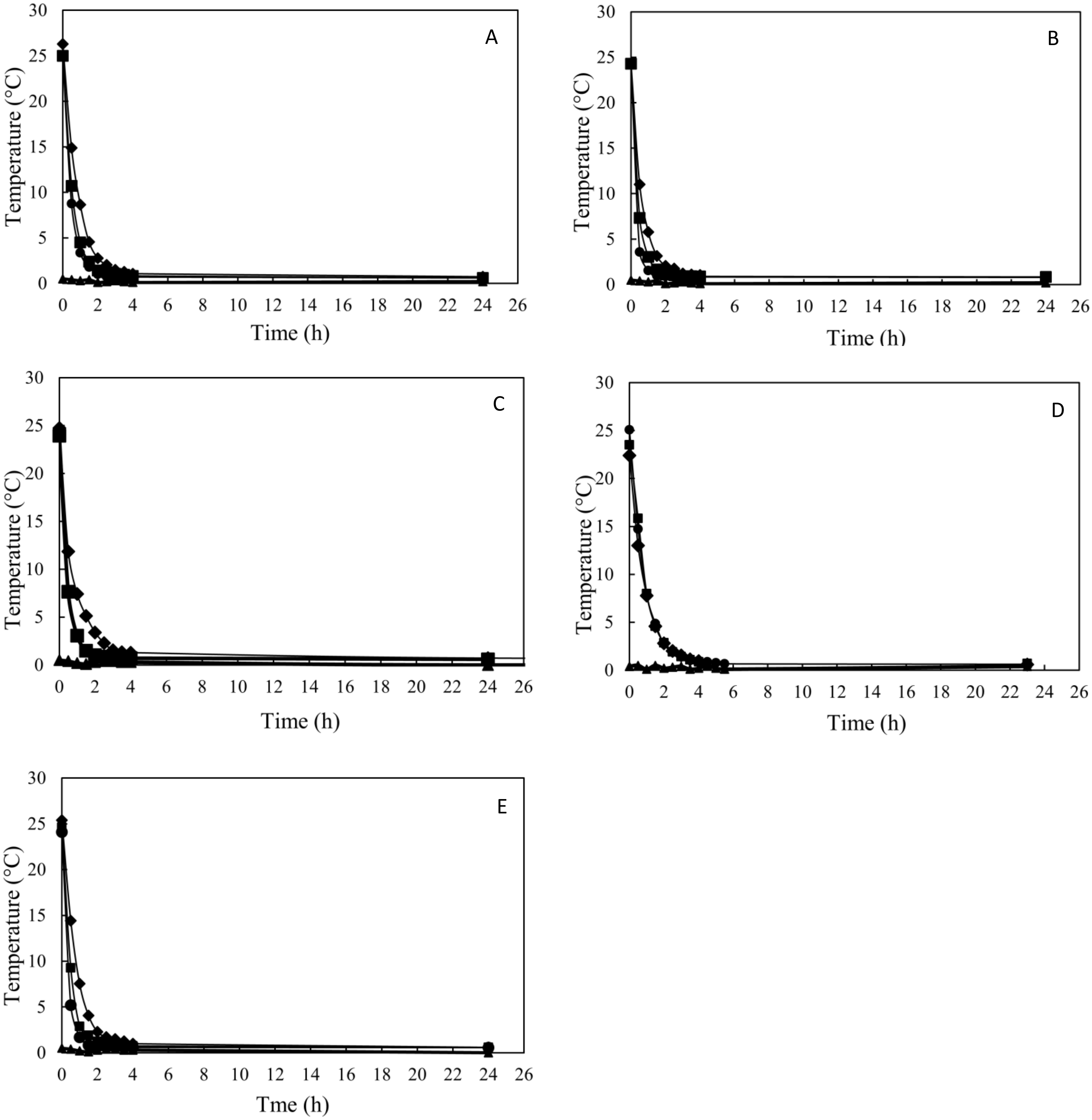

Figure 1. Cooling rate of apricot (A), white mushroom (B), potato tuber (C), pear (D) and strawberry (E) in the sample mass ranges (1)—●—; (2) ; —■—; and (3) —◆—. Temperature of the glycol solutions —▲—

In contrast to the small strawberry fruits, in pear a cooling gradient was observed within the fruit. The thinner proximal region of fruit cooled faster than the medial and wider region of pears (data not shown). Therefore, the reported values were measured in the medial region of the pear in order to give higher reliability in the results.

The temperature difference between fruits and vegetables tested and the refrigeration fluid after 24 h was in the range of 0.3 °C, increasing to 0.5 °C in the case of white mushroom. This difference was attributed to heat generation by respiration and to the slower heat transfer from inside the glass jars to the outside glycol solution since there was no active ventilation inside the glass jars. Mushroom did not cool below 0.9 °C likely due to its high respiratory heat generation [3] and the very low density [10, 11] (Table 4), indicating a higher percentage of insulating internal air.

In conclusion, the cooling properties of fruits and vegetables are not completely explained by their specific heat and respiratory heat production; density can be an important determinant of cooling properties.

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