Efficient cooling at post-harvest phase: a comparative study between peach air-cooling and hydro-cooling processes

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Abstract: *The pre-cooling of peaches is a very demanding process regarding energy conservation and management. Inappropriate cooling techniques and cooling times lead to post-harvest phase losses, resulting in wasted energy and produce. This work studies the difference in cooling time between air and hydro-cooling and the influence of peach size in their cooling time in the post-harvest phase. A numerical model was developed to evaluate the peach temperature during the pre-cooling stage. The results from the model were compared with experimental data and a set of correlations of the half-cooling time and the seven eighth cooling time as a function of the peach size were developed. Globally, the information provided in this work in terms of cooling times in both air and hydro cooling equipments could be used to improve the efficiency of the pre-cooling process by keeping the quality of the produce but reducing the energy consumption by peach.*

Keywords: Pre-cooling; Computer modeling; Post-harvest; Peach; Experimental behavior

1. INTRODUCTION

Energy and resources management are essential in order to ensure the sustainability of our planet. Most pre-cooling facilities rely on empirical experience regarding the pre-cooling of fruits and vegetables, thus leading to an increase of losses on the post-harvest phase due to improper cooling, resulting in energy and produce being wasted due to the employment of inappropriate cooling times. Projections of population growth estimate that in 2050 world population will reach 9.1 billion. In order to sustain this increase in population, it's necessary to increment the food production in 70%. Food and energy waste reduction are important in order for produce to be readily available without overloading the existing natural resources (FAO, 2009). Particularly fruits and vegetables present the higher wastage rates with almost half of the products been wasted during the agricultural process (FAO, 2012). In fact, most fruits quality diminishes as soon as they are harvested and keeps decreasing until they are consumed. Moreover, temperature has the most impact and influence in the postharvest phase regarding the quality of fruits: a higher produce temperature is correlated to a higher rate of biological processes that affects fruit quality as color, flavor, nutrients and change in texture (El-Ramady *et al.*, 2015). Thus, to be properly preserved and to reduce it's after harvesting deterioration it is necessary to cool the produce as quick as possible (Nunes, 2008). This rapid removal of the field heat to the optimal storage temperature is usually named as pre-cooling. It is one of the most important operations used in the preservation of fruit and it is essential in order to prolong their life time (Senthilkumar *et al.*, 2015).

The cooling process of fruits in the post-harvest phase, including the pre-cooling stage, has been studied and improved over the past years both experimentally and numerically (Brosnan and Sun, 2001; Fricke, 2006; ASHRAE, 2010a; Zhao *et al.*, 2016). Although air-cooling and hydro-cooling appear as the most common methods to provide the pre-cooling of peaches, these techniques require different equipment in terms of initial investment, cooling power and energy consumption. Besides, their energy needs are distinct from regular cold rooms used to store produce at constant temperature (Nunes *et al.*, 2014).

Regardless the pre-cooling method used, to efficiently cool peaches it is necessary to know the appropriate cooling time that ensures a peach core temperature change from the field value to the optimal storage value. Moreover, the cooling times of fruits are mainly dependent of their initial temperature, their dimensions and of the cooling fluid characteristics and flow behavior (ASHRAE, 2010b). Furthermore, considering a batch of peaches, if they are not cooled long enough can be wrongly considerate suitable for storage considering its surface temperature, but its interior might have not have its temperature reduced enough, jeopardizing subsequent steps of cold chain (Han *et al.*, 2015).

The purpose of the present study is to highlight the importance of the peach size in the duration of the pre-cooling process. Thus, using a three-dimensional (3D) spherical model developed on COMSOL Multiphysics, verified with experimental data, the hydro-cooling and air-cooling in the post-harvest of the peach are studied in order to provide empirical correlations of the half cooling time and the seven-eighths cooling time as a function of the peach size.

2. MATERIALS AND METHODS

2.1. Experimental

Two types of cooling equipment were used, a shower type hydro-cooling and a cold chamber as an air-cooling. The hydro-cooler (see Fig. 1a) consists of a metal box with internal dimensions of 4.0x1.5x2.6 m3 (length, width and height). The box is divided into two equal compartments to allow the cooling of fruit placed inside each of them alternately. A water tank with a capacity of 2500 liters is located in the lower part of the box and includes the evaporator of the refrigeration system. Two hydraulic pumps ensure a 7 m3/h water flow from the reservoir to the water injectors located on the top of each compartment. The refrigeration system with a nominal power of 13.6 kW allows the temperature of the water in the tank to remain practically constant during the cooling process. The rapid cooling procedure of the fruit in the hydro-cooler consists of placing a pallet with several layers of boxes of peaches inside the compartment (15 to 20 boxes with about 20 kg each). After closing of the door, the hydraulic pump starts to circulate water from the reservoir to the injectors. The cold water then flows by gravity over the fruit contained in the boxes and also passes through the empty spaces between the fruits until it reaches the reservoir again. The air-cooler (see Fig. 1b) consists on a cold chamber with internal dimensions of 4.0x2.0x2.8 m^3 (length, width, and height) and 10 cm thick polyurethane panels. An evaporator with a built-in fan is placed inside the chamber and linked to a refrigeration system with 2.6 kW nominal power to provide a uniform distribution of the cooled air throughout the space. Particularly, the air circulates throughout the peach boxes, and passes in the empty spaces between the fruits cooling them. In both equipments, to monitor the temperature drop over time, a multifunction device (Testo 435-2) with a T-type thermocouple is used (see Fig. 1c).

The thermocouple was introduced into the peach pulp until it reached the core (peach pit). This peach was placed in the center of a box among the various peaches, and in turn this peach box was also placed in the center of the set of peach boxes over a pallet. The temperature measurements were performed at 1 minute intervals for the hydro-cooler and 5 minutes for the air-cooler with an accuracy of ±0.3 °C. A second T-type thermocouple was used with same device to check every 10 minutes the cooling fluid temperature during the experiment. A set of three experimental tests were performed on each equipment and a representative averaged temperature was calculated.

a) b) c)

Fig. 1. Experimental devices used in this work: hydro-cooler (a); air-cooler (b); digital temperature recorder (c).

2.2. Simulation model

The study of the cooling process of peaches is comprised of a 3D model of transient heat conduction with imposed convection on its surface. The governing differential equations describing the heat conduction process were solved with COMSOL Multiphysics software, version 4.3 (COMSOL, 2012). In the development of the model the following assumptions were made: homogenous sphere; constant thermal properties; uniform initial temperature; no internal generation nor mass transfer; constant convective heat transfer coefficient; unsteady state conditions. According with these assumptions, the set of heat transfer equations solved is given by Eq. (1)-(3). The inward heat flux, normal to the boundary, is evaluated from Newton's law of cooling Eq. (4).

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot q = 0 \tag{1}$$

$$-\boldsymbol{n} \cdot \boldsymbol{q} = q_o \tag{2}$$

$$\mathbf{q} = -k\nabla T \tag{3}$$

$$q_o = h(T_\infty - T) \tag{4}$$

The mesh used to discretize the computational domain comprises 8415 tetrahedral elements, all with the same size. The parameters used in simulation for both air-cooling and hydro-cooling are represented on Table 1 with thermophysical properties evaluated from ASHRAE (2010c). The convective heat transfer coefficient (h) for air-cooling was computed according to Fikiins correlations for packed layers of peach (Fikiin *et al.*, 1999) considering a mean air velocity of 2 m/s, and was found to be 6 W/m^{2}K. The convective heat transfer coefficient for hydro-cooling was estimated according to Dincer *et al.*(1992) for a mean cooling coefficient of 0.00118 s^{-1} based on experimental data and was determined to be 680 W/m^{2}K. For the comparison of simulation results with experimental results as well as for the parametric study, a dimensionless temperature that includes the peach initial temperature and the cooling fluid temperature is introduced by Eq. (5). According with Eq. (5), the well-known half cooling time ($t_{1/2}$) and seven-eighths cooling time ($t_{7/8}$) are obtained when θ reaches 1/2 and 1/8, respectively. Additional details of the computational model can be found in (Ferreira, 2016).

$$\theta = \frac{T - T_\infty}{T_i - T_\infty} \tag{5}$$

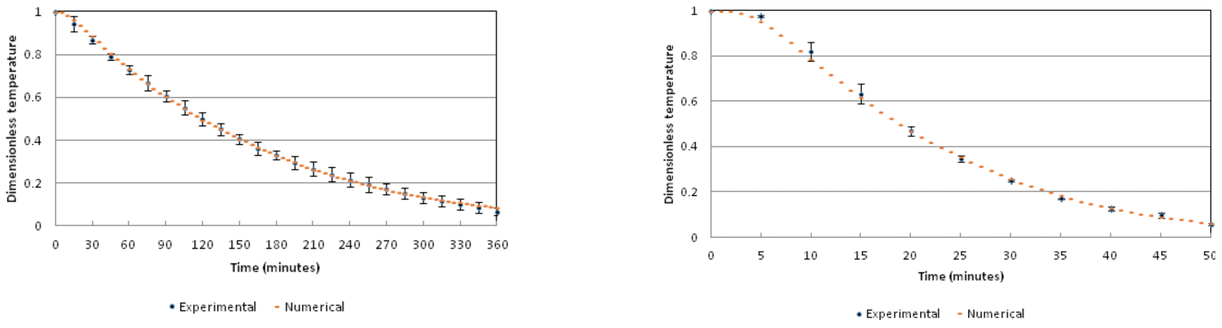
Table 1. Parameters for both air-cooling and hydro-cooling models.

Parameters	Air-Cooling	Hydro-cooling
Radius (mm)	32.3	
Density (ρ,kg/m^3)	1105.6	
Thermal conductivity (k, W/mK)	0.551	
Specific heat (c_p,J/kgK)	3868.7	
Initial temperature (T_i, ºC)	21.1	22.1
Fluid temperature (T_∞,ºC)	1.6	1.8
Study duration (min)	360	50
Study time step (min)	5	1

3. RESULTS AND DISCUSSION

3.1. Comparison between experimental and numerical results

The averaged temperatures of the cooling fluid system and peach core at the beginning and at the end of the experimental air-cooling and hydro-cooling tests are summarized on Table 1. The final peach core temperature was obtained after 360 minutes at the air-cooling experiments, 2.9ºC, and after 50 minutes at the hydro-cooling experiments, 2.3ºC. This time duration of about one sixth between both air and water cooling processes is usual and denotes a well-known greater efficiency of the hydro-cooling process. The dimensionless temperature calculated according Eq. (5) and using the peach core temperature is shown in Fig. 2 along the air and hydro-cooling processes. Both figures show the 95% confidence intervals for each of the averaged temperatures. The averaged relative error was found as 2.95% at the air-cooling experiment and 3.82% at the hydro-cooling experiment attesting a good performance of the numerical model in both situations.



a) b)

Fig. 2. Dimensionless temperature over time based on experimental and numerical data: peach air-cooling (a); peach hydro-cooling (b).

At the air-cooling process the $t_{1/2}$ presents the same value of 120 minutes when evaluated from experimental or numerical data. A $t_{7/8}$ of 307.5 minutes was found from experimental data and 310 minutes from the numerical model meaning a difference less than 1%. At the hydro-cooling process $t_{1/2}$ and $t_{7/8}$ are 19 minutes and 41 minutes, respectively, regardless of using numerical or experimental data. Comparing the two cooling processes the results show that the hydro-cooling process reaches the $t_{1/2}$ 6.3 times faster and the $t_{7/8}$ 7.5 times faster. In other words, the hydro-cooling process assures 6.3 or 7.5 more peach cooling production than the air-cooling process to the same half cooling time or seven-eighths cooling time, respectively.

3.2. Parametric Study: peach size effect on cooling time

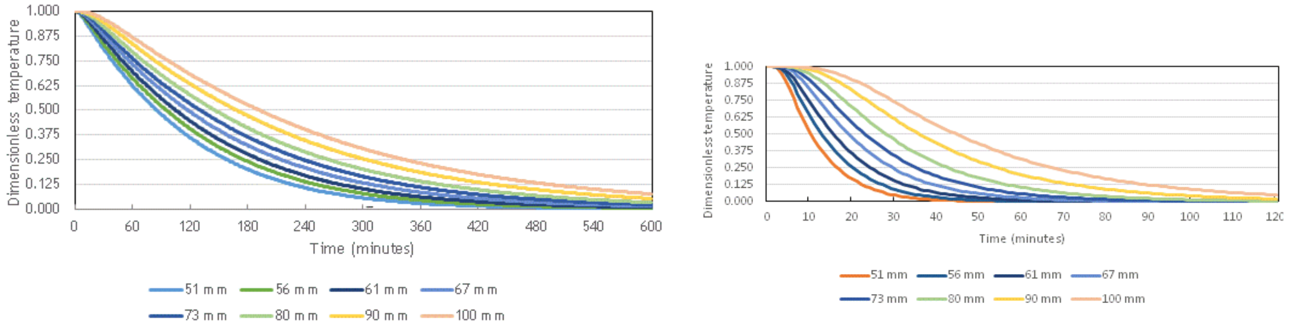
A parametric study was conducted to predict the peach thermal response as function of the peach diameter according with the values proposed by the standard for peaches and nectarines (UNECE, 2010). The available classes and corresponding diameters for each class are represented on Table 2. To ensure higher peach classes to reach the $t_{7/8}$ the simulation period was extended to 600 minutes for the air-cooling process and to 120 minutes for the hydro-cooling process. Furthermore, the lower limit of the peach diameter in each class was considered and the Class AAAA was represented by a reference peach diameter of 100 mm. The computational results for the transient dimensionless temperature of the peach core are shown in Fig. 3.

Table 2. Reference cooling times for each peach class.

Peach class	**Diameter range (mm)**	**Air-cooling**		**Hydro-cooling**	
		$t_{1/2}$ (min)	$t_{7/8}$ (min)	$t_{1/2}$ (min)	$t_{7/8}$ (min)
D	51-56	90	238	12	25
C	56-61	100	263	14	30
B	61-67	111	291	17	36
A	67-73	124	324	21	43
AA	73-80	138	359	26	52
AAA	80-90	157	405	32	64
AAAA	>90	>168	>433	>36	>72

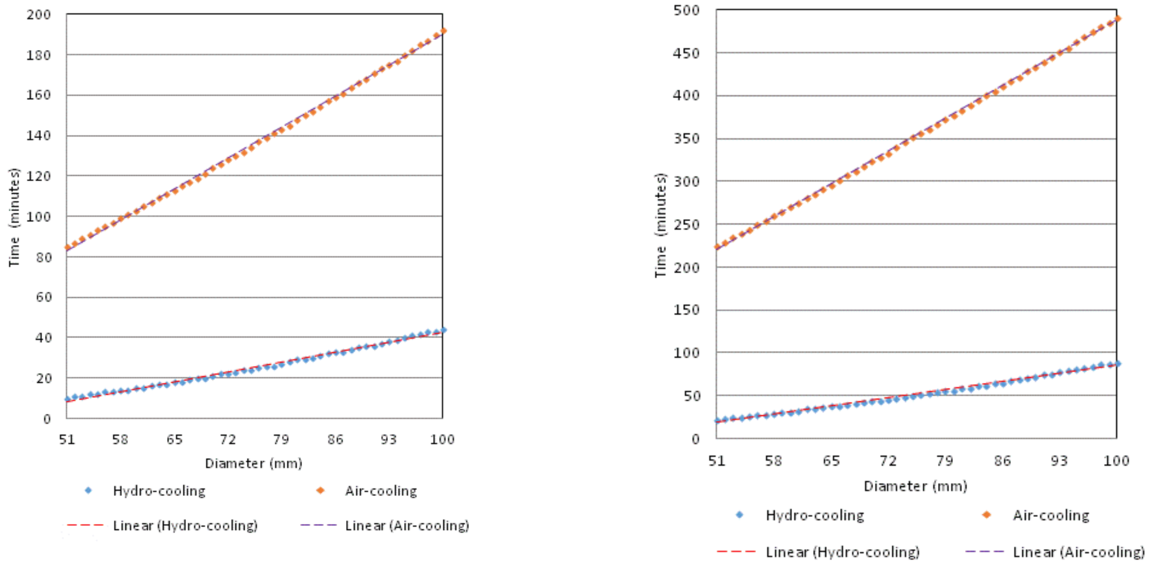
As expected, a higher rate of cooling is obtained for the hydro-cooling process and for peach small diameters. An initial lag is also verifiable for the hydro-cooling of peaches, and it is also more noticeable for the larger diameters. Fig. 4 shows the $t_{1/2}$ and $t_{7/8}$ for both cooling processes as a function of the peach size.

Comparing peach diameters of 51 and 100 mm, $t_{1/2}$ increases 2.3 times and $t_{7/8}$ increases 2.2 times for the air cooling process and respectively 4.4 and 4.0 for the hydro-cooling process.



a) b)

Fig. 3. Peach core transient dimensionless temperature for the selected diameters: air-cooling (a); hydro-cooling (b).



a) b)

Fig. 4. Variation of the half-cooling time (a) and seven-eighths cooling time (b) with the peach size.

Table 2 lists reference cooling times resulting from the numerical simulations in each peach class. This table allows the user to quickly obtain a reference peach pre-cooling time, corresponding to the time period that the peach box must be inside the air cooler or hydro cooler to ensure the temperature storage conditions obtained from an half cooling time or a seven-eighths cooling time. Alternatively, resulting from the almost linear trend between $t_{1/2}$ and $t_{7/8}$ and the peach diameter, a set of linear correlations with the corresponding determination coefficients are proposed on Table 3. Although some cooling heterogeneity may be expected to each one of the fruits within the peach box and pallet, and larger on air pre-cooling situation, the difference of temperature-related fruit quality degradation as a result of this cooling heterogeneity is insignificant for individual fruit (Wu and Defraeye, 2017).

Table 3. Statistical correlations for the half cooling time and seven-eighths cooling time.

Parameters	**Air-Cooling**	**Hydro-cooling**
Half cooling time ($t_{1/2}$, minutes; D, mm)	$t_{1/2} = 2.1817 \cdot D - 28.175$ (R^2= 0.9990)	$t_{1/2} = 0.6972 \cdot D - 27.082$ (R^2= 0.9929)
Seven-eighths cooling time ($t_{7/8}$, minutes; D, mm)	$t_{7/8} = 5.4563 \cdot D - 57.569$ (R^2= 0.9996)	$t_{7/8} = 1.3662 \cdot D - 51.111$ (R^2= 0.9923)

4. CONCLUSIONS

A numerical model was developed in order to predict the transient temperature change of peaches in the pre-cooling stage. The model results were compared with real data from two experimental devices: a hydro-cooler and an air-cooler. Overall, the proposed model provides a good representation of the peaches behavior during the cooling processes using air or water as cooling fluid. Moreover, it illustrates that hydro-cooling processes are more efficient to provide the pre-cooling of peaches than air-cooling processes allowing less time to reach the optimal temperature of peach conservation. The results show that using the hydro-cooling instead of the air-cooling can increase up to 7.5 times the peach production for the same final storage temperature. From the developed model, a parametric study was ensued. The effect of the peach size on cooling time was studied and the half-cooling time and the seven eighth cooling time were evaluated. A set of correlations from the numerical studies were provided to allow a rapidly estimation of the half-cooling time and the seven eighth cooling time as a function of peach size.

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