WFL Publisher
Science and Technology
Food, Agriculture & Environment Vol.2 (1) : 135-140. 2004
www.world-food.net

Container opening design for horticultural produce cooling efficiency

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Received 12 September 2003, accepted 15 January 2004.

Abstract

Rapid cooling is recommended to decrease postharvest losses of fruits and vegetables. Cooling rate and homogeneity are affected by the package design. Thus, the aim of this research was to evaluate the effect of different container opening configurations on cooling process. The variables analyzed were: thirteen opening designs and four airflow rates. Twenty-eight out of the 224 produce simulators inside the container were instrumented with thermocouple. The configurations of the openings on the package walls were compared in terms of three individual orifice areas (0.67, 1 and 2%) distributed in 4 and 3 positions in width and height (X and Y directions), respectively. The statistical analysis demonstrated that airflow rate was the most important variable in explaining the variations of half-cooling time. The opening position in Y direction had no significant effect on pressure drop, cooling rate and its uniformity. At the maximum airflow rate studied, individual area and position of the openings had no significant effect on half-cooling time. Increasing total opening area for more than 8% did not produce significant cooling rate increment. The 14% opening area generated cooling rates as uniform as the ones obtained using fully opened configuration as well as negligible differences in pressure drop.

Key words: Package openings, airflow, cooling rate, uniformity, pressure drop.

Introduction

Postharvest losses are estimated to range from 30-40% of total harvested produce in the world[1]. Precooling is a critical step in slowing down the metabolic processes of the perishable produce, extending their shelf life, and decreasing the rate of deterioration by microbiological activity and water loss[2]. Forced-air cooling is the most common and efficient precooling technique used commercially, particularly for produce that are sensitive to water contact [3-5].

The efficiency of the forced-air cooling process is mainly evaluated by the rapidity and the uniformity in produce temperature reduction compared to the energy input. Therefore, process improvement is a function of the cooling rate optimization. In terms of air distribution, uniformity is directly related to the number and distribution of openings[6] on the container walls. Increasing the total opening area causes a decrease in pressure drop through the container[6, 7] but a decline in its structural resistance. Thus, the design of a container for handling horticultural produce must consider both the cooling efficiency and the structural aspect.

A wide variety of containers for storage and transportation of fruits and vegetables have been adopted over time. Container design was generally based on production capability and structural rigidity while adequate air distribution was not considered[8]. Rather than shape, opening area plays a more important role in airflow restriction[2, 9-11]. A total opening area less than 25% of the container surface restricts airflow considerably[6, 11]. Reducing the opening area below 10% generates a lower cooling rate and sharply increases the cooling cost[10].

Opening position has also an important effect on cooling rate uniformity[12]. Openings must be evenly distributed on package walls to provide homogeneous temperature reduction of the entire packed produce. When choosing opening positions, the package stack pattern must be considered to ensure that the openings of side by side packages are aligned to avoid obstruction by other container walls[13, 14].

Since air movement is driven by the pressure differential, it follows the path of least resistance, generally creating air dead zones inside of the container. Secondary packaging and produce reduce the air movement[15, 16]. Even produce positioning has a significant effect on air circulation; for example: although straight stacking of oranges resulted in the same porosity value as randomly stacked ones, straight stack generated a better defined airflow path, and consequently, a lower pressure drop for the same airflow rate[17]. The number of layers and orientation of the produce inside a package also generates an important effect on airflow resistance[9, 11, 17-19]. Many authors also observed that increasing the distance of the produce from the air inlet caused lower cooling rates[10, 12, 20-23]. Increasing airflow rate enhances average cooling rate of produce[12, 14, 16, 22, 24] as well as decreases the temperature gradient inside the container[10, 21].

Horticultural crops exhibit differences in physical and chemical properties, which also modify as they ripen[25]. For this reason, it is very difficult to maintain similar produce positioning patterns and thermal properties when replicating experiments with packed produce. Therefore, they are occasionally replaced by more stable produce simulators which help to minimize test variability[6, 12, 26, 27].

The objective of this research was to evaluate the effect of the area and distribution of openings on cooling rate and uniformity using straight stacked produce simulators.

Material and Methods

Produce simulator: Two hundred twenty-four hollow polychlorinated vinyl (PVC) balls, 68.0 mm outside diameter, 0.8 mm wall thickness, and 9.50 g mean weight, were used to simulate spherical horticultural produce. Twenty-eight balls were filled with 3% mass-base agar-agar and water solution, and instrumented with a 24-gage type T thermocouple positioned at their center. The instrumented balls were stacked along with non-instrumented balls forming a 224-ball orthogonal matrix of eight rows (X direction) by four layers (Y) and seven columns (Z) (Figure 1). The matrix was supported by a metallic grid to provide stability. The metal grid consisted of a 1.5 mm-diameter wire, 25.4 mm orthogonally spaced resulting in an 88.5% total opening area. The matrix dimensions were 560 by 280 by 490 mm in the X, Y and Z directions respectively, which resulted in 47.6% porosity. Table 1 presents the relative position of the 28 instrumented balls.

Experimental set-up: Figure 2 shows a diagram of the experimental set-up which consisted of a tunnel containing the ball matrix, a fan, and an airflow measuring device. The setup was controlled using a data acquisition and control unit. The tunnel was made of wood with a 560 by 280 mm inside cross-section and 1700 mm in length and insulated with 12-mm-thick rubber foam. The matrix was positioned at a 14 00 mm distance from the end of the air-inlet tunnel. The air-outlet of the tunnel consisted on a 600 mm long plenum allowing the measurement of the air pressure drop (APD) across the matrix of balls with the use of a pressure transmitter in the range of 0 to 0.250±0.0025 mm of water (Model 607-0, Dwyer Instruments Inc. Michigan City, IN, USA). The end of the air-outlet tunnel was air-tightly connected to the inlet of a backward-curved centrifugal fan driven by a 2.3 kW variable speed motor. The experimental setup was placed inside a refrigerated room maintained at 5°C.

The airflow measuring device consisted of a 97 mm-diameter and 1830 mm-long tube attached to the fan outlet. A Pitot tube was placed at the center of the 97 mm tube. Two pressure transmitters 0-0.250±0.0025 and 0-6.25±0.0625 mm of water (Model 607-0 and 607-1 respectively, Dwyer Instruments Inc. Michigan City, IN, USA) were used to measure the dynamic pressure of the air circulating during the tests. These two transmitters were selected to cover the entire range of measurement and guaranty an acceptable precision according to standard recommendations[25]. The air-measuring device was calibrated before the experimentation using a 16-point measuring pattern, according to the same recommendations[25]. A calibration curve was developed to express the airflow rate as a function of the dynamic pressure measured at the center of the tube.

Twelve pairs of polypropylene plates, 560 wide by 280 high and by 2 mm thick, were perforated. One, two, four and seven columns (X direction), and one, two and three layers (Y direction) of square openings were made through these plates (Table 2). The total opening areas (TOA) through the plates were 2, 4, 8, and 14% using holes having individual opening areas (IOA) of 0.67, 1, and 2%. These pairs of plates were spaced 490 mm apart to simulate a package. A "fully-open-configuration" was also tested which covered 88.5% of the cross-sectional area of the tunnel due to the metallic grid.

Four airflow rates equivalent to 0.5, 1, 2 and 4 $L \cdot s^{-1} \cdot kg^{-1}$ were tested, by adjusting the fan speed until the desired dynamic pressure was obtained.

A data acquisition system (DAS, model CAD1232/MCS1000, Lynx Tecnologia Eletrônica, São Paulo, Brazil) was used to record on a 20 s-interval base simultaneously, the temperature inside the balls along with the air temperature before and after the ball matrix, the pressure drop and the dynamic pressure at the Pitot tube.

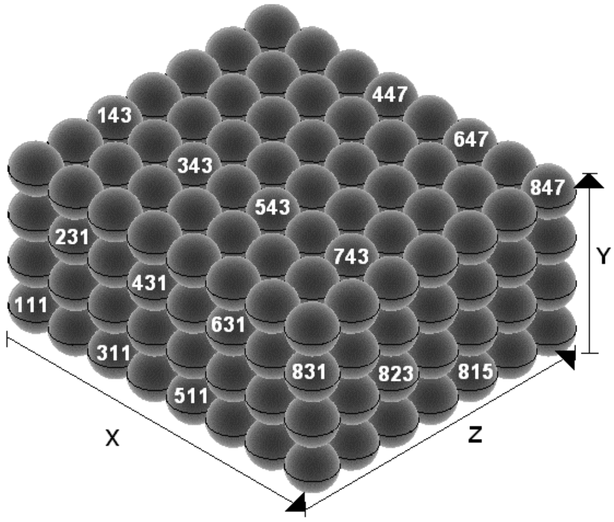

Figure 1. Overview of the matrix of balls. The numbered balls are instrumented. The three digit number on a ball represents the X, Y, and Z positions, respectively.

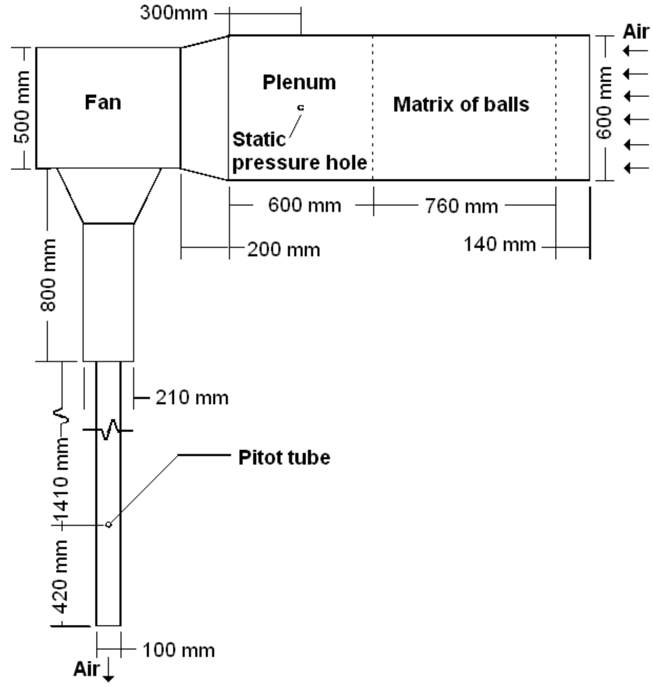

Figure 2. Top view of the experimental set-up.

***Experimental procedure*:** Thirteen opening areas and four airflow rates were tested in a complete block design, to determine the effect of the total opening percentage, the airflow rate and the ball positioning on the cooling rate of the balls. Each test was repeated three times. Prior to the start of each test, the tunnel holding the balls was placed at ambient temperature, approximately 25°C. An axial fan forced the air through the matrix to reheat the balls for approximately 60 minutes. After this conditioning period, a pair of perforated plates was installed and the tunnel was placed in the cold room. The tunnel was connected to the inlet of the centrifugal fan, which was then turned on immediately. The results were recorded until the temperature of the warmest ball had reached 7°C. The temperature-time data recorded were used to calculated the cooling coefficient of each ball for all treatments based on their half-cooling time (HCT) using a dedicated Excel™ macro developed by Goyette et al[29]. The uniformity (CU) of the cooling process was determined as the inverse of the standard deviation of the HCT of the balls for each test. A Stepwise Forward-Backward Regression[30] was performed to determine the effect and the interactions between the airflow rate (AFR), the number of openings in the X (NOX) and Y (NOY) directions, the individual opening area (IOA), as well as the position of the balls in the X, Y, and Z directions (PXD, PYD, PZD) on the HCT, CU, and APD. The goodness of fit coefficient (R^2_i) was calculated to determine the increase in variance explained by adding a dependent variable i to the other variables in the regression equation.

Results and Discussion

The statistical analysis showed a rather large experimental error. The latter is most likely due to difficulties of uniformly filling the balls with agar-agar solution and the wide imprecision of airflow measurements, which allowed identifying only large differences.

As expected, the following parameters produced a significant effect ($P<0.0001$) on the HCT: AFR ($F_{3, 4360} = 6633$), position of the balls in X ($F_{3,4360} = 387$), Y ($F_{1, 4360} = 134$), and Z directions ($F_{3, 4360} = 169$), NOX ($F_{3, 4360} = 183$), and IOA ($F_{3, 4360} = 31$), and NOY did not have a significant effect on HCT ($F_{2, 4360} = 3.68$, $P = 0.055$). The Stepwise Forward-Backward Regression allowed evaluating the relative importance of the independent variables in explaining linearly the variation of HCT. In a decreasing order, AFR explained 55.8% of HCT variation, followed by PXD (3.2%), PZD (1.6%), NOX (1.5%), PYD (1.1%), IOA (0.2%), and NOY (<0.1%) for a total of 63.3% in the linear regression. The variables AFR, IOA, and NOX provided all a significant effect on CU and APD, but not NOY, as observed for HCT. These results are shown in Table 3a.

Airflow rate: When increasing AFR from 0.5 to 1, 2, and 4 L•s^{-1}•kg^{-1}, the average HCT was reduced by 24, 50, and 61% respectively, while the coefficient of uniformity (CU) increased by 33, 156, and 290% respectively. Similar results in the diminution of HCT were noticed[12] when doubling an AFR of 2 L•s^{-1}•kg^{-1}. A regression analysis determined a non-linear model to infer the HCT response as a function of AFR and TOA (Equation 1).

Table 1. Relative position of the instrumented balls in the matrix. The air was flowing in the increasing number direction of the Z axis.

# of ball	X	Y	Z
1	1	1	1
2	3	1	1
3	5	1	1
4	2	3	1
5	4	3	1
6	6	3	1
7	8	3	1
8	4	2	3
9	6	2	3
10	8	2	3
11	1	4	3
12	3	4	3
13	5	4	3
14	7	4	3
15	2	1	5
16	4	1	5
17	6	1	5
18	8	1	5
19	1	3	5
20	5	3	5
21	7	3	5
22	1	2	7
23	3	2	7
24	5	2	7
25	7	2	7
26	4	4	7
27	6	4	7
28	8	4	7

$$HCT = 26.1544AFR - 58.5849 \ln(AFR) + 2.6618 \ln(TOA) \quad R^2=0.892 \qquad (1)$$

Where:

HCT = half-cooling time, min;
AFR = airflow rate, L•s^{-1}•kg^{-1};
TOA = total opening area, %.

The fairly high goodness of fit coefficient (R^2) obtained confirms the previous assertion, which stated that airflow rate explained most of the variation in produce cooling time response. The latter agrees with the results found by Arifin and Chau[21] who also claimed a non-linear relationship between AFR and cooling time, and disagrees with other author findings [22]. On the other hand, Boyette's[16] results point to a linear correlation between airflow rate and cooling time for the tested range, but the author suggests an exponential function over a larger range.

At the maximum AFR (4 L•s^{-1}•kg^{-1}), the only variables to be considerate in the HCT response are PXD and PYD (Table 3b). Thus, the opening area had an effect on HCT only for the lower values of AFR (Figure 3) which agrees with Arifin and Chau's findings[21]. Therefore, it is possible to compensate the effect of the open area on both cooling rate and uniformity by increasing the airflow rate.

Ball position: In general, ball position in every direction had a significant effect on the HCT, which agrees with the results presented by many authors[12, 20, 22]. For the statistical analysis of the effect of the ball positions in X and Y directions (PXD and PYD), the matrix center was considered as the origin reference, instead of the matrix left inferior edge as it had been used for ball positioning purposes. All openings were also distributed symmetrically relative to that point, permitting a symmetric approach. This allowed detecting a significant effect of the distance separating the balls and openings on HCT.

The position of the balls in Z direction (PZD) had significant effect (Table 3b) on HCT for the lower airflow rates (≤1 L•s^{-1}•kg^{-1}), but not for the higher AFR values (≥4 L•s^{-1}•kg^{-1}). No linear decrease in cooling rate was observed as the depth increased (PZD), which does not agree with the results obtained by other authors[22]. This result could be explained by the fact that most balls were not filled with agar-agar; hence the air was not warmed up as it usually occurs.

However, because the balls were empty, it was possible to identify another phenomenon. Although, in general, the balls of the first layers cooled faster, the highest HCT values were observed in the penultimate instrumented layer (PZD = 5), not in the last layer (PZD=7). A possible reason for the values found in the last layer is the proximity of layer 7 to the air outlet openings which could have increased the air velocity through the layer, forming a turbulent zone, and compensated for the lower temperature differential between the air and the balls of this last layer. The same phenomenon stated by different authors[12, 10, 20, 22] was observed at the beginning of cooling process, regarding the increase of air temperature as it passes through the hot produce, keeping warm the rear produce. The lower the AFR, the longer is the period of warm air production and the higher the difference of air temperatures between the inlet and the outlet sides of a package are.

***Opening area*:** NOX had an effect on HCT for the lowest airflow rates (AFR≤2 L•s^{-1}•kg^{-1}) (Table 3b). This effect disappeared at higher AFR. NOY had a significant effect on HCT only at the airflow rate of 1 L•s^{-1}•kg^{-1} (Table 3b). The proximity of the openings to the balls could explain this almost absent effect. In fact, the largest distance separating the balls and the openings in this direction was equal to double the diameter of a ball.

Lower NOX resulted in lower cooling uniformity (CU). The CU could then be predicted by a linear equation model considering AFR (L•s^{-1}•kg^{-1}) and NOX (Equation 2).

$$CU = 0.079\ AFR + 0.014\ NOX \qquad R^2=0.911 \qquad (2)$$

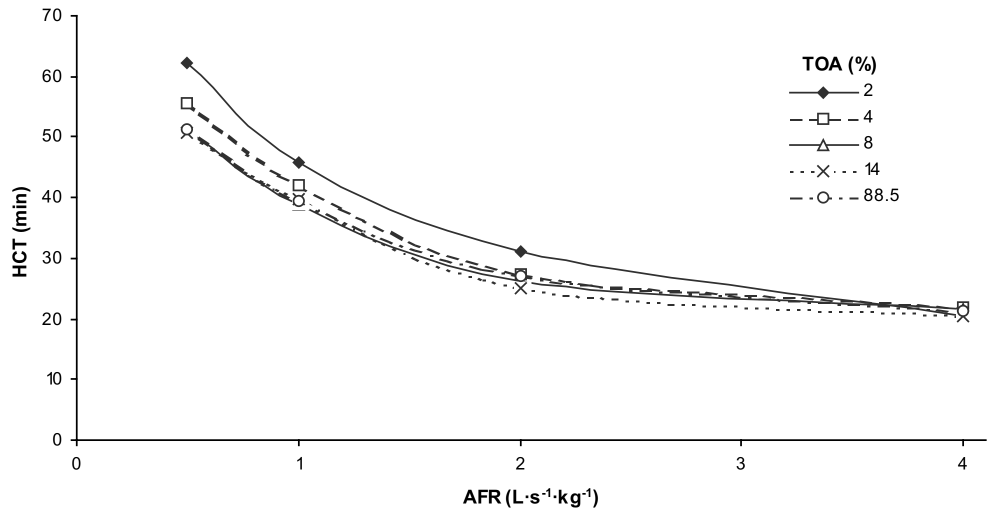

Figure 3. Half-cooling time (HCT) as a function of airflow rate (AFR) and total opening area (TOA).

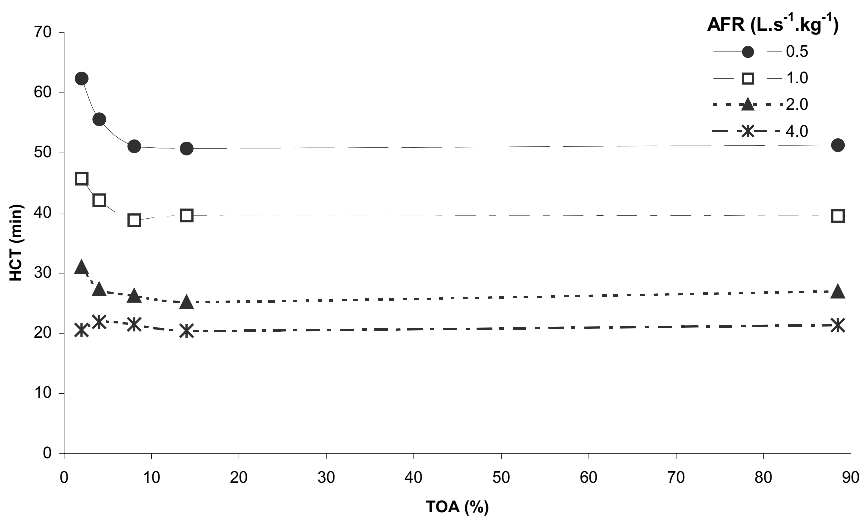

Figure 4. Half-cooling time (HCT) as a function of total opening area (TOA) and airflow rate (AFR).

Table 2. Combinations of the number of openings in X and Y directions and individual opening area (IOA) to produce total opening area (TOA).

TOA (%)	IOA (%)					
	2		1		0.67	
	NOX	NOY	NOX	NOY	NOX	NOY
2	1	1	1	2	1	3
4	2	1	2	2	2	3
8	4	1	4	2	4	3
14	7	1	7	2	7	3

Table 3. Results of the statistical analysis showing the level of significance of the correlations between the independent variables and: a) air pressure drop and cooling uniformity, and b) half-cooling time.

a)	AFR	NOX	IOA	NOY
APD	<0.0001***	<0.0001***	<0.0001***	0.516
CU	<0.0001***	<0.0001***	0.002***	0.698

b)

HCT	AFR				NOX				
	0.5	1	2	4	1	2	4	7	Full
AFR					<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***
PXD	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	0.016*	<0.0001***	<0.0001***	0.012*
PYD	<0.0001***	<0.0001***	<0.0001***	0.002***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	0.344
PZD	<0.0001***	<0.0001***	0.057	0.511	<0.0001***	<0.0001***	<0.0001***	<0.0001***	0.001***
NOY	0.312	0.015*	0.326	0.264	0.741	0.638	0.889	0.760	
IOA	<0.0001***	0.003***	0.0001***	0.363	0.881	0.944	0.713	0.810	
NOX	<0.0001***	<0.0001***	<0.0001***	0.094					

*** = has a significant effect, P<0.01
* = has a significant effect, P<0.05

Where:

AFR	=	Airflow rate
APD	=	Air pressure drop
CU	=	Cooling uniformity
HCT	=	Half-cooling time
IOA	=	Individual opening area
NOX	=	Number of openings in X direction
NOY	=	Number of openings in Y direction
PXD	=	Position of the ball on X-axis direction
PYD	=	Position of the ball on Y-axis direction
PZD	=	Position of the ball on Z-axis direction
TOA	=	Total opening area

Pressure drop: Using different IOA to form specific TOA did not produce any significant effect on ADP but, varying TOA produced a significant effect on ADP ($F_{2, 69} = 152.07$, $P<0.0001$). The latter results demonstrate the TOA affects the cooling rate and not the individual value of the opening, which is in agreement with Vigneault and Goyette's findings[6].

The APD (mm water) could then be modeled as a function of AFR ($L•s^{-1}•kg^{-1}$) and TOA (%) using Equation 3.

$$APD = 37.487\ TOA^{-1.5}\ AFR^{2} \qquad R^2=0.993 \qquad (3)$$

This relationship agrees with many authors[6, 17] who observed that APD through a vented package follows approximately a quadratic relationship with the average velocity which is related to airflow rate. Other authors[7] also stated that pressure drop scales to $TOA^{-1.5}$.

The cooling rate was generally stable when the total opening area ≥8% (Figure 4). Similar results[10] stated that an opening area < 10% increases the cooling time. TOA of 14% produced a pressure drop responses 2.5 times greater than a fully opened end, 5 compared to 2 mm of water, respectively. This difference could be considered negligible in terms of its impact on the energy required compared to the increase in pressure drop of 71 mm of water generated by using a TOA of 2%. Furthermore, no significant improvement was observed on HCT or on CU when increasing TOA from 14% to fully opened end. This 14% TOA could be considered as the maximum TOA required for the container design in view of cooling rate and energy.

Conclusions

The effect of position and surface for the openings of a container used for horticultural crop handling on the cooling rate was partially determined. The accuracy and repeatability of the results can be improved by designing a more stable produce simulator. Among all independent variables studied, airflow rate was found to contribute the most for half-cooling time of horticultural produce. Increasing the airflow rate could compensate for the negative effect of less opening area but, it would also raise the pressure drop through the container, and consequently the energy required for the process. Distribution of openings in Y direction did not produce a significant effect on the pressure drop and the cooling rate and its uniformity. The effect of ball position in the Z direction (depth) on HCT was significant only for airflow rates ≤ 1 L•s^{-1}•kg^{-1} but this finding should be carefully used because it could be due to the presence of a large proportion of empty balls. A total opening area of 14% could be recommended as a maximum for the container design in terms of cooling efficiency, i.e., considering cooling rate and its uniformity and energy costs, as long as the package structural resistance restrictions are also taken into account.

Acknowledgement

The authors would like to thank the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), for the financial support and scholarship provided.

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