Plastic container opening area for optimum hydrocooling

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Vigneault, C., Goyette, B., Markarian, N.R., Hui, C.K.P., Côté, S., Charles, M.T. and Émond, J.-P. 2004. **Plastic container opening area for optimum hydrocooling.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **46**: 3.41 - 3.44. The water distribution inside plastic collapsible containers used for handling fruits and vegetables was investigated for non-uniform water supply using three types of produce. This study allowed the determination of the optimum percentage opening at the base of containers for efficient hydrocooling process in the event of non-uniform water supply over the containers. The results show that better water distribution is obtained when the container base opening is 5.2% as compared to 7 and 12%. In general, the 12% container base opening provided the least uniform water distribution through the produce filled container. It is recommended to use a container base opening that covers approximately 5.2% of the bottom surface. This will allow a more uniform water distribution and insures the fastest cooling rate by obtaining higher minimum flow rate in each section of the container.

La distribution de l'eau à l'intérieur d'un contenant pliable en plastique utilisé pour la manutention des fruits et légumes frais a été étudiée à l'aide de trois types de produits et d'une source d'eau non uniforme. Cette étude a permis de déterminer le pourcentage optimal d'ouverture au fond des contenants en terme d'efficacité du procédé de refroidissement à l'eau. Les résultats montrent que les meilleures distributions d'eau ont été obtenues à l'aide d'une ouverture totale de 5.2% par rapport à 7 et 12%. En général, les ouvertures de 12% ont donné des distributions d'eau moins uniformes à travers la masse de produit que les autres ouvertures à plus faibles pourcentages. Il est donc recommandé d'utiliser une surface totale d'ouverture d'environ 5.2% au fond de ces contenants pour permettre une distribution d'eau plus uniforme et un refroidissement plus rapide en obtenant un débit minimum plus élevé dans chacune des sections du contenant.

INTRODUCTION

In addition to protecting fruits and vegetables against damage during transportation and distribution, package containers are often used during precooling and, therefore, should be designed to allow rapid heat transfer (Sargent et al. 1989; Vigneault et al. 2004). For most crops, precooling is the recommended procedure to improve noticeably storage life from harvest to retail. The use of cold water to quickly cool produce, known as hydrocooling, has been used for many years to effectively cool a wide range of fruits and vegetables in bins or in bulk before packing or in containers after packing (Brosnan and Sun 2001; Talbot et al. 1991; Thompson et al. 1998). Hydrocooling requires less capital cost than the three other cooling methods, which are forced-air, vacuum, and liquid-ice (Thompson et al. 2002); generates faster cooling rates than forced air and liquid-ice (Rennie et al. 2003); offers the possibility to uniformly distribute the electric-power demand by creating a heat sink in ice (Cortez et al. 2002); avoids water loss and may even add water to some commodities (Vigneault et al. 2000). Efficient hydrocooling depends upon adequate water flow over the produce surface, which is between 10 to 17 L s^{-1} m^{-2} (Thompson et al. 2002), and water distribution uniformity.

The design of the container and the stacking arrangement of the produce are critical to achieve efficient hydrocooling (Boyette et al. 1992; Sargent 1990). Water distribution inside the containers and the amount of water leaving the container by flowing through the side-walls affect the efficiency of hydrocooling (Maul et al. 1997). Very little research has been performed on container opening design related to hydrocooling. Vigneault and Émond (1998) have recently designed a family of standard collapsible plastic containers to be used efficiently for various cooling methods. The design of the container base openings is one of the factors that may affect the uniformity of water distributed underneath the container, through the stacked containers during hydrocooling. Based on an empirical equation, Vigneault and Goyette (2002) established that for an optimum container design, openings should cover approximately 5% of the bottom surface and mean opening width should be 3.2 mm. Hui et al. (1999) also presented conclusive evidence showing that for uniform water distribution, there was no significant difference in the water loss from container side-walls when 5.2, 7, and 12% base-container openings are used.

Most research has been conducted on the assumption that the cooling water is distributed uniformly over the fresh produce (Maul et al. 1997; Hui et al. 1999; Vigneault and Goyette 2002). However, in practice, water uniformity is not always guaranteed because the shape of produce affects the water distribution. The presence of produce may block the container openings and force water to the sides. Hui et al. (1999) showed that there was more water loss through container side-walls when corn was placed horizontally in the container as opposed to vertically. Water uniformity is also very important since the precooling process duration should be based on the temperature of the produce showing the lowest cooling rate (Vigneault and Goyette 2004). That is, the cooling process should be terminated only when the warmer produce reaches the set point temperature. Poor water distribution uniformity results in longer cooling process duration, increases energy use, deceases efficiency, and increases quality degradation. Therefore, increasing the

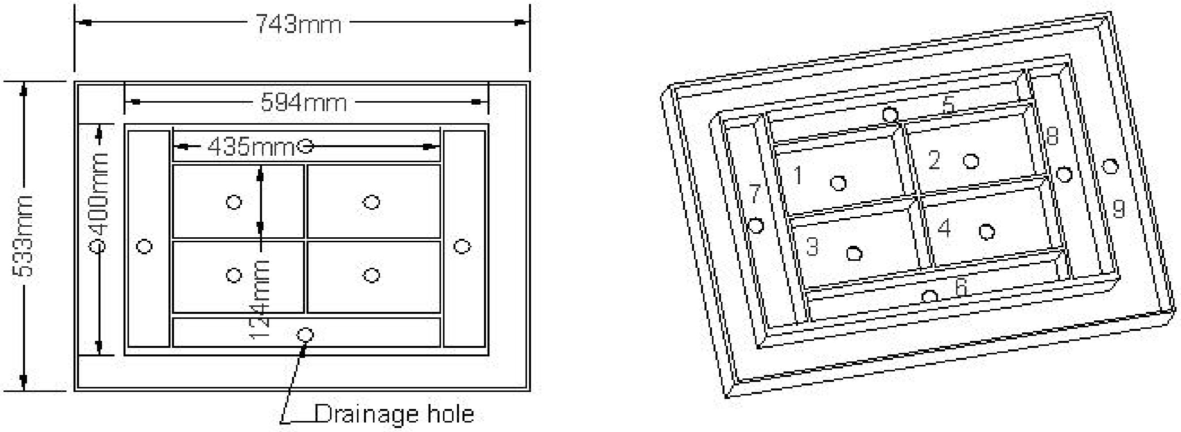

Fig. 1. Schematic diagram of the WCD with its sub-sections.

uniformity of the water distribution is important to minimize the variations in the precooling rate of the produce.

The objectives of the present study were: (1) to investigate the water distribution inside the container and the water loss through the side-walls for non-uniform water distribution using various container base openings and various types of produce; and (2) to determine the optimum percentage of container base openings required to reduce the amount of water loss through the container side-walls.

MATERIALS and METHODS

The tests were performed using a custom-made laboratory setup. The latter was composed of a water reservoir (375 L), a manual valve, a container to hold the produce, a water-collecting device (WCD), nine collection buckets, and a water pump.

Testing container

The testing container consisted of a plastic container, 600 mm long, 400 mm wide, and 337 mm high (Vigneault and Émond 1998). The percentage of base openings of the container was originally 19.8% of its bottom surface. However, based on the experimental results presented by Hui et al. (1999), the percentages of openings were reduced by covering the bottom of the container with duct tape to provide uniformly distributed openings corresponding to 5.2, 7, and 12% of the bottom surface. The height on the container side walls from the interior bottom to the lowest edge of the side wall openings was 25 mm.

Water- collecting device

Figure 1 shows the WCD, which was divided in two main parts, the central and outer parts. The central part was further subdivided into eight sections of equal surface area, numbered 1 to 8. The total area of these sections corresponded to the surface area of the bottom of the testing container. Sections 1, 3, and 7 were grouped and referred to as "near sections" as they were located closest to the water source, and sections 2, 4, and 8 correspond to the "far sections". Sections 5 and 6 were not considered since both cover partly the near and far sections. The outer part (9) was used to collect water flowing to the exterior of the testing container, the so called "water loss".

Water supply

A single water jet was used to simulate the worst-case scenario of a non-uniform water supply. The water jet, set above the plastic container, supplied the cooling water pumped from the reservoir. The containers were stacked on the WCD, one at a time. The WCD collected the water flowing from nine different sections of the container and drained it to the corresponding collection buckets. The water jet was located a distance of approximately 100 mm from the corner of the container, in section ''3'' of the WCD (Fig. 1).

Testing procedure

To simulate the most critical case of maximum water loss, the water flow was set at 4 L/s over the 0.24 m^2 distribution surface, which corresponds to 1000 L min^{-1} m^{-2}, the maximum recommended water flow rate (Thompson et al. 2002). A manual valve allowed water flow adjustments to desired levels. After a one-minute period of operation, the pump was turned off and the collection buckets were weighted to determine the amount of water flow through each section of the WCD. The data were then converted into fraction of total water flow and used for statistical analysis. Observations were also noted with respect to the water exiting through the sides of the containers.

Three types of produce were tested to evaluate the effect of different produce shapes on water distribution. Apple and bean represented round and fibrous produce, respectively. Corn was arranged in both horizontal and vertical orientation to determine the effect of produce arrangement and represented cylindrical and leafy produce, which were considered as two different produce types in the analysis. The corn silk was placed facing upward in the vertical arrangement.

A total of 24 tests was performed with three openings, four produce types, and two replicates for each test. A variance analysis was performed using ANOVA and GLM procedures (SAS Institute 1988) to compare the water diverted into the far and near sections as well as the water loss through the side-walls (exterior) for each produce and container percentage openings. Duncan's multiple comparison range test was used to establish significant differences among the calculated means (SAS Institute 1988).

Table. 1. Mean fraction of water accumulated in each section for the three container base openings for all produce.

Openings (%)	Sections		
	Near	Far	Exterior
5.2	0.444 c*	0.153 a	0.191 a
7.0	0.534 b	0.116 b	0.163 b
12	0.587 a	0.076 c	0.144 c

*Data within the same column with the same letter are not significantly different at $p < 0.05$ according to Duncan's multiple range test.

RESULTS and DISCUSSION

The water distribution inside the container and the water loss to the exterior were investigated for non-uniform water supply. The data presented in Table 1 indicate that there was a significant difference in water loss for the various base openings for unevenly distributed water. Approximately 30% more water was found in the near section for the 12% container base opening compared to the 5.2% container base opening. Twice as much water was collected in the far section for the 5.2% base opening as comapred to the 12%. Under non-uniform water supply condition, the water dispersion was greater for container base openings of 5.2% than for the 7.0 and 12% for all types of produce or orientations tested. Thus, contrary to the findings for uniformly distributed water (Hui et al. 1999), the percentage opening at the base of a container influences the water distribution in the subjacent container. More water was driven out through the side-walls for containers with 5.2% base openings. However, the gain in water distribution uniformity compensates for the drop of efficiency resulting from the loss of water which is not the case when the container openings do not force uniform water redistribution (Maul et al. 1997). Furthermore, the loss of water could be partially neglected since the containers are generally palletized during the precooling process. Palletizing allows partial recovery of the water loss through the side-walls of the container. From these results, it is obvious that containers having 5.2% opening yield more uniform water distribution through the produce.

Table. 2. Mean fraction of water accumulated in each section for the four shapes of produce for all container base openings.

Produce	Sections		
	Near	Far	Exterior
Apple	0.486 b*	0.135 a	0.150 b
Bean	0.598 a	0.097 c	0.080 c
Corn (horizontal)	0.402 c	0.115 b	0.354 a
Corn (vertical)	0.600 a	0.101 c	0.080 c

*Data within the same column with the same letter are not significantly different at $p < 0.05$ according to Duncan's multiple range test.

Table. 3. Mean fraction of water accumulated in the far section for the four shapes of produce and the three container base openings.

Openings (%)	Produce			
	Apple	Bean	Corn (horizontal)	Corn (vertical)
5.2	0.218 a*	0.071 b	0.167 a	0.157 a
7.0	0.089 b	0.166 a	0.077 c	0.092 b
12	0.097 b	0.053 b	0.100 b	0.055 c

*Data within the same column with the same letter are not significantly different at $p < 0.05$ according to Duncan's multiple range test.

The results of the statistical analysis to differentiate the mean fraction of water diverted into each section for the four types of produce tested are presented in Table 2. These results show that the various shapes of produce influenced the water flow through the container. Among all the produce tested, the greatest amount ($p<0.05$) of water collected in the near section was with elongated produce (bean and vertical corn). The least amount of water collected in the near section was for the horizontally oriented corn (0.402). The largest amount of water collected in the far section was for apples (0.135), followed by the horizontally oriented corn (0.115). A significant difference ($p<0.05$) in the mean water accumulated in the far section was found between vertically and horizontally oriented corn, while no difference was detected between bean (0.097) and vertically oriented corn (0.101). The largest amount of water loss ($p<0.05$) was for horizontally oriented corn (0.354) compare to the smallest amount of water (0.080) recorded for vertically oriented corn and bean. This large amount of water loss is likely due to the fact that the horizontally oriented corn blocked the openings and diverted water towards the side-wall openings which is why this type of arrangement is not recommended for efficient hydrocooling (Sargent 1990).

The mean amount of water accumulated in the far section for the four shapes of produce and the three container-base openings are shown in Table 3. In general, except for the bean, the largest amount of water collected in the far section was obtained with the 5.2% opening container. That is, the use of 7% container base opening resulted in increased water dispersion for the bean (Table 3). The mean fractions of water accumulated in the near and exterior sections for bean at 7% container base opening were 0.570 and 0.018, respectively (data not shown). This large number for the near section (0.570) is likely due to the fact that the water did not spread horizontally from the source because of the high porosity of the bean (0.645) as opposed to vertically oriented corn (0.435), and apples (0.394) (Vigneault et al. 2004).

In general, the presence of spherical produce provides the best water distribution at 5.2% container base openings. In addition, improved water distribution was found for containers having a base opening of 5.2% compared to larger base openings of 7 and 12%. This is likely due to the fact that at lower percentage openings, the water is slowed down by the restrictions of the container and has more time to distribute horizontally and evenly inside the container before flowing through the openings. These experimental findings agree with the results presented by Vigneault and Goyette (2002) based on water flow rate through different opening shapes, which established the optimum container base opening to cover approximately 5% of the bottom surface.

CONCLUSION

The water distribution inside the container and the water loss to the exterior were investigated for non-uniform water supply. The results show that for all the produce tested, the mean water accumulated in the far section is the highest when the container base opening is 5.2%. That is, the water is dispersed to the far section when the container base opening is 5.2% resulting in a better distribution of the water from its original source. The 12% container base opening provides the least mean water accumulated in the far section. Thus, based on the result presented by Vigneault and Goyette (2002) and the results of the present research, it is recommended to use container base openings that cover approximately 5.2% of the bottom surface. A slower flow rate along with uniform distribution will ensure a greater cooling effect.

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