Effect of tapered wall container on forced-air circulation system

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Vigneault, C. and Goyette, B. 2003. Effect of tapered wall container on forced-air circulation system. Canadian Biosystems Engineering /Le génie des biosystèmes au Canada 45: 3.23-3.26. A family of standard, reusable, and recyclable plastic containers for handling, storage, and transportation of horticultural crops from field to market, has been developed. The aim of this study was to evaluate the effect of the shape of the container wall. Vertical-wall and tapered-wall containers were compared to maximize the air circulation through horticultural crops. The results showed that with tapered-wall containers, air mostly short-circuits through the tapered areas between the containers rather than through the mass of produce. For example, a 2° standard tapered-wall container filled with lima beans and submitted to a 25 mm of water pressure drop would let 68% of the air bypass the produce. For vertical-wall containers, air must travel through the produce resulting in a more effective cooling process. Keywords: packaging, packing, handling, fruit, vegetable, pressure drop, horticultural crop, precooling.

The objectives of this study were to quantify the airflow bypassing the produce when using tapered-wall containers of different angles with forced-air, and to determine the maximum angle that could be used without having an important effect on forced air-precooling efficiency.

The results of this study are protected by patents in both the USA and Canada (Vigneault and Émond 1997, 1998).

INTRODUCTION

Containers for storage and transportation of horticultural crops have been used in the industry for many years. In early years, wooden boxes were used for the storage and shipment of produce. Wooden boxes have many disadvantages and have been mostly replaced by corrugated cartons, particularly with ones coated to resist moisture damage. Currently, waxed corrugated cartons have limited recycling or secondary use, which is why collapsible plastic containers are gaining popularity.

In Europe, the use of returnable plastic containers (RPC) has been steadily growing. The high density in the population and short transport distances decreases the delay in the use of the RPC. In North America, a few giant stores have tested the RPC in the fruit and vegetable handling systems. Other studies have been looking at different styles of RCP transported from the state of California to the province of Québec. Although Britain has largely stayed with tapered-wall containers, the big move in Europe has been to the vertical-wall collapsible containers (Peggie 2000). Following Europe, North America is keen to adopt a standard using recommendations set by the Produce Marketing Authority.

Tapered-wall containers can be quickly nested to occupy a small volume when they are empty, so the cost of return to the owner is relatively low. On the other hand, the vertical-wall containers are generally collapsible which decreases their empty volume; but, they require more time to handle than nesting containers. However, they offer a better volume occupancy efficiency. Being palletized tight together, the vertical-wall containers do not generate space between each other. The latter may have an effect on air circulation and indirectly influence the cooling rate.

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LITERATURE REVIEW

Precooling is widely used in North America. Precooling of horticultural produce is very important for maintaining the quality of fruits and vegetables (Kader and Barett 1996). A container should be designed to provide efficient and uniform cooling throughout the entire container and throughout the entire stack of containers (Vigneault et al. 2002). Therefore, to minimize energy losses during precooling, it is essential to design a new container that facilitates the circulation of chilling fluid, such as air or water.

Haas and Felsenstein (1987) determined that the main factor affecting pressure drop is the cartons. Haas et al. (1976) showed that, regardless of the size and shape of the container wall openings, the resistance of the carton container to airflow decreases with the increase of relative surface of openings on the sides perpendicular to airflow for oranges or similarly shaped fruits. Vigneault and Goyette (2002) showed that opening widths of 3.2 to 12.7 mm on the surface of containers have a negligible effect on pressure drop during air circulation through container walls. However, the relative surface area of the openings has an important effect on air circulation and
Experimental setup

A V-shape channel was constructed to simulate a 500 × 300 mm tapered-wall container stacked in a six-column pattern on the longest direction of a standard 1200 × 1000 mm pallet. Plywood boards were used to simulate the outside surface texture of tapered-wall containers since the latter varies from very smooth to rough. The V-shaped channel consisted of three walls, one fixed, one adjustable, and a cover wall, and was built from three 9.5 mm thick plywood boards (305 mm high and 1200 mm long) (Fig. 1). The fixed wall was placed vertically. An airtight hinge fixed the adjustable wall lengthwise to the bottom of the fixed wall. A second airtight hinge fixed the top of the fixed wall lengthwise to the cover wall. A flexible plastic liner was used to join the adjustable wall lengthwise with the cover ensuring air-tightness. This V-shaped channel was adjustable from 0° to 20° to simulate channels formed by tapered side boxes of the same height placed side by side but of different angles.

The inlet of the V-shaped channel was free to air circulation and its outlet was fixed to a 400 mm cubic plenum. The air inlet of a Delhi™ fan (Model 612, Delhi Industries Ltd., Delhi, ON), powered by a 0.75 kW variable speed motor was fixed to the plenum to create a negative pressure by forcing the circulation air through the channel. A Pitot tube placed at the center of a 305-mm diameter galvanized steel cylinder (3050 mm in length) was mounted at the outlet of the fan and was used to measure the airflow rate conforming to the method described by ASHRAE (2001). A pressure transducer and a data acquisition system (DATA Shuttle™, Strawberry Tree®, Sunnyvale, CA) were used to measure the static pressure inside the plenum and the dynamic pressure in the pitot tube. For each measurement, the pressure data were averaged and recorded every 15 s for a five-minute period.

The flow rate of the air circulating in the channel was calculated from the dynamic pressure in the pitot tube following the method described by ASHRAE (2001).

Airflow measurement

Trials were performed in order to simulate air circulating through a channel created between two side-by-side tapered-wall containers. The airflow rate was measured under five pressure drops (every 10 mm of water from 10 to 50 mm) between the inlet and outlet of the channel and seven wall angles (every 2° from 2 to 14°). The airflow rate was also measured for five pressure drops (every 5 mm of water from 10 to 30 mm) for three angles (16, 18, and 20°), which corresponded to the maximum airflow capacity of the fan. The fan rotation frequency was adjusted to obtain the desired pressure drop. The airflow was then measured after a two-minute delay to allow for airflow stabilization. Trials were randomly repeated three times for each pressure and angle combination, readjusting the angle and the fan rotation frequency every time.

A variance analysis was performed using a GLM procedure (SAS Institute 1988) to determine if the pressure drop and the tapered-wall angle have an effect on the airflow rate. The natural logarithm values were calculated for the airflow rate (Q), the pressure drop (P), and the tapered-wall angle (α). A regression analysis, using Microsoft Excel™ software, was performed to develop an empirical equation describing the relationship between these variables.
Fig. 2. Airflow rates measured (symbols) and calculated (lines) as a function of pressure drop for various angles for a tapered channel (300 mm wide, 1200 mm long).

effect of the pressure drop and the tapered-wall angle on the airflow rate, and the regression coefficient (R) was calculated.

Air loss ratio
Since the airflow rate is proportional to the differential pressure, the air loss ratio was calculated based on the available published information of pressure drop through various produce. For each produce, the amount of air circulating through commodities was calculated based on a 25 mm water pressure drop and the results were compared to the air bypassing through airspaces between tapered-wall containers calculated using Eq. 1. Calculations were performed for airflow rates through various channel angles, 1200 mm long by 300 mm high, and through four horticultural crops: lima beans and snap beans (Wilhelm et al. 1983), orange (Chau et al. 1985), and sweet potato (Gaffney and Baird 1977). The air loss ratio was graphically presented as a percentage of the total airflow bypassing the produce.

RESULTS

Experimental set-up
The experimental setup allowed the measurement of the airflow rate as a function of the pressure drop and the wall angle with a coefficient of variation (CV) of 8.09%. This lack of precision was likely due to the difficulty of measuring the angle and to the inaccurate measurement of the static and dynamic pressures. However, the relatively low value of CV shows repetitive results allowing the determination of the relation of the flow rate of air circulating within a tapered-wall to pressure drops and angles.

Airflow measurement
Figure 2 presents an example of the experimental results of airflow rates as a function of all pressure drops for 2, 4, 8, and 16° wall angles. The statistical analysis performed on all the results demonstrated significant effect of pressure drops ($F_{4,99}, P<0.001$), wall angles ($F_{9,99}, P<0.001$), and an interaction effect between pressure drops and wall angles ($F_{36,99}, P<0.001$) on the flow rate of air.

Using the regression analysis, an empirical equation (Eq. 1) was derived relating the airflow rate to the pressure drop and tapered-wall angle with an R of 0.992.

\[ Q = 0.001231 P^{0.45} \alpha^{1.18} \]

where:
- $Q$ = airflow rate (m$^3$/s),
- $P$ = pressure drop (mm of water), and
- $\alpha$ = tapered-wall angle.

Air loss ratio
Both the rate of air flowing in the channel formed by two tapered containers placed side by side and through masses of horticultural crops were calculated using a 25 mm water pressure drop. The percentage of air bypassing the produce as a function of the tapered-wall angle is presented in Fig. 3.

Results show that the percentage of air bypassing the produce increases with increasing angle. A 4° tunnel (1200 mm in length), formed by 300 mm high boxes having 2° tapered-walls and placed side by side, has a 21 mm space at the base. The 2° tapered-wall is generally recognized as the minimum angle that could be used for nestable containers. When considering the produce presented in Fig. 3, a channel angle as low as 4° leads to an air loss equal to or greater than 28%. It increases to 62% for low porosity produce such as lima beans. This amount of air bypassing the produce is very important and could have a major impact on the precooling process of horticultural crops. To improve the cooling process of
horticultural crops, tapered-wall containers should be avoided. Moreover, based on these results, when using vertical-wall containers, care should be taken to place the containers side-by-side tightly to avoid air bypassing the produce through open areas between the containers.

**CONCLUSION**

An experimental setup was developed to measure the flow rate of air circulating in a tapered channel as a function of pressure drops and angles. The airflow rate was measured and a statistical analysis demonstrated a significant effect of pressure drops and wall angles on the flow of air. An empirical equation was developed to describe the relation of the airflow rate to pressure drop and tapered-wall angle. These results allowed the calculation of the percentage of air bypassing the produce when using tapered-wall containers of different angles.

According to the results, it is recommended to avoid using tapered-wall containers to improve the efficiency of the cooling process of horticultural crops. Although this study did not aim at determining proper air spaces, the results strongly suggest eliminating any air space between the containers thus avoiding air bypassing them.

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