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Research paper

Computational modeling of airflow and heat transfer in a vented box during cooling: Optimal package design

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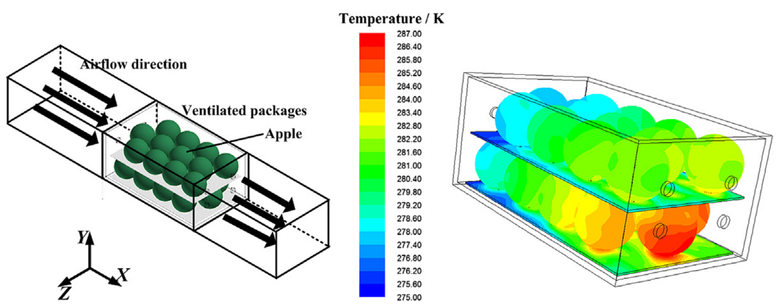
HIGHLIGHTS

- A model based the geometry of produce stacked in boxes was developed.
- The local and average airflow through stacks of horticultural products was studied.
- Heat from respiration, transpiration, condensation, and convective heat flow, were considered.
- A new vented box was developed with a greater number of vents.

GRAPHICAL ABSTRACT



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ABSTRACT

Optimization of fresh fruit packaging designs is required to reduce energy loss by minimizing the precooling time and to enhance fruit quality by providing more uniform cooling without inducing chilling injuries. In this work, a computational fluid dynamics (CFD) model is developed to study the airflow patterns and heat transfer inside an existing container and a newly developed container. The CFD model employs an unsteady-state approach based on a two-equation eddy-viscosity turbulence model (SST-κ −ω model). The cooling performance of the existing container and the new container are evaluated experimentally and numerically with the CFD model. The CFD results reveal a complex and uneven distribution of the airflow inside the existing vented package. Such airflow leads to a non-uniform temperature distribution over the produce, with a maximum temperature difference of ~8 °C between two layers of stacked produce. For the new boxes, the half-cooling time and coefficient of temperature variation are about twofold less than those for the existing boxes, and the maximum temperature difference is ~2.5 °C between two layers of stacked produce. Thus, the new package design clearly shows significant improvements in cooling performance. The numerical model is verified by comparing the simulation results to those of experiments, and the predicted results are consistent with the measured results. The maximum temperature deviation is less than 1.5 °C, and the maximum root-mean-square error and average relative error for produce temperature are 1.452 °C and 13.6%, respectively. This research provides a reliable theoretical and experimental basis for improving airflow and produce-

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temperature uniformity and for minimizing energy consumption during the forced-convection cooling of produce.

1. Introduction

To ensure the quality and safety of horticultural products and extend their storage and shelf life across the entire cold chain, a critical step in the postharvest cold chain is rapid precooling after harvest to remove field heat [1–5]. The cooling performance and rate depends on the packaging design (vent area, shape, number, position, etc.), the fruit-stacking pattern in the package, thermophysical properties, physiological mechanisms, initial temperature of the agricultural products, and required storage temperature [6,7]. In recent years, an increasing number of researchers [7–14] have done in-depth studies and analyses of the characteristics of airflow and heat transfer inside ventilated packages during precooling. The aim of such studies is to improve precooling efficiency, ensure rapid and uniform cooling of agricultural products.

A number of researchers have studied [1,7,15,16] the airflow as well as heat and mass transfer in packaging cases of agricultural products using experimental methods. However, such studies are restricted due to complications caused by handling biological materials and fluctuations in the physical properties of agricultural products. In addition, experimental studies are usually expensive and time consuming, and thus difficult to conduct. With the rapid development of computational fluid dynamic (CFD)modeling techniques, CFD models have become widely used in various fields because they reduce the need for complex field experiments [17–23]. In particular, the use of CFD models is becoming more popular because they can obtain airflow patterns and temperature values at a high spatiotemporal resolution [2,3,24]. Some researchers [25–29] have used CFD simulations to analyze how packaging design impacts airflow as well as the heat and mass transfer processes of agricultural products that are packaged in vented cases. These works demonstrate that such simulations are not only feasible but also reliable. For the packaging of fresh apples, the trays are critical for protecting the produce against a significant portion of the mechanical damage that occurs during the precooling, transportation, preservation, and marketing processes. Thus, to obtain reliable results from a simulation, the trays must be including in the model. Unfortunately, very few studies currently exist that consider the effects of the trays on airflow and the produce-cooling characteristics within complex packaging structures. In addition, there are also some deficiencies in the existing literature.

For example, Defraeye et al. [2] analyzed the sensitivity of a CFD model to evaluate the cooling performance of an existing corrugated fiberboard container (CFC) and compare it with two new containers (Supervent CFC and Ecpack reusable plastic container) for forced-convective cooling of orange stacked on a pallet. The accuracy of the CFD simulation was closely consistent with the results of experiments. In the study, individual oranges were modeled by CFD, thus avoiding the porous-medium approach to model flow in the containers, which is based on the Darcy–Forchheimer–Brinkman equation [30]. This discrete approach was quite accurate but involved a high computational cost [3]. In addition, the effect of the heat of respiration and transpiration on produce temperature was not considered. Delele et al. [4,31] developed a three-dimensional (3D) computational fluid dynamics model to study how vent area, vent shape, and vent number and position affect airflow and heat transfer during postharvest handling of produce. The results indicate that the number of vents and their position and shape mainly affect the uniformity of airflow and cooling. An increase in vent area by up to 7% gave a reasonable increase in cooling rate; however, further increase in vent area only led to a relatively low increase in cooling. The predicted results were consistent with the measured results: average relative errors of predicted pressure drop and produce temperature were 13.80% and 16.27%, respectively. However, the study did not consider the effect of the evaporative heat on the heat flow inside the produce zone. Dehghannya et al. [8,14,32] developed a mathematical system to model airflow and heat transfer during forced-convection cooling of produce to investigate airflow patterns and the resultant temperature distribution during the cooling process. The results show that the airflow distribution during the cooling process is not homogeneous. A more uniform airflow distribution is obtained by increasing the vent area from 2.4% to 12.1%. However, the authors used plastic spheres instead of real produce, which decreases the reliability of the simulation results.

In the latest studies, to simplify the mathematical model and reduce computational time and simulation costs, the produce zone is usually treated as a homogenous porous medium [33–35]. However, this assumption cannot be justified when the container-to-product equivalent-diameter ratio is less than ten, which is common for retail packages of horticultural products (e.g., apples, strawberries, tomatoes, etc.) [9–11,30,36,37]. In these cases, the heterogeneity in the local airflow pattern significantly impacts the transport phenomena within the system, and the continuous-medium assumption inherent to a porous medium is no longer valid [38]. The objective of the present study is to develop a reliable 3D CFD model to predict the airflow and heat transfer within a complex packed structure. The performance of an existing two-layer corrugated box (EC) for the forced-convective cooling of apples is compared with a new container design (NC). The phenomena of respiration, transpiration, condensation, and convection in the produce zone are modeled with a user-defined function (UDF) written in the C programming language. The results of the simulation are verified by comparing with experimental data.

2. Materials and methods

2.1. Physical model

Double-walled “B” flute and regular slotted container style (FEFCO0201) boxes (45 cm × 27 cm × 20 cm high; 6 mm thick) were used in this study. The trays were 42 × 25 × 0.3 cm^3 with a single-walled “B” flute construction. Apples of similar size were used; they averaged 310 g and 90 mm in diameter. The apples were stacked inside the package in a staggered pattern. The detailed structural parameters of the packaging case and the internal fruit placement are given in Fig. 1.

2.2. Experiment design

2.2.1. Setup

The experiment was done in a refrigerated room. The ventilated package was placed inside a virtual-wind-tunnel system (see Fig. 1).