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Mathematical modelling of cooling efficiency of ventilated packaging: Integral performance evaluation

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ABSTRACT

The current packaging designs and the efficiency of forced-air cooling (FAC) of fresh produce can be considerably improved by comprehensively comparing and evaluating the existing packaging designs. This study presents a market survey that studies samples of typical apple cartons used in China. Furthermore, by combining experiment and computational fluid dynamics (CFD) modelling, a novel integral approach is proposed to evaluate cooling rate and uniformity, energy efficiency, and fruit quality (including safety) as a result of FAC for different ventilated-packaging designs. The process uses CFD to simulate the three-dimensional spatio-temporal distributions of airflow and product temperatures during precooling. In addition, experiments on chilling injury and mass loss are also reported. The results show that the optimum fresh-fruit packaging design depends on the product size and the location of the product and tray inside the packaging. For all existing package designs, the optimal air-inflow velocity is found to lie in the range 0.4–1 m/s (or 3–5 $L\,s^{-1}\,kg^{-1}$), any further increase in airflow rate simply wastes energy because it leads to a relatively low increase in cooling rate and uniformity. The level of chilling injury and mass loss per box show a different trend with increasing air-inflow velocity. The accuracy of the CFD simulations was confirmed by a good agreement with experiments. The maximum root-mean-square error and mean absolute percentage error for produce temperature are 0.727 °C and 18.69%, respectively. This research unveils the advantages and disadvantages of the various existing packaging designs and provides a reliable theoretical and experimental basis for achieving an integral evaluation of the performance of FAC.

1. Introduction

Apples are a good source of various nutrients (e.g., vitamin C, red pigments, phenolic constituents and fiber, etc.), which is important to maintain human health and reduce the risk of several diseases [1,2]. Therefore, apples are a highly appreciated fruit and an economically important agricultural crop in several countries of Asia, Africa, Europe, and America [3,4]. In the last 10 years, apple production has increased considerably around the world. According to the FAO (2016) the main area of apple production is located in China, which accounts for more than half of the world production [5]. However, the postharvest lifetime of apples is very sensitive to temperature variations, which is a major cause of deterioration and economic loss in apple products during transportation, postharvest handling, and consumption. To reduce the metabolic rate and slow the deterioration of fresh apples before they are put in long-term refrigerated storage or transportation, a critical step in the postharvest cold chain is rapid precooling after harvest to remove field heat [6]. A variety of precooling techniques are available in the agriculture industry (e.g., room cooling, forced-air cooling, hydro-cooling, vacuum cooling, liquid icing, etc.); of these techniques, forced-air cooling (FAC) is the most prevalent precooling technique used to remove field heat [7]. This process involves using a powerful fan to generate the necessary driving force to create a pressure differential across a container, which forces air in from the surroundings, through the container openings, and around each individual unit of produce [7]. The efficiency of FAC is related to the speed of the process (e.g., cooling rate, half-cooling time, or seven-eighths-cooling time) and the uniformity of the produce temperature [8–10]. Meanwhile, the cooling performance and cooling rate depends on the packaging design (vent area, shape, number, position, etc.), the fruit-stacking pattern in the packaging, the thermophysical properties of the fruit and packaging, physiological mechanisms, the initial temperature of the

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agricultural products, and the required storage temperature [10,11]. In recent years, an increasing number of in-depth studies and analyses have appeared that treat the characteristics of airflow and heat transfer inside ventilated packaging during precooling of the products [10,12–19]. The aim of these studies is to promote rapid and uniform cooling of horticultural produce, increase precooling throughput, reduce precooling energy consumption, and optimize packaging design.

Due to the complex internal structure within packaging filled with trays and produce, some physical phenomena are difficult to measure with high spatial and temporal resolution [e.g., the characteristics of airflow and heat transfer inside ventilated packages, the convective heat transfer coefficients (CHTC), the temperature variation of the whole fruit, etc.] [20]. Therefore, if restricted to field tests, it is difficult to obtain detailed information on the local airflow and heat- and mass-transfer processes during cooling, which further restrict the possibility of improving packaging design and commercial-cooling operations. In addition, experimental studies are usually expensive and time consuming, making them difficult to conduct [21,22]. Computational fluid dynamics (CFD) is a simulation tool for modelling fluid-flow problems and is based on the solution of the governing flow equations. It constitutes a sophisticated design and analysis tool that uses the significant computing power of modern computers to simulate fluid flow, heating (drying, cooking, sterilization, chilling), mass transfer (transpiration or dissolution), phase change (freezing, melting, or boiling), chemical reactions (combustion or rusting), mechanical movement (impellers, pistons, fans, or rudders), stress or deformation of related structures, and interactions between solids and fluids [23]. The last two decades, however, have seen enormous advances in computing power and commercial CFD packages, allowing them now to meet the sophisticated modelling requirements of the food-processing industry. As a result, this technology has been widely used in agricultural cold-chain logistics over the past few years, particularly to simulate the precooling process of fresh horticultural produce. CFD models not only reduce the need for complex field experiments but also provide a detailed understanding of complex flow through the intricate and chaotic structure that is the agricultural produce packaging; and all this with a high spatiotemporal resolution. Moreover, the accuracy of CFD models and their reliability have been validated by many scholars [24–29].

Several studies developed detailed simulations of the local-airflow field and heat-transfer process within the packaging of various fresh produce by using the explicit geometry of the produce stacked in boxes [8,9,13,14,21,26]. The results of these studies indicate that the design of the packaging system significantly affects the cooling rate, cooling uniformity, mechanical strength, and production costs. Meanwhile, various corresponding optimization strategies were also proposed to improve the cooling efficiency of existing packaging designs. However, very few studies currently exist that collect samples of all available apple cartons from the agricultural wholesale market and compare the cooling efficiency of different ventilated packaging designs by an integral approach. Moreover, although a multiparameter approach has been proposed to evaluate cooling rate and cooling uniformity, airflow resistance, and energy efficiency during FAC of the products [13,30], fruit quality (e.g., chilling injury and mass loss) was not considered for different packaging designs or cooling strategies. Furthermore, Hoang et al. [31] and Dehghannaya, et al. [32,33] applied a sensitivity analysis of a CFD model to investigate how different packaging designs or cooling strategies affect product weight loss, but these studies do not present detailed data on chilling injury and energy consumption during FAC of the products. To promote the optimization of packaging design and make future food cold chains in a cost-effective way, Defraeye, et al. [34] discuss and summarize all relevant package functionalities to directly compare the cooling performance of various packaging designs, which provides an important enlightenment and referential meaning to future packaging designs in a more integrated approach. Unfortunately, very few studies currently exist that optimize the design and cooling efficiency of various packages by evaluating simultaneously all relevant packaging-performance parameters. To overcome these drawbacks, this study begins with a market survey, which reveals ten different corrugated-carton designs used in commercial handling and marketing of apples. The objective of the present study is to develop a reliable three-dimensional CFD model to evaluate the cooling characteristics of ten different corrugated-carton designs based on various packaging performance parameters (i.e., energy consumption, cooling rate, cooling uniformity, chilling injury, and mass loss). Furthermore, the optimal air-inflow velocity was determined for ten different carton designs by combining the relationship between cooling rate and uniformity with precooling energy consumption.

2. Materials and methods

2.1. Market survey

To collect samples of typical apple cartons used in commercial handling and marketing, a market survey was done in two major fruit and vegetable wholesale markets (Xinfadi and Hanjiashu) in Beijing and Tianjin, China. The survey took place between April and June 2016 in the Xinfadi market because it is the largest agricultural wholesale market in China, and even in Asia. The following three broad geometric characteristics were recorded for each package: (a) carton dimensions (length, width, and height); (b) ventilation (size, number, and position of holes); and (c) presence of internal packaging (trays and fruit-stacking pattern).

2.2. Physical model

Ten different corrugated cartons are studied in this work, including the regular slotted container style (FEFCO02) and the telescopic carton (FEFCO03). Two types of trays were used for different corrugated cartons: polyvinyl chloride foam plastics and corrugated board. Fig. 1 and Table 1 summarize in detail the design parameters of each carton.

2.3. Mathematical model

2.3.1. Model assumptions and governing equations

Some simplifications and assumptions were used to reduce computational cost and still properly describe the experimental system. The individual apples were modelled as spheres. Furthermore, buoyancy effects and radiation were assumed negligible and were not taken into account in the simulations. Some previous studies [15,25,30] reported that heat from respiration and latent heat of evaporation have no significant effect on the simulated temperature during product precooling. However, the accuracy of the simulation results is improved when these sources of heat are considered [6,35].Thus, the heat of respiration and evaporation were considered in the simulations. The thermo-physical properties of air and apples are assumed to be independent of temperature and humidity, which means that the density, specific heat capacity, and thermal conductivity are all constant (see Table 3).

The computational domain contains three distinct subdomains: a free-airflow zone, a produce zone (i.e., the apple), and a solid zone (i.e., package walls and trays). The governing equations for each zone are based on our previous work [6,21].