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A review of computational fluid dynamics for forced-air cooling process

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HIGHLIGHTS

- We review the fundamentals of applying CFD to precooling of fresh produce.
- We summarize the parameters used to analyze packaging performance.
- We review recent studies that focus on optimizing the design of fresh produce packaging.
- We discuss various challenging issues.

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ABSTRACT

Optimizing the design of fresh produce packaging is vital for ensuring that future food cold chains are more energy efficient and for improving produce quality by avoiding chilling injuries due to nonuniform cooling. Computational fluid dynamics models are thus increasingly used to study the airflow patterns and heat transfer inside ventilated packaging during precooling. This review discusses detailed and comprehensive mathematical modeling procedures for simulating the airflow, heat transfer, and mass transfer that occurs during forced-air precooling of fresh produce. These models serve to optimize packaging design and cooling efficiency. We summarize the most commonly used parameters for performance, which allows us to directly compare the cooling performance of various packaging designs.

Contents

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1. Introduction

Even after separation from the parent plant, fresh horticultural produce (e.g., fruits and vegetables) is composed of living dynamic systems [1]. The respiration and transpiration of living biological entities results in a loss of the organic material and moisture from these systems. In general, these alterations result in the degradation of the quality of agro-products and limit their shelf life [2,3], to the detriment of transregional and transnational long-distance sales of fresh produce and of the economic performance of the entire cold chain. The physiological changes due to respiration, transpiration, and biosynthesis are affected by intrinsic (i.e., the thermal properties of the produce or climacteric vs. non-climacteric commodities) and extrinsic (i.e., temperature, concentration of ethylene, O_2, and CO_2) factors [1,4], of which temperature is the single most important environmental factor affecting the deterioration rate and postharvest lifetime of produce [5–8]. 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 [9–12]. In this way, horticultural produce is cooled from the harvest temperature to an optimal temperature, which slows the physiological activities within the produce, reduces disease development and weight loss by transpiration, and minimizes the destruction of the pigments, colors, texture, and nutrients [13–16]. Thus, precooling fruits and vegetables after harvest effectively extends the shelf life of the produce and extends the sales zone, making it the most essential of all value-adding services demanded by increasingly more sophisticated consumers [1,17,18].

The performance and rate of the precooling process for fresh produce depend on the packaging design (vent area, shape, number, position, etc.), the fruit-stacking pattern within the package, the thermophysical properties, physiological mechanisms, air-to-produce initial temperature difference, air-to-produce final desired temperature difference, produce geometry (size, shape, surface/volume ratio, internal structure, etc.), and ambient relative humidity [19,20]. All of these factors are important because they affect heat and mass transfer during the precooling process [2,9] and directly affect the uniformity of airflow and cooling as well as energy consumption. Because packaging strongly impacts the quality and shelf life of produce, the relatively low cost of packaging and the ease of altering its design [21,22] is one of most cost-effective ways to enhance rapid and uniform cooling of horticultural produce, increase precooling throughput, reduce precooling energy consumption, and prevent cold damage. For fresh, highly perishable produce, packaging serves several purposes. It not only promotes rapid and uniform precooling to quickly remove field heat but also protects the produce from mechanical damage during handling, processing, storage, and transport. Therefore, packaging technology plays a critical role in transportation, preservation, and marketing of fresh produce [23–27].

In recent years, an increasing effort [12,17,28–32] has been devoted to in-depth studies and analyses of the characteristics of airflow and heat transfer inside ventilated packaging during precooling. These studies were based on laboratory experiments, numerical simulations (e.g., Computational Fluid Dynamics, CFD), or a combination of both. The aim of these studies was to improve packaging design, ensure rapid and uniform cooling of agricultural products, avoid hot spots, and prevent cold damage. Table 1 summarizes the recent studies on precooling of fresh produce and packaging design. During precooling, the complexity of the cold-air movement inside a single fruit-packing crate or through the entire ensemble of goods renders difficult the task of measuring temperature variations solely via field tests. As a result, obtaining detailed information on the local airflow rate and heat- and mass-transfer processes within complex packaging structures is a serious challenge. In addition, extending the test cycle requires significant human and material resources.

The last two decades, however, has seen enormous advances in computing power and commercial CFD codes to meet the sophisticated modelling requirements of the food-processing industry (e.g., drying, cooking, sterilization, chilling, cold storage, etc.). Thus, the above-mentioned difficulties can be reduced or avoided by using numerical CFD simulations to create three-dimensional spatio-temporal distributions of airflow and temperature during precooling [33–40].

Despite this vast amount of research on packaging design for fresh horticultural produce, most researchers have concentrated mainly on a single unit of produce during precooling or on only one or a few particular functions of the packaging (e.g., cooling performance or energy consumption). Thus, conflicting packaging design requirements often result when multiple cold-chain operations or different functions are simultaneously targeted [10]. For example, increasing the number of box vents and the air-inflow speed can improve cooling rate, throughput, and cooling uniformity but compromises the mechanical strength of the packaging and induces more chilling injuries and moisture loss. Furthermore, a preferential pathway is created when too many box vents are used because the airflow can easily bypass the produce, thereby reducing the airflow rate through the produce and consequently increasing the energy required for precooling [11]. Thus, to comprehensively evaluate the performance of ventilated packaging, all functions of the packaging across the entire cold chain should be simultaneously assessed in future studies. In addition, future studies should also compare the cooling performance of packaging designs as a function of how the produce is stacked on a pallet.

The goal of this paper is to review the current state of CFD as applied to the design of ventilated packaging for fresh produce. Because new packaging can be evaluated from several viewpoints, we summarize herein the most commonly used performance parameters, which we use to quantitatively compare existing packaging with regard to each function separately or for multiple functions at the same time. In addition, to improve the accuracy of CFD