Thermo-Mechanical Analysis in Cold Chain

Subjects: Food Science & Technology

Contributor: Alemayehu (Alex) Ambaw

In agro-food research and industry, mathematical models are being used to develop and optimize preharvest and postharvest operations, and their use has grown exponentially over the last decade. Generally, transport phenomena (such as airflow, heat, and mass transfer) during the cooling of horticultural products are complex; therefore, the use of computational modeling techniques is a valid alternative to expensive and difficult experiments because computers continuously become more powerful and less expensive, the software is readily available, and once a model is validated, it is a versatile tool to evaluate the effects of the operating and design parameters involved.

simulation modeling computational fluid dynamics computational structural dynamics postharvest cold chain food loss and waste

1. Introduction

Mathematical modeling complements testing and experimentation by reducing the total effort and cost of data acquisition in the agricultural sector. Mathematical models help to explain systems and quantify the effects of various factors on the performances of preharvest and postharvest handling processes. This approach stimulates interdisciplinary research on the topic. Most of the studies in this area were published in the journal category of horticulture and food science technology.

In the preharvest period, mathematical models of 3D tree architectures are used in the development and optimization of automated field operations including automated pruning, automated tree branch training, and orchard spray applications [1][2][3]. A diverse range of mathematical models exists to describe the 3D geometric structure of plants. Traditionally, tree structure modeling methods such as the medial axis thinning algorithm [4][5] and stripe programming [2] were used to compute tree skeletons from a gradient intensity map. In another area, computational fluid dynamics (CFD) models of airflow and particulate transport within plant canopies were applied to analyze and optimize pesticide and fungicide spray application to agricultural fields and to assess the accompanying environmental contamination [3].

During harvest, models are used to develop and optimize picking robots. For instance, “stripe programming” was used to reconstruct the 3D structure of Chinese hickory trees, followed by the finite element method (FEM) to optimize the excitation force-frequency and amplitude that is efficient for harvesting [2]. The current trend in this area is to support the various automated field operations with deep-learning-based artificial intelligence (AI) technology for fruit and tree branch detection [2][6].

Geometric parameters (shape, size (major and minor diameters), volume) and physical properties (texture, firmness, color, density) of agricultural products are widely used to model crop growth and variations in physicochemical characteristics [7][8]. Particularly, fruit diameter is considered a very important index of fruit growth dynamics that can be monitored non-destructively during the growing season. To this end, it is frequently used to forecast harvest size [8].

During the postharvest period, mathematical models are used to study mechanical damages such as bruising from postharvest handling and road transport operations [9][10][11]. The thermo-mechanical analysis of packaging and cold chain management logistics has been assessed using various types of mathematical models [12][13][14][15]. Biophysical phenomena taking place during precooling [12][13][14], cold storage [15], refrigerated transport [16][17], retail (display) cooling systems [18][19] have been studied using mathematical models.

In this paper, progress made in the application of mathematical models in the postharvest period is reviewed. This paper consolidates and relates the various numerical modeling studies, specifically CFD and computational structural dynamics (CSD) in the last 10 years. The objectives, basic procedures, and implementation of the modeling approaches are reviewed. Advances achieved and current trends are discussed.

2. Numerical Methods in the Produce Cold Chain Management

Because of their low cost and versatility, corrugated fiberboard cartons (CFCs) are the dominant and economical material for making shipping containers that are widely used for the distribution, transportation, and storage of produce. A significant challenge that affects the use of CFCs is the ability to maintain the mechanical strength of the cartons under cold chain conditions over a long period of time [20][21][22][23][24]. The load may be exposed to fluctuations in temperature and humidity, as well as other factors that affect performance such as excessive handling, pallet patterns, pallet deck board spacing, and box overhang. For fresh fruit packaging with ventilation holes, several factors have been reported to influence its strength including the location, sizes, and shapes of the ventilation holes [20][21][22][23][24][25].

Therefore, reliable analysis tools for the prediction of both the structural integrity and its interaction in the cold chain of new package designs are very important. This involves discretizing a large domain into many small elements, developing element equations, assembling the element equations for the whole domain, and solving the assembled equations to simulate and predict the mechanical responses in CFCs upon loading [26][27]. Although FEM started out as a mathematical technique, most FE analyses are now run through commercial software such as ABAQUS, MSC, ANSYS, and COMSOL, etc. The pre-processing stage includes simplifying and modeling the geometry, selecting appropriate element types, and defining material properties including applying loads, boundary conditions, and constraints [26][27][28][29].

The internal flesh (core) temperature of the fruit determines the rate of respiration and other enzymatic reactions. Internal temperature also determines respiration heat generation [30]. The type of produce, maturity, presence of injuries, etc., are important factors that determine the effect of temperature. For most perishable horticultural commodities, a temperature near 0 °C is optimal.

Rapid cooling is commonly accomplished by a forced air-cooling (FAC) system placed in refrigerated rooms. Forcing the cold air through the stack increases the cooling rate significantly, allowing produce to be cooled much faster compared to room cooling [31][32]. A tarpaulin sheet or cover is placed over the pallets and the channel, and a fan draws air from the channel, directing the chilled air of the cold room through the produce [33]. The presence of additional packaging materials (such as bags, plastic films, paper wraps, etc.) increases the airflow resistance and hence the cooling time.

The ease and uniformity of the cooling air distribution are significantly affected by the vent hole design (shape, position, and proportion) of the packaging box and package arrangement. Mathematical modeling methods, mainly computational fluid dynamics (CFD), have been successfully used to analyze the cooling rate and cooling uniformity of produce cooling processes [12][13][14]. Packaging design also affects the energy efficiency and carbon footprint of precooling operations [12][13][14][34]. For instance, the comparison of several pomegranate packaging designs showed significantly different cooling uniformity, cooling rate, and energy usage in a precooling process [13][34].

The uniform distribution of moisture and gas in the cold room atmosphere is crucial for efficient quality preservation. The design and operation of a cold storage room should consider the heat load factors, such as solar radiation on the walls and ceiling (especially when a cold room is not accommodated in a bigger building), the infiltration of air by frequent door openings, the heat of respiration from stored produce, cooler fan load, light load, and other miscellaneous loads [15][35]. Uneven distribution of cooling air, humidity, and gas in the room can cause non-uniform produce quality and safety.

For refrigerated containers used for sea, rail, and road transport throughout the world, compliance with the ISO standard 1496-2 must be attained [36]. Like the precooling and cold storage units, package design (size of boxes and vent hole design) and arrangement (stacking patterns) play crucial roles in determining the performance of energy and space utilizations [36]. In particular, reefers are designed to distribute cold air from the floor via specific T-shaped decking. Hence, it is crucial that package design provide vent holes to facilitate vertical airflow inside a reefer [16][17].

Radiation and other sources of heat should be minimized during sales in stores and supermarkets. Retail (display) cooling systems accomplish this by employing a specialized refrigeration technique that allows good visibility and ensures free access to stored food for shop customers using a virtual insulation barrier called an air curtain [37]. Simultaneously, heat is also transferred from the shop environment to the air curtain. To this end, display cabinets are characterized by their large consumption of electrical energy because of their direct interaction with the ambient environment.

A 3D CFD model was used to assess the effect of air curtain velocity, width, discharge angle, and positioning of the air curtain outlet from the front edge of the top shelf, etc. Moreover, it is important to quantitatively determine the amount of the air curtain reaching the bottom of the case to be cooled and the amount that escaped into the shop environment. This is important to optimize energy usage and reduce the discomfort of the consumer [18]. Hence, the study of air curtains is required because these can be easily disrupted by air circulation in front of the cabinet or by consumers taking food from the shelves [18][19][37].

The objective of mathematical modeling in the produce cold chain is to provide qualitative and quantitative data for a better understanding and interpretation of the produce–environment interaction. This information is used to make predictions about produce shelf life for efficient and cost-effective postharvest loss prevention. Energy-saving and material usage are crucial aspects of the produce cold chain to protect the natural environment for sustainability [15]. The analysis, design, and optimization of these systems, in experimental conditions alone, is time consuming and expensive due to many complex factors.

Many studies involved the 3D airflow velocity field, the spatiotemporal temperature distributions, cooling rate, cooling uniformities, and refrigeration heat loads of stacked produce [12][13][14][15][16][17]. Such models are used to predict the precooling time, identify hot spots and cold spots in the cooling environment, and calculate energy utilization to optimize the operation of the cooling process. Package design, mechanical stability, and safety are investigated using CSD models.

3. Notable CFD Studies

However, apple fruit is the most-studied fruit. There are also studies conducted on artificial spherical balls mimicking fruit [38][39]. Such generalized spherical artificial fruits are only used to investigate airflow distribution. Model geometry considered in the CFD model of the produce precooling ranges from individual fruit [40] to an entire pallet stack of fruit [13][14][41][42].

In a typical analysis, [38][39] studied packaging boxes are designed with a range of vent hole sizes, shapes, and positions, with respect to cooling rate, cooling uniformity, and pressure drop. However, beyond a certain limit, increasing the vent hole proportion has no significant benefits on the cooling rate and causes problems in stack statics. In another study, the cooling characteristics of existing package designs and package accessories such as liners were analyzed and characterized through a detailed quantification and visualization of the airflow, pressure drop, and temperature distributions across the stack [13]. Here, the authors demonstrated that liners had a strong effect on cooling rate and delayed cooling time by factors of three compared to stacks with no liners.

If strawberries are left without cooling for a few hours, their quality will be reduced to an extent that a proportion of marketable fruit is lost. Hence, strawberries need stricter temperature management than many other fruits. Ferrua and Singh [43] undertook CFD analysis of the FAC process of retail packages of strawberries. [44] used experimental and modeling approaches to design a new package and cooling system for the precooling of strawberries.

[45] studied the effect of carton designs on airflow resistance, cooling rate, cooling uniformity, and energy usage in the precooling of apple fruit. Four carton designs with different vent hole areas were compared. The authors used an experimentally validated CFD model to investigate the airflow resistance, cooling rate, cooling uniformity, and package-related energy consumption of the four designs. Experiments were used to quantify box compression strength and study the effect of vent hole proportion on the mechanical strength of the carton.

Through the redesign of the vent holes, airflow short circuits were removed, and the rate and uniformity of the cooling process were enhanced. The energy usage, fruit quality preservation, and throughput of the process were also significantly improved by the new design. In this work, the authors used an experimentally validated CFD model to investigate the warm loading of citrus fruit into refrigerated containers for cooling during marine transport for logistic and economic savings. The authors underlined the importance of box design and proper stacking to reduce airflow short-circuits between pallets.

Objectives, numerical techniques, and results of computational-fluid-dynamics-based analysis in precooling studies.

Airflow distribution, particulate transport, and gaseous substance distribution inside cold storage rooms are the major problem categories that have been investigated using a CFD model. Additionally, the effect of packaging design on the airflow and heat transfer, and the accompanying energy usages of cold storage rooms, have been subjects of interest. The finite volume method (FVM) is frequently implemented in commercial software packages such as ANSYS Fluent and ANSYS CFX to model cold storage rooms. Due to the relatively complex geometry of the actual system, stacked fruit in cold storage rooms are normally simplified as porous domains, initially at a uniform temperature (7/8th cooling temperature) as it is received from a precooling unit.

[15] used a porous medium CFD model of airflow and temperature dynamics inside a fully loaded cool storeroom of apple fruit. Using this model, the authors analyzed several load-shifting scenarios by cycling the temperature set point between 1.2 °C and 0.6 °C following a day/night regime to reduce energy cost. The air circulation fan was shown to be the major source of heat load. Discontinuous use of the cooling operation, including 12 h on/12 h off, 10 h on/14 h off, and 8 h on/16 h off, was investigated.

In another approach, a porous medium CFD model was used to numerically analyze the distribution of 1-Methylcyclopropene (1-MCP) in cool stores for apple fruit [46]. This study performed a detailed analysis of the effects of air circulation, room shape, and bin material on the convection–diffusion–adsorption of the gas in fruit and other non-target solid materials in the cold room. The authors showed that wooden bins deplete 25% more of the active substance than rooms filled with fruit in plastic bins. Using this approach, the author investigated the effect of airflow rate and different bin handling parameters on fungicide particle flow, and depositions on fruit surfaces were quantified.

Objectives, numerical techniques, and results of computational-fluid-dynamics-based analysis in cold storage room studies.

Inside the cold store, the cooling airflow direction is mainly horizontal, while in reefer containers, airflow is mainly vertical (from bottom to the top of the stacked produce). To this end, the design of package vent holes and package arrangement should take this into account so that enough vertical airflow is attained. The cooling unit of the reefer container is limited in capacity, and it can only lower the pulp temperature very slowly. The understanding of the effects of factors such as ambient temperature, sunlight, heat from the motors of the evaporator fans, packaging, packaging arrangement, produce physiology, heat from defrosting the evaporator coil, etc., is crucial for successful reefer temperature control.

Modeling the moisture transport phenomena requires modification of the heat transfer equations of the CFD model so that it incorporates the respiration and transpiration processes of the produce. Moreover, the model should incorporate the heat loss/generation due to the evaporation/condensation of water at the surface of the produce. Qris the respiration heat generation, andQvis the heat loss due to the evaporation of water from the surface of the produce. the diffusivity of moisture in the air,Dtis the turbulent diffusion coefficient, andmis the rate of evaporation of water from the surface of produce into the cool store atmosphere, which is governed by the equilibrium between the room moisture content and the water activity of the produce.

For the product phase, the heat generation of the produce and the heat loss/generation, due to evaporation/condensation of water at the surface of the produce, are incorporated into the energy conservation equations (Equations (11) and (12)) as follows:(11)ρp∂∂trpHp = ∂∂xirpλp∂Tp∂xj+hTAspecTa−Tp+rpq−hfgm (12)m=−∂Mp∂t = hmAspecρpv−ρav

During the storage of fruit, quality attributes such as taste, firmness, color, and flavor are measured to follow the evolution of quality degradation. The coupling of fruit quality models with the CFD model equations is interesting because such a model can be used for a virtual investigation of the effect of storage conditions on the quality of the produce. This will further make it possible to identify critical operational requirements during postharvest storage and to improve decision-making in the cold chain logistic management and inventory control. Wu and Defraeye [35] incorporated a generic quality model (Equation (13)) into the basic CFD model of airflow and heat transfer inside ventilated cartons for different cold chain scenarios and modeled the quality evolution of individual fruit in a pallet.

Enzyme kinetics is used to quantify produce quality in time. The zero-order kinetic (Equation (13)) is frequently used to estimate produce quality while a commodity passes through the precooling, cold storage, and refrigerated transport stages (Equation (15)), which measures the temperature sensitivity (a measure of the rate of change) of an enzymatic reaction rate or a physiological process due to a temperature increase of 10 °C. TheQ10coefficient is commonly used in postharvest studies regarding fruit respiratory activity.

4. Model Validation

CFD models must be validated before being used to perform analysis studies to compare scenarios or in any decision-making design steps. The main objective of CFD model validation in postharvest applications is to quantify confidence in the accuracy of airflow and temperature predictions under certain assumptions so that it is used with acceptable levels of uncertainty and error. On the other hand, absolute quantities such as the local magnitude of flow velocity, temperature, and other transport variables require the highest level of accuracy. The validation of model-predicted absolute quantities requires quantification of the prediction errors.

For the postharvest period, airflow prediction capabilities of CFD models are compared against velocity and temperature measurement data taken from different spatial locations [15][16][17][42][47], measured the local temperature and airflow velocity on sampling points. In addition to the properties of the cool store atmosphere, the temporal history of fruit core temperatures is used to validate predicted cooling rate and produce temperature distribution during the precooling of pomegranate fruit [13][48].

References

1. Majeed, Y.; Zhang, J.; Zhang, X.; Fu, L.; Karkee, M.; Zhang, Q.; Whiting, M.D. Apple Tree Trunk and Branch Segmentation for Automatic Trellis Training Using Convolutional Neural Network Based Semantic Segmentation. IFAC-PapersOnLine 2018, 51, 75–80.
2. Wu, C.; He, L.; Du, X.; Chen, S.; Ni, K. 3D reconstruction of Chinese hickory tree for dynamics analysis. Biosyst. Eng. 2014, 119, 69–79.
3. Duga, A.T.; Ruysenc, K.; Dekeyserb, D.; Nuyttensb, D.; Bylemansc, D.; Nicolaia, B.M.; Verbovena, P. CFD based analysis of the effect of wind in orchard spraying. Chem. Eng. Trans. 2015, 44, 1–6.
4. Karkee, M.; Adhikari, B.; Amatya, S.; Zhang, Q. Identification of pruning branches in tall spindle apple trees for automated pruning. Comput. Electron. Agric. 2014, 103, 127–135.
5. Karkee, M.; Adhikari, B. A Method for Three-Dimensional Reconstruction of Apple Trees for Automated Pruning. Trans. ASABE 2015, 58, 565–574.
6. Prusinkiewicz, P.; Lindenmayer, A. The Algorithmic Beauty of Plants; Springer Science and Business Media LLC: New York, NY, USA, 1990.
7. Parra-Coronado, A.; Fischer, G.; Camacho-Tamayo, J.H. Model of pre-harvest quality of pineapple guava fruits (Acca sellowiana (O. berg) burret) as a function of weather conditions of the crops. Bragantia 2017, 76, 177–186.
8. Orlandini, S.; Moriondo, M.; Cappellini, P.; Ferrari, P. Analysis and modelling of apple fruit growth. Acta Hortic. 1999, 137–146.
9. Salarikia, A.; Ashtiani, S.-H.M.; Golzarian, M.R.; Mohammadinezhad, H. Finite element analysis of the dynamic behavior of pear under impact loading. Inf. Process. Agric. 2017, 4, 64–77.
10. Opara, U.L.; Pathare, P. Bruise damage measurement and analysis of fresh horticultural produce—A review. Postharvest Biol. Technol. 2014, 91, 9–24.

11. Kabas, O.; Vlăduţ, V. Determination of Drop-Test Behavior of a Sample Peach Using Finite Element Method. Int. J. Food Prop. 2014, 18, 2584–2592.

12. Mukama, M.; Ambaw, A.; Opara, U.L. A virtual prototyping approach for redesigning the vent-holes of packaging for handling pomegranate fruit—A short communication. J. Food Eng. 2020, 270, 109762.

13. Ambaw, A.; Mukama, M.; Opara, U. Analysis of the effects of package design on the rate and uniformity of cooling of stacked pomegranates: Numerical and experimental studies. Comput. Electron. Agric. 2017, 136, 13–24.

14. Defraeye, T.; Lambrecht, R.; Delele, M.A.; Tsige, A.A.; Opara, U.L.; Cronjé, P.; Verboven, P.; Nicolai, B. Forced-convective cooling of citrus fruit: Cooling conditions and energy consumption in relation to package design. J. Food Eng. 2014, 121, 118–127.

15. Ambaw, A.; Bessemans, N.; Gruyters, W.; Gwanpua, S.G.; Schenk, A.; De Roeck, A.; Delele, M.A.; Verboven, P.; Nicolai, B.M. Analysis of the spatiotemporal temperature fluctuations inside an apple cool store in response to energy use concerns. Int. J. Refrig. 2016, 66, 156–168.

16. Getahun, S.; Ambaw, A.; Delele, M.; Meyer, C.J.; Opara, U.L. Analysis of airflow and heat transfer inside fruit packed refrigerated shipping container: Part I—Model development and validation. J. Food Eng. 2017, 203, 58–68.

17. Getahun, S.; Ambaw, A.; Delele, M.; Meyer, C.J.; Opara, U.L. Analysis of airflow and heat transfer inside fruit packed refrigerated shipping container: Part II—Evaluation of apple packaging design and vertical flow resistance. J. Food Eng. 2017, 203, 83–94.

18. Roşca, R.; Ţenu, I.; Cârlescu, P. Food Chilling Methods and CFD Analysis of a Refrigeration Cabinet as a Case Study; IntechOpen: London, UK, 2017.

19. Chaomuang, N.; Flick, D.; Laguerre, O. Experimental and numerical investigation of the performance of retail refrigerated display cabinets. Trends Food Sci. Technol. 2017, 70, 95–104.

20. Fadiji, T.; Berry, T.M.; Coetzee, C.; Opara, U.L. Mechanical design and performance testing of corrugated paperboard packaging for the postharvest handling of horticultural produce. Biosyst. Eng. 2018, 171, 220–244.

21. Berry, T.; Ambaw, A.; Defraeye, T.; Coetzee, C.; Opara, U.L. Moisture adsorption in palletised corrugated fibreboard cartons under shipping conditions: A CFD modelling approach. Food Bioprod. Process. 2019, 114, 43–59.

22. Pathare, P.; Opara, U.L. Structural design of corrugated boxes for horticultural produce: A review. Biosyst. Eng. 2014, 125, 128–140.

23. Pathare, P.B.; Berry, T.M.; Opara, U.L. Changes in moisture content and compression strength during storage of ventilated corrugated packaging used for handling apples. Packag. Res. 2016,

1, 1–6.

24. Fadiji, T.; Coetzee, C.; Opara, U.L. Analysis of the creep behaviour of ventilated corrugated paperboard packaging for handling fresh produce—An experimental study. Food Bioprod. Process. 2019, 117, 126–137.
25. Maheshwari, T.; Shenoy, R. A Study of the Effect of Squareness of the Corrugated Box on its Box Compression Strength. Int. J. Latest Technol. Eng. Manag. Appl. Sci. 2017, 6, 26–28.
26. Fadiji, T.; Ambaw, A.; Coetzee, C.; Berry, T.M.; Opara, U.L. Application of finite element analysis to predict the mechanical strength of ventilated corrugated paperboard packaging for handling fresh produce. Biosyst. Eng. 2018, 174, 260–281.
27. Velloso, N.S.; Costa, A.L.G.; Magalhães, R.R.; Santos, F.L.; De Andrade, E.T. The Finite Element Method Applied to Agricultural Engineering: A Review. Curr. Agric. Res. J. 2018, 6, 286–299.
28. Fadiji, T.; Coetzee, C.; Berry, T.M.; Ambaw, A.; Opara, U.L. The efficacy of finite element analysis (FEA) as a design tool for food packaging: A review. Biosyst. Eng. 2018, 174, 20–40.
29. Cook, R.D.; Malkus, D.S.; Plesha, M.E.; Witt, R.J. Concepts and Applications of Finite Element Analysis, 4th ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2002.
30. Lufu, R.; Ambaw, A.; Opara, U.L. The contribution of transpiration and respiration processes in the mass loss of pomegranate fruit (cv. Wonderful). Postharvest Biol. Technol. 2019, 157, 110982.
31. Fraser, H. Forced-Air Cooling Systems for Fresh Ontario Fruits and Vegetables; Ontario Ministry of Agriculture, Food and Rural Affairs: Toronto, ON, Canada, 2014.
32. Praeger, U.; Jedermann, R.; Sellwig, M.; Neuwald, D.A.; Hartgenbusch, N.; Borysov, M.; Truppel, I.; Scaar, H.; Geyer, M. Airflow distribution in an apple storage room. J. Food Eng. 2020, 269, 109746.
33. Elansari, A.M.; Fenton, D.L.; Callahan, C.W. Precooling. In Postharvest Technology of Perishable Horticultural Commodities; Woodhead Publishing: Cambridge, MA, USA, 2019; pp. 161–207.
34. Mukama, M.; Ambaw, A.; Berry, T.M.; Opara, U.L. Energy usage of forced air precooling of pomegranate fruit inside ventilated cartons. J. Food Eng. 2017, 215, 126–133.
35. Wu, W.; Cronjé, P.; Verboven, P.; Defraeye, T. Unveiling how ventilated packaging design and cold chain scenarios affect the cooling kinetics and fruit quality for each single citrus fruit in an entire pallet. Food Packag. Shelf Life 2019, 21, 100369.
36. Martin, S.; Martin, J.; Lai, P. International container design regulations and ISO standards: Are they fit for purpose? Marit. Policy Manag. 2018, 46, 217–236.
37. Sun, J.; Tsamos, K.M.; Tassou, S. CFD comparisons of open-type refrigerated display cabinets with/without air guiding strips. Energy Procedia 2017, 123, 54–61.

38. Delele, M.A.; Ngcobo, M.E.K.; Getahun, S.T.; Chen, L.; Mellmann, J.; Opara, U.L. Studying airflow and heat transfer characteristics of a horticultural produce packaging system using a 3-D CFD model. Part I: Model development and validation. Postharvest Biol. Technol. 2013, 86, 536–545.
39. Delele, M.; Ngcobo, M.; Getahun, S.; Chen, L.; Mellmann, J.; Opara, U.L. Studying airflow and heat transfer characteristics of a horticultural produce packaging system using a 3-D CFD model. Part II: Effect of package design. Postharvest Biol. Technol. 2013, 86, 546–555.
40. Ambaw, A.; Beaudry, R.; Bulens, I.; Delele, M.A.; Ho, Q.T.; Schenk, A.; Nicolaï, B.M.; Verboven, P.; Tsige, A.A. Modeling the diffusion—adsorption kinetics of 1-methylcyclopropene (1-MCP) in apple fruit and non-target materials in storage rooms. J. Food Eng. 2011, 102, 257–265.
41. Gruyters, W.; Verboven, P.; Diels, E.; Rogge, S.; Smeets, B.; Ramon, H.; Defraeye, T.; Nicolaï, B.M. Modelling Cooling of Packaged Fruit Using 3D Shape Models. Food Bioprocess. Technol. 2018, 11, 2008–2020.
42. Wu, W.; Beretta, C.; Cronje, P.; Hellweg, S.; Defraeye, T. Environmental trade-offs in fresh-fruit cold chains by combining virtual cold chains with life cycle assessment. Appl. Energy 2019, 254, 113586.
43. Ferrua, M.; Singh, R. Improved airflow method and packaging system for forced-air cooling of strawberries. Int. J. Refrig. 2011, 34, 1162–1173.
44. Nalbandi, H.; Seiiedlou, S.; Ghasemzadeh, H.R.; Rangbar, F. Innovative Parallel Airflow System for forced-air cooling of strawberries. Food Bioprod. Process. 2016, 100, 440–449.
45. Berry, T.M.; Fadiji, T.; Defraeye, T.; Opara, U.L. The role of horticultural carton vent hole design on cooling efficiency and compression strength: A multi-parameter approach. Postharvest Biol. Technol. 2017, 124, 62–74.
46. Ambaw, A.; Verboven, P.; Delele, M.A.; Defraeye, T.; Tijskens, E.; Schenk, A.; Verlinden, B.E.; Opara, U.L.; Nicolaï, B.M.; Tsige, A.A. CFD-Based Analysis of 1-MCP Distribution in Commercial Cool Store Rooms: Porous Medium Model Application. Food Bioprocess. Technol. 2013, 7, 1903–1916.
47. Wu, W.; Defraeye, T. Identifying heterogeneities in cooling and quality evolution for a pallet of packed fresh fruit by using virtual cold chains. Appl. Therm. Eng. 2018, 133, 407–417.
48. Pathare, P.; Opara, U.L.; Vigneault, C.; Delele, M.A.; Al-Said, F.A.-J. Design of Packaging Vents for Cooling Fresh Horticultural Produce. Food Bioprocess. Technol. 2012, 5, 2031–2045.