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Title: The use of CFD to characterize and design post-harvest storage facilities: Past, Present and Future

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Keywords: horticultural product; refrigeration; mathematical model; CFD; storage; fruit

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Abstract: There has long been an interest on the use of mathematical models for optimization of postharvest refrigeration systems operation and design. These mathematical models are applied to predict the biophysical phenomena that take place during postharvest handling of horticultural products. CFD has now become feasible to investigate the flow, heat and mass transfer processes in such details that include complex aspects such as product stacking, gas diffusion and kinetics, and droplet or particle dispersion. This review paper summarizes the advances in the application of CFD applied to postharvest storage of horticultural products. Due to the geometrical complexity of postharvest products, packages and systems and limitations due semi-empirical models for turbulence and porous media, new strategies using multiscale methods are starting to be successful.

Highlights

- This article review the recent CFD approaches in post-harvest storage facilities.
- Airflow, heat and mass transfer in different postharvest applications are considered.
- New trends and directions for future research are presented
- There is progress towards using CFD on detailed geometrical models of products and packages.
- We are at the advent of a true multiscale approach to CFD simulation of postharvest systems.

Reviewers' comments:

Reviewer #1:

However, as a review paper it runs short in discussing and synthesizing the contribution of these works. The authors just provided a general overview of the approach followed by different research groups, but they did not provide a basic discussion and/or analysis of their particular works. In general it focuses too much on negative aspects and/or limitations of these works. Although these comments are appropriate (we need to be aware of those limitations to define new ways of action), Too little has been said about their actual contributions to the field.

1. For instance, the reviews of the works of Martins et al. (2011) and Dehghannya et al. (2011) focus too much on their limitations and unjustified assumptions, but nothing is said about the reasons that led to these papers being published (if there is none, I would not include them in this review).

   ANSWER: Comment accepted and appropriate correction is made. See paragraph between line 158 to 165 in the reviewed manuscript.

2. In particular, the work of Dehghannya et al. (2011) is not the only one that simplifies the system geometry to 2D (which I agree with the authors of this review that it is not quite appropriate), but it is the only one that has been specifically and strongly criticized by doing so.

   ANSWER: Comment accepted and appropriate correction is made. See paragraph between lines 166 to 173 in the reviewed manuscript.

I personally believe that it would be really valuable if a better analysis of the work done during this period could be made. In particular, the contribution of this paper will become significantly higher if the works were analyzed similarly to the way the work of Delele et al. (2009a) was analyzed in the current manuscript.

3. Specific comment for the authors to address: Section 1.Introduction (Lines 63-65). The Navier-Stokes equations only govern the motion of laminar flows (i.e., not the transport of mass or energy). The modeling of turbulent flows relies on the Reynolds-Averaged Navier-Stokes equations (which despite being similar to the N-S ones, they depend on a series of constants and parameters to provide closure to the model).

   ANSWER: What the reviewer pointed out is noted. In principle, the Navier-Stokes equations describe both laminar and turbulent flows without the need for the series of constants and parameters or closure in general in what is called "Direct Numerical Simulation (DNS)". However, The Direct Numerical Simulation (DNS) of practically encountered flows requires computing power which is many orders of magnitude higher than available in the foreseeable future. Turbulence models including Reynolds-Averaged Navier-Stokes equations have been specifically developed to account for the effects of turbulence without the need of a prohibitively fine mesh and direct numerical simulation.

Reviewer #2:

However, this paper is limited to a summary of the most interesting publications, and lacks a critical assessment of the current state of the art pointing out the remaining difficulties.

1. Therefore, I suggest adding at the end of the paper a new section to increase the focus on critical assessment of CFD approach, the importance of validation, current difficulties/limitations, numerical aspects (meshing, grid dependency, boundary conditions) and finally the new challenges and future research directions, etc. Some parts from the current text can be moved to or rewritten for this section.

   ANSWER: The suggestion is appreciated and appropriate changes are taken to incorporate the reviewer's suggestions: A new section "5. The challenge for postharvest CFD modeling" is added discussing the issues suggested by the reviewer. A part which was in section "2 Essential elements of CFD of postharvest systems" which was between line 90 and line 111 is moved to the new section and in place of it additional discussion is made in "2 Essential elements of CFD of postharvest systems.

END OF REVIEWER COMMENTS

The use of CFD to characterize and design post-harvest storage facilities: Past, Present and Future

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Abstract

There has long been an interest on the use of mathematical models for optimization of postharvest refrigeration systems operation and design. These mathematical models are applied to predict the biophysical phenomena that take place during postharvest handling of horticultural products. CFD has now become feasible to investigate the flow, heat and mass transfer processes in such details that include complex aspects such as product stacking, gas diffusion and kinetics, and droplet or particle dispersion. This review paper summarizes the advances in the application of CFD applied to postharvest storage of horticultural products. Due to the geometrical complexity of postharvest products, packages and systems and limitations due semi-empirical models for turbulence and porous media, new strategies using multiscale methods are starting to be successful.

Keywords: horticultural product; refrigeration; mathematical model; CFD; storage; fruit

1 Introduction

Postharvest storage facilities for horticultural products are mostly used to preserve quality of horticultural products by minimizing respiratory heat generation, retarding the ripening process, and preventing moisture loss and microbial spoilage (Verboven et al., 2006; Ambaw et al., 2011a). Generally cooling is employed to meet these requirements. Different methods of cooling are available, these include: natural convective cooling, forced-air cooling, mist-flow cooling and hydrocooling. Due to its flexibility, efficiency and low cost, forced-air cooling is the most commonly used method (Allais and Alvarez, 2001). Forced-air systems commonly consist of a cooling unit assembly with cooling coils in which the refrigerant is circulated and a fan that forces cooling air over the coils and on to the stacked product (Fig. 1). The cooling unit can be a direct one where the refrigerant evaporation takes place in the cold room or an indirect one where a secondary fluid cools the air.

Horticultural products can either be stored in large bulks or in small units or packages. In practice, a wide variety of packages, bins or containers with different size, design and consisting of different materials are being used. These units frequently have vents or slots that allow for flow of the cooling air to the produce. The cooling efficiency depends on the arrangement of these units in the store room and by the flow resistance induced by them and the contained product. Non-homogeneous flow of the cooling air inside the stack may cause uneven cooling and product quality; certainly in the case of respiring and transpiring horticultural products. Hence, packages are stored in particular arrangements as to optimize air penetration (Alvarez and Flick, 1999; Alvarez et al.,2003; Verboven et al., 2004; Verboven et al., 2006; Alvarez and Flick, 2007). Generally the transport phenomena (airflow, heat and mass transfer) in such systems are complex coupled processes and mathematical models are recommended to support understanding and designing refrigerated storage systems (Nahor et al., 2005a,b; Smale et al., 2006; Verboven et al., 2006; Alvarez and Flick, 2007).

Numerical models are being extensively used in many areas to analyse or improve an existing process and design, and to develop new designs. Because of the high cost of experiments at commercial scale, computer-based simulation and evaluation tools are an attractive alternative. Such tools allow engineers to, in an early stage of the design cycle, test different concepts up to, in a later stage, optimize a complete process or system. With the enhancement of computing power and efficiency, and the availability of affordable computational packages mathematical simulation has been accepted as a successful method in engineering. In the postharvest field, mathematical models are being used to optimize and develop equipment and operational strategies, and their use has grown to a great extent over the last decade (Verboven et al., 2006; Rennie and Tavoularis, 2009; Delele et al., 2010).

Different modelling approaches have been proposed for predicting fluid flow, heat and mass transfer during cooling, storage, transportation and display of horticultural products. The Navier-Stokes equations are the governing mathematical equations describing mass, momentum and energy transfers in postharvest storage facilities. These coupled partial differential equations can be solved completely by using computational fluid dynamics (CFD), that uses the detailed appropriate geometry, and the equations can be solved numerically to a high degree of accuracy on a very fine mesh of discrete points in the geometry. At the other end of the spectrum, various assumptions can be made, empirical equations incorporated and the problem be solved in a simplified and more approximate manner.

Nowadays computational requirements for direct CFD simulations are still large in order to accurately resolve every detail in postharvest systems. Alternative methods using lattice Boltzmann schemes have recently been proposed as a viable alternative (Verboven et al., 2006; van der Sman, 1999), although there it was limited to laminar flow at low Reynolds number. The state of the art is such that CFD models today incorporate some degree of approximation in order to be feasible. To a large extent, the CFD result depends critically on the assumptions and approximations made in the model and solution. A review is therefore appropriate to identify progress made to more robust and accurate CFD models.

Several reviews on the application of CFD in the agro-food domain have been presented previously (Xia and Sun, 2002; Wang and Sun, 2003; Norton and Sun, 2006; Smale et al., 2006; Verboven et al., 2006; Delele et al., 2010). This article will review the most recent CFD approaches to model and simulate the transport phenomena in food bulks, packages and stacks in post-harvest storage facilities. Airflow as well as heat and mass transfer in different existing and emerging postharvest applications are considered. New trends and directions for future research are presented.

2 Essential elements of CFD of postharvest systems

CFD consists of a numerical solution of coupled differential equations. To this end, usually commercially available software is used. Broadly spoken, the strategy of CFD is to replace the continuous problem domain with a discrete domain using a grid. Rather than solving the problem everywhere, a solution is then calculated only at the grid points using numerical techniques that find approximate solutions to the governing fluid flow equations. The quality of the results depends largely on the careful selection of the appropriate model equations and implementing the correct solution strategy including an appropriate grid. The finite difference, finite element and finite volume methods are commonly used for discretisation of distributed mathematical equations. Difficulties with the handling of complex geometries by the finite difference technique and difficulties involved in the programming and implementation of the finite element method for fluid flow has led to the finite volume method to become the most commonly used numerical techniques in CFD code development (Norton et al. 2007). The finite volume method is also the most commonly used technique in postharvest CFD studies (Table 1.)

Pre-processing, solving and post-processing are the three essential steps in performing CFD analysis with commercial software. In pre-processing the main aspects of the problem to be modelled are identified and specified. This includes geometry creation, mesh generation, setting-up of physical properties, selection of appropriate solving techniques and corresponding parameters. Important decisions about the governing equation and boundary conditions are made at this step. Flow conditions (laminar or turbulent), flow dimension (1D, 2D or 3D), consideration of symmetry plane, problem specification (steady or unsteady) are also made at this step.

The solving step is basically iteratively solving the set of discretised equations. The solution of the governing equations on a given computational grid depends heavily on the choice of scheme for the convective terms. The upwind differencing scheme (UDS) is often used because it almost always results in a converged solution and, furthermore, the solution is bounded (Sørensen and Nielsen, 2003). Higher order schemes are usually preferred for more accurate solutions (Defraeye et al., 2010).

Post-processing allows the user to visualize and scrutinise the resulting field solution using both graphical and quantitative results features such as isosurfaces, slices, vectors, surface plots, animations and streamlines. The quantitative capability allows the user to easily extract values of interest, which can be used to obtain better understanding of the problem at hand.

CFD models have to be verified and validated. During verification, errors in the computational model and its solution should be identified and quantified. This can be accomplished by comparing the CFD solution with analytical solutions or highly accurate numerical solutions. The validation is to assess how accurately the computational results compare with the experimental data.

3 CFD applications in postharvest storage

This review considers publications on CFD in postharvest storage applications from 2006 to present. For older work, one is referred to one of the previous reviews in this field (Xia and Sun, 2002; Wang and Sun, 2003; Norton and Sun, 2006; Smale et al., 2006; Verboven et al., 2006; Delele et al., 2010). Table 1 summarises the recent applications of CFD in describing and designing of post-harvest storage facilities. CFD is applied in the modelling and simulation of various types of the postharvest storage facilities. The analysis may be on actual products or artificial replica. When replicas are used to represent the actual model, most often spherical plastic objects filled with water or jell are used. Systems like chilling, forced air cooling or heating, natural air cooling, cold storages, air curtains, hydrocoolers, refrigerated trucks have been dealt with. In the subsequent sections, we present a more detailed review for the following categories: (1) products and packaging, (2) storage facilities and (3) refrigerated transport. In a final section, some emerging applications of CFD in postharvest are discussed.

3.1 Products and packaging

The basic element of importance in postharvest storage is the product and how it is stacked and packed. Computation of airflow, heat and mass transfer in stacked products has since long received attention from modellers. The difficulty for accurately predicting this system arises from, one, the often complex and variable geometry of the products and the stack, and, two, the different time and spatial scales of heat and mass transfer in the stacks (Verboven et al., 2006). In large stacks, the porous media approach for resolving the average airflow in relation to the room airflow may be appropriate, but internal gradients of temperature, gas concentrations and water content in individual products are then more difficult to resolve. Resolving the geometry and the package in all details may overcome this problem but will require more computational resources (Fig. 2).

Ferrua and Singh (2011) proposed an improved airflow method and packaging system for forced-air cooling of strawberries based on a series of previously developed and validated CFD models of the process (Ferrua and Singh, 2009a) considering laminar flow in the trays. Their work involved not only the design of individual clamshells and trays, but also the overall circulation and heat and mass transfer across the palletized structure. CFD simulation used the true 3D shape of the strawberry generated by combining digital images of slices, as well as how they were stacked inside the package. The airflow distribution (Ferrua and Singh, 2009b) and the energy model (Ferrua and Singh, 2009c) were validated by gathering experimental data using a custom-built forced-air cooling system using transparent spheres that had the same equivalent diameter to the strawberries. The good comparisons clearly showed that if the problem can be reduced to a small geometrical domain (such as one row of trays in this case), and if laminar flow holds, CFD can be applied with very good confidence in combination with a resolved geometry of the stack. However, even in this case, it must be realized that it is difficult to account for the obvious randomness in product shapes and stackings from package to package that are expected to affect the process. In their work, Ferrua and Singh used a repetitive stacking in each package.

Martins et al. (2011) studied conjugated cooling of Fuji apples in tandem arrangements on trays. The model used a finite volume based CFD code to study the heat transfer process. The true apple shape was used in this study with a simplified configuration of two apples. Also in this case, laminar flow and high Reynolds number regimes were assessed. The numerical model was first evaluated and compared well to available data on spheres and blocks. The model demonstrated that, during the cooling process, the heat dissipated by the leading apple delayed the cooling of the following inline apple. The Nusselt number over the apple surfaces were calculated showing local variations over the surface.

Dehghannya et al. (2011) studied the influence of different package vent configurations on the temperature distribution in spheres of equal diameter in a regular stack during forced laminar convection cooling, using a 2D transient finite element based CFD model. The enormous computational demand of the meshing and solving of the 3D problem initiated the simplifications to a 2D configuration. Though such simplification led to losing 3D connectivity of air spaces and flow conditions, it is shown that the error encountered in predicting the temperature field was not significant in this particular case. The study used experimental temperature profiles taken at several positions inside a stack for validation.

Tutar et al. (2009) also used a regular stack of spheres and studied the effect of product positioning and container venting on airflow patterns and temperature distribution inside the ventilated package by using a CFD model. The geometry was simplified and the spheres did not touch one another. This study did consider turbulent flow and compared different turbulence models and appropriate meshing for each. The authors highlighted the importance of using a turbulence model in the appropriate Reynolds number regime. The study indicated that the duration of the cooling process is more affected by the air inflow rate than by the size of the opening area or turbulence conditions. The influence of increasing opening area becomes insignificant over a certain threshold. Two different RANS equations based turbulence models (the standard k–ε and the RNG k–ε model) were tested in comparison with a laminar model to determine the effect of flow modeling technique on physical behavior of the flow. The two turbulence models gave similar results and predicted shorter cooling times than the laminar model.

To study the flow through the bulk and loaded vented box with a random configuration of spheres of different sizes, Delele et al. (2008) developed a combined discrete element (DE)-CFD model. In this model, the DE method was used to generate a random stack of discrete spheres and the CFD was applied to study explicitly the airflow through the bulk and loaded vented box. The CFD model used the SST k–ω model for turbulence. The model was used to study the effects of confinement ratio, flow direction, stacking pattern, product size, porosity, vent hole ratio and randomness of the filling on the pressure drop coefficient of the stacks. For flow through a vented box with products, a linear addition of the individual pressure drops of the flow through the box and the bulk by considering as series of resistances was shown to seriously underestimate the real pressure drop.

Based on a semi-empirical model, Alvarez and Flick (2007), developed a validated 2-D model that predicted turbulence, velocity, pressure and local heat transfer coefficient and product temperature during forced-air cooling of stack of food products represented by PVC spheres. The model considered the stack as a macro-porous medium. It used the Darcy–Forchheimer momentum equation to predict the average superficial velocity. This model included the dissipation and generation of turbulence in the porous medium that was not considered in most relevant other studies (Xu and Burfoot, 1999; Hoang et al., 2003; Moureh and Flick, 2004; Nahor et al., 2005; Chourasia and Goswami, 2007; Delele et al.; 2009).

Chourasia and Goswami (2007b) applied a 3D finite volume based model for airflow, heat and mass transfer to a partially impermeable enclosure containing potato during natural convective cooling. The model assumed the single bag of potato as a porous medium and used the Darcy-Forchheimer equation to model the pressure drop. The velocity vectors, contours of temperature and rate of moisture loss were presented for transient cooling as well as steady state cooling and compared to experimental profiles.

To investigate the airflow and heat transfer in ventilated packaging for horticultural products, Zou et al. (2006a) developed a volume-averaged CFD model and later validated it with measured results (Zou et al., 2006b). The study was done for both in bulk and layered packaging systems based on a porous medium approach.

For designing of hydrocoolers for horticultural products, Thorpe (2006) used a semi-continuum approach that treated the individual horticultural products as discrete particles; their averaged properties, along with those of the cooling water and interstitial air were treated as continuum. To determine the cooling efficiency, the study stressed the importance of using the mass weighted average temperature instead of the core temperature of the produce. The model was used to study effects of cooling water flow rate and temperature, and size and depth of the bed of the produce on cooling rate. Later Thorpe (2008) used the same approach to calculate the velocity, temperature and moisture distribution in bulk stored grains by CFD. Available CFD software needed a dedicated customization to be used in this application. The paper demonstrated how these modifications can be made and how the results can be presented graphically in a way that permits insights into the processes that occur in grain stores.

3.2 Cool stores

While considerable advances have been made recently in modelling of airflow and heat and mass transfer through individual or an assembly of packages with products, such approach is not yet feasible to compute an entire cool stores containing tons of product. Alternative approaches using porous media formulations are still required here. Also, the main circulating airflow in cool stores is mostly turbulent and needs to be properly taken into account.

Tanaka et al. (2011) used a transient 3D CFD model to investigate the cooling performance of a partially loaded cold store with large solid objects without porous media. The model accounted for turbulence by means of the standard k-ε model with standard wall profiles. Validation data on temperature and velocity was collected from a cool room partially loaded with stacks of corrugated fiberboard containers holding water filled PET plastic bottles. The authors studied the effect of different loading patterns on cooling effectiveness. The result of their study showed that flat loading with air gaps to be the optimal configuration to achieve high uniformity of temperature and rapid cooling.

Delele et al. (2009a) were the first to introduce a multiscale CFD modelling to study airflow in loaded cold stores (Fig. 3). At the smallest scale, the flow through stacked products in boxes was predicted using a direct DE-CFD modelling (Delele et al., 2008); from this the anisotropic pressure loss coefficients were determined. At larger scale, a loaded cool room model predicted the airflow, temperature and humidity considering the porous media model of the stack using the calculated pressure loss coefficients. Different turbulence models were compared with experimentally measured air velocity patterns in the cold store. For the standard k–ε, RNG k–ε, realizable k–ε, standard k–ω and SST k– ω turbulence models, the overall average relative error of the predicted velocity relative to the measured values inside a loaded cool room was 24.3%, 22.4%, 23.5% and 18.2%, respectively. After comparing the accuracy and the convergence of the solution, the SST- k– ω model that uses k– ω in the wall region and k–ε in the bulk flow region was selected. Flow patterns in large scale loaded cold stores were evaluated using the same model (Delele et al., 2009b).

Chourasia and Goswami (2007a) developed a 3D model that predicted the airflow, temperature and moisture loss in a commercial potato cold store. The model considered the bulk of potato as porous medium and the RNG (Renormalisation group) k-ε turbulence model was used. The model was in good agreement with measured results. With the model it was possible to locate the hot and cold spots inside the storage room, and the regions with poor air circulation where the relative humidity was about 7% lower compared to that of the surrounding air.

Foster et al. (2007) applied a validated 3D CFD model to investigate air curtains that are used to restrict cold room infiltration. The model was used to evaluate effectiveness of air curtains at different air velocities. Boundary conditions need to be carefully defined in order to avoid numerical problems. The standard k-ε model was compared to the SSG Reynolds stress model. Results were within 10% depending on turbulence and natural convection assumptions made. Overall accuracy of the 3D model was 20-32%. The results showed that flow of air curtains cannot be considered as 2D.

Xie et al. (2006) used a 2D CFD model to study design parameters of empty and filled cold stores. The model was used to evaluate effects of storage corner baffles and product stacks on airflow and temperature fields. The model used uniform boundary conditions and source terms, the k-ε turbulence model with wall functions, geometrical approximations, and a relatively coarse grid that made the model simpler but limited the quantitative accuracy of the model. The product was considered as a solid domain without airflow passing through.

3.3 Cooled transport

Transport is an important part of the postharvest cold chain. However, this part has to date received minor attention with respect to CFD analysis, although the same principles apply as in refrigerated storage rooms.

Using a reduced-scale model and CFD, Moureh et al. (2009a, b) investigated the airflow profiles in a typical refrigerated truck configuration loaded with vented pallets filled with spherical objects. The authors underlined the fact that the standard k–ε turbulence model overestimates the Coanda effect of the wall jet and fails to predict its separation. Based on several studies, the authors concluded that only RSM was able to accurately predict the separation of the jet from the wall and the general behaviour of airflow patterns related to the primary and to the secondary recirculations. This concerned loaded and unloaded long enclosures where the wall jet was subjected to an adverse pressure gradient and the turbulence anisotropy effect was pronounced.

In the above model, the loaded vented pallets were taken as a porous medium where the pressure loss coefficients were determined in a separate wind tunnel experiment. Since there was a large difference between the pallet dimension and the small gaps between them, direct meshing of this small gap leads to a large number of meshes that is computationally very demanding. To avoid this difficulty, the approach that was proposed by Tapsoba et al. (2007) was applied. In this approach, this small gap was replaced by a fictitious porous medium that gave the same airflow resistance to the actual gap. Based on this assumption the equivalent permeability of the fictitious porous gap was calculated. There was a reasonable agreement between predicted and measured results.

4 Emerging applications

4.1 Misting systems

The humidity level of a storage room can be controlled by using artificial misting systems. The advantages of such misting systems on decreasing saleable weight loss and maintaining the product quality during storage and handling has been thoroughly discussed in literature; however, there have been only limited studies on mathematical modeling for design of misting systems.

Allais et al. (2006) modelled the cooling kinetics of a stack of spheres during mist chilling. The model was based on empirical coefficients to calculate the heat and mass balances in air and finite volume discritization method to calculate the radial heat transfer in the solid spheres. This model considered local droplet collection on the outer surface of spheres. Solving of the transport equations was by using custom computer code written in Pascal. The simulated results were in good agreement with experimental results. The use of such two-phase flow system for cooling reduced the half cooling time by 30% relative to the single phase flow method. The paper reported the effects of air velocity, water mass flux density and air temperature on cooling kinetics.

Delele et al. (2009a) used the multiscale CFD modelling described above to study a high pressure nozzle cold storage humidification system (Fig. 3). To track the path and evaporation of the fogged droplets, a Lagrangian particle tracking multiphase flow model was used. The loaded product was treated as a porous medium taking into account the information from lowest scale. Using the model it was possible to quantify the amount of droplets that were completely evaporated and the amount of non-evaporated droplets that were deposited on the product and other room surfaces. The amount of deposition was affect by humidifying nozzles position and direction. The agreement between measured and predicted results was good. Later, Delele et al. (2009b) applied the above model to evaluate a humidification system of chicory root cold storage room. The efficiency of the humidification system was affected by length of cold air deflector, stack height, number of nozzles and duration of humidification.

The use of mist flow to improve the performance of Refrigerated Display Cabinets (RDCs) was investigated by Moureh et al. (2009) using a CFD model of the tow-phase flow. They also adopted an Euler-Lagrange approach to predict the transport of droplets and their spatial distribution. They considered the evaporative flux of droplets on the product surface. By using the developed two-phase model they performed an analysis on the performance of the mist cooling process in terms of surface temperature decrease and homogeneity of droplet deposition on the product surface of the RDC as a function of inlet droplet injection configurations.

4.2 Gas circulation, diffusion and kinetics

The control of the concentration of gasses is crucial for the storage of horticultural products. So-called controlled atmosphere (CA) and ultra-low oxygen (ULO) storage methods use reduced oxygen concentration and modified carbon dioxide concentration that are optimal to minimize the respiration of the products and preserve quality for several months of storage. CFD models have been developed to calculate the diffusion of gasses inside fruits (Ho et al., 2006a,b, 2008, 2011) and inside modified atmosphere packages (Rennie and Tavoularis, 2009a,b). The model of Ho et al. (2006a, 2008) considered the permeation, diffusion and respiration kinetics of oxygen and carbon dioxide in pear fruit and showed considerable gradients inside individual fruits. The model was recently elaborated into a multiscale model to calculate gas exchange in plants using the microscale geometry of the tissue, or vice versa, local concentrations in the cells from macroscopic gas concentration profiles (Ho et al., 2011). Dedicated experiments were conducted to verify the model.

Rennie and Tavoularis (2009a and b) considered the modelling of gas concentrations inside modified atmosphere packaging combining product respiration kinetics with Darcy's law in the commodity layer and the Navier–Stokes equations in the headspace, perforation, and surrounding ambient storage area. Transport of oxygen, carbon dioxide, water vapour and nitrogen was modelled based on Maxwell–Stefan equations. The model was implemented for strawberry packages and validated with available literature data.

Several other gasses are important for CA storage. 1-methylcyclopropene (1-MCP), has become popular as a postharvest treatment for horticultural products. 1-MCP has been shown to suppress ethylene responses and extend the postharvest shelf life and quality of numerous fruits and vegetables (Ambaw et al., 2011a). The effectiveness of the 1-MCP treatments is partly determined by the uniformity of the distribution of the gas from the generator over the whole storage space. The air circulation in the cool room must ensure the distribution of the gas in the cool room and on the fruit. The uniformity of the distribution of the gas is thus strongly influenced by the design of the cool room, arrangement and stacking of fruit bins inside cool room, and bin design and materials of construction. To investigate the distribution of 1-methylcyclopropene (1-MCP) in cold stores for apples Ambaw et al. (2011b) modelled and validated the fumigation process in a container filled with apples. The authors implemented a DE-CFD method to explicitly model the diffusion and adsorption of the gas in individual fruits. The air flow, profiles of free (unbounded) and adsorbed (bounded) 1-MCP in air and in fruit were successfully estimated. The effect of the air flow on the distribution and adsorption of the gas was considered. Large room applications have not yet been considered.

4.3 Fogging

Another new postharvest application are fungicide treatments inside cold stores. Since postharvest treatments directly target the fruit rather than the whole orchard, they have been claimed to be more effective, environmentally friendly and cheaper than the corresponding preharvest application (Delele et al., 2012). Thermonebulisation is one such method that generates fine fungicide particles by an aerosol electrical generator at ± 190°C. In this system, the fungicide is directly applied to the stacked fruits and distributed by a forced airflow in the storage room. The effectiveness of this treatment is highly dependent on the amount and uniformity of fungicide distribution on the stacked product, and achieving the required uniformity is very challenging. To investigate the effectiveness of postharvest storage fungicide fogging systems, the DE-CFD approach in combination with Lagrangian particle tracking was applied and validated (Delele et al., 2012). The CFD model showed explicitly the air and fungicide particle flow through the bin vent holes and through the voids of the stack, and predicted the deposition behaviour of the fungicide particle on the products.

5 The challenge for postharvest CFD modeling

CFD will provide important information on the performance of postharvest activities, as well as the effectiveness of computer aids in the area. However, the CFD designer still has to cope with several inaccuracies. Modelling and numerical errors are inherent and must be given special attention when results are presented. Modelling of turbulence, handling of boundary conditions, choice of differencing scheme and computational grid are discussed by many CFD studies and guidelines (Sørensen & Nielsen, 2003, European Research Community on Flow, Turbulence And Combustion).

In most cases, these aspects are coupled, for instance, the selection of a specific turbulence model with a specific wall treatment has consequences for the discretization to use. Fig. 4 clearly shows that some turbulence models perform superior to others for predicting airflow patterns in enclosures such as storage facilities. For the application in Fig. 4 (Moureh et al., 2005), the Reynolds stress model (RSM) was found to be better than conventional k-ε type models. But, the RSM is not commonly applied in this field of applications. One reason is that it is more computationally expensive than the more common k-ε model. Also, some authors have found different models that were suitable to predict the airflow pattern in their postharvest application. Delele et al. (2009a,b) found the SST- k–ω model to produce the smallest error in air velocity prediction in a cool room compared to other models. Furthermore, when the heat and mass transfer to products and other parts is important, boundary layers need to be resolved accurately enough to predict the correct transfer rates. Turbulence wall function models have been shown to have limited accuracy when complex objects (such as stacks of fruits) are involved, but they do not require extremely fine meshes near the surface. Resolving the boundary layer accurately with a fine mesh and low-Reynolds number formulations to resolve the entire boundary layer into the laminar sub-layer does not always offer superior solutions (Fig. 5), although they are expected to be more realistic but computationally more demanding. There is a continued interest to further improve turbulence models in order to balance accuracy and computational effort (Defraeye et al., 2011). More commonly in the postharvest application field, standard turbulence models available in the software are being used without further consideration, which could lead to severe errors in the results if not carefully validated.

Usually the flow in and around stacked or packed postharvest produce depend on small details of the packaging and stacking materials, arrangement, shape and details of stored produce. This demands the calculation to handle dimensions of one-tenths of a millimetre to several meters. This wide range of scales requires a large number of cells in the numerical procedure increasing the computing demand. For this case, grid generation is usually the most time-consuming task. Usually it is also not possible to generate structured grids on which a clearly defined technic of grid independence tests be implemented. Verboven et al. (2006) discussed a method of simplification by using porous medium approach. The porous medium approach has been used for modelling temperature and species concentration inside a packed bed with considerable reduction of computing demand. This approach is necessary when computational resources do not allow modelling each particle and interstitial space individually and is more suitable for large stacks of particles.

In recent years, realistic geometry models have been made available from 3D image data (such as magnetic resonance imaging (MRI), computed tomography (CT) or microtomography). Existing mesh generation techniques only handle models generated by computer-aided design (CAD) tools and have difficulties meshing from 3D imaging data. Image-based meshing is opening up exciting new possibilities for the application of CFD to a wide range of problems that were previously intractable owing to the difficulty in obtaining suitably realistic models (Young et al. 2012). Improvement with respect to these realistic geometries will further improve the use of CFD in the postharvest.

The physics to be incorporated in postharvest systems are also diverse. Since it involves dealing with biological systems, all the variability apparent in biological systems have a corresponding effect on the development and accuracy of the CFD model. The fluid flow is usually coupled to transport of mass and heat in the fluid as well as in the biological materials of usually dissimilar transport properties, shapes and sizes. Usually simplifying assumptions are imposed to reach to acceptable solutions within reasonable computational time. Inaccuracies associated are assessed by using verification and validation studies. Analytical solutions of heat transfer of known geometries are frequently used to verify whether equations being solved correctly. Apart from this a detailed and thorough analysis of numerical errors is not yet common practice, but highly recommended. Temperature, velocity and pressure measurements are frequently used to validate postharvest CFD models with marginal consideration of the associated experimental uncertainties.

Ahmad and Matthews (2003) articulated a good assessment on what the future holds for the application of CFD in process industries by taking several influencing factors. The perpetual advances in computational technology (microprocessor speed, parallel processing and parallel computing algorithms), a sustained effort by CFD providers to implement comprehensive physical models, and advances in numerical methods (in terms of handling turbulence) were indicated as prime factors that make it possible for CFD to be more integrated in many industries. Similarly, a more complex and comprehensive CFD analysis of postharvest storage facilities will be conceivable in the near future.

6 Conclusions

This review discussed the different applications of CFD modelling of postharvest refrigeration processes. In most cases, porous media approaches and two-equation turbulence models are still being used. There is progress towards using CFD on detailed geometrical models of products and packages to explore further the transfer processes in postharvest storage. This direct numerical simulation also can be used to identify porous media and turbulence models that can significantly improve the accuracy of CFD simulation of large scale facilities. We are still at the advent of a true multiscale approach to CFD simulation of postharvest systems and the first comprehensive studies are to be presented in the coming years. Such breakthrough will soon be possibility with the availability of accurate 3D geometrical models in CFD and correctly implemented turbulence models.

7 Acknowledgements

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8 List of figures

Fig.1. Typical postharvest storage room for horticultural products.

Fig. 2. Realistic CFD geometry modelling is becoming feasible. (a) The random stacking of spheres in the plastic bins is achieved by using the discrete element method (Delele et al., 2010; Ambaw et al., 2011). (b) Complex strawberry packaging geometry is generated from 3D image analysis (taken with permission from Ferrua and Singh, (2009a))

Fig. 3. Multiscale CFD. (a-d) Simulated velocity contours inside a single EPS box loaded with 32 randomly packed spheres of 75 mm diameter, horizontal cross section at 7 cm above the bottom of the box, superficial velocity = 1 m/s. (e-f) Calulcated pressure drop through vented EPS boxes for different vent hole ratios: (a) fitted with the Darcy–Forchheimer equation; (b) fitted with the Ramsin equation; O = 11.03%, ● (CFD), — (fitted); O = 14.36%, ■ (CFD), - - - (fitted); O = 19.11%, ▼ (CFD), • • • (fitted) with O the vent hole ratio. (g) CFD of cool room including droplet tracks of humidification spray, temperature and humidity (taken with permission from Delele et al., 2008)

Fig. 4. Importance of turbulence modelling on airflow distribution. The figure shows the airflow pattern in a slot-ventilated enclosure, comparing the measured profile with the result from different turbulence models. In this case, the RSM model (b) gave superior results to the other two (taken with permission from Moureh and Flick, (2005)).

Fig. 5. Importance of turbulence modeling for heat transfer. The figure shows the local heat transfer coefficient over a cube on a surface in an approaching airflow for turbulence models solved on fine meshes resolving the boundary layer: the standard k–ε model (sk–ε), the realizable k–ε model (rk–ε) and the Shear Stress Transport k–ω model (SST k–ω). The coefficient on a

vertical (a) and horizontal (b) centreplane is compared to experimental data (taken with permission from Defraeye et al., 2010).

Table 1.

Summary of recent applications of CFD in characterizing and designing of post-harvest storage facilities

Physical description			CFD modeling				
Ref.	**Produce**	**Modelled system**	**Time dependency**	**Turbulence model**	**Porous media**	**Numerical technique**	**Validation**
Allais et al. (2006)	Gel filled celluloid spheres	Mist chilling of a stack of spheres	Transient	No	No	Empirical correlation plus finite volume	Air velocity and water mass flow rate measurements
Alvarez and Flick (2007)	PVC spheres	Cooling of stack of food products	Steady and Transient	Macroscopic turbulence model	Darcy–Forchheimer	Empirical correlation plus finite volume	Air velocity and temperature measurements
Amara et al. (2008)	Not specific	Flow field inside domestic refrigerator	Transient	No (Laminar flow)	No	Finite volume	Particle image velocimetry (PIV)
Ambaw et al. (2011b)	Apple	Diffusion and adsorption of gas in cold store for fruits	Transient	SST	Darcy–Forchheimer	Finite volume	1-MCP concentration measurements
Martins et al (2010)	Apple	Forced air cooling of fruits	Transient	No (Laminar flow)	No	Finite volume	Comparison of model calculated Nusselt number with reported in literature
Chourasia and Goswami (2007 a, b)	Potato	Airflow, heat and mass transfer in partially impermeable enclosure	Steady and Transient	No	Darcy-Forccheimer	Finite volume	time-temperature history and weight loss of product
Cuesta and Lamúa (2009)	Not specific	Heat conduction during chilling of fruit and vegetables	Steady	No	No	Empirical correlation (Fourier series based)	No validation
D’Agaro et al. (2006)	Not specific	Air flow and temperature distribution in display cabinet	Steady and Transient	Standard and RNG k-ε	No	Finite volume	Measured refrigeration power

Table 1. *(Continued)*

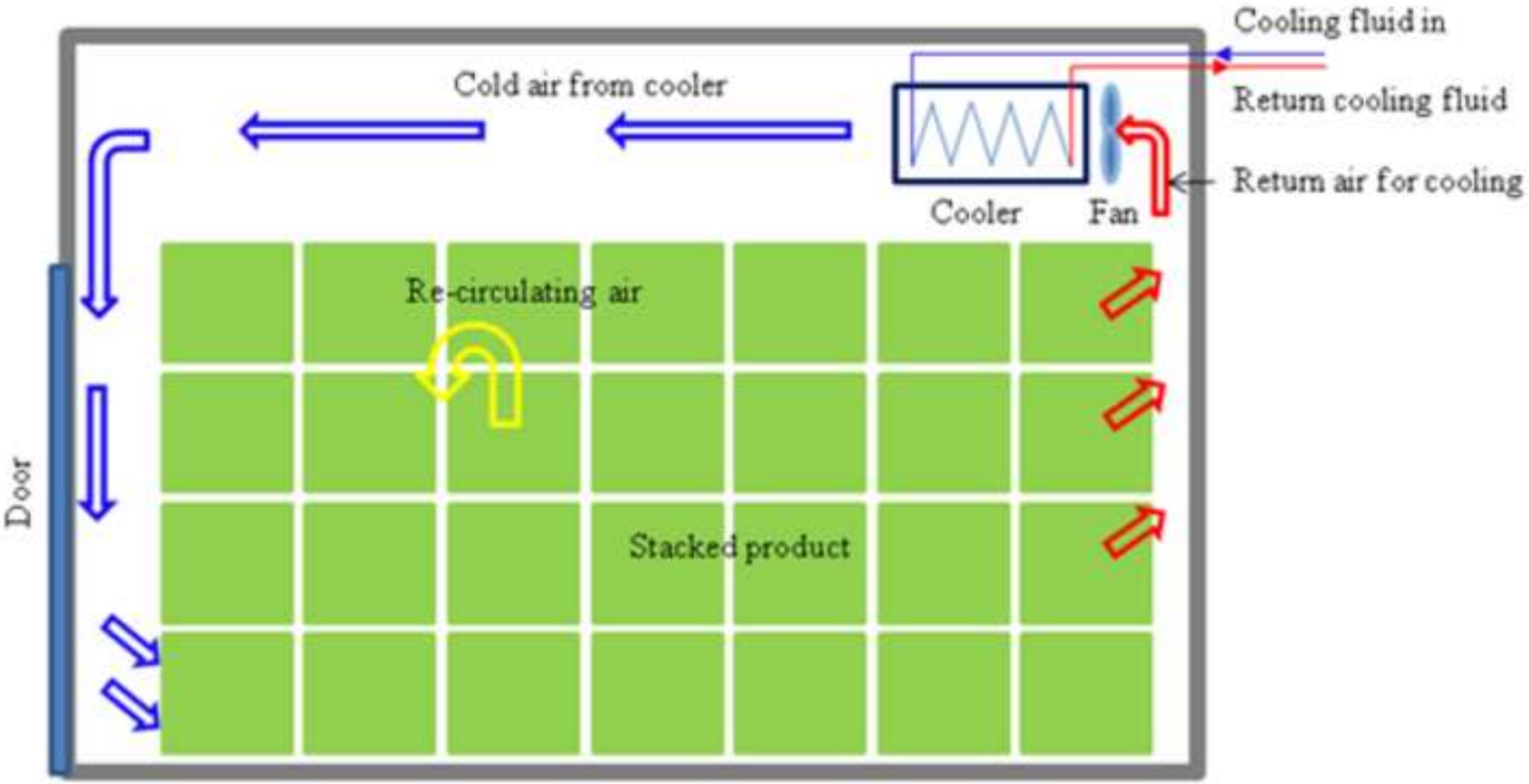
Physical description			**CFD modelling**				
Ref.	**Produce**	**Modelled system**	**Time dependency**	**Turbulence model**	**Porous media**	**Numerical technique**	**Validation**
Dehghannya et al. (2011)	Solid polymer balls	Forced air cooling	Transient	No	No	Finite element	Temperature measurements
Delele et al. (2008)	Water filled PVC spheres	Airflow through random stacking of horticultural products	Steady	SST	No	Finite volume	Velocity profile measurements and comparison with equation of Ergun (1952) for pressure
Delele et al. (2009)	Chicory root	Evaluation of chicory root cold store humidification	Steady and Transient	SST	Darcy-Forccheimer	Finite volume	Mean air velocity
Delele et al. (2009)	Water filled PVC spheres	Optimization of humidification of cold storage	Steady and Transient	SST	No	Finite volume	Wind tunnel measurements
Delele et al. (2011)	Apple	Thermonebulisation fungicide fogging system	Steady and Transient	SST	Explicit sphere stack	Finite volume	Particle deposition as a function of position in the stack
Ferrua and Singh (2009a, b, c and d) ; Ferruh and Singh (2011)	Strawberry	Forced-air cooling process of fresh strawberry packages	Steady and Transient	No (Laminar flow)	No	Finite volume	Particle image velocimetry (PIV), temperature measurements
Foster et al. (2006); Foster et al. (2007)	Not specific	Air curtain to restrict cold room infiltration	Transient	k- ε	No	Finite volume	Temperature and velocity measurements
Hao and Ju (2011)	Not specific	Flow field of low temperature mini-type cold store	Steady			Finite volume	No validation
Ho et al. (2006, 2008, 2011)	Apple and pear fruit	Gas permeation, diffusion and respiration kinetics	Transient	No	Darcy	Finite element	Gas concentration profiles and fluxes

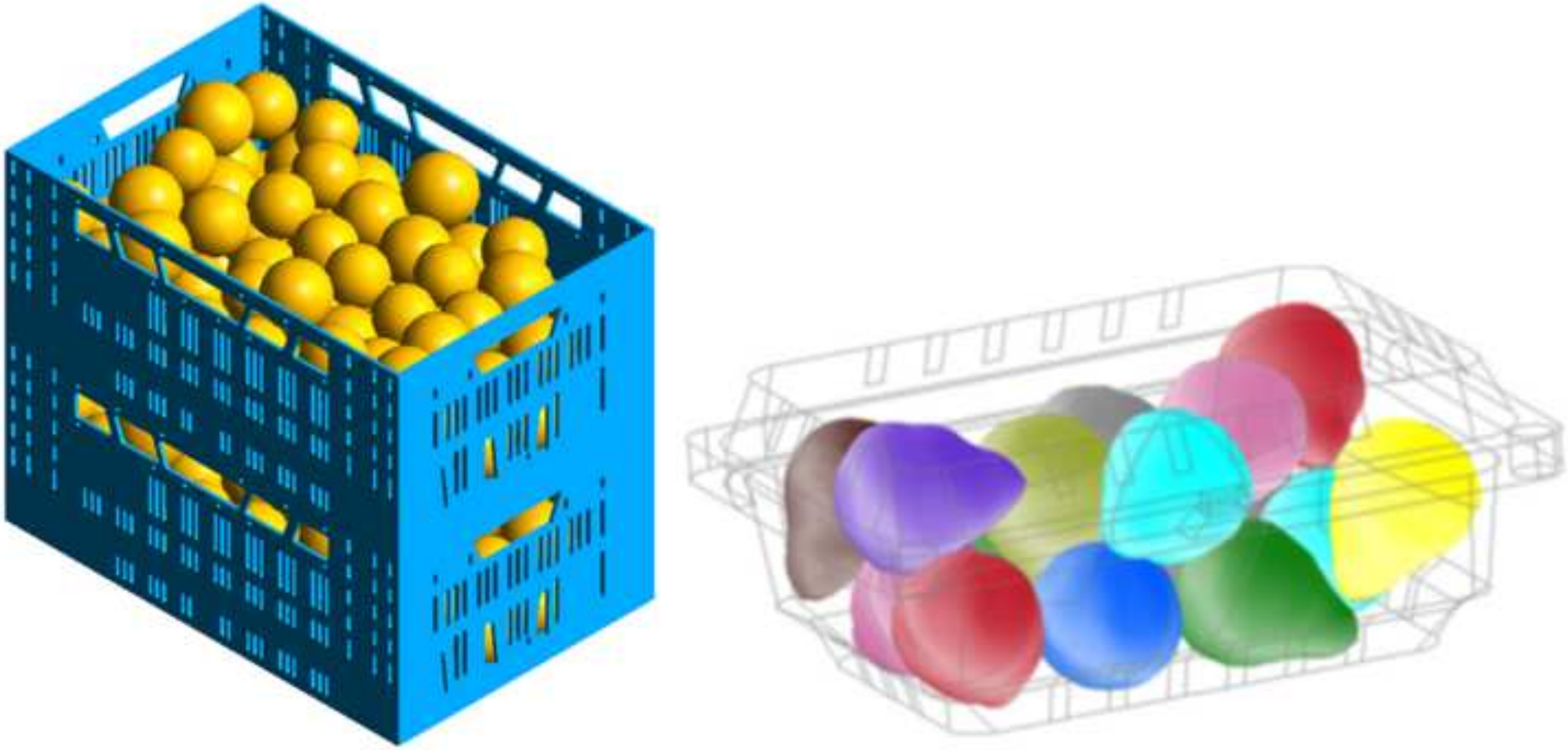
Table 1. *(Continued)*

Physical description			CFD modelling				
Ref.	**Produce**	**Modelled system**	**Time dependency**	**Turbulence model**	**Porous media**	**Numerical technique**	**Validation**
Moureh et al. (2009a, b)	Spherical objects	Airflow in a slot-ventilated enclosure partially filled with porous boxes	Steady	RSM	Darcy-Forccheimer	Finite volume method	Laser Doppler Velocimetry and pressure measurements
Moureh et al. (2009)	Spherical objects	Air velocity characteristics within vented pallets loaded in a refrigerated vehicle	Steady	RSM	Darcy-Forccheimer	Finite volume method	Temperature, pressure and velocity measurements
Moureha et al. (2009)	Cheese and meat products	Mist flow process in refrigerated display cabinets	Steady	RNG k– ε	No	Empirical correlation	velocity and temperature measurements
Rennie and Tavoularis (2009a, b)	Strawberries	Perforation-mediated modified atmosphere packaging	Steady and Transient	No	Darcy's law	Finite element	O_2 and CO_2 evolution comparison with experimental results of Silva et al. (1999).
Tanaka et al. (2011)	Water filled PET plastic bottles	Cold store	Transient	k- ε model	No	Finite volume	Air flow and temperature measurements
Tapsoba et al. (2006)	Spherical objects	Airflow in an enclosure loaded with slotted pallets	Steady	RSM	Source term	Finite volume method	Laser Doppler Velocimetry and pressure measurements
Tapsoba et al. (2007)	No	Airflow patterns inside slotted obstacles in a ventilated enclosure	Steady	RSM and k– ε		Finite volume method	Laser Doppler Velocimetry and pressure measurements

Table 1. *(Continued)*

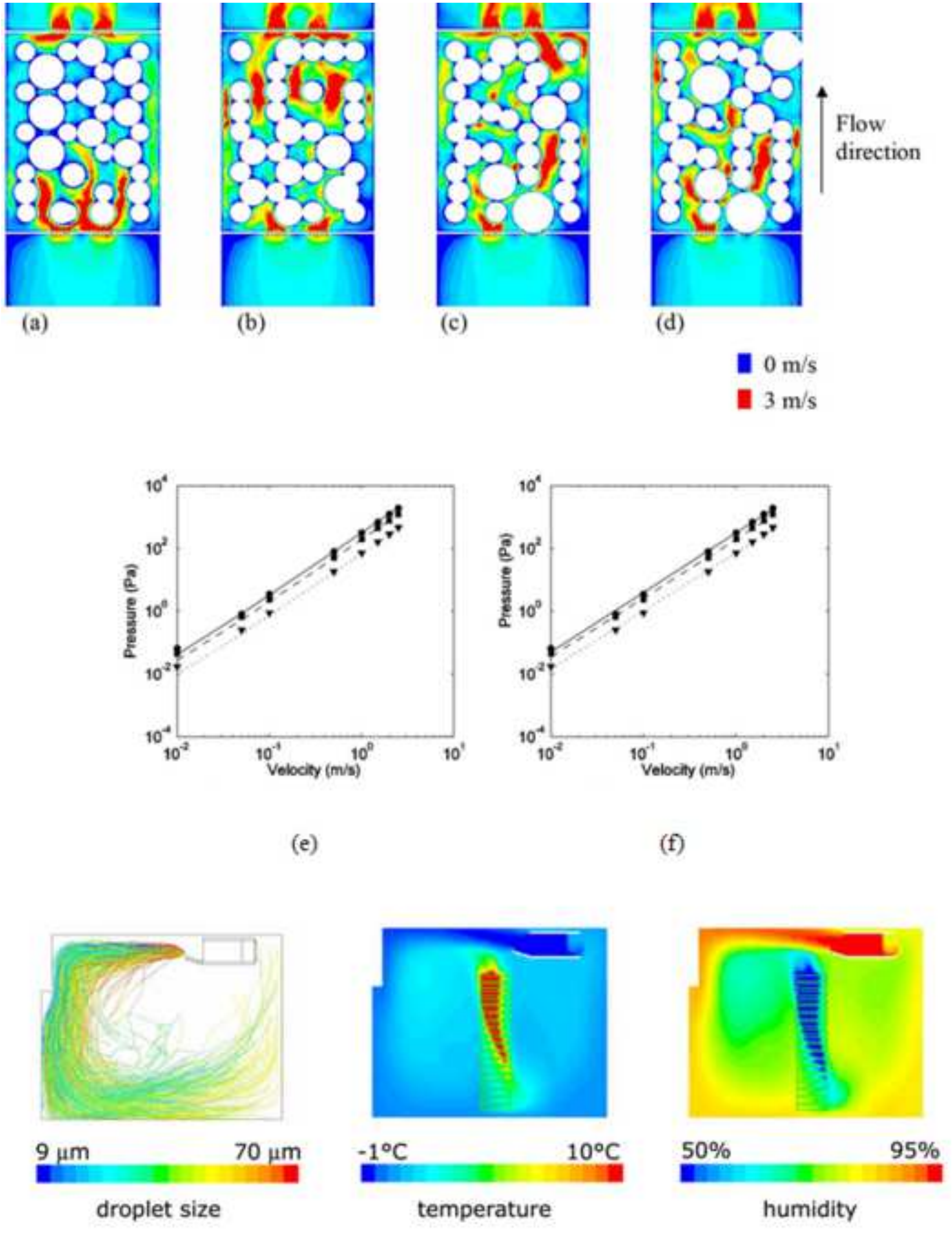
Physical description			CFD modelling				
Ref.	**Produce**	**Modelled system**	**Time dependency**	**Turbulence model**	**Porous media**	**Numerical technique**	**Validation**
Thorpe (2006)	Not specific	Hydrocoolers for horticultural produce	Transient	No	No	Finite difference	No validation
Tutar et al. (2009)	Hypothetical spheres	Airflow patterns and heat transfers through stacked layer of products in a vented box during cooling	Transient	k – ε and RNG k– ε	No	Finite volume	No validation
Xie et al. (2006)	Not specific	Flow and temperature fields of a cold store	Steady	K– ε	No	Finite volume	Velocity and Temperature measurements
Zou et al. (2006a and b)	Apple	Airflow and heat transfer in ventilated packaging for fresh foods	Transient	No	Darcy-Forccheimer	Global and local grid method	Temperature measurements


Cooling fluid in
Cold air from cooler
Return cooling fluid
Return air for cooling
Cooler
Fan
Re-circulating air
Door
Stacked product



(a)

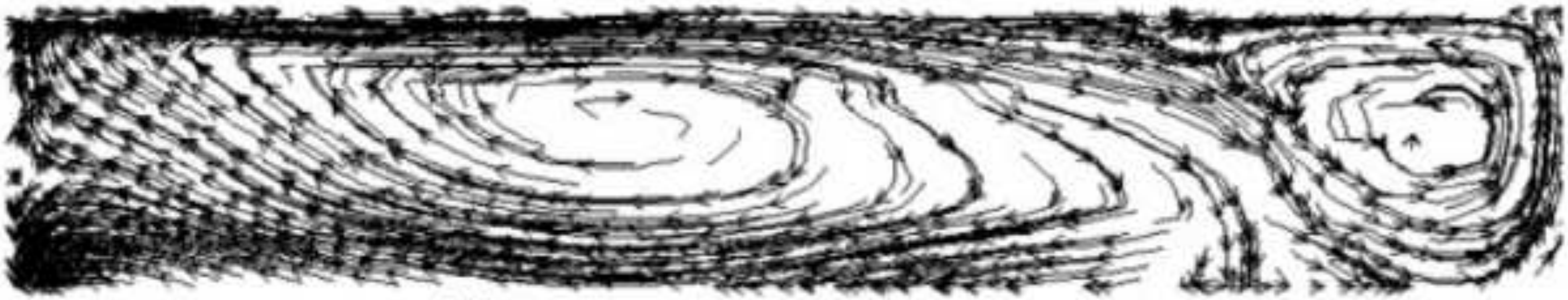
(b)


Flow direction
0 m/s
3 m/s
10⁴
10²
10⁰
10⁻²
10⁻⁴
Pressure (Pa)
10⁻²
10⁻¹
10⁰
10¹
Velocity (m/s)
10⁴
10²
10⁰
10⁻²
10⁻⁴
Pressure (Pa)
10⁻²
10⁻¹
10⁰
10¹
Velocity (m/s)
9 μm
70 μm
droplet size
-1°C
10°C
temperature
50%
95%
humidity

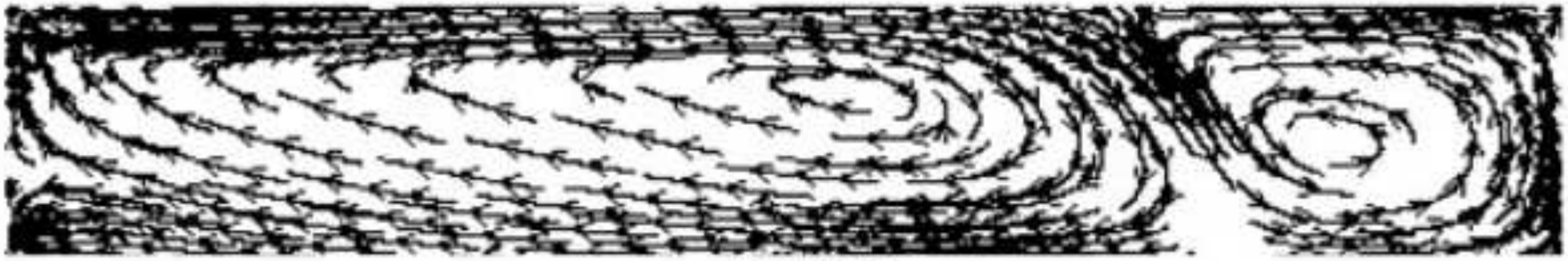
(a) (b) (c) (d)

(e) (f)

(g)



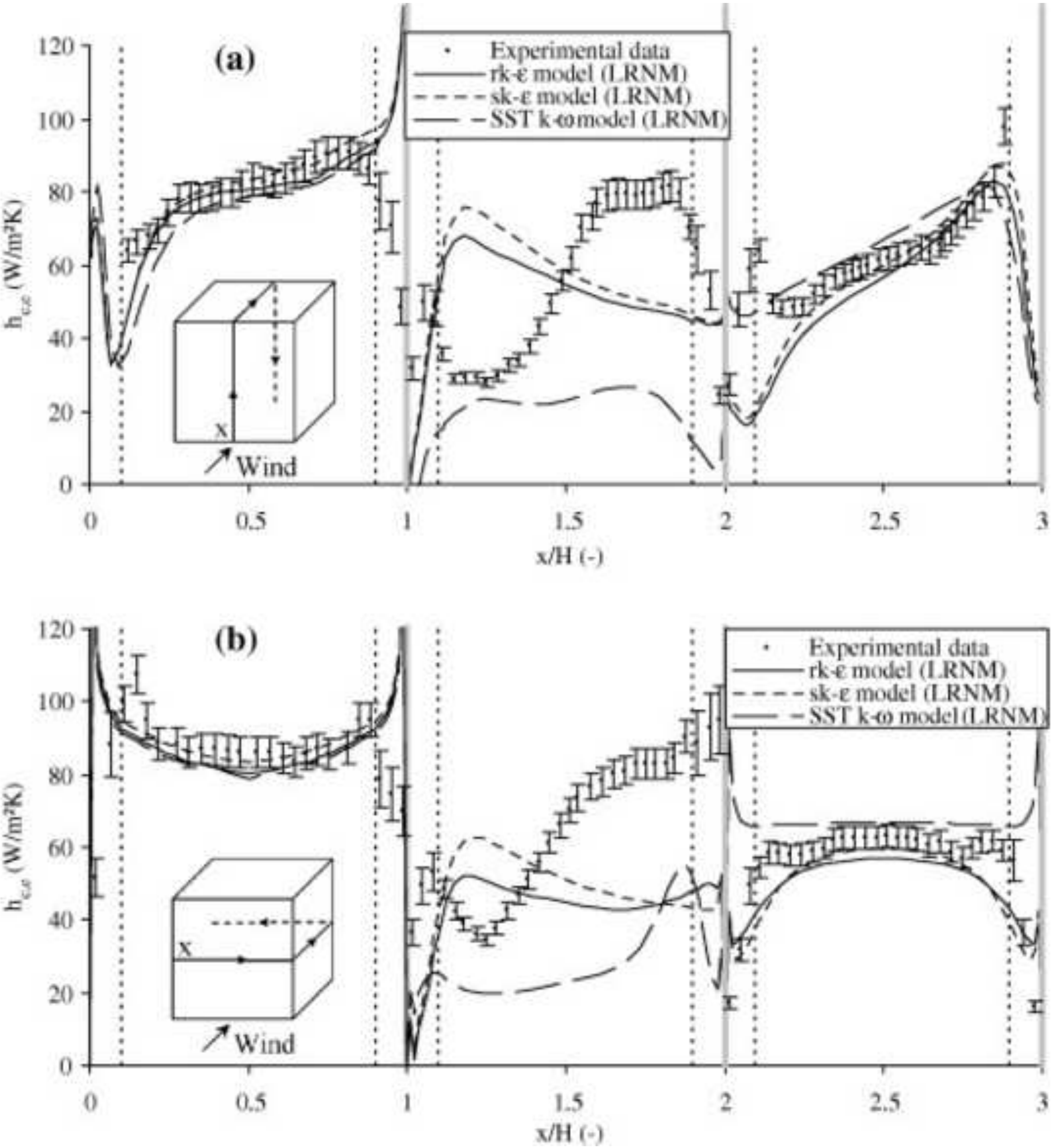
(a) Experiment (1080 measurement points)



(b) RSM

(c) High Reynolds *k*-*ε* model

(d) LRN *k*-*ε* Lam-Bremhorst model


(a)
Experimental data
rk-ε model (LRNM)
sk-ε model (LRNM)
SST k-ω model (LRNM)
$h_{c,e}$ (W/m²K)
0
20
40
60
80
100
120
x
Wind
0
0.5
1
1.5
2
2.5
3
x/H (-)
(b)
Experimental data
rk-ε model (LRNM)
sk-ε model (LRNM)
SST k-ω model (LRNM)
$h_{c,e}$ (W/m²K)
0
20
40
60
80
100
120
x
Wind
0
0.5
1
1.5
2
2.5
3
x/H (-)