CFD Modelling to Study the Effects of Table Grape Packaging and Stacking on Cooling and Moisture Loss

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Abstract

Optimal packaging and storage are critical technologies in maintaining quality of fresh produce. Computational fluid dynamic (CFD) model was used to investigate airflow, heat and mass transfer characteristic during cooling and handling of packed table grapes. The model was applied to study effects of plastic liner, bunch carry bag and box stacking on airflow, heat and mass transfer characteristics. The model was also used to study alternative cooling and handling procedures. The carton box was explicitly modeled, and grape bunch with the carry bag was treated as a porous media. Plastic liner was modeled as porous jump. The porous media and porous jump loss coefficients were determined using separate wind tunnel experiments. The presence of bunch carry bag and plastic liner increased the cooling time of the grapes significantly. The lowest moisture loss was observed for the package that used non-perforated plastic liner. However, packing with non-perforated plastic liner generated the highest amount of condensate inside the package. Cooling of bulk grapes using a relatively high RH air before covering with the plastic liner has a potential for improving the cooling rate while minimizing moisture loss and amount of condensation. Airflow and heat transfer characteristics were also highly influenced by the orientation and stacking pattern of packages.

INTRODUCTION

During postharvest handling and storage of fresh table grape, produce is usually packed in vented cardboard boxes with multiple inner packaging materials that include plastic liner, SO_2 pad, moisture absorber and bunch carry bag. The main functions of these package components are to maintain the quality of the grape by providing a shield against mechanical injuries, minimizing product moisture loss and retarding microbial decay. Low temperature handling and storage condition is usually applied to control the rate of respiration, moisture loss and microbial growth. Suboptimal storage and handling condition may cause high level of moisture loss and decay (Nelson, 1985; Lichter et al., 2008; Costa et al., 2011; Ngcobo et al., 2011).

Both experimental and mathematical modeling techniques have been used to study airflow, heat and mass transfer processes during precooling, transportation and storage of horticultural produces (Alvarez & Flick, 1999; Nahor et al., 2005; Delele et al., 2009; Ferrua & Singh, 2009; Opara & Zou, 2007; van der Sman, 2002; Tutar et al., 2009). Some researchers have studied the airflow, heat and mass transfer processes within the individual and packed grapes using experimental (Nelson, 1978; Gentry & Nelson, 1964; Frederick & Comunian, 1994) and modeling techniques (Acevedo et al., 2007; Dincer, 1995). However, there is a lack of a comprehensive 3-D model that is capable of predicting the airflow, heat and mass transfer within and around multiple package components such as that used for fresh table grape. Nowadays, validated mathematical models such as computational fluid dynamics (CFD) modelling technique are becoming an alternative to the difficult, time consuming and expensive experimental methods. The objective of this study was to develop a validate 3-D CFD model of table cooling process that predicted the cooling air velocity, temperature, RH and product moisture loss, taking into account the detailed geometries of the packaging components.

MATERIALS AND METHODS

Table grape package and Stacking

Grape bunches were packed using vented carton box with dimensions of 0.4 m long, 0.3 m wide and 0.133 m high (Fig. 1). Bunches were placed inside a vented carry bag. Every box contains about 4.5 kg of grape; equivalent to 6-8 carry bags depending on the size of the grape bunch. During packing, each carry bag containing a bunch of berries is placed inside the plastic liner, and moisture absorption and SO_2 pads were placed over the carry bags and the liner was closed and sealed using a plastic tape. A corrugated paperboard sheet is placed at the bottom of the box to protect the berries against bruising. To evaluate the effect of stacking and orientation, 30 boxes of grape were stacked on a pallet in three levels (10 boxes per level) according to the commercial guideline (Fig. 1).

CFD model formulation

1. Governing equations. The governing equations were solved using Reynolds-averaged procedure. In Cartesian coordinates, for flow in a porous medium, the Reynolds-averaged fluid flow equations based on interstitial fluid velocity are as follows:

$$\frac{\partial(\rho_a)}{\partial t}+\frac{\partial(\rho_a u_i)}{\partial x_i}=S_m \tag{1}$$

$$\begin{aligned}\frac{\partial(\rho_a u_i)}{\partial t}+\frac{\partial(\rho_a u_i u_j)}{\partial x_j}=-\frac{\partial(p)}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu_a\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]-\frac{\partial}{\partial x_j}\left(\rho_a\overline{u_i'u_j'}\right)\\ -\left[1-\alpha\left(T-T_o\right)\right]\rho_a g+S_u\end{aligned} \tag{2}$$

By assuming a local thermal equilibrium between the air and the porous solid matrix, the energy equation is:

$$\begin{aligned}\frac{\partial}{\partial t}\left(\phi\rho_a C_{pa}T+(1-\phi)\rho_p C_{pp}T\right)+\frac{\partial}{x_j}\left(\phi\rho_a C_{pa}u_j T\right)=\frac{\partial}{\partial x_j}\left[\lambda_e\left(\frac{\partial T}{\partial x_j}\right)\right]\\ -\frac{\partial}{\partial x_j}\left(\phi\rho_a C_{pa}\overline{u_j'T'}\right)+S_e\end{aligned} \tag{3}$$

The transport equation for vapour mass fraction is:

$$\frac{\partial(\phi\rho_a Y_v)}{\partial t}+\frac{\partial}{\partial x_j}\left(\phi\rho_a u_j Y_v\right)=\frac{\partial}{\partial x_j}\left[\rho_a D_e\left(\frac{\partial(Y_v)}{\partial x_j}\right)\right]-\frac{\partial}{\partial x_j}\left(\phi\rho_a\overline{u_j'Y_v'}\right)+S_m \tag{4}$$

The values of the porosity for the bulk, free air and solid regions were 0.53, 1 and 0, respectively. The momentum source due to the airflow resistance of the bulk grape was determined using the Darcy-Forchheimer equation.

2. Boundary conditions and simulation procedure. Detail geometry of the package was developed and meshed using tetrahedral hybrid mesh. The plastic liner was modelled using a porous jump boundary condition. For this boundary, the pressure drop is expressed as: $\Delta p = -\left(\frac{\mu}{K}u + \beta\frac{1}{2}\rho u^2\right)t_l$, where t_l is the thickness of the liner. The coefficients ($\frac{1}{K}$ and β) were determined from a wind tunnel experiment. For instance, for 120 × 2mm vented plastic liner, the values of t_l, $\frac{1}{K}$ and β were 16 mm, 4.64×10^7 and 1.90×10^4, respectively. Bulk product region (grape bunch plus carry bag) was treated as porous media. These porous regions were defined in the form of Darcy-Forchheimer equation ($\frac{\Delta P}{L_b} = -\frac{\mu}{K}u - \beta\frac{1}{2}\rho u^2$), where the pressure loss coefficients were determined from a separate wind tunnel experiment. Measured values of $\frac{1}{K}$ and β were 1.74×10^7 m^{-2} and 358.08 m^{-1}, respectively. Cooling was done by forcing air at temperature of -0.5^0C and 90 % RH and uniform velocity through the package. 21^0C was taken as an initial temperature of the grapes.

The equations were discretised using a second order upwind scheme and pressure-velocity coupling was done using a SIMPLE algorithm. A time step of 120 s and 50 iterations per time step were used. The simulation was converged to a solution with a normalized scaled residual below 10^{-4} for all equations. The calculation was done using 64-bit, Intel® Core™2 i7 CPU, 2.93 GHz, 8 Gb RAM, Windows 7 computer and the CPU time of calculation was more than 22 h.

RESULTS AND DISCUSSION

The predicted air velocity, temperature and RH humidity profiles are shown in Fig. 2. The airflow profile and velocity is highly influenced by the orientation of the box in reference to the incoming airflow direction (Fig. 2a). The side with higher vent area gave better penetration of the cooling air with lower pressure drop. Due to the high flow resistance, the tendency of the air to pass through the plastic liner was very limited. For non-perforated liner, the flow through it was completely blocked. In the case of perforated liner, there was a relatively small flow of air through the liner. For instance, after 4 h of cooling, the average velocity of the air inside non perforated and perforated liner was 0.008 m s^{-1} and 0.019 m s^{-1}, respectively. Grape cooling rate and temperature uniformity were highly influenced by the airflow characteristics (Fig. 2b). The RH humidity was also affected by the orientation of the box relative to the incoming cooling air (Fig. 2c).

The cooling rate was faster in the case of perforated liner than non-perforated liner (Fig. 3a). Non-perforated liner showed higher rate of moisture condensation inside the package than perforated liner (Fig. 3b), however rate of grape moisture loss was higher in perforated liner than non-perforated liner. Cooling of package without a plastic liner with high RH (RH ≥ 95 %) air increased the cooling rate while minimizing the amount of moisture loss. Predicted airflow and temperature profiles of boxes that were stacked according the commercial guideline are given in Fig. 4. The flow behaviour was highly dependent on the orientation of the stack to the incoming cooling air. For this stacking pattern, forcing the cooling air from direction 2 gave better cooling rate than forcing from direction 1 (Fig. 4b). These results show the applicability of CFD modelling in optimizing packaging system design and stacking.

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Figures

Fig. 1. Typical table grape package stacked over a pallet

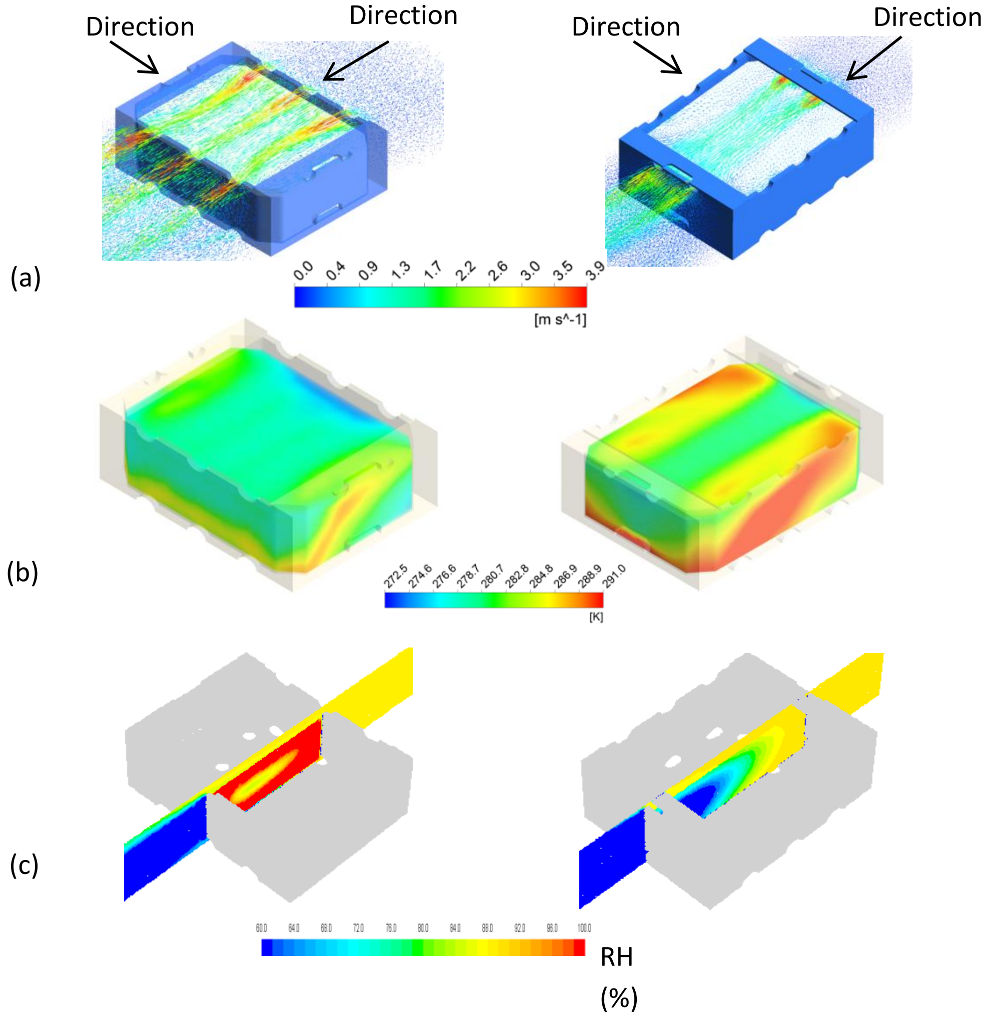

Fig. 2. Predicted airflow, temperature and RH profiles around and inside the package; (a) air velocity vector when air was forced along direction 1 (left), air velocity vector when air was forced along direction 2 (right); (b) temperature distribution after a cooling time of 4 h from an initial temperature of 21 ^{0}C; (c) RH distribution after a cooling time of 4 h from an initial temperature of 21 ^{0}C

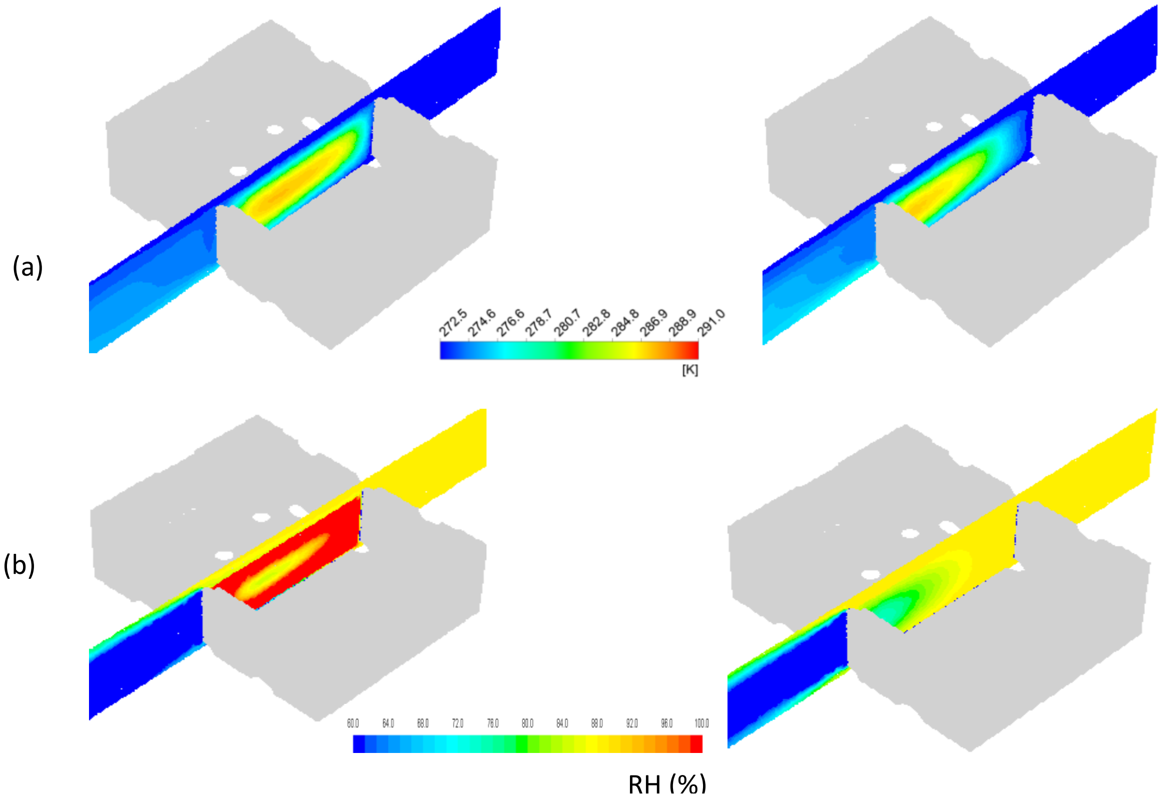

Fig. 3. Effect of plastic liner on heat and moisture transfer: (a) Temperature profile after cooling time of 4 h, non-perforated liner (left), perforated liner (right); (b) RH profile after cooling time of 4 h, non-perforated liner (left), perforated liner (right)

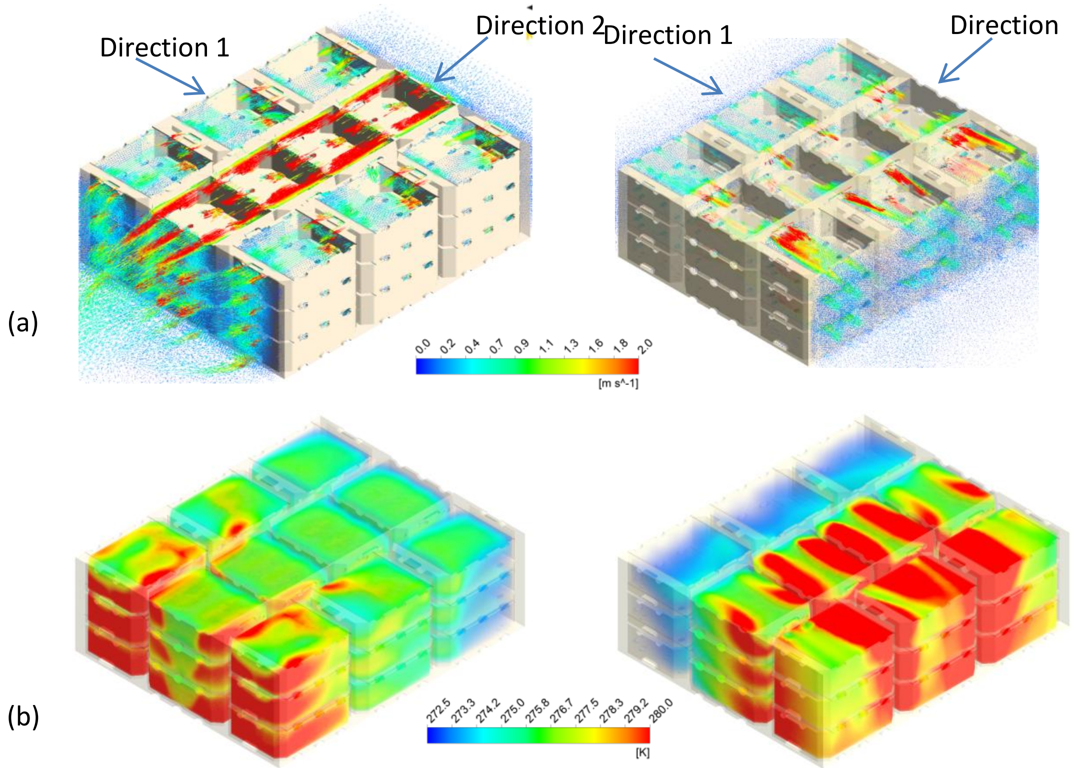

Fig. 4. Effect of stacking pattern on airflow and heat transfer: (a) air velocity vector when air was forced along direction 1 (left), air velocity vector when air was forced along direction 2 (right); (b) temperature distribution after a cooling time of 8 h