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Research Paper

Transport phenomena modelling during produce cooling for optimal package design: Thermal sensitivity analysis

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ARTICLE INFO

Article history:
Received 13 September 2011
Accepted 2 January 2012
Published online 30 January 2012

Mathematical modelling of transport phenomena was performed to assess the cooling of produce with respect to package design during forced convection cooling. Nine different vent designs including 1, 2, 3 and 5 vents corresponding to 4 different vent areas of 2.4, 4.8, 7.2 and 12.1%, respectively, were simulated. More uniform produce cooling with less cooling time was obtained where there were properly distributed vents on package walls with enough opening area. Experimental validations were performed considering produce centre temperature at 4 positions inside 3 different ventilated packages. Good agreement between experimental and simulated temperatures was obtained with mean absolute error of 2.2 °C considering all the 3 vent configurations. The study showed that for a suitable package design, with respect to different vent areas and positions on package walls, it is necessary to consider both produce cooling time as well as cooling uniformity during the cooling operation.

1. Introduction

Precooling of fruit and vegetables is among the most cost-effective and efficient quality preservation methods for retarding ripening and controlling microbial processes. It is available to commercial crops and is the most essential of all the value-added marketing services demanded by increasingly more sophisticated consumers (Baird & Gaffney, 1976; Brosnan & Sun, 2001; He & Li, 2003; Sullivan, Davenport, & Julian, 1996). Forced convection precooling processes are commonly used to decrease agricultural produce temperature following harvest (Castro, Vigneault, & Cortez, 2005; Kader, 2002; Kumar, Kumar, & Murthy, 2008). To maintain optimum quality of the commodities during storage or transportation (Rodriguez-Bermejo, Barreiro, Robla, & Ruiz-Garcia, 2007), the process should provide uniform cooling throughout the stacked produce during the treatment (Goyette, Vigneault, Panneton, & Raghavan, 1996). However, heterogeneous airflow distribution at different locations in the package occurs resulting in produce deterioration and shrivelling during storage (Alvarez, Bournet, & Flick, 2003; Alvarez & Flick, 1999; Ben Amara, Laguerre, & Flick, 2004; Castro, Vigneault, & Cortez, 2004; Gowda, Narasimham, & Murthy, 1997; Smale, Tanner, Amos, & Cleland, 2003). In practice, experiential combinations of air temperature and velocity are chosen by designers to rapidly cool the produce to a suitable temperature. This is because the thermal performance of containers is neither supplied, nor considered, in package design due to the

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doi:10.1016/j.biosystemseng.2012.01.001

Nomenclature

$c_{p,a}$	air specific heat capacity ($J\,kg^{-1}\,^{\circ}C^{-1}$)
$c_{p,p}$	produce specific heat capacity ($J\,kg^{-1}\,^{\circ}C^{-1}$)
k_a	air thermal conductivity ($W\,m^{-1}\,^{\circ}C^{-1}$)
k_p	produce thermal conductivity ($W\,m^{-1}\,^{\circ}C^{-1}$)
P	pressure (Pa)
Q_{resp}	respiratory heat generation per unit package volume ($W\,m^{-3}$)
T_a	air temperature at different positions inside ventilated packages (°C)
T_p	produce temperature at different positions inside ventilated packages (°C)
u	velocity vector ($m\,s^{-1}$)
μ_a	air dynamic viscosity (Pa s)
ρ_a	air density ($kg\,m^{-3}$)
ρ_p	produce density ($kg\,m^{-3}$)

lack of available tools. A more logical approach to designing new packages is to develop a model that would be able to predict package performance rather than requiring costly experiments.

The airflow and heat transfer models in the literature during forced convection cooling process have not considered the effects of package vent design, including vent area and position, on produce cooling uniformity (Ferrua & Singh, 2008; Opara & Zou, 2007; Zou, Opara, & McKibbin, 2006a, 2006b). Opara & Zou (2007) applied sensitivity analysis using a computational fluid dynamics (CFD) model to study the effect of variations in package vent area and position during the forced convection cooling process. The authors noticed some considerable variations in produce cooling rate. However, the effect of multiple vents on cooling uniformity considering different vent area and position was not examined in the study. Dehghannya, Ngadi, and Vigneault (2008) developed and experimentally validated a mathematical model of airflow and heat transfer for aerodynamic analysis during forced-air precooling inside ventilated packages. Direct numerical simulations and analysed velocity distributions were applied and their resultant airflow heterogeneity indices inside different ventilated packages. However, temperature distribution at different positions of the packages was not considered. Dehghannya, Ngadi, and Vigneault (2010) critically reviewed comprehensive and detailed mathematical modelling procedures for the airflow, heat and mass transfer occurred during forced convection cooling of produce in order to optimise the cooling process. Two main modelling procedures used during the process, namely the porous medium approach and direct numerical simulation, were extensively explored in the study. In a further study, Dehghannya, Ngadi, and Vigneault (2011) simulated and analysed temperature distributions inside different ventilated packages so that more uniform temperature distribution could be achieved during the process. The results of the investigation confirmed that produce temperature distribution is influenced by different ventilated package designs. It was also shown that produce cooling uniformity is increased by increasing number of vents. In the present study, a sensitivity analysis was conducted. In addition to packages with different number of vents, packages with the same number of vents but different vent distributions on package walls were considered. This was to investigate the simultaneous effect of the vent numbers and the vent distribution on produce cooling efficiency during the forced-air precooling process.

Thus, the aim of this study was to assess sensitivity of produce cooling uniformity and cooling time with respect to package vent design during forced convection cooling of produce. The effect of different package designs including various vent areas and positions on produce cooling were considered.

2. Material and methods

2.1. Model development and numerical method

A transient two-phase air-produce mathematical model of simultaneous airflow and heat transfer inside ventilated packages containing spherical produce was considered (Fig. 1 and Table 1). For air domain, the governing equations in Cartesian coordinates were applied for incompressible airflow as follows:

$$\nabla \cdot u = 0 \tag{1}$$

$$\rho_a \frac{\partial u}{\partial t} + \rho_a (u \cdot \nabla u) = -\nabla p + \nabla \cdot \left[\mu_a \left(\nabla u + (\nabla u)^T\right)\right] \tag{2}$$

$$\rho_a c_{p,a} \frac{\partial T_a}{\partial t} + \rho_a c_{p,a} (u \cdot \nabla T_a) = \nabla \cdot (k_a \nabla T_a) \tag{3}$$

where u denotes the velocity field ($m\,s^{-1}$) at different positions inside the package, ρ_a air density ($kg\,m^{-3}$), t time (s), P pressure (Pa), μ_a air dynamic viscosity (Pa s), $c_{p,a}$ air specific heat capacity ($J\,kg^{-1}\,K^{-1}$), T_a air temperature at different positions inside ventilated packages (°C) and k_a air thermal conductivity ($W\,m^{-1}\,K^{-1}$).

For the produce domain, the respiratory heat generation can be incorporated into the energy conservation equation as follows:

$$\rho_p c_{p,p} \frac{\partial T_p}{\partial t} = \nabla \cdot (k_p \nabla T_p) + Q_{resp} \tag{4}$$

where ρ_p represents produce density ($kg\,m^{-3}$), $c_{p,p}$ produce specific heat capacity ($J\,kg^{-1}\,K^{-1}$), T_p produce temperature at different positions inside ventilated packages (°C), k_p produce thermal conductivity ($W\,m^{-1}\,K^{-1}$) and Q_{resp} respiratory heat generation ($W\,m^{-3}$).

At inlet, velocity and temperature; at outlet, pressure and convection; at package walls, no slip and insulation; and on air-produce interface, no slip and continuity ($T_a = T_p$) boundary conditions were applied (Dehghannya et al., 2008). Different model parameters including heat generation by respiration (Q_{resp}) and mass transfer rate were formulated. It was shown that three-dimensional (3-D) modelling of airflow