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A nonintrusive flow measurement technique to validate the simulated laminar fluid flow in a packed container with vented walls

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ABSTRACT

A nonintrusive flow measurement technique (particle image velocimetry) was used to determine the airflow field in a package with a container-to-product diameter ratio of less than 10. The complexity and uneven distribution of the measured flow field supported the requirement of a geometrical and mathematical model capable of describing the geometry and physics of flow within the package. Using novel computational fluid dynamics (CFD) codes, an accurate model of the packed structure was developed and the 3D Navier–Stokes equations were solved. A good agreement was obtained between experimental and predicted velocities. The detailed insight on the airflow pattern provided by the CFD analysis makes this approach an ideal tool to analyze the effect of different vent designs in the airflow field distribution in complex packaging systems.

Technique non envahissante utilisée pour mesurer l’écoulement laminaire simulé dans un conteneur chargé aux parois munies d’évents

Mots clés : Conteneur ventilé ; Procédé ; Mesure ; Écoulement laminaire ; Air ; Imagerie ; Particule ; Modélisation ; Dynamique numérique des fluides

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Nomenclature

$\dot{Q}$	volumetric flow rate ($m^3\,s^{-1}$)
u_i	velocity component in x_i direction ($m\,s^{-1}$)
p	static pressure ($N\,m^{-2}$)
x_i	Cartesian tensor notation of the spatial coordinates
x, y, z	spatial coordinates

Greek symbols

ν	kinematic viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)

1. Introduction

Optimal design and efficiency of the forced-air cooling process are vital for minimizing postharvest losses of fresh horticultural commodities. During forced-air cooling, commodities packed either in bulk (potatoes, oranges) or in individual consumer packages (high-value commodities such as berries) are stacked on pallets and placed inside a cooling room, where cool air is forced through them. The design of these vented packages is largely based on their mechanical strength; their ability to promote rapid and uniform cooling of the packaged products is often deficient.

Experimental research conducted during the last several decades has shown that the design of vent openings in individual consumer packages plays a major role in the efficiency of the cooling process (Émond et al., 1996). However, these experimental studies have remained limited in their scope because of the cost and time required to gather appropriate data for meaningful results (Vigneault and Goyette, 2002; Anderson et al., 2004; Castro et al., 2004).

An alternative approach to study potential improvements in the efficiency of the forced-air cooling process is to develop mathematical models capable of predicting the airflow field and heat transfer within packaged commodities during forced-air cooling (Talbot, 1988; Xu and Burfoot, 1999; Hoang et al., 2001, 2003; van der Sman, 2002; Tanner et al., 2002a,b; Alvarez et al., 2003; Zou et al., 2006a,b). Verboven et al. (2006) and Ferrua and Singh (2007) recently reviewed these mathematical approaches. In general, due to the limitations in computational resources, these models required simplification of the geometrical characteristics of the system. They assumed the packed structure as a porous medium and relied on a large number of effective parameters to model the transport phenomena through it. Although a wide range of correlations have been suggested to predict these effective parameters, a lack of consensus among them has prevented a reliable solution.

A common drawback in many of the available models is to assume the packed structure as a porous medium. This assumption cannot be justified when the container-to-product diameter ratio is below 10 (Whitaker, 1986), a common occurrence in the case of individual packages of horticultural products. In these cases, the heterogeneity in the local airflow pattern within the horticultural packages has a major impact on the transport phenomena during the forced-air cooling process and the continuous medium assumption is not valid anymore (Alvarez and Flick, 1999a,b). The difficulty in measuring the flow field within packages and the limitations of computational resources to model the complex packaging structure have limited progress in improving the design and efficiency of the forced-air cooling process.

When modeling the transport processes within individual horticultural packages, the limitation of the porous media approach is evident when the container-to-product diameter ratio of the packages is calculated. Table 1 shows the container-to-product diameter ratio for commonly used retail packages. The characteristic dimension of the container was assumed to be equal to its hydraulic diameter. The characteristic dimension of the product was defined as the diameter of a sphere whose volume represents the average volume of the product.

Recent advances in computational fluid dynamics (CFD) codes and computational resources have provided powerful tools to obtain detailed simulations of the local airflow field within complex packaging structures. In the chemical engineering literature, novel CFD codes have been used to simulate the fluid flow and heat transfer process within fixed-bed reactors of small tube-to-particle diameter ratio (Logtenberg et al., 1999; Dixon and Nijemeisland, 2001; Freund et al., 2003; Nijemeisland and Dixon, 2004; Guardo et al., 2005). Recently, Verboven et al. (2006) suggested the use of this approach to model transport phenomena in different types of food processes, in particular to model the airflow through a box randomly filled with spherical objects.

Up to now, these novel CFD models have been validated using intrusive pointwise velocity measurements or indirect techniques (such as measurements of pressure drop or heat transfer parameters). These studies indicate the potential capability of a given model to predict the general features of the flow field within a system. However, these techniques are unable to validate the predicted local airflow behavior, especially in the case of turbulent regimes. Nonintrusive image-based techniques such as Laser-Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) have been identified as possible methods to determine the flow field inside complex packed structures, but their application is still subject to severe limitations. Tapsoba et al. (2006) investigated, both experimentally and numerically, the airflow pattern within a refrigerated truck loaded with two rows of slotted pallets. However, due to difficulties in direct measurements of air velocity within a complex packaged structure using LDV, their study was limited to empty pallets.

The objective of our research was to investigate the use of PIV in combination with novel CFD models to develop a mathematical model capable of accurately predicting the airflow field within a complex packed structure where the container-to-product diameter ratio is below 10.

2. Experimental setup for nonintrusive flow field measurements

The design of the physical model used in this study was based on a typical 0.5-kg strawberry package used for retail marketing. The packed test section consisted of 22 spheres of 16.3 ± 0.2 mm diameter, arranged in a cubic centered