INTERNATIONAL JOURNAL OF REFRIGERATION 32 (2009) 349–358

available at www.sciencedirect.com

journal homepage: www.elsevier.com/locate/ijrefrig

Modeling the forced-air cooling process of fresh strawberry packages, Part II: Experimental validation of the flow model

*M.J. Ferrua, R.P. Singh**

Department of Biological and Agricultural Engineering, University of California at Davis, One Shields Avenue, Davis, CA 95616, United States

ARTICLE INFO

Article history:
Received 18 January 2008
Received in revised form
24 April 2008
Accepted 28 April 2008
Published online 10 May 2008

Keywords:
Strawberry
Post-harvest processing
Cooling
Packaging
Pallet
Experiment
Comparison
Simulation

ABSTRACT

The aim of this study was to validate a previously developed mathematical model for predicting the airflow behavior within individual packages of strawberries (clamshells) during forced-air cooling applications. The model was validated by using a non-intrusive flow measurement technique (PIV). The use of PIV required the development of a simplified transparent system that reproduces the packaging structure of typical retail clamshells. The validation was achieved by comparing the velocity field predicted by the model within this system against experimental data. The model not only predicted the main flow features, but also the location of steep acceleration within the packed structure voids. This work shows that, assuming that the momentum transport can be decoupled from the transport of energy and mass during forced-air cooling applications, the steady-state Navier–Stokes equations can accurately predict the airflow within individual clamshells of strawberries.

Modélisation du processus de refroidissement par air forcé des fraises fraîches emballées. Partie II : validation expérimentale du modèle de l'écoulement

Mots clés : Fraise ; Traitement après récolte ; Refroidissement ; Emballage ; Palette ; Expérimentation ; Comparaison ; Simulation

1. Introduction

Ferrua and Singh (Ferrua and Singh, 2009) presented a mathematical model for predicting the local airflow behavior and cooling rate of packed strawberries during a typical forced-air cooling application. The model assumed that the complex interaction of transport phenomena that occurs during the

* *Corresponding author*. Tel.: +1 530 752 0811; fax: +1 530 752 2640.
E-mail address: rpsingh@ucdavis.edu (R.P. Singh).
0140-7007/$ – see front matter
doi:10.1016/j.ijrefrig.2008.04.009

Nomenclature

A	surface area, m^2
d	characteristic dimension, m
$\dot{M}$	mass flow rate, $kg\,s^{-1}$
P	static pressure, $N\,m^{-2}$
Re_p	Reynolds number based on particle diameter and upstream velocity
u_i	velocity component in x_i direction, $m\,s^{-1}$
v	2D velocity, $m\,s^{-1}$
V_{avg}	average velocity within the experimental plane under study
x_i	Cartesian tensor notation of the spatial coordinates
x, y, z	spatial coordinates, m

Greek symbols

μ	dynamic viscosity, $kg\,m^{-1}\,s^{-1}$
υ	kinematic viscosity, $m^2\,s^{-1}$
ρ	density, $kg\,m^{-3}$

Subindexes

a	dry air
s	strawberry

cooling process can be modeled by decoupling the momentum transport from the transport of energy and mass.

The airflow that develops inside the package system was modeled as a steady, laminar and incompressible fluid flow of dry air. The thermophysical properties of the air were assumed constant and equal to those of dry air at the temperature of the air forced into the system. By using a computational fluid dynamics solver the flow model was used to predict the airflow that develops within one of the most common package systems used by the strawberry industry. The numerical results showed that the heterogeneity of the cooling process is significantly affected by the local airflow behavior, which in turn is largely influenced by the packaging structure and the shape and vent design of individual packages (clamshells) and trays. Due to differences in the shape of clamshells and trays, $75 \pm 2\%$ of the total amount of airflow bypassed the clamshells (Ferrua and Singh, 2009). Furthermore, $46 \pm 5\%$ of the total mass flow rate forced through individual clamshells bypassed the strawberries by the combined effect of an open headspace within clamshells and the clamshell vent design (Ferrua and Singh, 2009).

Until now, the validation of mathematical models used to predict the airflow behavior within horticultural packages has been limited to the use of intrusive pointwise velocity measurements or indirect techniques (such as measurements of pressure drop or product temperature). Ferrua and Singh (2008) demonstrated the possibility of using a non-intrusive flow measurement technique, called particle image velocimetry (PIV), to trace the flow field within complex packed structures. However, they also found that in order to use 2D PIV diagnosis as a validation tool of a 3D flow, a series of experimental limitations should be considered. In particular, PIV measurements should be performed within a transparent setup of the package system, which involved not only a transparent model of the solid packed structure, but also a perfect refractive index matching between the transparent material (fused silica) and the working fluid (mineral oil mixture). In addition, the use of a 2D PIV system limited the possibility of accurately measuring the highly 3D flow that develops within the strawberry package system. Although these experimental constraints prevented the use of PIV to trace the flow model within the entire package system modeled in Part I, 2D PIV diagnosis can be used to trace the flow within a simplified package system of an individual clamshell. By considering that more critical airflow features occur within the clamshells, and the lack of fundamental information to justify the laminar regime assumed by the model within them (Ferrua and Singh, 2009), the use of PIV to trace the flow field even within this simplified package system would provide useful information to analyze the suitability of the model to a great extent.

The objective of the present study was to prove the capability of the model to predict the flow field that develops within a simplified system of an individual strawberry clamshell, during a typical forced-air cooling application.

2. Materials and methods

2.1. Experimental design of the transparent packed structure

Ferrua and Singh (2008) developed a simplified transparent model of the strawberry clamshell used in Part I. This simplified setup modeled the strawberries as spheres (approximation that has been customarily done to perform experimental and numerical studies of horticultural products such as strawberries and potatoes (Émond et al., 1996; van der Sman, 2002; Alvarez and Flick, 1999a,b)), and reproduced the geometric proportions, porosity, headspace dimension and venting design of the clamshell. However, the highly 3D flow that develops close to the headspace within the model limited the accuracy of the PIV measurements in that region.

In order to overcome this problem and use a 2D PIV system, a new simplified design of the package structure within clamshells was pursued. In particular, the transparent package system to be used should support the development of a 3D flow whose x, y and z velocity components are of the same order of magnitude. This requirement allowed accurate measurement of 2D velocity fields within the system, by carefully designing the PIV acquisition parameters.

The final system consisted of a symmetrical packed structure of 35 spheres 6.6×10^{-3} m in diameter with a maximum variation of 7×10^{-9} m (Fig. 1). By arranging the spheres in a cubic centered distribution, the packaging factor of the simplified package system (51%) closely resembled the packaging factor of the retail strawberry clamshells (54%).